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Diffuse sediment in Waikato waterways – sources, practices for reduction, and policy options

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Executive summary

Sediment loss is driven mainly by precipitation, with geology and land use/ land cover explaining much of the residual difference between sites. Climate change is expected to increase sediment loss.

Pasture slopes generate 2-5 times more sediment than comparable forestry slopes, except during forestry harvest periods. Harvest causes a rapid peak in sediment generation, but with good practice in harvesting, sediment loss can return to pre-harvest levels within 1-2 years. A twelve-year monitoring study of paired pine and pasture catchments, including the harvest period, showed that the suspended sediment yield from pasture exceed that of the pine catchment by 1.5 times (Eyles and Fahey 2006). This figure would be higher over the whole forestry rotation as pasture yields would exceed forestry yields in all years except the immediate post-harvest period.

Sediment loss is highest when landslides occur near waterways. In forestry catchments, slips and side-cast associated with tracking are important for sediment generation. In all catchments, valley floors are storage areas for historic landslide sediment, making riparian management an important determinant of actual sediment reaching waterways. Streambanks contribute significant quantities of sediment in both forested and pastoral catchments, and can dominate in years and sites without major landslide activity. Slopewash from forestry and pasture contributes a lesser quantity of sediment. However surface run-off from intensive pastoral land carries a range of contaminants to waterways including nutrients, faecal microbes and fine sediment.

Mitigation practices are well studied and there is a long history of promoting these through catchment soil conservation and riparian schemes.

Establishing forest cover can reduce the risk of landslides by an order of magnitude on the most erosion-prone slopes, once canopy closure is achieved.

Space-planted poles are effective if susceptible land is planted before erosion events occur. In order to be effective, poles must be planted in appropriate numbers and positions on the slope, and maintained in good health and correct densities.

Riparian areas with rough vegetation can help to slow run-off and allow large particles to settle out, and may even result in total infiltration effectively removing sediment. Where grassy riparian filters intercept low to moderate sheet-flow, sediment removal efficiency may reach 70-90%. The filtering effectiveness of grass buffer strips reduces in steeper terrain and where overland flow is channelised. Buffers are ineffective where run-off occurs mainly as sub-surface flow or through tile drains. However, stock exclusion in itself has benefit in protecting stream banks and preventing disturbance of bed sediment. Alternatively, trees planted on banks can reduce erosion even in the absence of riparian fencing. If riparian trees cause high levels of shading of grassy banks, there may be an initial release of stored sediment as the channel widens; this effect may last several decades. Riparian management is also important during forestry harvest, as part of a range of forestry practices to control generation and movement of sediment.

Within pastoral systems, higher risk practices for sediment loss include deer grazing (where deer wallows are connected to waterways) and grazed winter fodder crops.

Wet conditions can result in both greater run-off volumes and higher sediment concentrations, which combine to increase the load of sediment exported to waterways. Grazing management to minimise bare ground and treading damage can decrease the risk of pollutants reaching waterways from run-off. In any landscape, critical source areas (often near waterways) that contribute sediment can be identified. Careful grazing management and attenuation measures (e.g. silt traps or buffer strips) can be targeted to these areas for greatest effect.

Comprehensive catchment work has been able to achieve a 40% reduction in sediment in the Waitomo Stream. Significant changes also occurred after catchment work at Whatawhata and Waiokura (Taranaki). However, none of these streams reached the clarity required for contact recreation standards. This standard will be difficult to achieve in many Waikato waterways.

There are economic and production impacts from sediment loss and from land uses associated with high sediment loss risk. Erosion reduces soil productivity, and production on landslide sites is slow to recover. Retiring erosion-prone areas can have practical and economic benefits on many properties. Inputs can be focused on the better classes of land, and fences can be used to improve stock flow and for internal subdivision to enhance pasture utilisation. Riparian fences can also prevent stock losses in gullies or swamps. Economic barriers include the initial cost of fencing, installing alternative stock water and any additional planting. Practical issues include weed control, flood damage to riparian fences, and fencing in steep country or where waterways meander. The economics of poplar planting depend on high-risk sites being targeted and trees being established before slips occur. In this case, the savings from preventing slips can offset the cost of the planting and the depressed pasture production from shading. Pugging and treading, which compact the soil and expose the surface to erosion, also result in depressed production, particularly during the following season. It is therefore a win-win option to carry suitable classes of stock matched to land types and season, and to manage grazing to prevent pugging.

Where there are benefits to the farm, policy approaches based on education and advice (including farm planning) can see greater uptake of these practices. Incentives help to overcome the initial barrier of capital costs. Such incentives have been a strong policy plank of regional councils under catchment schemes and targeted rating systems. Incentives for tree establishment under climate change policy have proven popular where they have not been tied to carbon trading (e.g. the Afforestation Grants Scheme), but so far there has been limited uptake of 'carbon farming' where the farmer takes on the liability for surrendering carbon credits upon harvest. Planting tree cover for carbon credits may prove economically attractive in the future (for example, as agricultural emissions come under the trading regime, or if carbon prices rise).

Apart from consents associated with earthworks and forestry operations, sediment has not generally been managed through regulatory means. Several councils are now considering stock exclusion rules, and there is also a rule in place in Gisborne District requiring effective tree cover on the most erodible classes of land. This latter rule applies only as long as subsidies from central government continue to be available. Nutrient capping rules which include phosphorus (such as Rule 11 for the Rotorua lakes and the One Plan for Horizons) may prompt some activities (such as riparian management) that also have a sediment reduction benefit.

1 Introduction

This report presents information on land use practices giving rise to sediment loss to waterways. The emphasis is on diffuse sources of sediment, rather than consented activities.

Sediment loss is of concern in waterways due to

- Water quality impacts on in-stream aquatic ecosystems
- Water quality impacts on human uses and values of the water
- Downstream sedimentation, flow changes, and flooding which affect both people and the aquatic ecology.

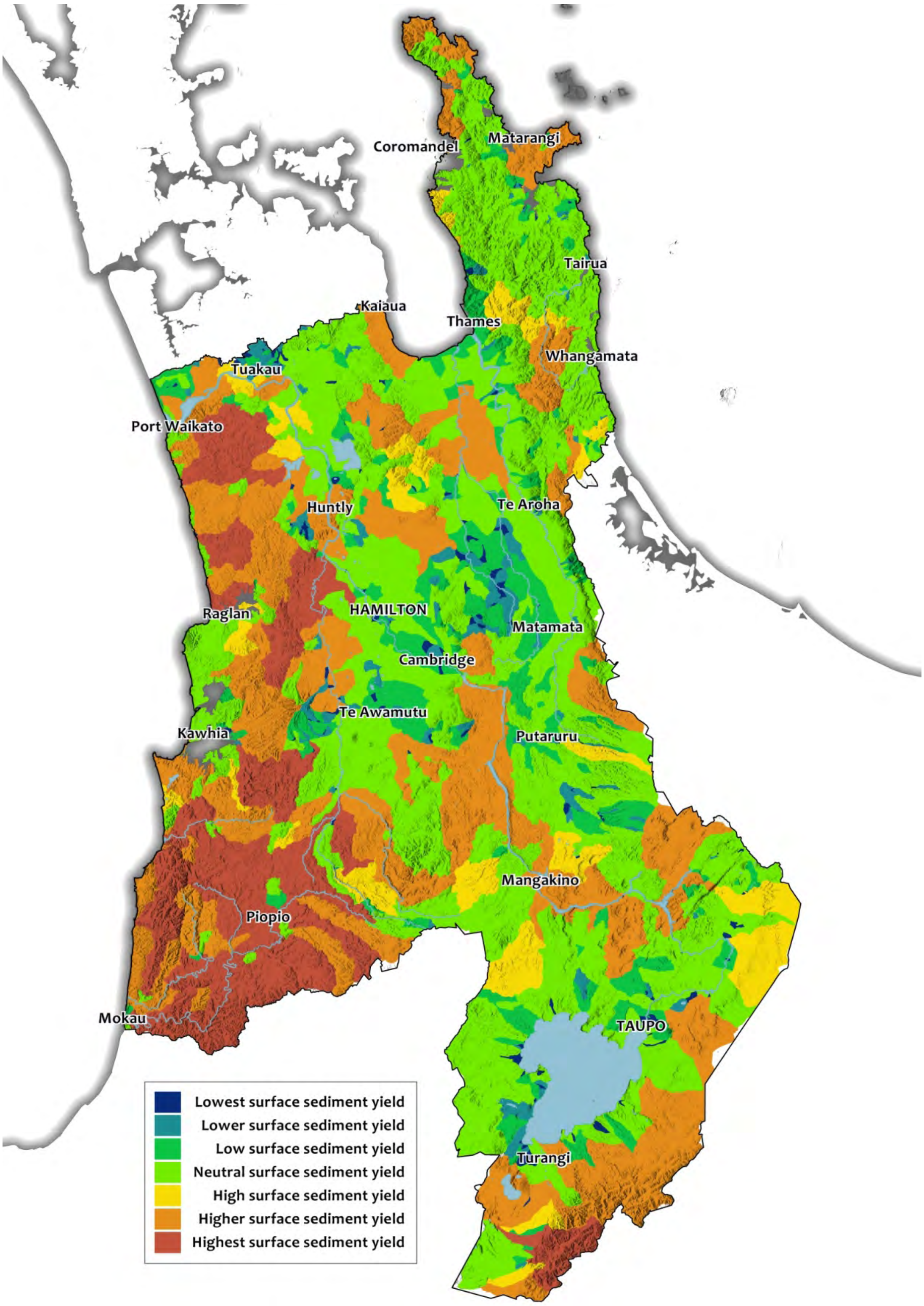
There are also on-site issues when soil erosion occurs such as diminished productive capacity, infrastructure damage from slips and landscape effects.

This report reviews published information on sediment sources, and on the effectiveness, economic and practical impacts of land management practices to reduce sediment in waterways. Wider issues such as the water yield effects or social impacts of large-scale afforestation are beyond the scope of this study.

Land use and sediment were reviewed in an earlier report on hill country resource management issues for Environment Waikato (Ritchie 2000). MAF has since published a comprehensive review of hill country erosion, information resources and social learning about this issue (Basher et al. 2008). The main findings of those earlier reports relating to sediment loss are included in this current review, supplemented by recent research.

2 Factors determining sediment loss

Sediment loss may refer to sediment generation or mobilisation (which occurs whenever soil is eroded), and sediment yield (which is the amount of sediment that actually reaches a waterway). Differences in sediment yield, both between and within catchments, are determined by many factors. These include precipitation, topography, geology and soil type, vegetation, infiltration/ run-off patterns, land cover, land management and grazing, and tectonic activity (after Hicks and Griffiths 1992, DeRose 1998). Precipitation appears to be the dominant factor (Griffiths 1982), with geology and land use explaining much of the residual variation. A study of specific suspended sediment yields at 23 sites in the Waikato region showed that the variation was mainly due to runoff/rainfall, mean slope and land cover (Hoyle et al. 2011). The tendency for forest cover to be on steeper, wetter terrain and for pasture to be on flatter, drier country serves to reduce the range of sediment yields over the region. Figure 1 shows sediment yield across the region derived using a NIWA model (see Hicks et al. 2003).



Source: After Environment Waikato 2007a:30

Figure 1: Sediment yield data derived using the NIWA Suspended Sediment Yield Model

Unlike nutrient loss pathways, sediment transport occurs almost entirely as overland flow. In one study, sub-surface flow accounted for less than 1% of total sediment loss (McDowell and Houlbrooke 2008). The exception is where preferential flow through large soil pores or cracks carries sediment to sub-surface drains (McDowell and Wilcock 2004).

The intensity of rainfall events has a large effect on sediment loss. In small rainfall events, run-off may only travel a few metres, before particles resettle without reaching waterways (McColl and Gibson 1979). Heavier rainfall increases sediment generation and sediment transport. In a Whatawhata study, Quinn and Stroud (2002) found that a pasture catchment exported three times more sediment in a wet year than a dry year. Severe slipping on hill country land is often associated with intense, localised climatic events, making it difficult to predict where and when it will occur (East Cape Catchment Board 1986). In a study of forested and pasture catchments in Hawke's Bay, Fahey and Marden (2000) estimated that between a quarter and a third of the total suspended sediment yield over 29 months was contributed by one storm. Historical studies of sediment deposition in river valley bottoms indicate greater erosion and sedimentation during eras of warm, stormy conditions (Hicks and Griffiths, 1992).

This raises concern over the implications of climate change. Considering this issue, Hicks et al. (2001) estimated that a steady increase of annual rainfall by 12% over 35 years would increase sediment yields averaged over that period by 14%. Estimates across the Waikato Region of mean annual precipitation change (Li et al. 2010) show a highly variable picture both annually and seasonally depending on different models, ranging between a decrease of 4.58% and an increase of 7.19% by 2050. The expected increase in precipitation is highest in the southern parts of the region around the Waitomo, Otorohanga and Taupo districts, (all of which have erosion-prone soils). Changes in extreme daily precipitation (storm events) are highest in Hauraki, Thames-Coromandel and parts of Franklin. Peak streamflows as a result of storms are also expected to occur more frequently. A study of sediment in Tauranga Harbour (Hume et al. 2009) predicted that sediment load to the harbour could be 42.8% higher by 2051, representing an increase of 19.8% when averaged over the intervening years.

In addition to heavy rainfall, land instability is also associated with tectonic activity (O'Loughlin 2005). While earthquakes are a significant driver for deep-seated earth movement, they are a much lower frequency event than storms (Hancox et al. 1997).

The underlying rock type is important, as weathered soft rocks have relatively low shear strength, and therefore the slope angle which they can support without sliding is much lower than that of harder rocks. (Note, though, that unweathered soft rock with closed joints can support high, steep relief in parts of the hill country (Crozier et al. 1982) - the mudstone of the Mahoenui/ Awakino area is one example in this region.) Low slope angles imply a less free-draining relief which can retain water, leading to both deep-seated and surface landslides. Water retention is also increased by the presence of some types of clay in weathered rocks which expand and take up water, resulting in earthflows and mudflows (ibid). By contrast high infiltration and lower run-off in pumice soils acts to decrease sediment yield (Table 1).

Table 1: Effect of soil type on specific yields of sediment in different parts of the Waikato catchment (Hicks and Hill 2010).

Region of the Waikato catchment	**Average specific yields of sediment (t/km^2/yr)**
Taupo rhyolite country	69
Taupo pumice basins	34
Hamilton basins	58
Upper Waipa above Otewa – Tertiary marine sediments, ignimbrite and greywacke	291

Forest cover enhances slope stability through its effect on both hydrology and soil strength. Trees intercept rainfall and also reduce rainfall impact on the soil. In summer especially, trees draw water from the soil depths and release it to the atmosphere through transpiration. This helps to reduce slumping, slipping and earth flows. Tree roots are deeper and stronger than pasture roots and therefore bind and anchor greater depths of soil. This effect depends on species, age and spacing of trees, but can be in the range of a 60-300% difference between trees and grass (Crozier et al. 1982; see below: Sediment losses under different land uses). Slips which occur some years after deforestation are often attributed to decay and loss of strength in root networks of a former forest cover (Glade 2003). Finally, forest removal can reduce the organic matter in the topsoil and expose the soil to cracking. Soil cracks may facilitate the entry of water and increase the risk of slips under pasture (Quinn and Stroud 2002).

The effect of forest cover removal is shown in sediment core studies in Coromandel estuaries comparing sediment accumulation in pre- and post-European periods. These studies show marked (10- to 50-fold) increases after European settlement (Environment Waikato 2008). Much of this is attributed to shallow landslides after clearing tree cover.

Four physical factors have therefore been recognised in shallow landsliding: slope angle, storm rainfall, soil strength and vegetation cover. A model designed to predict landslide risk in Manawatu-Wanganui assigned high susceptibility to steep land not protected by woody vegetation (Dymond et al. 2006). The model assumed all land that was not steep was not susceptible to landslide, which was proven false - in the 2004 storms, only 58% of erosion scars occurred on hillslides classified as susceptible under this model. The authors concluded that all sandstone and mudstone hill country, no matter what the slope, was susceptible to landsliding, and that moderate slopes also required attention to soil conservation. The model also assumed that land under woody vegetation was less susceptible to landslide, and this was borne out.

Vegetation cover is only one factor influencing soil erosion, but it is the factor readily influenced by management. Dymond et al. concluded that forest cover generally reduces landsliding probability by 90%, and scrub reduces it by 80%. This information was then incorporated into a new model based on erosion terrain, annual rainfall and vegetation cover (Dymond et al. 2010). This can be used to prioritise soil conservation effort or predict land use effects over time.

On a site-by-site basis, a further assessment can also be made to determine if a slope is connected or disconnected to a waterway. 'Disconnected' is defined by having a sediment deposition zone of at least 30m of low slope between the erodible land and the waterway (ibid).

Channel and flood-plain environments tend to moderate or buffer sediment transfer, and can store considerable amounts of sediment (DeRose 1998). Sediment budgets at Lake Tutira, where landsliding was the dominant erosion process, showed that 43% of sediment remained in temporary storage (Page et al.; cited in DeRose 1998).

Stock type may have an effect on sediment disturbance and on soil compaction, influencing overland flow rates and overall sediment yield. For example, McDowell and Wilcock (2008) analysed 38 reported studies of contaminant loads from different stock types and found that deer produced significantly higher sediment loads to waterways than other stock types. No other significant differences were found, but mean loads were higher in mixed stock type than in sheep, which had higher mean loads than in dairy studies (see Table 2B). In intensive grazing, cattle impacts may be higher. McDowell and Houlbrooke (2008) found significantly more overland flow was produced from forage crops grazed by cattle (45mm) than those grazed by sheep (25mm). Stock may also exhibit different behaviours around stream channels, with cattle more inclined to enter water and cause bank collapse than sheep.

However, as sheep stocking rates rise, water quality impacts also increase. For example Buck et al. (2004) sampled water from two adjacent Otago catchments of similar size, one with 100 sheep and one with 500 sheep grazing. They found the catchment with the higher stocking rate had 10 times higher turbidity than the lower-stocked catchment. Stocking rate thresholds for requiring stock exclusion were considered by McKergow and Hudson (2007) for Environment Canterbury. Based on a range of factors, including erosion damage, they recommended that below an average stocking rate of 4 stock units/ha livestock access (cattle and sheep) could be a permitted activity, but above 8 SU/ha it should be prohibited, with intermediate stocking rates discretionary.

Changes in catchment land use (vegetation clearance, soil compaction and drainage of wetlands) can have a combined impact on water infiltration and catchment storage. This affects the speed and quality of water run-off, which influences sediment transport. An assessment in the Upper Waikato showed that infiltration is an order of magnitude lower under pasture soils than under pine, due to stock trampling and use of machinery (Taylor et al. 2009). The resultant rise in run-off after pine-to-pasture conversion is expected to increase peak flows and erosion susceptibility.

2.1 Sediment losses under different land uses

Various studies have shown that catchments with forest cover produce 1.5 to 5 times less sediment that those under pasture, and this holds for both base flows and storm events. For example, Hicks (1990) compared storm sediment yields from twelve small catchments that were either in pasture or exotic forest, and found that pasture basins yielded 1.6 - 4.5 times more sediment than exotic forest basins. Table 2 shows some other comparative figures.

