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Effectiveness of riparian buffers for trapping sediment in steepland plantation forests

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Summary

Project and client

NZ Forest Owners Association (NZFOA), with the support of the Forest Growers Levy Trust, contracted Manaaki Whenua – Landcare Research to conduct a pilot project to assess the effectiveness of riparian buffers for mitigating sediment entry into streams in recently harvested steep plantation forests.

Objectives

- To determine the effectiveness of vegetated riparian buffers or setbacks in steepland plantation forests for trapping hillslope-derived sediment, including assessing the relative importance of slope versus vegetation in mitigating sediment entering streams.
- To develop a reconnaissance-level methodology to assess the effectiveness of vegetated riparian buffers or setbacks for trapping or mitigating sediment entering streams.
- To produce a report, with photographic evidence, outlining the results of field and desktop investigations and present the results at the annual NZFOA conference.

Methods

- Contact forest companies to find suitable study sites.
- Undertake a literature review.
- Assess buffer effectiveness by:
    - surveying study sites across a range of geology, soil type, region, buffer width, buffer density, buffer type, and time since harvesting
    - visual ground-based inspection of selected sites to determine evidence of sediment tracking through, or trapped within, the buffer.

Results

- Three study sites were chosen in consultation with NZFOA members and forestry companies. Eight stream reaches about 0.5–1.5 km long were assessed. Site selection was based on available satellite or aerial photograph imagery, recent harvesting, and the occurrence of storms that had produced landsliding.
- Stream channel scour, basal slope or riparian failure, and hillslope landslides were the key erosion processes observed at all sites.
- The key determinants for predicting the effectiveness of a vegetated riparian buffer to trap sediment in harvested steepland forests based on this pilot study appear to be

the presence of a flatter slope or terrace near the stream, coupled with dense and mature riparian vegetation.

- In several places landslides were observed to transport sediment through riparian buffers, or to initiate within the buffer. In only one locality was riparian vegetation observed to trap landslide material. Here the vegetation was mature kānuka, which was growing on a lower-gradient slope adjacent to the stream.
- The effectiveness of riparian buffers for trapping sediment (both mass movement generation and runoff filtering) increases as the slope decreases, but large storms resulting in landslides, debris flows and floods override this.

Conclusions

This pilot study has added to our understanding of the role and effectiveness of riparian buffers in plantation forestry in New Zealand for removing sediment. It failed to confirm that vegetated riparian buffers rather than slope changes are the primary control for trapping or reducing sediment delivery to streams in steep forested catchments. That said, damage during harvesting to existing riparian buffers consisting of mature woody species probably increased the proportion of landslide-derived sediment reaching a stream channel.

Our findings support those of previous work in other countries, but because of the limited number of localities investigated do not provide definitive evidence that vegetated riparian buffers in steepland forests are effective at mitigating sediment delivery to streams. The effect of tree removal on runoff generation results in increased re-distribution of sediment on hillslopes, scouring of the stream channel floor and banks, and localised slope failures where subsurface flow pathways exit streamside banks, often located within the zone designated as a marginal strip. If a storm coincides with the post-harvest period, landslides become the dominant source of sediment and the mode of sediment delivery to stream channels.

Recommendations

To confirm the value of riparian buffers for mitigating sediment in steepland forest catchments, a more in-depth study should be conducted that covers a broader range of physical site attributes, buffer widths, species density and composition, and storm sizes. To reduce the transaction costs