Table 2: Comparative sediment loss under different land uses

A. Comparative sediment yields from paired catchment studies	
Hill country (Whatawhata):	(Quinn and Stroud 2002)
Pasture	988 kg/ha/yr
Bush	320 kg/ha/yr
Approximate Ratio = 3.1:1	
Pumice soil (Estimated):	(Dons 1987)
Pasture	220 kg/ha/yr
Mature pines	40 kg/ha/yr
Approximate Ratio = 5.5:1	
Hawkes Bay (Estimate of total in 29 mths):	(Fahey and Marden 2000)
Pasture	1044 kg/ha
Mature pines	327 kg/ha
Approximate Ratio = 3.2:1	
Hawkes Bay (Storm yields measured concurrently):	(Fahey et al. 2003)
Pre-harvest period (9 storms over 29 mths)	
Pasture	212 kg/ha
Mature pines	76 kg/ha
Approximate Ratio = 2.8:1	
Logging period (10 storms over 2 years)	
Pasture	438 kg/ha
Forestry logging	844 kg/ha
Approximate Ratio = 1:1.9	
Post-harvest period (5 storms over 2 years)	
Pasture	1290 kg/ha
Forestry post-harvesting	1768 kg/ha
Approximate Ratio = 1:1.4	

B. Reported median sediment loss from 38 studies of different stock types (McDowell and Wilcock 2008)	
Deer	2034 kg/ha/yr
Mixed	1156 kg/ha/yr
Sheep	598 kg/ha/yr
Dairy	299 kg/ha/yr
Non-agricultural	174 kg/ha/yr
C. Comparative sediment data from some other situations	
Sediment mobilised from forestry tracks (SW Nelson)	3200 kg/ha/yr (Fahey and Coker 1989)
Sediment mobilised by forestry harvest (Whangapoua, Coromandel)	590-1160 kg/ha/yr (Phillips et al. 2005)
Market gardens catchment yield (Franklin)	490 kg/ha/yr (Hicks 1994)
Market garden paddock yield (Franklin)	7000-30000 kg/ha/yr (Basher and Ross 2002)
Sheetwash from sheep-grazed hillslopes (Tauwhare)	374 kg/ha/yr (Smith 1987)
Dairy pasture yield (Toenepi, Waikato)	38-142 kg/ha/yr (Wilcock et al. 2007)
Grazed dairy winter forage crop (Otago)	969-1499 kg/ha/yr (McDowell 2006)
Tile drainage (Tokomaru silt loam)	90-1000 kg/ha/yr (Sharpley and Syers 1979)
Sediment yield from a 1-in-10 year storm without landslide activity (Waitetuna)	300 kg/ha (McKergow et al. 2010)
Estimated sediment eroded from a hill site affected by a slip (Whatawhata)	41300 kg/ha over 10 months (Quinn and Stroud 2002)
Highest specific yield ever recorded in North Island (Waiapu, East Coast)	199700 kg/ha/yr (Griffiths 1982)

The differing sediment exports under various land uses are reflected in water quality results. Smith et al. (1993) found that base flows in streams draining agricultural catchments in the Wellington region were four times more turbid than those in native bush catchments. In a national review of monitoring data from lowland waters, Larned et al. (2004) found that the median clarity of streams draining pastoral and urban land cover was 40-70% lower than that of streams in native and plantation forest classes. Water quality in plantation forests was not statistically different from that in native forest.

While Larned et al.'s (2004) work shows a broad pattern relating water quality to land use, smaller-scale studies suggest that at times, water quality is affected by local events. In particular, mass movements (slips) can have a dramatic effect on sediment yields (see Sediment sources within a catchment, below). For example, at Whatawhata, a mixed land use catchment (pasture and forest) with a major earth-flow slip in the pasture section exported eight times more sediment than a pasture catchment unaffected by mass movements (Quinn and Stroud 2002). By contrast, in the nearby catchment of Waitetuna, streambank erosion was attributed as the main source of sediment during a 1-in-10 year storm event and landslides were an insignificant source. One tributary stream with an actively eroding channel contributed almost half the total catchment yield (McKergow et al. 2010). In another storm the following year in the same area, landslides were more important, leading these authors to conclude that the timing and intensity of rainfall is important, in addition to total depth of precipitation in a storm event.

Other water quality effects may arise from the particular site history and conditions, especially changes in catchment land use. Quinn et al. (1997) studied sediment in streams under various land uses at Whatawhata. They found that streams in pasture and in 15-year old pine forest had similar amounts of suspended solids and fine sediment stored in the streambed, three times more than native forest streams. In further studies, Quinn and Stroud (2002) found that pine streams at Whatawhata had the lowest visual clarity, with turbidity and suspended sediment typically 2- to 4-fold higher than the pasture and native streams. This was attributed to erosion of sediment deposits built up during the pasture phase, with bank sediment previously held by grass being released as the stream channel widened under a shady forest regime. This effect was observed even 28 years after pine planting. Further studies at Whatawhata (Hughes et al. 2010) show that in the sub-catchment retired from pasture and planted in pines stream clarity has not increased, whereas improvement is occurring in a pasture stream where cattle were excluded from riparian areas and poplars planted. The timing of sediment and flood peaks in this study indicates that the sediment from the pine forest may originate from stream banks, whereas the pasture sediment may be transported from hillslopes. This suggests that excluding heavy stock from the riparian areas has had a beneficial effect, whereas full scale afforestation has not yet improved clarity at Whatawhata. In nearby Waitetuna, pine forest exported more sediment in a storm event than native forest, and yields from pasture were much lower (McKergow et al. 2010). The low yield from the pasture catchment compared with the forested catchments even though soils, slopes and rainfall were comparable was attributed to the presence of numerous ponds and wetlands in the pasture catchment. Similarly, in a central North Island site, a native forest stream channel exported more sediment than either a pasture or pine stream (Dons 1987). This was attributed to greater shading in the native forest stream. In this case, stream channel erosion was the dominant sediment source due to high infiltration in the pumice soils of the catchments.

These studies suggest that while in general, forest cover yields less sediment than pasture cover, there will be situations where stream channel shading increases sediment loss from stored streambank sources, particularly in the transition from pasture back into tree cover, an effect which may last over several decades. There may also be cases where sediment generated in pasture catchments is trapped in catchment ponds or wetlands before it reaches streams, reducing pasture catchment yields.

Forestry activity has high yields of sediment in certain phases of the production cycle, notably tracking and harvesting. Forestry harvest can increase sediment inputs to streams in several ways (Harding et al. 2000):

- Tracks and roads can contribute sediment
- Exposed slopes are vulnerable to erosion
- Stream channels may be subjected to additional run-off post-harvest and release sediment by scour
- Unstable debris dams in streams can be mobilised in floods, eroding streambanks.

The scale and duration of forestry effects on sediment yields depend on mitigation practices such as riparian management, sediment retention, and techniques for harvest, (including managing landing areas), tracking and revegetation.

While forestry can contribute significant amounts of sediment at particular stages of the production cycle, the effects tend to diminish rapidly. A Nelson study found that when road construction was at its peak, the sediment mobilisation rate was about 3200 kg/ha/yr; this subsequently decreased to around 10% of this figure (Fahey and Coker 1989). Not all of this sediment was predicted to reach a stream. Similarly, Marden et al. (2007) studied slopewash in pumice terrain and found sites with deep disturbance generated 3800 kg/ha, but by 21 months after harvest when groundcover occupied 80% of plot area, sediment generation had declined to almost zero.

Sediment yields from plantation forestry and pastoral farming were compared by Fahey et al. (2003) over a seven-year period in the Hawke's Bay (see Table 2). Sediment yields were higher from pasture in the pre-harvest period but this situation was reversed during and just after harvest. The increase in sediment yields during harvesting was thought to come predominantly from road sidecast, landslides and channel bed scouring (in decreasing order of importance). Slope disturbance was minimal and estimated to contribute only 1% of sediment lost, but the extent of ground disturbance during harvest at this site was considered to be at the lower range of common practice. The reduction in sediment yield after harvesting was attributed as much to a decline in harvest-related activities as to a steadily increasing grass cover across the disturbed sites, which effectively halted slopewash losses within a year. These authors suggested that weather conditions in the post-harvesting recovery period would have a strong bearing on sediment yields until canopy closure occurred. They noted that the post-harvest sediment yield increase in their study was low compared with a Northland study by Hicks and Harmsworth (1989), who found that landing construction and road upgrading before harvesting caused storm yields to rise to 40 times more than yields from similar storms before harvesting. Fahey et al. (2003) suggested that the difference in the two studies could be due to weather conditions, harvest practices or both.

The Hawkes Bay study continued over 11 years, with several years' further monitoring of the post-harvest period (Fahey and Marden 2006). In the first year of the post-harvesting (recovery) period (2000), the suspended sediment yield for the forest catchment was still almost twice that from the pasture, but in the next year (2001) it had declined to the point that the pasture site was generating 4 times as much, a situation not seen since 1995, suggesting that sediment yields had returned to pre-harvest levels. This situation was repeated each year between 2002 and 2005. The study's main conclusions were that pasture generated 3 times more sediment than forest before harvest, and half as much as forestry after harvest. For the first year after harvesting, suspended sediment yields exceed those from comparable catchments in pasture, but with the rapid implementation of management practices such as replanting and over-sowing, sediment yields from harvested areas can be back to pre-harvest levels within 2–3 years. Over the 12-year period of record, the total suspended sediment yield from the pasture catchment was over one and-a-half times that for the catchment going through the forest rotation (Eyles and Fahey 2006). This figure would be higher over the whole forest rotation as pasture would yield more than forest over the remaining years.

In modelling Tauranga harbour, Hume et al. (2009) found that pasture covered 33.7% of the catchment but was predicted to make the largest contribution to sediment load (62.5%). Bush, scrub and native forest covered 43.9% of the catchment and covered the steeper and higher-rainfall parts of the catchment, but only 27.3% of total sediment load was predicted to come from these land uses.

In recent years, work has been done on bio-markers of sediment that give an indication of the land use from which the sediment sample originated. The method uses analysis of naturally occurring fatty acids derived from plants to link transported sediments back to areas in the catchment under specific vegetation types (Gibbs 2008). This has been used on sediment in the Whangamarino wetland, Mahurangi and some Coromandel harbours, and more recently in the Waitetuna valley (results not yet available).

These and other studies (Gibbs 2006; Swales et al. 2005; Gibbs and Bremner 2007) show that sedimentation effects are influenced by site-specific wave action and transport patterns within an estuary, the location of catchment land use activity, and the timing of any storm events with respect to catchment activity such as forest harvesting.

A Whangapoua study (Gibbs 2006) found pastoral soils contributed only a minor proportion (10%) to estuarine sediment, even though 21% of catchment land area was pastoral. This was attributed to the pastoral area mainly occupying the gentler terrain. In Gibbs' study, pine forest contributed 54-75% of the sediment but only occupied 50% of the catchment area. Land around one of the estuarine arms was being actively logged at the time of sampling, and it was concluded that sediment from that activity dispersed across the harbour. By contrast, another study in the Whangapoua harbour (Roddy 2010) used a different sediment 'fingerprinting' technique and found less estuarine sediment originating from pine forest, and more originating from native forest, mostly situated on steep land subject to landsliding. Roddy found that native forest (21% of the catchment area) contributed 62 ± 17% of estuary sediment, with 23 ± 12% from the exotic forest (61% of the catchment area), and 15 **±** 10% from the agricultural land (18% of the catchment area). Roddy suggested that the difference between his findings and those of Gibbs could be because Gibbs' technique was based on samples from only the top 2cm of soil, which would therefore only trace surface erosion. Roddy's work suggested that the great majority of the sediment in the estuary originated from subsurface sources, with only ~8% from surface soils. He also noted several heavy rainfall events in the years leading up to his sampling, which would have generated landsliding even on land protected by native forest.

In Mahurangi, Gibbs (2008) found that the major sources of sediment were pine forest (46%), pasture (19%), and native forest soil (14%). As these three main land use types in the catchment occupied 16, 64 and 18% of the area respectively, the contribution of pine forest soil in the river delta sediments was almost three times greater than its proportion as a land use in the catchment. However, mature undisturbed pine forest was found to contribute only very small proportions of sediment (along with native forest with kauri and flat farmland). The pine sediment appeared to come from two distinct areas of recently harvested forest.

In the Whangamarino wetland study (Gibbs 2009), the three major sediment sources reaching the wetland were the water flowing from Lake Waikare (during flood events), steep headwater pasture in the Hapuakohe range, and to a much lesser extent run-off from lowland alluvial plains, including cropping areas.

While pine harvest has a marked impact on sediment contribution, Gibbs (2008) suggested that similar effects could arise from other land use practices producing large areas of bare soil for extended periods such as tillage, road cuttings, excavations and slips. Uncontrolled earthworks can have a high sediment yield, but controls on consented earthworks and the small area they occupy mean that overall they were predicted by modelling to be only small contributor (~ 0.5%) to total sediment load in Tauranga harbour (Hume et al. 2009). Similarly, bare earth associated with cropland makes only a small contribution to sediment load in Tauranga, as the areas are small. In the Whangamarino study only ~5% of sediment deposited on the sampled wetland surfaces was attributed to alluvial plain soils used for cropping or maize (Gibbs 2009).

This range of sediment marker studies indicates that the impact of land use at a landscape scale depends on topography, catchment hydrology and timing of activity such as forestry harvest. The contrasting findings in Whangapoua also suggest that different sediment ‘fingerprinting’ techniques may give varying results.

Gibbs (2008) noted that in an estuarine environment, the benthic community may adapt to chronic exposure to low levels of suspended sediment from farmed land, but suffer catastrophic effects from acute events during pine harvest. In Coromandel estuaries, it has been suggested that slip material stored in flood plains can continue to wash into the estuary and exacerbate chronic effects on benthic marine life for several years (Gibbs and Bremner 2007; Gibbs 2006).

3 Sediment sources within a catchment

Reviews show very large ranges in reported losses of sediment within any given land use (McDowell and Wilcock 2008). This is due to differences in local soil, slope and climate, together with management factors (e.g. erosion protection work, riparian management).

Shallow landslides are the most common form of erosion in hill country terrain; earthflows, slumps and gully erosion are less extensive and frequent (Basher et al. 2008). Studies at Whatawhata indicate that over the course of time, mass movements (landslides, earthflows and slumps) have been the principle generator of sediment from pastoral hill country there, prior to transportation effects (see Table 3).

Table 3: Sediment sources for the Mangaotama catchment (Whatawhata)

“Order of magnitude” estimates for principal erosion sources, prior to floodplain and channel storage effects. These are estimates of the overall contribution over time; the relative importance of landslides as a sediment source has declined since 1943	
Landslides	15400 kg/ha/yr
Streambanks	2200 kg/ha/yr
Sheetwash	uncertain (but at least 400 kg/ha/yr)

(Source: DeRose 1998:24, 28, 30)

DeRose's figures in the table above are averaged over a long time period. There is evidence both from his study, and from previous work in Taranaki (DeRose et al. 1995) and Wairarapa (Trustrum et al. 1984) that the majority of large mass movements occur in the years immediately after clearance of the original forest cover, and that rates then decline substantially. Glade (2003) reviewed studies from a number of North Island sites and concluded that following deforestation, sedimentation rates increased 7-18 times. Other studies have shown that sediment yields may surge up to 100-fold in the years following forest clearing (see Hicks and Griffiths 1992). While the resulting sediment is still being reworked from valley floors and streambanks, the slips that are occurring now on Whatawhata hillsides yield up to 10 times less sediment than would have been the case, for example, before 1943 (Table 4).

Table 4: Current and historical sediment yield from mass movements at Whatawhata

Historical (pre-1943) rate of sediment yield	15400 kg/ha/yr
Current rate of sediment yield from landslides	1100 kg/ha/yr*
Rates of deposition of sediment from mass movements (storage in the high terrace):	
Historical (pre-1943) rate of accumulation from deposition	1700 kg/ha/yr
Current rate of accumulation from deposition	80 kg/ha/yr**
*based on June 1998 storm yields of 45000 kg/ha, (assumed to be a 40-year event).	
** based on June 1998 storm deposition averaging 13mm on the high terrace	

(Source: DeRose 1998:20; 28)

In a catchment study in Whangapoua, Roddy (2010) used sediment 'fingerprinting' to trace the origin of sediment in the estuary. He estimated that in terms of the erosion process, the main source was from subsoil (79% ± 6%), then streambanks (13% ± 5%), then surface soils (8% ± 6%).

Large storms, or long wet periods drive mass movement (landslides, earthflows and slumps). Therefore, high-magnitude, low-frequency storm events create high sediment generation peaks. During lower-magnitude, high-frequency storms fluvial erosion processes (gullying, bank and channel erosion) may dominate sediment budgets (Basher et al. 2008). During Cyclone Bola, Page et al. (1994) estimated that landslides contributed 89% of the sediment in the Tutira catchment, whereas shallow landslides were estimated to contribute 64% of the sediment load at the mouth of the Waipaoa catchment (Page et al. 1999). The latter study also estimated that over the long term, landslides would contribute only 10-19% of the suspended sediment yield in the Waipaoa. This is because other processes, such as gully and streambank erosion produce significant sediment during the frequent storms that are too small to generate landslides, and contribute sediment directly to a waterway. By contrast, 50% of landslide material may be retained in the landscape (ibid).

Landslides are also less significant outside hill country areas, meaning streambanks and topsoil run-off are likely to be the dominant sources of sediment in dairy catchments. In Bog Burn (Southland), McDowell and Wilcock (2004) identified the likely sources of sediment in the stream and concluded that the dominant source of sediment was topsoil entering the stream through tile drains, and to a lesser extent overland flow. This catchment is extensively artificially drained, and has relatively high rates of streambank fencing and a lower rainfall than Waiokura (Taranaki), where McDowell and Wilcock (2007) found that streambank sources were more important. Their analysis in Waiokura suggested a seasonal difference in source dominance. While topsoil was the dominant source of suspended sediment in summer and to a lesser degree in autumn, bank sediment was minimal in summer and autumn but a greater contributor in winter and spring (Table 5). This was attributed to scouring of steep streambanks during winter and spring rainfall.

Table 5: Range of probable solutions by season for the percentage of source materials in trapped sediments from the Waiokura stream

Source	Summer	Autumn	Winter	Spring
	%			
Topsoil	83–100	0–93	0–73	0–84
Subsoil	0–5	0–32	0–50	0–40
Bed sediment	0–4	0–23	0–43	0–30
Bank sediment	0–17	0–1	23–96	21–100

(Source: McDowell and Wilcock 2007:546)

Overseas research has attributed variable proportions of sediment to different sources. In a New South Wales catchment with forestry activity on steeper slopes, Wallbrink et al. (2003) found that subsoil sources dominated (~70%) over surface sources (~30%) in sediment deposits at the catchment outlet. By contrast, Gruszowski et al. (2003) found in a mixed-land use catchment in the UK that subsoils only accounted for 34.8%, with 29.9% from road sources, 27.4% from topsoils and 7.9% from banks (see Table 6). A different picture again emerged from a flat, cropping catchment in Canada, where Culley and Bolton (1983) estimated that bank erosion contributed 32% of sediment discharge to an agricultural stream, and subsurface tile drains from the clay soil also carried a significant proportion (18%) of exported sediment. Clearly, sediment sources vary depending on site-specific features and management practices.

Table 6: Proportions of catchment sediment sources contributing to suspended sediment transported by the River Leadon (UK)

Source	Mean percentage
Subsoil (eroding rill and gully systems)	34.8
Road sources	29.9
Grassland topsoil	13.8
Arable topsoil	13.6
Channel bank	7.9

(Source: Gruszowski et al. 2003:2676)

Notably, in 7 of their 8 sampling periods, Gruszowski et al. (2003) found that channel bank sources were not evident at all, but in one period a bank-collapse event occurred and channel bank sources contributed 62.9% of sediment in that period. The picture gained is that the relative contributions of different catchment sources are both seasonally and geographically variable.

Some trials have been carried out to measure sediment in sheetwash (surface run-off). Smith (1987) measured sheetwash sediment of 374 kg/ha/yr in run-off from gley soil slopes set-stocked with sheep near Tauwhare, indicating this source is of a lower magnitude than streambank and landslide sources in hill country (see, for example, Table 3). DeRose (1998) found a mix of topsoil and subsoil sources in sediment deposits at Whatawhata, with more topsoil on slowly aggrading sites. He concluded that “the possibility that a significant proportion of sediment has come from sheetwash, including areas of severe stock treading or run-off from farm tracks, cannot be ruled out” (p27). However, Adams and Elliott (2006) used a rainfall simulator over a small catchment (1050m^2) at Whatawhata to study in detail the processes involved in surface run-off, and found the yield from these simulated run-off trials was relatively low, ranging from 0.4-120 kg/ha/yr. Similarly, Elliott and Carlson (2004) estimated a run-off yield of 20 kg/ha/yr from grazed sheep paddocks at Whatawhata. Given overall catchment yields at Whatawhata of 988 kg/ha/yr (Quinn and Stroud 2002), these studies indicate that surface run-off is not the major source of sediment in hilly terrain. Run-off rates and sediment concentrations increase following heavy grazing and treading by cattle (Elliott et al. 2002) or sheep (Elliott and Carlson 2004).

While sheetwash contributes smaller quantities of sediment than streambanks and landslides, the sediment originating on pasture surface contributes disproportionately to nutrient and faecal run-off, as it has been exposed to weathering, fertilisation and stock. In the five “best practice dairying catchments”, 20-40% of suspensoids in stream water was organic matter, with the balance being suspended sediment (Wilcock et al. 2007). Sheetwash also contains a high proportion of fine material which is likely to be removed from the catchment in suspension, rather than stored. This can exacerbate turbidity in downstream waters. Surface sources may be a larger proportion of sediment run-off where soils are cultivated (Wallbrink et al. 2003).

Forestry roads and tracks can produce high sediment loss. Sediment can be generated from road surfaces, road cuttings (cutbanks), loose material left from construction (sidecast) and roadside drains. While cut-and-fill areas produce more sediment than road surfaces, sidecast plots show marked decreases in sediment yield over time, especially when grass cover is re-established (Fransen et al. 2001). Reported sediment yields on schist and pumice are an order of magnitude lower than those for granite (ibid). Traffic can increase the yield from road surfaces. A road trucking trial found that 20 passes of a truck can produce as much sediment as that generated in a year by natural road surface erosion on lightly used roads (Coker et al. 1993).

Of all of the road and tracking sources, Fransen et al.'s (2001) review found that the greatest risk was sediment generated from roadway-related slips, which can be up to 3 orders of magnitude greater than combined surface road erosion processes. Where roads are not associated with mass movements, surface erosion of new and upgraded tracks can increase sediment yield five-fold compared to pre-harvest ungraded and lightly used roads (ibid). The rate of mass erosion depends on the episodic nature of storms and timing of harvesting and planting activities, as well as road management and construction standards. In the absence of significant mass movements, road extension and upgrading associated with harvesting activities may produce an initial increase in annual surface erosion rates, but this is not expected to significantly affect the long-term erosion rates from forested catchments. Much of the sediment eroded from tracked areas is deposited on slopes and retained by slash and vegetation. The importance of slips was also shown by Marden et al. (2007) in pumice terrain. These authors found that a single storm-initiated landslide contributed the equivalent of 6000 times more sediment to Poumako Stream than was delivered by slopewash from 38 ha of clearfelled forest. They noted that the relative contribution of sediment delivered to a stream by slopewash and landslides was highly dependent on connectivity with stream channels. The above studies suggest that the siting of road cuttings away from streams and unstable slopes is important. Other management practices are the use of riparian buffers, up-hill hauling of logs away from and not across stream channels, and rapidly establishing ground cover over loose road material and disturbed slopes.

In horticultural land, compacted wheel tracks in paddocks are a significant source of erosion (Basher and Ross 2001). However, Basher and Ross (2002) note that much of the sediment lost from paddocks in Pukekohe does not reach rivers, as it is deposited in drains or roadways and removed by council trucks to landfill areas. There is also a lot of redeposition within paddocks.

The effect of roading in pasture catchments is not well studied. Quinn and Stroud (2002) compared sediment in water samples taken upstream and downstream of unsealed roading in a pasture catchment at Whatawhata. They found minimal roading impact in average conditions, but suggested that road run-off could be more important during storms, and contribute to annual exports. Smith and Monaghan (2009) studied the contribution of dairy farm laneways in Southland and found suspended solids concentrations in run-off of more than 2000 g/m^3 near the dairy shed, and 1000 g/m^3 at a more distant location. While contaminant concentrations and annual yields on a per-area basis were high from these lanes, when considered on a whole-farm basis, laneways made only a minor contribution to annual pollutant loads to the stream. This was due to the relatively small area laneways occupied on farms (0.55%), not all of which discharged directly to a waterway. Even if all laneways in this study farm situation had discharged directly to waterways, Monaghan and Smith (in press) calculated that this would represent 14% of the whole-farm sediment losses. However, the more likely situation was that ~5% of lane area discharged directly to waterways, representing <1% of whole-farm sediment losses. This contrasts with UK research (Gruszowski et al. 2003) which found roadways contributed 30% of the suspended sediment in a mixed land-use catchment. This may be because in that study, riverbank sources were minor (mean 7.9%).

The above example of laneways shows that while certain source areas or activities generate large quantities of sediment, the impact at a catchment or regional scale is related to the area of land under those uses. A review of aerial photos showed the total land in the Waikato region with bare soil exposed by disturbance was 2.85% of the region's area (Thompson 2009). Table 7 shows some of the activities exposing bare soil, while Table 8 shows the amount of exposed bare soil according to main rural land uses.

Table 7: Proportion of the Waikato region's area showing bare soil exposure by activities

Activity	% of region's area
Farm or forest tracks	0.89
Cultivation	0.81
Surface erosion (sheetwash, sandblow, rockfall or outcrop)	0.32
Slope failures (landslides, earthflows, slumps etc)	0.10
Harvest, including forestry harvest	0.08
Livestock grazing pressure	0.08

(Source: Thompson 2009: vii)

Table 8: Proportion of the Waikato region's area showing bare soil under rural land uses

Land use	% of region's area
Dairy pasture	0.81
Horticulture and cropping	0.52
Drystock pasture	0.42
Forest plantations	0.27

(Source: Thompson 2009: viii)

These figures indicate that only a small proportion of the region's land area is exposed as bare soil at any one point in time. In addition to the area exposed, sediment yield is influenced by how much soil loss occurs from the exposed area, (related to slope and rainfall), and connectivity with waterways. As bare soil may be exposed for short periods in some land uses, the occurrence of major rainfall events at these times will determine the risk of sediment loss.

In summary, mass movements generate large quantities of sediment, especially during large, infrequent storms. The actual quantity of landslide sediment reaching a waterway depends on connectivity between the site of sediment generation and the waterway. Where landslides occur near streams, they are likely to be the dominant source of sediment. The clearance of forest from hill slopes can be seen as the most important management factor contributing to mass movement in hill country soils overall, assuming underlying features of topography, geology, and climatic effects are given. However, since much of the sediment from mass movement is historical, and can be stored in the valley floor and stream channels, these latter areas are critical contributors to the *actual* catchment yield, and can dominate in years and in storm events without large mass movements (DeRose 1998; McKergow et al. 2010). Managing streamside areas is therefore very important. When streambanks and hillslopes are stable, other sources such as sub-surface drains, tracks or sheetwash run-off dominate sediment loss, but on a catchment scale these sources are likely to be less significant than slips or streambanks and gullies. The exception is where tracking activity (e.g. for forestry harvest) causes land disturbance close to a waterway. While the contribution of surface run-off to sediment yields is generally low, it carries nutrients and faecal matter from pastoral land and fine sediment that can affect downstream water quality.

3.1 Critical source areas

The above discussion highlights that there are points in a catchment that are more likely to contribute sediment than others (e.g. slip sites or bare ground, streambanks, or channelised flow directed towards a waterway). Such sites are termed critical source areas (CSAs), defined by a high concentration of pollutant available to flow and a high potential for flow, equating to a high potential for losses (Monaghan et al. 2010). Critical source areas are commonly near stream channels or in low infiltration areas that are connected to the stream channel (Srinivasan and McDowell 2009).

In one example, Smith (1987) reported that in a study catchment near Tauwhare with significant areas of gley soil near streams, run-off would be almost entirely derived from rainfall on saturated areas of the catchment with poorly-drained soil types. McColl et al. (1985) found that run-off from permanently or seasonally saturated areas in 14% of a catchment near Wellington accounted for most of the total run-off in small and medium events and about one third of total run-off over all events. About half the catchment area generated 95% of total run-off. They found flow patterns in heavy rainfall events were determined by soil surface characteristics, which in turn were strongly influenced by stock trampling. The seasonally saturated areas in their study were readily identified as they were typically associated with Juncus (rush) species. These authors suggested that land management could focus on these areas. However, they also noted that two substantial storms out of 81 rainfall events contributed one quarter of the total stormflow, and that the entire catchment area contributed run-off during these large events.

4 Practices to reduce sediment loss

The following practices are recommended to reduce sediment loss. Where quantitative results showing sediment loss reduction from the practice are published, this is presented. Similarly, information on economic and practical feasibility is included where available.

4.1 Forest or tree cover

Figures presented in Table 2 show that sediment yield under pasture is greater than that from mature pines or native forest. When severe storms produce highly visible landsliding, it allows a comparison of the susceptibility of different land uses to erosion in extreme conditions. Pain and Stephens (1990) examined aerial photographs from five sites after a storm in Taranaki and found landslides over 10% of pasture but only 1% of forested land and scrub. These findings are in a similar range to those of Marden and Rowan (1993) who examined aerial photographs of nine sites after Cyclone Bola. They found sites under older vegetation with a closed canopy (indigenous forest and exotic pines >8 years old) were four times less susceptible to landsliding than those under regenerating scrub and exotic pines 6-8 years old, and sixteen times less susceptible than those under pasture and young exotic pines (<6 years old). The differences in landslide density under the various vegetation types were less pronounced in photographs taken prior to Cyclone Bola (Figure 2). Even so, indigenous forest, older pines and advanced regenerating scrub had significantly lower landslide densities than did areas of pasture and young pines (<6 years) even before Cyclone Bola.

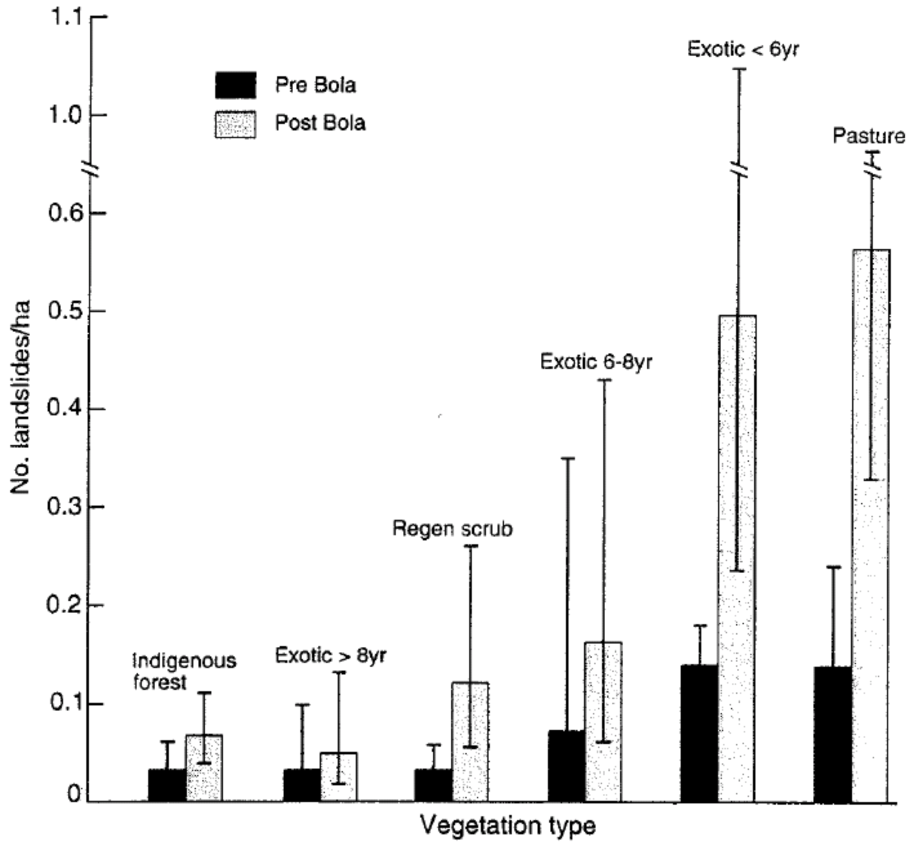


Figure 2: Landslide density pre- and post-Cyclone Bola under different vegetation cover

Error bars represent 95% confidence intervals, calculated on a log scale.
Source: Marden and Rowan 1993

Hicks found some protection from 5-8 year-old pines on “hard” hill country in his field study after Bola. He reported (Hicks 1991) that pasture was severely eroded at 37% of sites, compared to 5% of pine sites (7.4 times the frequency), with none of the native forest sites being so severely eroded. The incidence of fresh mass movements was significantly higher under pasture than under either pine forest or native bush (Hicks 1989a - Figure 3). Bush gave better protection than pines at low damage levels (70% of bush-clad hills had suffered minimal damage c.f. 48% for afforested hillsides). However, at high damage levels, the difference between these two was insignificant. Damage to small watercourses on hillsides was minimal under native bush, but severe under both pasture and young pines.

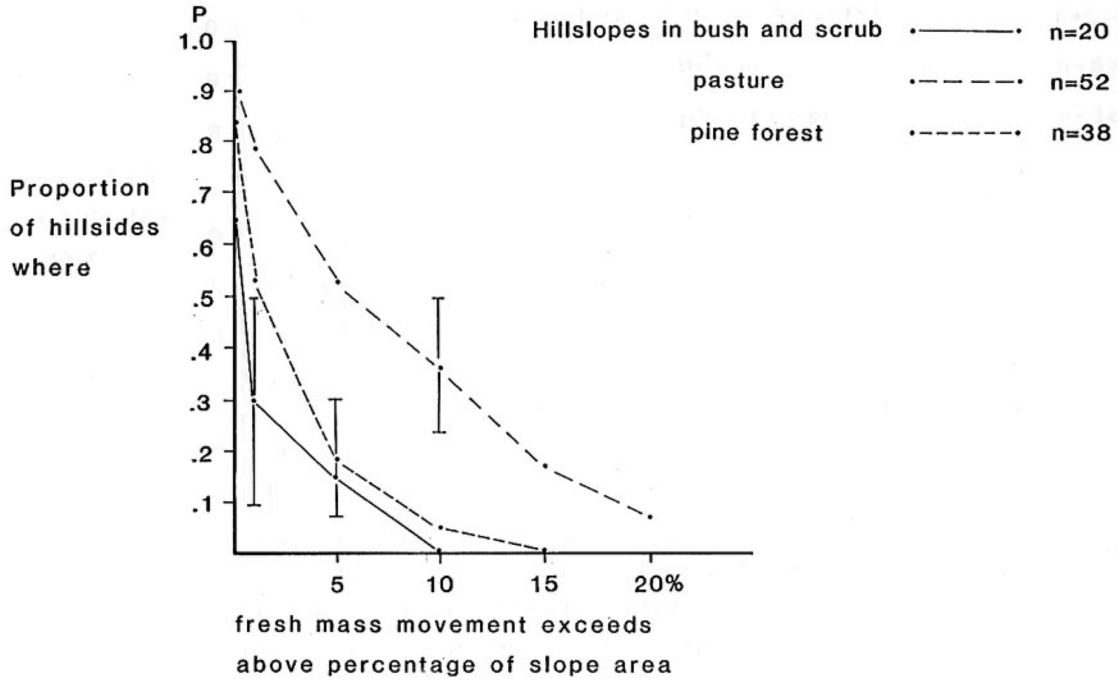


Figure 3 Mass movement of soil under different vegetation cover

Source: Hicks 1989a

Selby (1976, cited in Crozier et al. 1982), working in South Auckland, found that landslides were triggered on grassland slopes by intense rainstorms with a return period of about thirty years, whereas for similar sliding to occur on forested slopes, more intensive rainstorms were required, with return periods of about 100 years. Therefore, while mass movements do occur on forested slopes, more intense rainfall is required to trigger this than on similar slopes under pasture.

Bergin et al. (1995) evaluated the role of regenerating scrub (manuka and kanuka) in reducing shallow landslide damage on East Coast hill country. Compared to pasture, the scrub reduced landslide damage by 65% under 10 year old stands, and up to 90% under 20-year-old stands.

Thus, both exotic and indigenous forest cover can reduce storm erosion impacts, with a mature forest cover being most effective. Younger pines (5-8 years old) and regenerating scrub offer an intermediate level of protection but very young exotic plantations where canopy cover is negligible and root development is limited do not afford greater protection than pasture.

Pine afforestation may not always control gully erosion, and may increase rates compared to controlled grazing with paired plantings (Hicks 1995a). However, Marden et al. (2005a) found that a 24-year programme to establish forest cover in the headwaters of the Waipaoa River (East Coast) did reduce gully-derived sediment yields from 27 000 t/km^2/yr to 11 000 t/km^2/yr.

Pest numbers are unlikely to diminish the effectiveness of forest cover. In a review, Phillips and Davie (2007) found little evidence linking the presence of pest animals in forest areas to large-scale catchment water quality. They concluded the impact of pest animals in a catchment is smaller than other influences such as tectonics, storms, and agriculture.

For greatest impact, the retirement of pasture land to forest cover should be targetted at the steepest parts of the catchment. For example, modelling of Tauranga harbour (Hume et al. 2009) indicated that steep pasture areas (>20°) are about 2.3% of the catchment, but could contribute 21% of the sediment load to streams.

Forest cover also has other effects. In comparison with grazed pasture, forest cover is associated with:

- Less faecal pollution (Larned et al. 2004; Collins 2002)
- Less phosphorus and nitrogen loss (Larned et al. 2004; Quinn and Stroud 2002)
- Higher infiltration rates, lower water yields and reduced flood peaks (Rowe et al. 1997; Wood and Fahey 2006; Blaschke et al. 2008)
- Shading of streams and lower temperature for aquatic habitat value (Quinn et al. 1997)
- Habitat for terrestrial native biodiversity and adult forms of aquatic life (Collier et al. 1997)
- Carbon sequestration (Davis et al. 2009).

4.1.1 Economic drivers and other considerations for forest cover

The Waikato River Independent Scoping Study (NIWA 2010) found that retiring and afforesting steep hill country pasture currently used for sheep and beef grazing was among the most cost-effective measures for reducing sediment pollution (in terms of kg removed per dollar spent).

Pasture productivity declines dramatically after a slip and only recovers slowly. Lambert et al. (1984) measured pasture production on faces where slips had occurred since 1977 and found pasture production was 20% that of uneroded faces. Further assessment in 2007-09 found production had recovered to 80% that of uneroded faces, but was unlikely to recover further within human timescales, as earlier slip sites (1941 and 1961) had not made any further recovery (Rosser and Ross 2009).

The returns from forestry are highly dependent on the economics of harvesting, including issues such as road access, costs of logging, and distance to ports or market (Jones et al. 2008). They are also influenced by central government climate change policy (e.g. afforestration grants and carbon credits) as well as regional or central government sustainable land management grants. There are difficulties in determining costs and benefits of this sort of work as results depend on assumptions made about the discount rate, time horizon (for costs and benefits to be realised), and valuing labour. However, profitability analyses of farm forestry have shown that woodlots of pine may be more profitable than pastoral farming, particularly on land with a low livestock carrying capacity (Jones et al. 2008).

Profitability may increase further if carbon credits are claimed for new forests (Praat et al. 2010; West et al. 2009). Biofuels are another potential, although currently less certain, opportunity (SKM 2008). When carbon farming, revenue starts to accrue from age 3 onwards, providing an alternative income stream and reducing cash-flow issues associated with timber plantings. Carbon farming also increases the profitability of alternative species such as eucalypts, but native scrub regeneration is slower at accumulating carbon (West et al. 2009; Davis et al. 2009). Once forests are registered for carbon credits, changes in forest carbon stock must be accounted for in perpetuity (URS 2008). When trees are harvested, a proportion of the accumulated credits must be paid back. The farmer retains the right to the remaining sequestered carbon (in roots, stumps etc – around one third of the sequestered carbon) but this can only be claimed for one forest rotation on a site, i.e. the forest will generate income from carbon sequestration for only one harvest cycle (Praat and Wallwork 2009). This may make this option less attractive to farmers who want to retain flexibility of land use without liability for future deforestation. There are also a number of other risks and costs associated with carbon trading (URS 2008). As yet, the perceived risks and the low value of carbon are limiting the uptake of carbon farming (J-P. Praat, pers.comm.; June 2011). Risk mitigation strategies for farm foresters include having a range of planting dates and species so that at any point in time there are credits being accumulated which are of the same value as those being surrendered upon harvest.

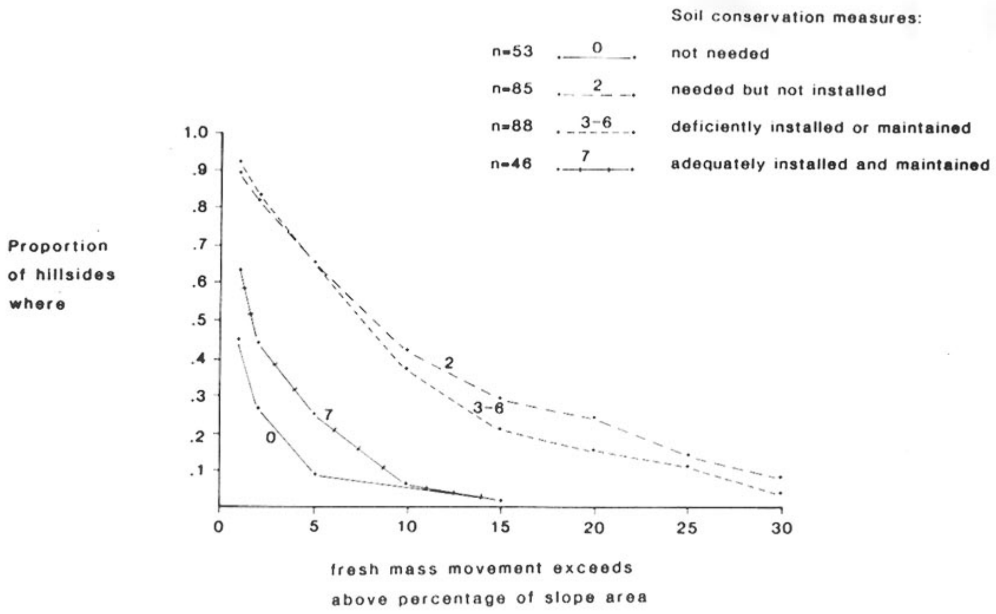
Farmers interviewed who had undertaken retirement of steep land as part of Project Watershed were asked about their motivation and the perceived benefits (Ritchie 2005). While few were motivated by the commercial value of timber, they found advantages of treed areas in a pastoral operation because they could reduce inputs to poor land (weed control, fertiliser) and focus their resources on the better country. This made it economically neutral to retire up to 20% of some farms. Stock losses down steep banks were reduced, and mustering was easier. Farmers did not have to worry about erosion on hillsides and cattle 'making a mess', and they observed that water running off the hillsides with tree cover was cleaner. One person felt that the trees softened the contour of the steeper parts of the land, being 'easier on the eye', and that this would make the farm more attractive to buyers when the time came to sell.

4.2 Soil conservation plantings, gully and earthflow stabilisation

Spaced plantings are exotic trees interspersed in pasture areas, 5 – 10m apart depending on susceptibility (Phillips et al. 2008). They can reduce slippage on erosion-prone slopes by up to 95% (Douglas et al. 2009). Space-planted trees act to stabilise soil by reducing water content in the soil layers and by reinforcing the soil with a root network. Lateral roots of broadleaved trees interlock for distances of up to 12m from the trunk, and form very dense networks within 5-6m of the trunk (Hicks 1995b).

Hicks (1989b) investigated the efficacy of soil conservation plantings after Cyclone Bola hit the East Coast. The plantings ranged from spaced planting of willows and poplars on slopes, to paired planting of poplars in watercourses, to close planting of pines in active gullies. He found that previously unstable hillslopes with effective soil conservation plantings had only slightly higher damage distributions than stable hillslopes. However, unstable hillslopes with ineffective plantings had much higher damage, similar to levels on unplanted slopes (Figure 4). Ineffective plantings were defined as those that were of the wrong type, not extensive enough, too far apart, or with trees too diseased or too young to have effect. Inadequate slope plantings like these gave very little protection. Recommendations arising from this work were as follows:

- Space planted poplars should be planted no more than 12m apart (70 trees/ha)
- Blanking (replacement of trees that fail to establish) should be carried out after planting
- Over-mature, dead or diseased trees should be removed and replaced.



Source: Hicks 1989b

Figure 4: Effectiveness of soil conservation plantings

The effectiveness of spaced plantings of poplar, willow and eucalypts in controlling hillslope erosion after storms in Manawatu (2004) and Wairarapa (2006) was assessed at 65 sites by Douglas et al. (2009; 2011). Slopes with spaced tree plantings had <1% slippage and the extent of slippage was 95% less than on comparable pasture slopes. This study concluded that while regional councils recommend planting poles at a spacing of 12–15 m on erodible pastoral slopes, if all poles survive, trees can be thinned to 18m apart to reduce pasture shading without compromising slope stability, providing tree diameter exceeds 30 cm. However, spacing trees too far apart at planting reduces their effectiveness because roots do not intermesh. Hawley and Dymond (1988) found that 20m-spaced trees reduced erosion by only 13.8% in Cyclone Bola.

Trees are most effective when planted on sites with potential to slip, rather than trying to treat actively moving slopes. When used on actively eroding areas, tree planting should also extend out to adjacent stable areas. Prediction of slips is not straightforward, however. O'Loughlin (2005) reviewed factors for predicting landslides in different sites and reported they may be associated with slope hollows or depressions where sub-surface drainage converges, above certain slope thresholds, on certain soil types, or associated with certain slope aspects.

Stabilising earthflows and gullies is more challenging than protecting slopes. Basher et al. (2008) concluded that planting appropriately-spaced poles provides protection against shallow landslides, but has had only limited success for the treatment of large and active mass-movement features (earthflow and slump) and gully erosion in the most highly erodible terrains. Poplars and willow plantings were found to be successful at only 63% of earthflow sites, and 42% of gully erosion sites in a study of 278 sites in Gisborne/ East Cape (Thompson and Luckman 1993). These study sites were in productive farmland, not the steepest sites. Treatment was judged to be technically, but not necessarily economically, feasible for gullies up to 5m deep, and for all earthflows other than those in bentonitic terrain. Severely eroded gullies should be retired from grazing and closely planted with trees (Hicks 1995b). This has been a focus in pumice country around Taupo, Reporoa and Upper Waikato. Deep-seated earthflows often require de-watering through subsurface drainage/ spring taps or diversion banks around the slumping areas in addition to space-planted trees (Hicks 1995b).

4.2.1 Economic drivers and other considerations for soil conservation plantings

There is some pasture suppression under broadleaved space planted trees (around 40% relative to stable ground) (Hicks, 1995b). However, on unstable ground Hicks found no net loss in feed, because pasture suppression by trees is counterbalanced by residual growth on areas that would have been lost to erosion, had the trees not been planted. While there may be no net loss in pasture production, when all costs are taken into account, Parminter et al. (2001) found that monetary drivers for planting poplars were marginal. Even at high expected erosion rates and repair costs, and with harvest values included, they found the internal rate of return was low (5-6%). They considered poplar planting could be worthwhile to farmers if poplars reduced lamb losses (due to shelter), if subsidies were available, or if non-monetary factors were important. Local factors that influence the productivity of the pasture slopes subjected to shading will determine the economic impact of poplar planting, so drivers may be weaker where pastures are more productive and less erosion-prone (Doug Hicks pers.comm. 2011). Carbon credits provide an incentive for denser plantings over spaced trees (West et al. 2009).

The costs of tree planting are greater if plantings are not targeted, or if erosion occurs after planting but before the trees become effective. To maximise economic benefits, then, it is important to predict unstable ground in advance and to carry out effective tree planting. In Hicks' economic analysis after Cyclone Bola (1989c), he found that *effective* soil conservation measures would have reduced the value of damage by 60%. This compared to an *actual* damage reduction of 20% by existing plantings, which were not always appropriate or sufficient.

Gully erosion should be treated early, as untreated gullies can increase in size rapidly, causing loss of productive land and reducing the chance of successful treatment (Basher et al. 2008). Debris dams are considered a highly effective means of control of gully erosion, but their use is limited because of high construction cost (East Cape Catchment Board, 1986). Their use may be confined to where high value assets are at stake, with total retirement and planting of some gullies a more cost-effective alternative.

Earthflow contouring and de-watering can allow pasture production to be raised to the same level as that on stable slopes, and stock carrying capacity can increase from 1-2 to 5-7 stock units/ha (ibid).

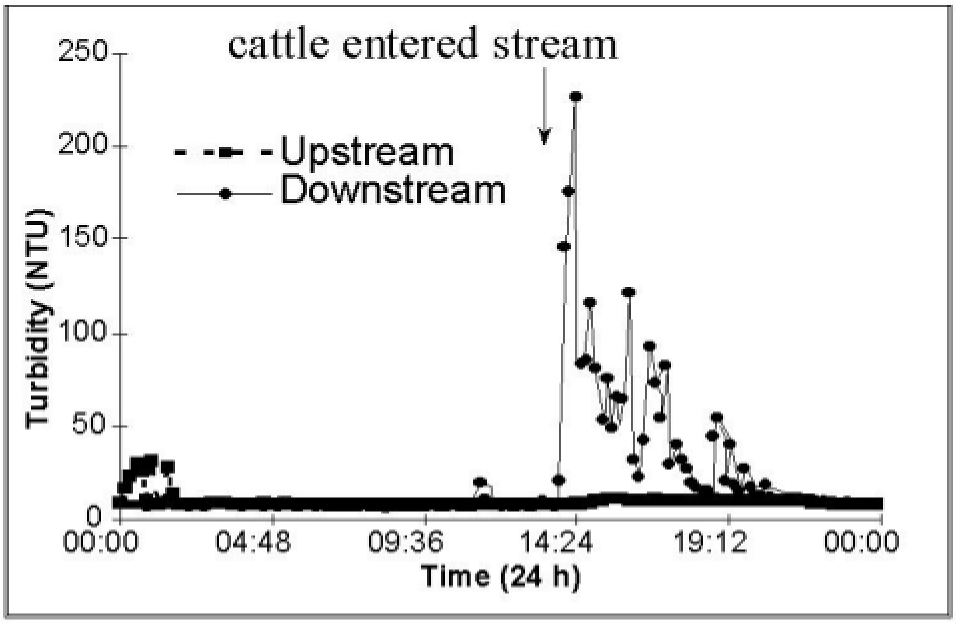
4.3 Riparian management

Streambanks and valley floors act as storage areas, which can become important sources of sediment if unstable. Riparian management can reduce sediment in waterways by:

- Excluding stock
- Creating buffer zones to slow run-off and allow sediment to settle out
- Establishing trees in streamside areas to help to stabilise stream banks

4.3.1 Stock exclusion

An important function of riparian management is exclusion of stock which would otherwise be attracted to water, such as cattle and deer. For example, one study at Whatawhata (Stassar and Kemperman 1997) found that cattle entering streams over several days increased the number of bank erosion sites by 66% and increased turbidity some 6 times above background levels (Figure 5).



Source: Stassar and Kemperman 1997

Figure 5: Turbidity effects of cattle access to streams

Cattle damage to stream banks is most severe when bank soil moisture is high (Trimble and Mendel 1995). Low banks are most susceptible to trampling, although cattle will also form ‘ramps’ up to higher banks and high-cut banks can shear off chunks due to cattle activity (ibid).

McDowell (2007) also found very high loads of sediment when deer had access to wallows. When a wallow was retired and planted, it acted as a settling area for sediment instead, and suspended sediment in the stream water declined 98% (McDowell 2008). In another trial where deer were provided with ‘safe’ wallows (unconnected to streams), a significant decrease in sediment loss to streams occurred (90%) compared to control catchments with in-stream wallows (McDowell 2009).

Catchments with stock exclusion are associated with a lower incidence of streambank erosion and higher water quality. Parkyn et al. (2003) compared reaches of stream with riparian protection with upstream areas in pasture and found that most of the pasture reaches had greater amounts of active bank erosion (e.g., pugging, trampling, undercutting) than buffered reaches. Generally, visual clarity was better in the buffered sites, often by over 50%, and some improvements were evident even at sites with relatively young buffer zones (2-6 years).

Catchment scheme activity on the Ngongotaha stream was effective at reducing streambank erosion exporting sediment to Lake Rotorua. Prior to catchment work, an estimated 30% of streambanks were actively eroding, but following comprehensive riparian retirement, this declined to 4% (Williamson et al. 1996).

A study of riparian characteristics for the Waikato region (Storey 2010) also noted that riparian fencing was strongly correlated with streambank condition. Whereas fencing on both banks was strongly correlated with reduced pugging and total erosion, fencing on only one bank was not significantly correlated, suggesting that fencing both sides of the stream is important for bank protection.

The Waikato Regional Council carries out focused monitoring in areas where catchment work is concentrated. In the Mangatutu stream, there has been an increase in riparian fencing over the total stream bank length from 45% in 2004/05 to 51% in the 2008/09 survey (Grant et al. 2010). The proportion of grass and woody vegetation has remained relatively constant, but the riparian bank length assessed as stable rose from 57% to 78% over the same period. This shows that stock exclusion fencing has an impact on bank stability, irrespective of vegetation changes. A similar trend towards greater bank stability with riparian fencing was evident in earlier monitoring of other catchments, except for the Pokaiwhenua which already had a high proportion of stable banks (see Table 9).

Table 9: Changes in bank stability and riparian fencing in monitored catchments

Catchment	% stream unfenced		% banks stable	
	2003/04	2007/08	2003/04	2007/08
Matahuru	30	15	47	75
Pokaiwhenua	29	2	88	85
Mangare	49	24	39	67

(Source: Grant et al. 2009)

Construction of crossings where herds regularly cross streams can reduce an important source of sediment. Davies-Colley et al. (2004) monitored water quality downstream from a dairy herd crossing in Sherry River (Motueka catchment). A return crossing of the herd of 246 cows yielded 35.2 kg of suspended solids (SS), even though a concrete ford was in place. It was calculated that with two return crossings a day, SS would be increased by 54% and visual clarity reduced by 11%, representing an “appreciable proportion” of light attenuation in streams draining dairy land. The authors noted that this included SS from faecal matter, wash-off from the cows’ legs and bed sediment disturbance when cows left the concrete pad and entered river gravels. While bridges may still contribute run-off to streams, they eliminate direct deposition, wash-off from legs, and bed sediment disturbance.

The Waikato River Independent Scoping Study (NIWA 2010; Appendix 9: Farms) estimated that on sheep and beef farms, suspended sediment could be reduced by 30% if cattle were fenced out of all streams. This was based on unpublished data from the Whatawhata catchment.

Overseas, riparian fencing at a catchment scale has also been found to reduce sediment in streams. In one Western Australian catchment, McKergow et al. (2003) measured a 90% reduction in sediment loads once livestock exclusion was in place. In Vermont, suspended sediment concentrations decreased by 34% when stock exclusion fencing was put in place along 49% of a pasture stream in a predominantly dairy catchment (Meals 2001). In North Carolina, the establishment of riparian buffers produced a significant 60% decrease in suspended sediment concentration (Line 2003) and an 82% decrease in mean weekly suspended sediment loads (Line et al. 2000). In this example, stock exclusion fencing was installed along 340m out of 390m of stream length in dairy pasture, with a 10-16 m riparian buffer and some bank rehabilitation in eroding areas. This comprehensive approach explains the magnitude of sediment reduction, which was twice the 40% decrease in soil loss reported by Owens et al. (1996) after beef cattle were excluded from an Ohio stream draining unimproved pastures. Line et al. also noted this could be because the North Carolina site had higher stocking rates, a larger stream, or more severe bank erosion than the extensive grazing reported by Owens et al. Owens et al. reported an increase in annual storm flows in the period following fencing, which could have obscured some of the benefit from fencing. Providing alternative water supply without stream fencing did not produce any significant difference in suspended sediment in Line et al.'s (2000) study.

4.3.2 Buffer or filter effect

While stock exclusion contributes to the reduction of bank erosion and faecal sediment inputs, a wider buffer zone has the added benefit of trapping sediment in overland run-off from paddocks. Parkyn (2004) reviewed a range of studies carried out overseas which reported sediment trapping efficiencies exceeding 50% for vegetated filter strips, usually consisting of rank paddock grasses.

She listed three mechanisms by which sediment is removed in buffer strips:

- Infiltration within the buffer zone which reduces run-off reaching the waterway and removes the sediment
- Reduction of flow velocities due to the rough vegetation, allowing sediment to settle out
- Physical filtering effect of dense vegetation

The third of these is considered to be less important, and only effective for larger particles. Gharabaghi et al. (2006) found that at low run-off flows (0.5-2 l/min), sediment removal efficiency increased from 50 to 98% as the width of the filter increased from 2.5 to 20 m. The first 5m of filter strip trapped 95% of the particles 40 µm or larger in diameter, and removal rates did not improve much beyond 10m of filter width. They concluded that for fine particles, only infiltration is effective. Infiltration may be enhanced in buffer zones because the removal of stock reduces compaction, and the vegetation develops more root channels (Collier et al. 1995).

Little information is available on the effect of different vegetation types, but Gharabaghi et al. (2006) found that some grass types were more effective for sediment removal (mixes containing Birdsfoot Trefoil and Creeping Red Fescue). Flow resistance is important, which is likely to depend on the density of vegetation (Muscutt et al. 1993). Phillips (1989) suggested that forest areas could have equivalent resistance to grass if there was dense undergrowth, abundant leaf litter and woody debris. Peterjohn and Correll (1984) found riparian forests removed sediments, but Smith et al. (1989) noted accelerated surface run-off erosion in a pine buffer due to insufficient ground cover. Thus, treed buffer zones would be most effective if the canopy allowed enough light through to form a dense understorey.

The buffer width required for sediment removal depends on the steepness of slope. A steep slope requires a wider buffer to slow the velocity of surface run-off (Collier et al. 1995). Dillaha et al. (1989) measured removal rates between 70 and 54% on slopes between 11 and 16° with 4.6m filter strips under shallow, uniform flow draining 18m strips of bare cropland. For a longer (9.1m) buffer width, they found effectiveness was significantly higher (84-73%) over the same range of slope. They cautioned these reductions might not occur in field conditions, due to longer upslope distances and flow concentration effects, although the rainfall they applied was heavy (equivalent to a 100-year return period event). Interestingly, a similar magnitude of removal was reported from a New Zealand field study on gley soils, where Smith (1989) found a sediment load reduction of 87% for a retired pasture buffer of 10-13m over 22 months of rainfall events, when compared with unretired riparian pasture areas nearby.

In steep, hilly terrain, buffers may be less effective because overland flow tends to concentrate in channelised natural drainage ways with high flow velocities (Parkyn 2004). Dillaha et al. (1989) formed this conclusion after surveying 10% of Virginia's filter strips established to reduce sediment from cropland. They did, however, find these strips had some benefits in protecting banks from erosion. Smith's (1989) study at Tauwhare sampled channelised drainage ways and did detect a substantial reduction in sediment loads where riparian areas were retired from grazing. Dillaha et al.'s (1989) experiment found that the filter strips were less effective in their later runs, partly because the soils were inundated and produced more run-off, and partly due to sediment accumulation in the filter strip. Parkyn (2004) also reports that over time, pore spaces in riparian buffer soils may clog with sediments, reducing effectiveness. However, Dillaha et al. suggested that in field situations, the filter strip vegetation would likely grow through the accumulated sediment and continue to effectively filter later stormflows.

The Waikato River Independent Scoping Study (NIWA 2010; Appendix 9: Farms) estimated that on sheep and beef farms, 5m buffers could reduce suspended sediment by 55-60% and this could increase to 65% with 15m buffers. These estimates were based on a number of the studies cited above.

4.3.3 Riparian planting for bank stabilisation

Whether or not stock exclusion is in place, riparian planting can provide bank stabilisation. Hicks (1992) reviewed the effectiveness of streambank planting for stability on the East Coast, Wairarapa and the Upper Waipa and found in all cases that adequate planting effectively reduced streambank erosion (see Tables 10 and 11 for the Waipa data). In 40-60% of the cases, plantings were inadequate to give protection - they were still immature, too far apart because trees that had died were not replaced, or they were diseased or stunted. However, even such inadequate plantings had some effect in limiting bank erosion (as opposed to inadequate slope plantings, reviewed above, which gave very little protection).

Table 10: Bank stability under different vegetation - Upper Waipa and tributaries

Reach vegetation	Percentage of bank eroded
Grass	23
Weed or scrub	12
Poplars	9
Willows	8
Osiers	1
Mixed tree plantings	5

Source: after Hicks 1992:12

Note: Survey results are for bank erosion under normal flow conditions (i.e. given minor to medium-sized floods expected in any year). The condition of plantings is critical, as the following table shows.

Table 11: Effectiveness of plantings - Upper Waipa and tributaries

Condition of reach and tree plantings	Percentage of bank eroded
Stable	12
Unstable, unplanted	27
Unstable, inadequately planted	8
Unstable, adequately planted	2

Source: after Hicks 1992:13

Note: stability of the site is assessed as resistance to flood damage. The better performance of planted, unstable sites compared to stable sites is attributed to the greater resistance of the former to cattle trampling.

The Waikato River Independent Scoping Study (NIWA 2010; Appendix 9: Farms) estimated that on sheep and beef farms, suspended sediment could be reduced by 55% with poplar planting and cattle exclusion (higher than the figure for cattle exclusion alone of 30%). This was based on unpublished data from the Whatawhata catchment where this practice was implemented.

An increase in active erosion caused by in-stream obstructions was noted in a NIWA study for the Waikato region of riparian characteristics (Storey 2010). Removal of such obstacles is therefore important along with appropriate riparian bank management.

The possibility of channel widening after riparian planting cannot be discounted. Studies at Whatawhata (Davies-Colley 1997) have found that small streams (catchment area <1 km^2, width in forest <2 m) are typically twice as wide in forest reaches as they are in pasture reaches. The degree of channel narrowing reduces as stream size increases, and was found to be minimal in large streams (catchment area >30 km^2, width in forest >10 m). There were some cases in Hicks' Wairarapa survey where scour of bed and banks increased from unplanted to inadequately planted, to adequately planted streams. This was attributed to suppression of bankside weed and grass growth beneath the trees. However, volume of sediment from this type of scour was slight, as the trees' root networks prevented it from degenerating into deeper gullying.

Some research has been conducted into the suitability of native plants for streambank soil conservation. The conclusions from these root studies are that, in general, native species have higher tensile root strengths than exotic species, are slower growing, and have shallower root systems (Phillips 2005). Marden et al. (2005b) report that many native plants are suited to colonising steep and unstable riparian slopes where shallow soil failure is prevalent and/or where stream banks are rocky with skeletal soils. These authors found that the effectiveness of riparian restoration using indigenous species, though potentially high for low-order streams, will be limited on larger rivers due to their relatively shallow-rooted habit (unless structural protection works are also used). On smaller streams, the strategy should be to select a mix of species with different rooting habits.

4.3.4 Economic drivers and other considerations for riparian management practices

The costs to farmers of riparian management are associated with fencing, planting, loss of grazing, weed and pest control and alternative water supply (Quinn et al. 1999). The amount of land required for effective buffering depends on local conditions.

Generally, buffers need to be wider where slope length, angle and clay content of the adjacent land are higher, and where soil drainage is impeded (Parkyn 2004).

The type of fencing has a strong influence on cost and practicality - 1-wire electric fencing for cattle is a fraction of the cost of 8-wire post and batten for sheep exclusion, and deer fencing is even more costly. Practical advantages of conventional fencing are relatively low day-to-day maintenance and functionality without an external power source even with rank vegetation alongside. Electric fencing is inexpensive and quick to construct or repair, and can be moved or 'washed away' in floods and re-erected. However, it requires a reliable electricity supply and regular checking to maintain function.

Flooding issues are also an important consideration for fencing riparian areas (Bewsell et al. 2005). Fences may need to be placed further from the waterway in flood-prone areas, meaning loss of more grazing area. Alternatively, more temporary styles of fencing may be used. Farmer modifications to fence design include the use of polyrods and light wire or tape designed to break in a flood and leave posts standing (Ritchie 2005). Small streams are often also important for drainage purposes and farmers may be reluctant to see vegetation causing any obstruction to drainage or to access for drain cleaning (Bewsell et al. 2005).

Riparian fencing is difficult to implement where there is a high density of streams, and steep topography. Fencing in steep country is more expensive if the fence-line needs to be benched. In the catchment land use project at Whatawhata, much of the less productive Class VII land was retired for forestry because of these topography and stream density issues (Quinn et al. 2007). Some deer farmers interviewed in Southland and Otago said that a requirement to complete fencing of all streams could make certain paddocks, or even the whole farm, unviable (Payne and White 2006).

Weeds are a concern to farmers considering fencing streams (Bewsell et al. 2005). Planting native trees adds a large additional cost to that of stock exclusion fencing, but may result in lower ongoing weed control issues if canopy closure is achieved. Plantings can create attractive landscape features with biodiversity value, but may also harbour animal pests.

Cattle exclusion from streams on sheep and beef farms was among the most cost-effective means of reducing sediment loss identified by the Waikato River Independent Scoping Study (NIWA 2010). Fencing for full stock exclusion and planting along streams was considered to give some added benefit but at high cost.

While most sediment loss occurs during storm events, it is at base flows that more water-based recreation is likely to occur (NIWA 2010). Therefore, activities like stock exclusion that increase clarity at base flows may have particular benefit in enhancing recreational values.

Some farm management benefits of riparian fencing are also identified by Quinn et al. (1999), such as:

- Better feed utilisation from fencing subdivision
- Less land lost near streams where there is active erosion
- Easier mustering
- Reduced liver fluke and easier facial eczema treatment with reticulated stock water.
- Stock losses reduced where riparian fences are established around gullies and swamps.

Farmers in four best practice dairying catchments were asked about their decisions on whether to fence streams from stock or not (Bewsell et al. 2005). The most frequent response was that fencing streams, wetlands and drains made stock management easier. Many did not believe that unfenced waterways were a water quality issue, as they did not observe animals accessing the water. The focus on stock safety was consistent across the four catchments, and priority was given to waterways that presented a risk to stock (e.g. steep-sided drains, swamps) (Bewsell et al. 2007). These farmers did not cite water quality or any other environmental benefit as a reason for fencing.

This contrasts with farmers from the Middle Waikato catchment who had done riparian and soil conservation work as part of Project Watershed (Ritchie 2005). Their most frequently stated motivation for this work was a responsibility to be good stewards of their land and water resources and protect them for the future. It is unclear why there should be such a contrast between these studies. In Toenepi, the researchers found that the silt-bottomed stream, while part of the landscape, was “not part of the farmers’ lives” and was not used for water extraction or recreation. In the Middle Waikato, farmers placed high value on the hydrolakes and their tributaries (which were mostly clear, hard-bottomed streams, sometimes used for stock water). Bewsell et al. (2005) did report that all the farmers they interviewed agreed that looking after the environment was important, whether or not they were implementing environmental practices. They also supported trying to achieve contact recreation standards for waterways. But it was their context and their specific needs and perception of farm benefits that influenced whether or not they adopted certain practices such as riparian fencing. Similarly, dairy farmers interviewed by Davies and Topperwien (2011) selectively fenced areas where stock management was a particular issue, but many did not see the fencing of all waterways was necessary. Weed control and repairs after flooding were of concern to these farmers.

The majority of the (mainly drystock) Middle Waikato farmers interviewed by Ritchie (2005) identified significant on-farm gains from fencing out riparian areas including better pasture utilisation, fewer stock losses and ease of mustering. Installing a solid fence carrying electric wire around the boundary of grazed areas allowed internal fencing and temporary electric wires to be easily put in place. This may be particularly advantageous in streamside flats where it allows a shift in stock types towards higher value finishing stock. Where stock previously drank from natural water, troughs were associated with improvements in animal health. Many farmers also appreciated the amenity value of a well-protected waterway, including plantings and more bird life, but some did not like the unkempt look of retired streambanks. Several of the farmers interviewed thought there was a property value improvement from the work or that it would make the farm easier to sell. Farmers did not believe there was much gain to them from preventing streambank slumping, and some said they had lost significant grazing in retiring riparian areas. However, the impact of streambank slumping on water quality was acknowledged. Farmers generally had not seen improvements in the clarity of their main waterways, but did observe less soil loss and cleaner water coming off steep areas in trees. They also noted more stable banks and run-off being filtered by swamps and riparian strips. Trade and consumer image were mentioned as a motivation by a small number of those interviewed.

In some cases, a production timber crop is possible, with the added environmental benefit of exporting nutrients in the crop which might otherwise reach the waterway. However, harvesting disturbance must be carefully managed to avoid further sediment loss to waterways.

The need to install alternative water when streams are fenced is an additional cost, but may also be seen to have some animal health benefits. Installing trough water systems can assist farmers in controlling liver fluke and facial eczema, but a literature review found little New Zealand evidence that clean water gives production gains (MAF 2004). Studies in Canada on dam water sources were reported in this review, which concluded that the detrimental effect of dirty water was due to its poor palatability for stock, leading to insufficient water intake. Cattle that drank clean water spent a longer time grazing and, in penned studies, ate more feed.

In addition to erosion control, riparian buffers in both pastoral and forestry land uses can provide multiple water quality and habitat benefits. Altering the riparian vegetation and effects on cover, in-stream habitat and temperature of streams can influence native fish and stream invertebrates (Jowett et al. 2009; Quinn et al. 2009a). The range of environmental benefits of riparian vegetation can be summarised (after Quinn et al. 1999) as:

- Shade for streams, to lower temperature and light inputs
- Debris and litter inputs (Both native and exotic leaves are suitable, but deciduous trees drop their leaves in a single seasonal pulse. A diversity is preferable)
- Habitat for adult stages of stream fauna
- Stopping stock access, and direct inputs of faeces
- If there is rough vegetation, faecal contaminants may be trapped and die before reaching the waterway
- Rough grass can also trap sediment and phosphorus in run-off, though the long-term fate of these contaminants is not clear
- If a buffer zone is left when applying fertiliser, direct phosphorus input is minimised
- Under forestry, a buffer zone prevents slash from disrupting normal stream inputs
- Riparian areas can also form important terrestrial habitat, and link isolated habitat areas.

However, there are some trade-offs in designing riparian areas, quite apart from the obvious loss of productive land and cost of establishment. Quinn et al. (1999) identify the following:

- Dense rough grass is an effective filter for water, but has less habitat value and shade value than trees on larger streams
- Tree planting has habitat and aesthetic value but may be ineffective when there are steep banks
- Shade can decrease the growth of aquatic plants, but such plants may be a way to remove unwanted nutrients, such as if the stream flows into a sensitive lake
- Shading a stream formerly in pasture can contribute to bank collapse, giving a period (10-20 years) of increased sediment.

The appropriate design will therefore vary according to the specific objectives, (sediment control, in-stream nutrient reduction, or habitat enhancement). The particular circumstances of a catchment, for example how much run-off occurs through surface vs sub-surface pathways, will alter the efficacy of mitigation practices like riparian management (Quinn et al. 2010).

4.4 Bank protection, in-stream and channel works

Some erosion issues may call for removal of obstructions, moving gravel or controlling flow with weirs, detention dams or flumes. Vegetation may be used for channel protection on its own or in combination with hard materials e.g. where groynes are used to train a river to flow in a certain path by anchoring vegetation to the bed of the river using steel or iron (Environment Waikato 2007b). Revegetation can reduce erosion on straighter parts of a river and where banks are less than 2-3m high (Phillips and Marden 2008). High banks and bends may require harder bank protection (ranging from geotextiles to rock or concrete). However, this sort of work can degrade stream habitat values and may also transfer the erosion hotspot further downstream. Construction time should be minimised and timing of in-stream works planned around fish migration/ spawning periods (Environment Waikato 2007b).

Best Practice Guidelines are now followed by the Waikato Regional Council when conducting in-stream works and these practices have been shown in some cases to greatly reduce the impacts. For example, gravel extraction is now focused on islands above the water level, or else a ‘lip’ is left between the running water and the deeper extraction areas. This has minimised the disturbance to the point that this work can now be carried out even during trout spawning season (David Spiers pers.comm. June 2011).

4.5 Forestry practices

The Logging Industry Research Organisation (LIRO) produced a Code of Practice (CoP) in 1990 outlining best management practices for forestry. The CoP was revised in 2007 by the Forest Industry Training and Education Council (FITEC) and a new code issued for NZ Forest Owners called The NZ Environmental Code of Practice for Plantation Forestry. There is an expanded section setting out industry best environmental practices. Individual companies also have their own Environmental Management Systems, incorporating aspects of the industry CoP, and helping them meet forestry certification under the Forest Stewardship Council system. Practices must then be implemented by the harvesting and engineering crews, responding to local conditions, where variability may arise (Robin Black; Hancock Forest Management pers.comm.). There have been several instances of abatement notices and infringement notices being issued for non-compliance with consent conditions (which refer to the industry CoP), particularly to forestry companies operating in the Coromandel (Grant Blackie, WRC, pers.comm. 2011).

The Ministry for the Environment released a proposed National Environmental Standard (NES) for Plantation Forestry in September 2010 and rereleased it in May 2011 following submissions. The stated intent of the proposed standard is to improve national consistency in local authority plan rules relating to plantation forestry, and to give certainty for those involved in the management of plantation forests (www.mfe.govt.nz/laws/standards/forestry/index.html). It covers the activity status and conditions that might apply to eight plantation forestry activities (afforestation, replanting, mechanical land preparation, harvesting, pruning and thinning to waste, earthworks, quarrying and river crossings). A key component of the policy is the development of an erosion susceptibility classification, used to identify land where forestry activities would be permitted or require resource consent. An effect of the NES is that regional council rules regarding earthworks cannot be more restrictive than the national standards. This may require revision of some current rules in the Waikato region, for example earthworks in forestry blocks may become a permitted activity under the NES (Grant Blackie, WRC, pers.comm. 2011). This raises concerns for parts of the region with high rainfall, erosion-prone soil and a sensitive receiving environment (e.g. Coromandel estuaries).

Forestry management practices range from planting designs including riparian buffers, through to harvest techniques, log removal, and slash management (Maclaren, 1996). Spreading harvest over several years or developing a ‘mosaic’ of harvested blocks in a landscape reduces the risk of large sediment inputs to estuaries due to mid-slope failures during storm events (Grant Blackie, WRC, pers.comm. 2011). Mitigation measures are available for both erosion control and sediment retention (Philips and Marden 2003). Erosion control measures include management of water flows (e.g. with contour drains and culvert flumes) and protection of exposed soil (e.g. by hydroseeding, mulching, riprap, erosion blankets, armoured water tables, brush layering, or surface roughening to encourage revegetation). Sediment control measures aim to prevent any eroded soil from being transported. They include silt fences, diversion channels or bunds, sediment traps, pits or retention ponds, and measures to reducing the hydraulic conductivity between roads and streams. Other mitigation measures are harvest planning including protecting steep slopes and water courses, road design and decommissioning, retention and enhancement of riparian vegetation and slash barriers and management (ibid).

Riparian strips can buffer the impact of forestry harvest. In the large-scale forestry harvest operations at Tairua studied by Quinn and Halliday (1999), where a 20m riparian buffer of mature redwoods was left, no changes were observed in stream temperature, water clarity, sediment particle size or periphyton biomass following harvesting, and there were minimal changes in invertebrate fauna. By contrast, in a nearby catchment where no riparian buffer was left after harvesting, there were marked changes in temperature and sediment levels following intense rain, and invertebrate communities were adversely affected. In another Coromandel study, stream channel widths were significantly wider at harvested sites without riparian buffers, whereas there was no difference between sites that were logged with buffers and unharvested pine and native forest sites (Boothroyd et al. 2008). Bank erosion was significantly higher in harvested sites without riparian buffers despite the greater percentage of grassed vegetation in the riparian area.

Management to promote grass growth along stream channels within pine forest is particularly important for pumice catchments (Dons 1987), to reduce sediment yield due to channel erosion.

Marden et al. (2007) found that natural recolonisation of indigenous groundcover species occurred at a similar rate as the spread of oversown exotic species following desiccation through spraying. They concluded that both species mixes therefore potentially attained a similar level of surface coverage and effectiveness against slopewash in an equivalent time, and that the incremental spread of groundcover from surrounding less-disturbed sites was also important for longer-term stabilisation. Where spraying does occur prior to replanting, then oversowing will help to speed the recolonisation of sprayed sites.

Leaving buffers around streams when harvesting forests was among the most cost-effective means of reducing sediment loss identified by the Waikato River Independent Scoping Study (NIWA 2010).

4.5.1 Economic drivers and other considerations for forestry practices

Sound environmental management in forestry may have market access benefits. For example, achieving Forest Stewardship Council (FSC) certification (requiring attention to environmental, social, economic, cultural and spiritual impacts of forestry activity) may help companies retain access to sensitive markets such as the US and Europe. Logs exported to China are often destined for further processing and on-sale to these markets, so FSC certification is also beneficial for export to China (Robin Black; Hancock Forest Management pers.comm.).

4.6 Pasture, soil and grazing management to control run-off

Grazing and pasture management are unlikely to greatly alter the incidence of mass movement under pasture (Hicks et al. 1993). However, pasture cover can affect the rate of surface erosion on grazed paddocks. Hicks (1995b) reports field trials showing that establishment of improved pasture on hill country reduced surface erosion by 50-80%, relative to unimproved pasture.

Hard grazing can result in greater sediment loss. A linear relationship has been found between sediment concentration in run-off and the amount of bare ground following grazing by cattle and by sheep (Elliott et al. 2002; Elliott and Carlson 2004). Smith (1987) showed a strong inverse relationship between grass length and sediment concentration in run-off from a Waikato sheep pasture. Sediment concentrations measured in run-off following sheep grazing can be 13-30 times more than concentrations in run-off samples taken before grazing (Elliott and Carlson 2004; Adams and Elliott 2006). The latter authors concluded that it is important to ensure good pasture cover to restrict the sediment generated by rainfall impact on bare ground.

Treading or pugging can expose more soil to erosion and increase run-off. Winter treading damage by cattle over 2-3 days was shown at Whatawhata to produce significant increases in sediment run-off, particularly on steep (>25^{o}) slopes and when soil surface damage exceeded 40% (Nguyen et al. 1998). Not only does treading increase sediment generation by exposing bare ground and physically eroding the soil, it also increases the volume of run-off by reducing infiltration rates (Nguyen et al. 1998; Elliott et al. 2002; Elliott and Carlson 2004). In Nguyen et al's (1998) study, the steep, damaged slopes had a 46% lower infiltration rate, and run-off from these areas contained 87% more sediment than undamaged areas.

Soils with treading damage caused by sheep recover faster than those damaged by cattle (Elliot et al. 2002; Elliott and Carlson 2004). Also, soils grazed by sheep in the post-treading period recover faster than those grazed by yearling cattle (Sheath and Carlson 1998). Therefore, cattle exclusion from paddocks with severe winter treading damage would be recommended.

Soil texture and organic matter content influence susceptibility to treading damage and compaction, while slope influences run-off rates (Nguyen et al. 1998). For example, Roach and Morton (2005) found that increasing stocking rates from 3 to 5 cows/ha had no effect on the quality of an allophanic soil in Taranaki, while Houlbrooke et al. (2009) found that even restricted grazing and no-pugging treatments resulted in some compaction and reduced soil macroporosity on a Pallic soil in Southland. Some authors have reported similar, or even less sediment loss from flat slopes after treading (e.g. Russell et al. 2001), because where the soil is only gently sloping, sediment can be trapped and retained in hoofprints.

Soil moisture at the time of animal treading is critical because soil strength is inversely related to soil water content (Climo and Richardson 1984). Sediment concentrations were found by Elliott and Carlson (2004) to be 2.5 times higher in winter than in summer for the same amount of bare ground. These authors concluded: "In winter, higher rates of run-off generation (low infiltration rates) will coincide with a higher likelihood of pasture removal (due to restricted feed supply), higher treading damage (due to softer ground) and higher soil erodibility. These factors are likely to lead to high contaminant loads in winter." Elliott and Carlson (2004) suggested that the practical implications are that winter is the critical period to manage feed reserves and stock numbers, and to monitor stock vigilantly to avoid over-grazing.

4.6.1 Economic drivers and other considerations for pasture, soil and grazing management

Treading can have a significant economic effect, as damage reduces subsequent pasture growth. On a heavy Te Kowhai soil under dairying, annual pasture production decreased 21% after moderate pugging and 45% after severe pugging (Menneer et al. 2001). Clover was affected by severe pugging more than grass (65% vs 38% respectively). N-fixation was shown to decrease 28% and 70% under moderate and severe pugging treatments. On a whole-farm basis, if moderate and severe pugging occurred on 50% and 10% of the farm respectively, modelling suggested this would represent a 16% decrease in milk production overall. In another trial, grazing strategies to minimise compaction on the Te Kowhai soil were compared (Drewry 2003). During the months of July to September, treatments that were ungrazed or never pugged had 35% and 28% greater pasture yields than conventional grazed pastures. A restricted 3-hour grazing treatment during times when soils were at risk of pugging resulted in better soil quality than conventional grazing, although this was not reflected in greater production. Based on studies like these and regional soil monitoring data, Environment Waikato (2010) estimated that lost production due to compaction could cost up to $200 million per year across the region.

The effect on pasture production is temporary, but timing may be critical. In hill country at Whatawhata, Sheath and Carlson (1998) estimated the reduction in spring pasture growth following treading damage was 5-10 kg dry matter/ha/day. Soil properties and pasture recovered and there was no effect from winter treading damage on growth rates from December onwards. However, these authors noted that reduced early spring pasture growth can significantly impact outputs, since this is a time when forage is at a premium.

Production impacts vary with soil type. Ledgard et al. (1996) measured pasture production on three soils after grazing on a wet day and found production on the Horotiu sandy loam, Te Kowhai silt loam, and Hauraki clay soil was depressed by 35, 45, and 80% respectively. On an annual basis, dry matter production was reduced by 2, 12, and 21% respectively.

Because soil properties differ, a key mitigation practice is farm planning that includes analysis of the strengths and weaknesses of the different soil types on the farm. If this guides paddock subdivision, it can allow similar classes of land to be used within their capability, as well as improving pasture utilisation. Sheath and Carlson (1998) recommend that animal type (species, weight, grazing behaviour) should also be aligned with soil resource condition. Grazing management should be adjusted for conditions (for example not grazing heavy soils when wet, not grazing cattle hard near waterways, or running lighter classes of stock in these situations). These actions can have economic benefits as well as protecting soils and waterways.

Standing stock off paddocks in winter can reduce sediment loss and protect pastures, and has other benefits for nutrient management. The economic impact of this practice depends on soil properties and climate. Monaghan et al. (2003) modelled the costs and benefits of standing cows off, including the cost of installing a low-cost pad ($100/cow). On a Pallic soil in Southland, an annual cash surplus of $17 000 a year was found for a typical Bog Burn 230-ha dairy farm where the pad was used 50 days a year (in addition to wintering off the farm). A smaller cash surplus of $3120 was generated for a Toenepi dairy farm on more robust soils in wet years (70 days standing off), with no cash surplus during average years (23 days standing off). Farmers interviewed about managing wet soils in Toenepi did not favour stand-off pads (Bewsell et al. 2005). Instead they tried to plan their grazing rotation so that soils prone to pugging were grazed in drier conditions, and they stood cows off in yards in wet weather or sometimes used sacrifice paddocks. These farmers did not perceive they had a macroporosity (soil compaction) problem.

Cost-benefit analysis of nil-grazing and restricted grazing by de Klein (2001) assumed that nil-grazing systems could increase the DM production of dairy pastures by up to 20% compared with a conventional grazing system, due to effluent being spread more evenly on the paddock and therefore used more efficiently. Even if this pasture boost could be realised and captured as production, her analysis suggested it could not provide a return on the capital invested in a herd shelter, feed harvesting and transport equipment and an effluent applicator. In contrast with the nil-grazing regime, restricted grazing systems were estimated to increase pasture production only 2-8% compared with a conventional grazing system, but lower capital and operating cost meant that this system did provide a return on capital of 5-9%.

Waikato dairy farmers were interviewed by Davies and Topperwien (2011) about their grazing decisions, in relation to recommended nutrient management practices. The farmers said their key aim in managing wintering practices was to ensure adequate feed through the winter. Some were focused mainly on avoiding pasture damage by stock in wet conditions, while others were also focused on managing a feed deficit due to slow pasture growth. The importance of protecting soils from damage depended on the susceptibility of their soils in wet weather. For example, Upper Waikato farmers on lighter soils were more likely to make decisions on wintering practices based on a pasture feed deficit than on the risk of soil damage. Farmers who do not currently winter stock off were considered unlikely to adopt the practice, either because they considered it unnecessary based on grass growth, or because they wanted to avoid the loss of control over the herd and cow condition. Other deterrent factors included the price and limited access to grazing in close proximity to the farm.

Farmers who kept their herds on the farm used a variety of strategies for standing cows off during wet periods. Those with more free-draining soils did not stand the herd off, but managed through the grazing rotation. The rest of the farmers used a mixture of yards, feed pads and stand-off pads to alleviate pressure on wet pastures. Four of the 36 farmers interviewed stood cows off on sacrifice areas, including crop paddocks, steeper hill country, holding paddocks and paddocks due for pasture renewal. Some farmers said they did not need a stand-off pad. Only five of the 36 farms interviewed had feed pads. These were usually incorporated to increase production flexibility (choosing when to dry off), to reduce wastage of supplements, to manage pasture in wet weather, to improve animal health, for control and flexibility with feed (e.g. in droughts) and to improve calving condition and rates. Feed pads involved greater workload, but some farmers said this was compensated by the reduction in feed waste. Farmers who chose not to use feed pads cited the extra work involved, difficulty in attracting labour to work with these systems, construction and running costs, and visual and environmental impacts. They believed that it was only financially viable to run this sort of system if you were a top-producing farmer.

Ten farmers with herd homes in Northland or Southland were interviewed about their reasons for purchase (Longhurst et al. 2006). They reported ease of farm management ('peace of mind' at having somewhere to put the herd in wet weather or flooding), and ease of feeding out without wastage, meaning feed quantities were reduced. Time was saved by not having to cart silage round the farm or clean yards after standing off (as herd homes have slatted floors for manure to drop through). They also reported less pugging damage with on-off grazing, and an increase in pasture (60% of farmers reported at least 20% more pasture being saved). Other pasture benefits were better composition, more control of grazing and an ability to build up a feed bank. Farmers also reported more content stock and improved stock condition (90% said that cow condition scores improved by 0.5%). Farmers also used the herd home for other purposes including calving, assessing stock condition and drafting. These farmers had only owned their herd homes for one season but did not report any stock health issues, other than the potential for smaller calves to get their feet stuck in the bare grating.

The catchment land use project at Whatawhata involved retiring steep land and intensifying pastoral farming on the gentler country. Part of this involved a shift to Friesian-cross bulls purchased at 6 months old in autumn and sold at 18 months before their second winter (Quinn et al. 2007). This served to reduce the amount of heavy stock carried over winter when erosion risk was highest. With an increase in tactical use of urea, beef productivity increased from 86kg LW/ha to 209 kg LW/ha, and sheep production figures also increased. However, at the farm scale, the annual surplus declined due to the extent of pasture area retired (Dodd et al. 2008).

In field trials reported by Hicks (1995b) improved pasture on hill country reduced surface erosion and enabled increases in stock carrying capacity from 2-7 units/ha up to 8-12.

Therefore, reductions in soil loss from surface run-off can be achieved by farm subdivision that follows land classes, choice of stock type for different areas of the farm and for seasons, improved pasture and careful management of feed and grazing over winter. These practices can often be expected to have some economic benefits.

4.7 Track design and management

Tracks in pasture and in forestry can produce high concentrations of sediment in run-off. The extent of run-off from tracks is affected by the proximity to waterways, slope, stability of cuttings and frequency of use. Designing regular cut-offs into vegetated ground before flows become strong enough to be highly erosive is a key means to reduce sediment from these sources (Quinn et al. 1999). At the design stage farm tracks and lanes should be located away from waterways and drains wherever possible (Smith and Monaghan 2009). Monaghan and Smith (in press) noted that the laneway site in their study which yielded the greatest volume of overland flow had a concrete surface, where on average 41% of total annual rainfall was measured as overland flow passing through the collector. In contrast, as little as 6 and10% of total annual rainfall input was measured as overland flow at sites where the laneway surface consisted of very soft, porous fines. This suggests that permeable surfaces reduce run-off, and that drainage from hard surfaces needs to be captured and directed away from waterways. The use of raised berms alongside lanes and on bridges and crossings can be used to divert run-off to paddocks.

4.8 Silt traps, drains and wetlands for sediment deposition

Sediment traps can be incorporated into drains to reduce water velocity and promote the settling out of coarse sediment (Environment Waikato 2007b). They need to be excavated frequently as they fill up, but this can reduce the need for drain cleaning downstream. Trials of a simple silt trap located alongside a race at Lake Rerewhakaaitu indicated that around 30% of sediment in the run-off was removed (Parker 2009). Further research is underway on sediment removal from silt traps that have been installed at Lake Kaituna, but results are not yet available (Rebecca Eivers, University of Waikato, pers.comm.).

At low flows, wetlands also act as sediment traps. Studies of the Okaro wetland, which was designed to remove nutrients, showed that the wetland retained 50% of Total P in the in-flow (Hudson et al. 2009), which is indicative of sediment settling (James Sukias, pers.comm. April 2011). A review of 57 wetlands for P removal (Fisher and Acreman 2004) found that 84% of them reduced P loadings, by a mean of 58%. In a natural headwater wetland at Toenepi occupying 1% of its catchment area, 95% of P in the in-flow was retained over three years. This was attributed to effective trapping of particulates along the narrow wetland path length of 360m (Wilcock et al. 2011). However, Nguyen et al. (1999) found that sediment retained in small hill-country wetlands at Whatawhata was washed out when surface flows exceeded 75 m^3/day. Over wet periods, then, wetlands may become a source of fine SS and particulate organic matter accumulated over time in the wetland. These authors suggested that to enhance wetland effectiveness, the use of additional buffer zones in the upper catchment and in the wetland's riparian zone could help trap particulates and reduce water flows by promoting infiltration.

It is also important to exclude stock in order to reduce exports of contaminants from wetlands. One study in the Taupo catchment (McKergow et al. 2007) found that one day of stock activity in a small seepage wetland contributed as much nitrogen export as nine days of baseflow with stock excluded. Much of this was organic nitrogen, with likely sources being wetland soil and dung. Turbidity was closely correlated to organic N and Total N concentration in this study.

McDowell (2008) showed that former deer hollows, once retired, acted as effective sediment traps and reduced suspended sediment in the stream by 98%.

In predicting the effects of mitigation practices in the Bog Burn, Quinn et al. (2010) suggested that converting 1% of catchment area to wetlands and using these areas to treat sub-surface drainage waters could reduce sediment by 58% (as a high proportion of farm drainage in that catchment occurred through artificial drains). However, this mitigation action had the highest impact on farm earnings. If wetlands are located at the bottom of the catchment, farmers with these properties have to retire large parts of their farms. An alternative is to create wetlands at various points in the catchment. Headwater wetlands are currently being trialled at Toenepi.

Farm drains should be fenced from stock to avoid sediment entering the drain and to minimise the need for drain cleaning (Environment Waikato 2007b). Clearing vegetation by spraying reduces the need for excavation and lowers drain cleaning costs. During drain cleaning, a buffer of weed at the lower end of the drain can be left to trap silt, which can then be dug out last.

Overseas, creating large grassed waterways to act as drains in cropping paddocks has been shown to reduce sediment delivery by 77-97% (Fiener and Auerswald 2003). The waterways were extensive (650m long and 10-50m wide). Without the waterway, sediment yields were 312 kg/ha/yr, compared to 16 kg/ha/yr with the waterway. The authors reported that the mechanisms were primarily infiltration of run-off during small events, and slowing of run-off allowing sediment to settle out. Filtering by plants was not considered important. Effectiveness was increased where the grassed waterway was larger in area, had long, gradual-sloping side walls, and a flat bottom.

The use of drains filled with slag to enhance P entrapment has also shown significant reductions in sediment in the outflow from the drain (McDowell et al. 2008).

4.9 Crop management

Crops represent a potential for sediment loss, both due to soil exposure during tillage, and also at the time of grazing (for forage crops). In one Australian study, cultivated land was found to export 84 times more sediment than pasture land (Wallbrink et al. 2003). Losses of sediment from crop production will depend heavily on management factors such as the gradient of cultivated slopes, cropping in vertical rows up a slope and leaving soil exposed during periods of high rainfall (Monaghan et al. 2010). Conversely, practices such as cover crops, contour ploughing, minimal tillage/ direct drilling and cultivation setbacks from waterways can help to decrease losses.

Wheel track management is a critical factor in market gardens on the clay soils of Franklin, as cultivated beds themselves can absorb a lot of rainfall without erosion occurring (Basher and Ross 2001). Wheel tracks have low infiltration rates and rainwater travels along the tracks, eroding the sides of the beds. Ripping of wheel tracks is a simple and effective mitigation practice to increase infiltration, reducing erosion rates by up to 95% (ibid). The use of improved soil management techniques in market gardening was the most cost-effective means of reducing sediment loss identified by the Waikato River Independent Scoping Study (NIWA 2010; Appendix 9: Farms). This assumed that the cost of implementing the practice was fully balanced by the value of the topsoil retained. The value of nutrients in the topsoil lost due to erosion in Franklin District has been estimated by Edmeades Consultants (2002) at $1-20/ha/yr lost from the catchment, and $35-570/ha/yr lost at the paddock scale (but redistributed within the catchment). Basher and Ross (2002) reported that growers they spoke to were not concerned about the economic impact of soil erosion and down-slope redeposition, as any production effect can be masked by fertiliser use.

Suspended sediment has been shown to increase 10-70% downstream of forage crop paddocks in Otago (McDowell 2006). Sediment loss can increase 25% following treading during forage grazing, and compared to an ungrazed cultivated plot 167% more sediment can be lost where treading during forage grazing has occurred (McDowell et al. 2003).

On-off grazing is one suggested strategy to reduce sediment losses from forage crops on susceptible soils (Drewry and Paton 2005). This involves grazing cattle for 3-4 hours and then removing them to a stand-off area. Australian studies have shown cattle can eat 80% of their total intake in the first four hours of grazing (Ward and Greenwood 2002). Drewry and Paton (2005) also suggested that using a back-fence when strip-grazing a fodder crop may be beneficial, though to a lesser extent than restricted on-off grazing.

The New Zealand studies of forage cropping have all been done on Pallic soils of Otago and Southland which are more prone to compaction than most Waikato soils. The findings are also more relevant to those regions because of the prevalence of winter forage-cropping practices.

5 What can be achieved through catchment-scale work?

Overseas, a catchment-scale riparian project in Vermont excluded stock from 49% of pasture streams and achieved a 34% reduction in sediment concentration in run-off and a 28% reduction in sediment export, measured over a 3-year period (Meals 2001).

A combination of riparian protection with erosion protection work in the catchment of the Ngongotaha stream saw sediment loads reduced by 84% (Williamson et al. 1996).

5.1 Waitomo Landcare

In the Waikato region, the effect of catchment works at Waitomo was reported in Hill and Quinn (2010):

"To reduce sediment loads and improve water quality, a landcare group was formed involving the community and a number of national and local agencies. During the 1990s, the group funded more than 60 km of fencing in the catchment (area about 30 km^2), excluding stock from about 6 km^2 of native bush, 20 km of streams and wetlands, and 3–4 km^2 of slip-prone land. In addition, the group has facilitated riparian planting and land retirement. Sediment monitoring was established to assess the extent to which these mitigation measures have reduced the sediment load conveyed by the stream. Stream flows have been continuously recorded in the Waitomo Stream at Ruakuri Caves bridge since 1984. Eighty-five depth-integrated sediment samples were collected there during run-off events in 1990–99, and 29 sets of samples were collected by automatic sampler during freshes in 1997–2000. The depth-integrated samples demonstrated that the concentration of suspended sediment for a given flow rate had declined by about 40%, much of this occurring over the period 1990–94. Even though large loads were conveyed by severe floods during the winter of 1998, the monitoring results indicated that the load would have been much higher without the land management programme. These results indicate that the landcare programme has been effective, confirming local observations that the stream was cleaner, carried less sediment, and had become visually more appealing. The cost of removing sediment from the town water supply was also reduced."

In spite of the reduction in sediment, trend analysis by Dr Deborah Ballantine at NIWA (reported in NIWA 2010) showed no significant change in turbidity over time in the Waitomo stream, possibly because of ongoing fine sediment supply.

5.2 Whatawhata catchment project

Further catchment-scale understanding has come from the land use experiment at Whatawhata (NIWA 2007; Hill and Quinn 2010). In 2001, the steepest part (58%) of the Mangaotama was converted from pasture to pine forest, riparian areas were protected by either fencing out cattle and planting poplars or fencing out all livestock and planting natives, and stock type was changed to better match the remaining pasture production and to avoid carrying heavy stock in winter. (This involved a change in the beef operation from cow breeding to a bull-rearing operation, with animals sold at 18 months of age). An intense storm (50-year return period, 97 mm in 4 hours) demonstrated the benefit of the pine plantings for erosion control. Aerial observations found 15 landslides per 100 ha on the land in pasture compared with just 1 per 100 ha in the area with six year old pines (Quinn et al. 2007). Annual sediment yield was reduced by an average 76% for the four years after these changes were introduced compared with the four years prior (ibid). Further analysis of data up to the end of 2010 has confirmed a significant decline in suspended sediment, with medians dropping from 7.30 to 4.65 g/m^3, and a corresponding decrease in turbidity from 8.40 to 6.45 NTU (Hughes and Quinn 2011). There was also a statistically significant increase in clarity measured by black disk, with median clarity rising 29% from 0.75 m to 0.97 m after the catchment changes (ibid).

The changes at Whatawhata also improved some indicators of economic performance (e.g. an increase in lamb and beef productivity and in the per hectare financial returns of the pastoral component). However, the returns at the system level were lower overall over this time period - because of the area retired there was less total revenue from pastoral production, despite a per hectare increase. The higher returns from plantation forestry are delayed, and thus the transition costs become prohibitive unless changes occur over a longer timeframe, or are supported by an outside source of capital (Dodd et al. 2008).

5.3 The "best dairying catchments" experience

The "best dairying catchments" were designed to promote and study changes in practice at the catchment scale in five dairying catchments throughout New Zealand. At Waiokura in Taranaki, statistically significant trends during 2001–08 were found for decreasing concentrations of suspended sediment and turbidity (Wilcock et al. 2009). Yields of suspended sediment declined 25-40% even though water yield and farming intensity increased in the same period (Shearman and Wilcock 2011). Calculations for the Waiokura catchment indicate that the flow-adjusted black disc water clarity increased between May 2001 and February 2011 at a rate of 0.03 m/year. That is, over 10 years there has been a 0.3 m increase in clarity from approximately 0.45 m in 2001 to 0.75 m in 2011 (Bob Wilcock, NIWA, pers.comm. 2011). Changed practices included a reduction in dairy pond discharges from eight to six and an increase in effective stream fencing in the catchment. Most of the farm plans were put in place since 2003, and between 2004 and 2009, 15 km of streambank fencing was carried out, representing an increase in protected streambanks from 45 to 54% (D. Shearman, pers.comm.). Waiokura sediment was mainly attributed to streambank erosion, and while a significant proportion of the streambank length remains unprotected, there has been a focus on riparian fencing and planting vegetation in the stream reaches near Skeet Rd, where 60-90% of the sediment was entering the stream (Shearman and Wilcock 2011).

In the Waikato "best dairying catchment" at Toenepi, an increase in visual clarity was measured between 1995 and 2004, and suspended sediment yields dropped from 142 kg/ha/yr averaged over 1995-97 to 67 kg/ha/yr in 2002-04. However, this was mainly thought to result from lower rainfall and hence lower sediment yields. There may also have been an effect from protection of stream banks from stock trampling, or increased trapping by macrophytes (Wilcock et al. 2006), but verified stream fencing data are not available for the period. Sediment yield continued to drop in 2004-06 to 38 kg/ha/yr (Wilcock et al. 2007), although mean suspended sediment concentrations increased between 2001 and 2006. This was attributed to cattle in the stream channel causing elevated suspended sediment values at base flows on two occasions.

The comprehensive catchment identification of issues and best management practices through the dairying model catchments has highlighted the fact that the solutions for managing water quality will vary according to local characteristics. According to Monaghan et al. (2003): "It would seem desirable that any suite of dairy farm BMPs is tailored and prioritised according to (i) the dairy farm management systems practised, (ii) the particular combination of physical resources, such as soils, rainfall, irrigation, topography, etc. present within each catchment, and (iii) the regional sensitivity of the receiving water body." In devising measures to reduce sediment, farming systems, sediment sources and mitigation opportunities and other water quality issues should be considered in an integrated catchment approach.

5.4 Modelling for the Waikato River catchment

The Waikato River Independent Scoping Study (WRISS) (NIWA 2010) identified actions that could be taken to achieve outcomes for the restoration of the river, including sediment reduction.

The costs of implementing selected actions throughout the catchment were estimated (see Table 12 for actions relevant to sediment).

Table 12: Estimated costs (capital and operational) for some key restoration actions to reduce sediment in the Waikato River catchment*

Restoration action	Cost ($M)	Comments and impediments
Dairy farms		
Run-off diversion (from laneways)	5	
Create wetlands over 1% of catchment	45	Requires incentives, information, design
E-fence and plant 5m buffers on all streams	263	Requires incentives, information, plants
Herd shelters for wintering stock	1090	High cost (capital and operational)
Dry stock farms		
Fence (single electric wire) and plant poplars on 1st and 2nd order streams	93	Requires incentives; high stream density
Fence (8-wire) and plant 10m native buffers on 3rd order and larger streams	66	Requires incentives, information, plants
Retire and afforest 68,000 ha of steep pasture	91	Cash flow issue. Excludes harvest income, carbon price
Forestry		
Leave uncut forest buffers on streams	225	

Source: after NIWA 2010:139; 186-7

*** Costs for controlling mass movements and river bank protection works were not available**

The study modelled the benefit of selected packages of actions (Scenarios 1-3). Actions in these scenarios that are relevant to sediment reduction are described in Table 13 below.

Table 13: Estimated sediment loss reductions for scenarios of restoration practices in the Waikato River catchment

Scenario	**Sediment- related practices**	**Estimated reduction in sediment***
1. (Current rules and accords fully implemented + some extra practices at low cost)	*On dairy farms*: Improved effluent management, and full exclusion of cows from streams.	Free-draining farm – 15% Poorly-draining – 15% Peat farm – 7%
	On sheep and beef farms: Trough water and shade away from streams, stock exclusion from inanga spawning areas and priority lake margins.	Not included in Appendices
2. (Additional restoration actions)	*On dairy farms*: As above plus wetlands installed on 1% of farm area, 5m buffers on streams, berms on laneways to direct run-off away from streams.	Free-draining farm – 51% Poorly-draining – 52% Peat farm – 77%
	On sheep and beef farms: As above plus fencing cattle out of streams and planting poplars on both stream banks.	18% (fencing cattle but not planting poplars) 34% (with poplars)
3. (More comprehensive restoration)	*On dairy farms*: As above plus winter herd shelters.	Not included in Appendices
	On sheep and beef farms: As above plus pine afforestation of 60% of pasture on SB3 and 25% of SB4 farms (as defined by Meat and Wool NZ); fencing (8-wire) and planting 15m native buffers.	40% (15m buffers) Afforestation reductions not included in Appendices

Source: after NIWA 2010:Main report and Appendix 9: Farms and Appendix 13: Water quality
*** These are catchment-scale reductions if these actions are 100% implemented, assuming these practices are already implemented over part of the catchment**

Modelling and cost-benefit analysis indicated that Scenario 1 (limited additional expenditure) would not meet the aspirations for the river. Under Scenario 2 (some additional restoration actions), progress would be made towards restoring the health and wellbeing of the river with a broadly neutral economic impact (when considered at regional and national scales). Scenario 3 added high cost actions and the national economic cost was high, with some further gain for the river. None of the scenarios achieved the bathing water clarity guideline of 1.6 m in the lower Waipa and lower Waikato Rivers, although pasture retirement was predicted to increase clarity from 0.7 to 1.0 m in the Waipa, and from 0.7 to 0.9 m in the lower Waikato. However, the study team did not include in the modelling the effects of retiring and replanting stream banks. The study team reported that even in fully forested conditions, stream clarity would have averaged only about 1.9 m, ranging from 1.3-3.2. Therefore, natural erodibility of the geology constrains the ability to achieve bathing water clarity standards under pastoral use. They cite the example of the Kaniwhaniwha, draining Pirongia, which is only 38% pasture but has baseflow clarity of 1.2 m, compared to a nearby forested stream with clarity of 3.2 m.

6 Policy options

Erosion has a cost to the wider public as well as to landowners. At a national scale, Jones et al. (2008) estimated that of the total cost of erosion in New Zealand:

- ~ 30% is due to agricultural production loss,
- ~ 30% is due to damage to property and infrastructure,
- 21% is due to off-site sediment effects, and

- 19% is the cost of soil conservation and other avoidance measures already in place.

A policy response can attempt to address the wider impacts of erosion (including off-site damage to property and infrastructure and sediment effects), which are otherwise externalities to farmer decision-making. This may occur by encouraging action through education or a subsidy for works, or by discouraging activity through a rule. The context for voluntary adoption, and encouraging this through education, is reviewed below. Other policy options such as incentives and regulation are then considered, and the range of initiatives taken by regional and central government are summarised.

6.1 Education and voluntary adoption

In a comprehensive review article, Pannell et al. (2006) conclude that adoption depends on a range of personal, social, cultural and economic goals, as well as on characteristics of the innovation itself. Perceptions about whether to adopt an innovation span three broad sets of issues:

- The characteristics of the practice
- The characteristics and circumstances of the landholder within their social environment
- The process of learning and experience.

Rather than promoting adoption through communication, education, and persuasion activities, these authors argue for ensuring that innovations are 'adoptable'. Adoptable practices are those that address the issue, are readily trialled within the existing farm system, help achieve farmers' goals and/or are economically preferable to current practice. If a practice is not adoptable, then communication and education activities will simply degrade the social standing and credibility of the field agents of the organisation. The learning process about the innovation can be enhanced through availability of information about its practical relevance, and the ability to integrate this by applying it to the farmer's own situation.

Most of the practices relevant to soil conservation can be integrated readily into existing farm systems and have been trialled on farms over decades. A shift into large-scale forestry may require higher investment and new skills, but riparian fencing, adjustments in stock classes or grazing practices and pole planting are readily incorporated into an existing operation. The economic and practical impacts of each of these have been presented above. Some of these practices have benefits from a farm system perspective. However, the lack of strong economic drivers and/or the cost barrier for their adoption is the reason why grants have been generally available to promote these practices.

Influences on decisions about up-take were investigated by Bewsell et al. (2005), who interviewed farmers in the "best dairying catchments". They found farmers' decisions about environmental practices are primarily based on a pragmatic evaluation of options available to them, with regard to the commercial and practical realities they face. Choices were not strongly influenced by attitudes to sustainability and the environment, suggesting that appeals to these values will be ineffective. Promoting a "one-size-fits-all" solution is also unlikely to be successful. Instead, they suggest that demonstration of practical benefits strongly linked to farm context is critical. Farmers in their study did acknowledge that there may come a time when they have to demonstrate environmental practices to the market or supply chain; but this was seen as a future concern. Only the dairy farmers in Canterbury cited external pressure as a reason for improved practices.

Rhodes et al. (2002) investigated factors influencing the adoption of riparian fencing, drawn from the survey responses of 278 Otago and Southland pastoral farmers. Positive, but weak relationships were found between information exposure and three factors: attitude, knowledge, and adoption of riparian fencing. Informed farmers were more likely to report intentions to carry out riparian fencing or planting within the next year. Farmers who were aware that funding was available were also more likely to state this intention, independent of information exposure.

The source of the information is important, and exposure to working examples of farms, or information from other farmers can be particularly powerful. Evaluation of the Australian Landcare programme (Curtis and DeLacy 1998) showed a positive effect of participation on knowledge as well as attitudes and behaviour. Other comparisons of users and non-users of information sources have shown no difference in adoption of a range of sustainable land management practices (Nimmo-Bell 1999).

While attitudes and knowledge do not always lead to changes in behaviour, they are prerequisites for change to occur. In other words, awareness of the existence of a problem, and knowledge of appropriate strategies to address it, are essential, but not sufficient, factors for action to occur (Hines et al. 1987).

Resources are another important prerequisite. In Rhodes et al.'s (2002) study, farmers identified financial factors as the most influential barrier to adoption of riparian fencing, while the third most common response was that water quality was not a problem. These authors concluded that provision of economic incentives was at least of equal importance as environmental education to influence the landowner's decision-making process. While information in their study was positively associated with initial adoption of fencing, the *extent* of work done on the farm to exclude stock was related to receipt of funding, but not to information level. This is consistent with other studies which have found that financial incentives increase the *rate* of adoption rather than the *number* of adopters (Pannell et al. 2006).

6.2 Financial incentives

In this region, financial incentives for erosion control have come through historical catchment schemes, targeted rating (e.g. Project Watershed) and the investment fund (Clean Streams).

Extensive work has been carried out by the regional council in the past to apportion the private and public benefit from soil conservation and catchment control schemes as part of scheme reviews and rate-setting exercises.

The Project Watershed funding policy (Environment Waikato 2002) reviewed the benefits, contributors and cost allocations that should apply to the regional council's soil conservation works. Soil conservation work is seen to have direct benefits to the landowner in terms of:

- Preventing the loss of pastoral production as a result of erosion and debris deposition
- Preventing damage to farm infrastructure
- Timber production benefits
- Farm/stock management benefits arising from retirement fencing.

The funding policy sets the landowner contribution for soil conservation work at 55-65%, depending on the zone. Pastoral landowners are also considered as contributors to erosion issues, and this level of cost allocation is set at 2-3%.

In a review of the Middle Waikato zone, Ritchie (2005) reported that farmers thought grants were appropriate because of the public benefits, and because finance is the biggest barrier to doing soil conservation and riparian work. Farmers also valued the direct contact with staff that came through the grant application process.

To varying degrees over time, central government has also had a role in funding soil conservation work, now mostly targeted at severely eroding land. The current Sustainable Land Management (SLM) Hill Country Erosion Programme focuses on building the technical capacity of regional councils and providing targeted funding for catchment initiatives. Councils can apply to a fund of $2 million per year, and to date there are projects in Manawatu/ Wanganui, Taranaki, Hawkes Bay/ Gisborne, and Wellington. Another $250,000 is used for capacity building initiatives, which includes $200,000 for establishing or enhancing catchment facilitation groups and $50,000 for training initiatives. The East Coast Forestry Project is another central government project that arose after Cyclone Bola. Over time this has evolved from a land purchase scheme to a subsidy based on a tender process, and is now a grant linked with a rule (see Regulation, below).

6.3 Farm plans and catchment management

Many regions address sediment issues through farm plans. Douglas et al. (2008) report on regional councils' approaches to farm planning as follows:

- Following the storm in Manawatu/Rangitikei in 2004, Horizons Regional Council has developed the Sustainable Land Use Initiative (SLUI) to address the region's soil erosion. A key component of the programme is to prepare 1500 whole farm plans over ten years, with 50% of them on the most at-risk land for erosion. The plans have a flexible subsidy rate and include physical, farm management and business plans.
- Greater Wellington provides farm plans and subsidised works, focused on erosion-prone areas. An objective is to establish 200 ha of forest woodlots per year and 400 ha of willow and poplar plantings a year. There are two types of plan – a Conservation Plan focused on soil conservation works (300 exist so far; there is a 30% subsidy for work) and a Sustainability Plan which is longer term and also looks at production from various land units and scenarios for income from forestry (25 in existence, 40% subsidy applies).
- Hawkes Bay Regional Council prepares plans aimed at sediment control, nutrient run-off, biodiversity and profitability.
- Taranaki Regional Council prepares farm plans to address soil erosion but offers no subsidy. Farmers have plans prepared for free, and can access advice from regional council officers. The implementation target of the Sustainable Land Management Programme is to cover 15,000 ha/yr and to cover 50% of the region's hill country in ten years (143,000 ha). The plan identifies soil conservation work for the whole property, and then during an annual follow-up visit specific works are costed, including production information, so that financial implications can be established. As at 30 June 2010, a total of 301 farm plans and 36 agroforestry plans had been completed, which together cover 186,605 hectares or 61% of the privately owned land in Taranaki hill country (Taranaki Regional Council 2010).
- Taranaki Regional Council also promotes voluntary Riparian Plans, and has prepared 2334 plans covering 95% of dairy farms and 12,428 km of streambank (Taranaki Regional Council 2010). In addition, 1.9 million plants have been supplied to farmers at cost under this scheme (Shearman and Wilcock 2011). Implementation is monitored by annual visits or contact to assess progress and discuss issues. Up until the 2009/2010 year, landholders had fenced 1,383 km and planted 769 km through implementing the riparian plans. Taking existing fencing and planting into consideration, this means 68% of stream banks are fenced and 59% planted. This degree of work has not been reflected in any significant trends in sediment across the whole region shown in State of the Environment monitoring (although some catchments like Waiokura have had significant changes). However, over the period 1995 -2007 there was a statistically significant positive trend in the Macroinvertebrate Community Index (a biotic index of stream health) at 17 of the 51 stream sites monitored regularly in the Taranaki Region, and no sites showed significant deterioration (Taranaki Regional Council 2009). This suggests that improved land and riparian management have been effective in managing some ecological impacts on streams in this region during a period of dairy intensification.

There have also been initiatives to help farmers identify differences in their land types and soil resources, so that they can better match their pastoral and tree-farming enterprises to land resources. An example of this is SUBS (Soils Underpinning Business Success) (Mackay et al. 1999).

While farm plans look at sediment generation, a further step can be taken to map out opportunities for attenuation. Tools are under development to help farmers assess where run-off is generated on the property, the main pathways for water flow, and options for attenuation (McKergow and Tanner 2011).

In monitoring the effectiveness of farm planning initiatives, Douglas et al. (2008) found that council staff recorded actions taken by the farmer, and monitored changes in vegetation cover and soil intactness surveys as part of State of the Environment monitoring. These authors recommended further monitoring of the effectiveness of works undertaken by recording, in addition to vegetation type and area, the age (from planting records) and canopy cover (from aerial photos). For space-planted trees, at least one on-site measurement of trunk diameter was recommended, because trunk diameter is directly related to root mass, and tree growth rates vary markedly, meaning that age is not a good indicator of size.

These measurement parameters can be linked to sediment loss through models. In one farm plan example from the Horizons region, Douglas et al. (2008) modelled the expected sediment loss under current land use at 2640 t/yr from the farm. Following a five-year programme entailing 860 space planted poplars, 140 poplars for gully control and afforestation of 30.6 ha, the sediment loss was expected to steadily decline to 820 t/yr after around fifteen years (close to a 70% reduction). This represents the amount of sediment eroded, not all of which is expected to reach waterways. Dymond et al. (2010) projected that if 500 farm plans were fully implemented in the Manawatu catchment, and a reduction of sediment of 70% were achieved, clarity in the middle Manawatu would rise from 0.9 to 1.8m. A catchment approach is supported by Brown (2004, cited in Environmental Communications Ltd 2010), who found that significant gains can be made at the property level through farm planning approaches, but that the most comprehensive gains can be made through a combination approach involving individual environmental farm plans set within an Integrated Catchment Management (ICM) framework.

A review of ICM approaches in New Zealand (Environmental Communications Ltd 2010) concluded that thus far, these approaches have not shown measurable outcomes in terms of land and water use indicators, partly because of a lack of measurable indicators, and partly due to the long timeframes required to show change. However, catchment-scale approaches theoretically offer scope for systematically addressing issues. According to Quinn et al. (2009b), "effects-based, systems approaches, that link farm management (including economics) to protection of key aquatic values, are likely to provide the most effective way forward to managing agriculture-aquatic interactions. This involves synthesis of knowledge on agroecosystems, hydrology, mitigation tools, aquatic ecosystems and human values."

In addition, Jones et al. (2008) recommend targeting policy responses to locations with a high economic value at risk from erosion, overlaying indicators of economic value over physical data. This can form part of catchment planning.

Industry Environmental Management Systems (EMS) are a voluntary approach which can have some of the rigour of regulation, depending on the degree of auditing and whether they are linked to conditions of supply. The sheep and beef sector has developed Land and Environment Plans; however the formal monitoring and auditing systems are not well developed and uptake has been slow (Paterson and Dewes 2011). The dairy sector has yet to release an industry self-management system, and sediment is unlikely to be a strong focus. Paterson and Dewes reviewed all sectors' progress and concluded that "all have major challenges ahead if they are to step up to ‘audited self-management’ in the context of provision of credible, transparent and demonstrable on-farm EMS”.

6.4 Regulation

Apart from requiring consent for earthworks and activity associated with forestry, sediment has not generally been managed through regulation. In earlier days the Soil Conservation and Rivers Control Act 1941 (superseded by the RMA) included the ability of former catchment boards to implement bylaws and to use Section 34 to control activities on land. In recent times, regulation specifically targeted at erosion and sediment reduction has been initiated by Gisborne District Council (GDC). The Proposed Combined Regional Land and District Plan (October 2009) outlines the approach.

Land use classifications across the District are shown in a series of overlays. Land Overlay 3 shows land in LUC Classes VII and VIII, the most susceptible to erosion, sediment generation and soil loss. Land Overlay 3A shows these areas mapped at a closer scale (1:10000), through field mapping, to accurately identify the land with worst erosion potential. Rules in Section 6.10 require that a sustainable hill country works plan be prepared for all such land by July 2011, and effective tree cover established by 2021. A template for a works plan is available on the website. The plan must be certified by the GDC and reported on annually. The regulation is contingent on ongoing availability of the East Coast Forestry Project (ECFP) grants, which apply to all land in Land Overlay 3A. Should the government retract the ECFP, the rule will cease to operate. Initiatives to encourage voluntary work have been in place in Gisborne for 40-50 years, so the rule is seen as a way to deal with the last remaining properties (Randolph Hambling, MAF Gisborne, pers.comm. June 2011). Extensive consultation was carried out prior to introducing the rule, including personal contact with farmers, and the rule went through without appeal (Trevor Freeman, GDC pers.comm. June 2011). The strength of the detailed field mapping process and staff time dedicated to working through the works plan with the largest properties have also been important. GDC staff do not address farm economics, other than assisting those farmers who wish to apply for the grant.

There have been few other attempts to regulate sediment-related activities of a diffuse nature. Priority catchments for livestock exclusion under the Waikato Regional Plan are an example of a regulatory policy which would be expected to reduce sediment loss, amongst other outcomes, if fully implemented and enforced.

Environment Canterbury has recently introduced a rule (Rule WQL 21) which will prohibit stock access to waterways in “intensively farmed land” from June 2012. The rule applies to wetlands and the beds of intermittently flowing rivers.

For the purpose of this rule, intensively farmed livestock is defined as:

1. Any stock grazed on irrigated land in or adjacent to the bed of a river or lake
2. Dairy cattle
3. Farmed pigs
4. Farmed deer
5. Livestock contained for break-feeding in or adjacent to the bed of a river or lake.

The explanation states:
"In areas where stocking rates are high, livestock are to be excluded from rivers and lakes. Under low stocking rates, such as occur under extensive grazing, the effects on water bodies are likely to be minor. As stocking rates increase, there is a greater risk of a decline in water quality, along with physical and ecological damage to water ways, riparian zones and downstream water bodies. The threshold - ‘intensively stocked’ - is based on several criteria, focusing on animals that exhibit a behavioural preference for water and activities that involve high stocking rates.” (Further discussion on the definition of intensively farmed land can be found in the NRRP Decision Report 34).

Environment Southland has had a stock exclusion rule for intensive winter grazing in place since May 2008. Under Rule 17 of the Water Plan, grazing or access of stock within 3 metres horizontally of water in a lake, river, modified watercourse, stream or artificial watercourse, when intensive winter grazing is being undertaken is a non-complying activity. This applies to all classes of stock.

Policies aimed at nutrient reduction where phosphorus is included, such as Horizons' One Plan and the Rotorua lakes Rule 11 could also result in sediment reduction. For example, the Bay of Plenty Regional Council website (www.boprc.govt.nz/environment/water/rotorua-lakes/rule-11) says that property owners could balance out extra stock numbers by planting and fencing off streambanks. This would have a beneficial effect on sediment loss.

Nutrient management regulations rely on models to establish the level of nutrient losses. If the regulations are tied to the results of the models, then sediment practices will be encouraged only to the extent that they are covered in the nutrient-loss models. The OVERSEER model for phosphorus takes into account some of the factors that affect overland flow such as soil type and rainfall (McDowell et al. 2005). It also considers grazing intensity, including stocking rates, the degree of pugging and use of areas like sacrifice paddocks and fodder crops (David Wheeler, AgResearch, pers.comm. June 2011). It has a riparian module, which reports on the effectiveness of filter strips at the block level, but not at the farm level. Riparian effectiveness is not included in the farm's P budget or reported P-loss. There are some other limitations of the OVERSEER programme used for benchmarking nutrient losses, as it may not account for the importance of Critical Source Areas in run-off losses (Park and MacCormick 2011). Generally, the OVERSEER model does not deal with storm events or mass erosion such as slips. There is a current proposal for a sediment risk loss model to be developed. For each block on the farm, this would give a risk indicator, rather than an actual value of sediment loss prediction (David Wheeler, AgResearch, pers.comm. June 2011).

6.5 Relationship of national climate change policy and regional soil conservation policy

Because of the strong effect of tree cover on erosion rates, a policy framework that encourages forest cover over pastoral land use for climate change purposes is likely to reduce overall sediment yields.

In relation to climate change, two possible roles for government identified by SKM (2008) are:

1. Ensuring that there is an efficient market for climate change business opportunities to be invested in and benefits to be realised by investors. This includes scientific measurement and verification technologies and services, Emissions Trading Schemes (ETS) rules that provide clear incentives for emission-reducing technology, and the free flow of information about the value of opportunities (education and extension). This latter could be a shared role between regional and central government.
2. To make public investment in opportunities where the government believes that:
    - There is significant (net) public benefit in that opportunity being realised;
    - The amount of public investment required to realise the opportunity reflects the public benefit.

This could also be viewed through a regional government lens, where regional government responsibility for soil stability is complementary to central government roles in overseeing sustainable resource management and climate change policy.

The interaction of climate change policy with sustainable land use policy is important in terms of altering the overall drivers towards afforestation. The government's Afforestation Grant Scheme currently assists with the capital costs of establishing forestry in return for the government assuming rights to the carbon accumulated by the forest for the first ten years. Proposals which also have benefits for soil conservation, water quality and biodiversity are given greater weight (MAF 2010). This scheme does not commit landowners to any liability at time of harvest (ibid), and has been oversubscribed.

Forestry is functioning under the existing Emissions Trading Scheme (ETS) with carbon credits available for forests planted since 1990 on previously unforested land, and disincentives for deforestation of land planted before 1990. This has already influenced the rate of land use change, and the application of the ETS to agriculture will be a new economic influence on land use choice in the future. Internationally, 14% of greenhouse gas emissions come from agriculture whereas in New Zealand 49% of emissions come from that sector (SKM 2008). While the phasing in of agriculture's responsibility for emissions will be gradual, it represents an extra cost on livestock farming in the future. This may be mitigated by integrating forested areas into farm businesses to neutralise the carbon price effects on the farm (Praat et al. 2010; Vibart et al. 2011).

7 Summary and conclusions

The conclusions to this review are presented as responses to some key questions:

- What are the main drivers of sediment loss?
- How site-dependent are the expected gains from mitigation practices?
- How much sediment reduction can be achieved by different mitigation practices?
- Will riparian work make a difference?
- Do grazing practices matter?
- Where can education, incentives and regulation be most effective?
- What effect will carbon trading have on farmers' decisions regarding land use?
- Is it feasible to achieve contact recreation clarity standards?

7.1 What are the main drivers of sediment loss?

Sediment generation is driven principally by precipitation, but there is an increased risk of erosion depending on geology and land use. Pasture catchments generate 2-5 times the sediment of comparable catchments under forestry. However, forestry losses exceed those of pasture during harvest times.

Once erosion occurs, transport factors are important in determining how much eroded sediment actually reaches a waterway. These factors include distance to the waterway and attenuation opportunities (e.g. settling out on flat areas).

In large storms, mass movements (slips or landslides) are the most significant generators of sediment, although not all of this reaches waterways. Where a mass movement such as a large slip occurs adjacent to a waterway, its sediment input will dwarf other sources. However, because streambanks and gullies are, by definition, adjacent to waterways, they are significant. Streambank sources dominate in smaller, more frequent rainfall events that do not generate landslides. This means that over the long term, streamside and gully sediment may outweigh landslide sources (Page et al. 1999). Streambanks are also often the most important sediment source in flatter or more stable landscapes. Sheetwash is generally less significant in terms of volume, but sediment from pasture surfaces carries nutrients and faecal matter into waterways.

Other factors may also play a role. Tracks and roads are an important sediment source in horticulture and forestry, but there have been few studies of sediment from tracks in pastoral catchments. Subsurface drains can be a dominant source of sediment in flat catchments where stock exclusion is in place. Different sources may dominate sediment yields during different seasons of the year.

7.2 How site-dependent are the expected gains from mitigation practices?

Site-specific factors will determine the magnitude of gains from mitigation practices on a particular property. Yet there are some general principles that hold across landscapes. Topography and tree cover have a strong overall effect on sediment generation. As described above, the most important sources of sediment can be stated for land uses – landslides and gullies/ streambanks in hill country, streambanks and possibly subsurface drains in dairying land, and wheel tracks in horticultural areas. After sediment is generated, because of preferential flow pathways, it moves in site-specific ways on each property. The connectivity between sources of sediment generation (e.g. landslides) and waterways has an important effect on the actual delivery of sediment to waterways. Therefore farm plans that create targeted solutions for both critical sediment generation sites and pathways will be most cost-effective. Site-specific factors account for the wide ranges of reduction figures from mitigation practices shown in Table 14.

7.3 How much sediment reduction can be achieved by different mitigation practices?

A summary of research findings about the effectiveness of practices to mitigate sediment is shown in Table 14. The most effective mitigation practice will depend on site-specific factors.

Table 14: Sediment reduction from mitigation practices

Practice	Magnitude of reduction	Situations studied	References
Converting hill pasture to forestry	Reduces catchment sediment yield by 33-67% in long term	Hill country in Whatawhata and Hawkes Bay. Losses under pasture are ~1/3 of those under forest but some increase occurs over the harvest period and there may be some initial sediment released from streambanks.	Quinn and Stroud (2002) Fahey and Marden (2000) Fahey et al. (2003)
Tree cover (closed canopy) on high-erosion risk slopes	Can reduce slips on erosion prone slopes by 90-94%	Studies of slip occurrence using aerial photographs before and after intense storms in Taranaki and Gisborne – slip area declines from 10% to 1% of slopes	Pain and Stephens (1990) Marden and Rowan (1993)
Spaced poplars on erosion-prone slopes	Can reduce slips on erosion-prone slopes by 95%	Hill country faces in Manawatu and Wairarapa. Plantings must be in good condition, large and correctly spaced to be effective	Douglas et al. (2009; 2011)
Poplar or willow planting on banks of streams/ rivers	Can reduce eroding banks by 40-95%	Studies in upper Waipa under normal flow conditions. Plantings must be in good condition and correctly spaced to be effective. WRISS used figure of 55% for poplars on banks, based on unpublished Whatawhata data	Hicks (1992) NIWA (2010)
Stock exclusion	Can reduce actively eroding banks by 86%	Ngongotaha catchment, Rotorua – comprehensive riparian retirement as part of catchment scheme	Williamson et al. (1996)
	Can reduce sediment concentration 34-60%	Overseas studies from dairy catchments; lower range figure was 49% fenced, higher range figure was 87% fenced	Meals (2001) Line (2003)
	Can reduce sediment load	Figures of 80-90% from Ngongotaha and overseas from a	Williamson et al. (1996)

Practice	Magnitude of reduction	Situations studied	References
	30-90%	dairy catchment (US) and a Western Australian catchment; WRISS used figure of 30% for excluding cattle only, based on unpublished Whatawhata data	Line et al. (2000) McKergow et al. (2003) NIWA (2010)
Constructed stream crossings	Herds crossing can increase suspended sediment 54%	Sherry River in Motueka, dairy herd of 246 cows crossing river twice a day	Davies-Colley et al. (2004)
Riparian filter strips	Can trap 50-98% of incoming sediment	Range of work reviewed in Parkyn (2004), including NZ and overseas studies. Less effective in steeper terrain, with fast or channelised flow	See, for example Gharabaghi et al. (2006) Smith (1989)
Riparian buffer in forestry harvest	Can effectively mask effects of harvest on streams	Coromandel studies on stream clarity and channel widening	Quinn and Halliday (1999) Boothroyd et al. (2008)
Sediment traps and wetland settling areas	Can trap 30-98% of inflowing sediment	Silt trap near race at Rerewhakaaitu (30%). Retiring deer wallows as silt traps (98%). Only effective long-term if silt traps are cleaned out regularly.	Parker (2009) McDowell (2008)
Pasture, soil and grazing management	Damaged slopes can decrease infiltration by 46% and increase sediment in run-off 87%	Hill country slopes at Whatawhata subjected to hard grazing in winter.	Nguyen et al. (1998)
Ripping wheel tracks in market gardens	Reduces erosion from these areas 95%	Franklin market gardens.	Basher and Ross (2001)

7.4 Will riparian work make a difference?

Stock exclusion from riparian buffer zones gives a dual benefit of stabilising streambanks from erosion and creating a filter area where soils are uncompacted and infiltration is promoted. Tree planting that stabilises streambanks also has benefits, whether or not stock are excluded.

In lowland catchments without significant hillslope erosion, riparian management is often the most effective means to reduce sediment loss. For example, in lowland dairying catchments, riparian stock exclusion has reduced sediment loads by 80-90% (see Table 14).

Streambanks and gullies can be the main source of sediment loss in small to medium storm events, and may dominate over the long term (Page et al. 1999). Streambanks also contain stored sediment from historical erosion events, so riparian management is an important influence on the actual loss of accumulated sediment from those events.

Riparian management is also important in loose soils (e.g. pumice) which are prone to gullying.

7.5 Do grazing practices matter?

Surface sheetwash is generally less significant than other sediment sources such as landslides and streambanks. The intensity of grazing is unlikely to increase the risk of landslides. However, intensive grazing of fodder crops or areas near waterways can cause a significant increase in sediment loss. This is for several reasons: intensive grazing increases exposure of bare ground, physically erodes soil and also compacts the soil, increasing run-off. If this occurs near an unfenced waterway, there are no further attenuation opportunities.

Different soil types and conditions have varying vulnerability to compaction from grazing. Allophanic, ash and pumice soils are less susceptible than heavy soil types such as gley soils. Wet soils carry much higher risk of compaction than dry soils.

Because pugging of soils also depresses production, grazing practices matter for economic reasons as well as for sediment loss.

7.6 Where can education, incentives and regulation be most effective?

In general, education efforts are most effective where there is some farmer benefit to be gained from adopting the practice. In the case of sediment practices, this might apply to grazing practices where pugging could depress production, to streambank retirement where fencing could have advantages for stock or pasture management, and to retiring steep land if this allows inputs to be focused on more productive areas of the farm.

Incentives can increase uptake where there is a public benefit but where on-farm economic or practical drivers are marginal e.g. poplar planting. Incentives may be particularly helpful to overcome barriers due to initial capital expenditure e.g. for riparian or steep land retirement.

Regulation can generate resistance, especially if it is proposed without consultation and dialogue. Its use is best reserved for when there is clear evidence of an issue and clear links between the practice being regulated and the issue, where the regulations are practical and enforceable, and where there is an intention to follow through with enforcement. Otherwise credibility may be lost.

Regulation may be linked to incentives, either by having incentives for a period before the regulation becomes operative to encourage transition, or by having rules coupled with grants to assist. In Gisborne District, regulations requiring tree cover on the most erodible land are coupled with national government financial contributions, and were introduced without appeal following extensive consultation with affected landowners.

7.7 What effect will carbon trading have on farmers' decisions?

The Emissions Trading Scheme has already had an effect in slowing deforestation of existing forested areas. In terms of incentivising new forests and encouraging ‘carbon farming’, there are mixed results. Farmers may be wary of registering forests for carbon trading, due to future liability should they wish to change their land use back to pasture. The government’s Afforestation Grant Scheme has been oversubscribed, as it provided a capital grant for forest establishment without committing the landowners to the carbon trading system.

The economics of carbon farming may become more attractive if carbon prices rise, or once agricultural emissions come under the trading system. In that situation, it may be beneficial for landowners to be accruing carbon credits of the same market value as those for which they are liable due to pastoral agricultural emissions.

7.8 Is it feasible to achieve contact recreation clarity standards?

The contact recreation clarity standard (1.6 m clarity) is based on safety for swimming, being the distance required to see your feet through the water. The ability to achieve the standard depends greatly on geology; parts of the region would not meet these standards even under natural forest cover.

The Waikato River Independent Scoping Study (NIWA 2010) found that in fully forested Waikato streams, clarity would have averaged only about 1.9 m, ranging from 1.3-3.2m. The introduction of pastoral agriculture causes a decline in clarity. For example in the Kaniwhaniwha stream draining Pirongia (hard-rock geology), which is only 38% pasture, baseflow clarity is 1.2 m, while a nearby forested stream has clarity of 3.2 m. The scoping study tested a number of scenarios of land management practice changes but none of them achieved the bathing water clarity guideline of 1.6 m in the lower Waipa and lower Waikato Rivers. Steep pasture retirement was predicted to increase clarity from 0.7 to 1.0 m in the Waipa, and from 0.7 to 0.9 m in the lower Waikato. However, the effects of retiring and replanting stream banks were not included in the modelling.

In smaller sub-catchments with high natural clarity, it may be possible to achieve contact recreational standards through comprehensive riparian retirement and catchment work. However, experience shows that natural background turbidity can be high. In a small Taranaki farm stream (Waiokura), an increase in clarity of around 0.3 m was achieved through a 10% increase in streambank protection, but the rise from 0.45 m to 0.75 m still did not achieve contact recreation standards. Similarly, at Whatawhata, comprehensive catchment management changes produced a significant trend in clarity, increasing 29% from 0.75 m to 0.97 m, but still short of the 1.6 m standard (Hughes and Quinn 2011). Extensive work was carried out in the Waitomo catchment, with retirement fencing protecting over 10% of the catchment area, and some farmers retiring up to 30% of their land (Ritchie 2001). Following this work programme, the concentration of suspended sediment for a given flow rate in Waitomo stream declined by about 40% (McKerchar and Hicks 2003). However, current clarity is still below 1.6m about 80% of the time (Environmental Indicators for Waitomo stream, www.waikatoregion.govt.nz).

Figure 6 below shows that areas that currently have 1.0 m clarity occur over much of the region; however intensively farmed locations generally have low clarity. The report, which summarises water quality results from monthly samples, shows that samples generally meet the contact recreation standard in Coromandel rivers and Lake Taupo tributaries, but elsewhere in the region they do not (unless located in headwaters). This suggests it will be challenging to meet the 1.6 m standard in agricultural catchments outside the Coromandel peninsula or Taupo catchment.

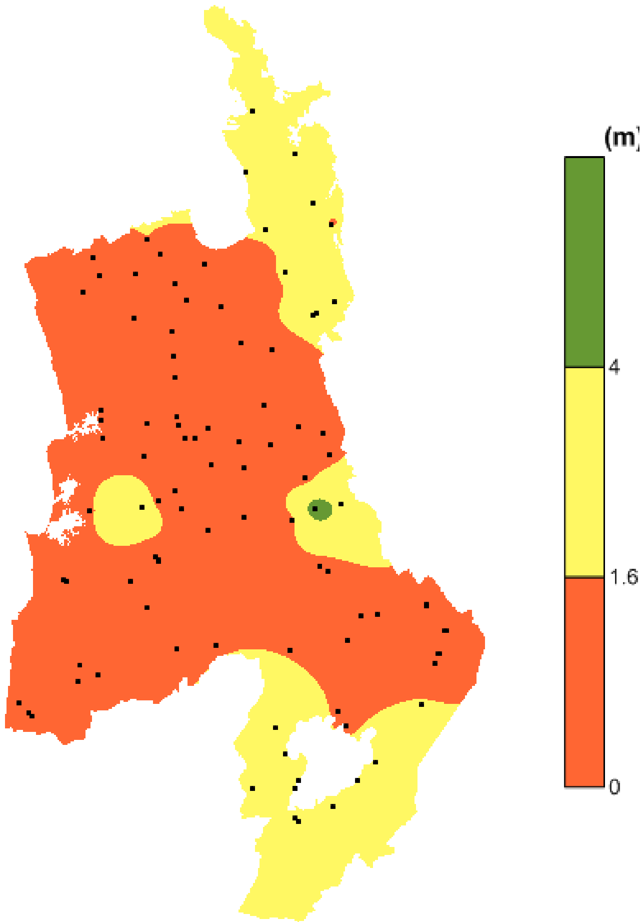


Figure 6: **Spatial contour plots of black disk clarity (based on 5 year median values, 2006-2010).**

Source: Waikato Regional Council, following methodology and using data as set out in Tulagi 2011.

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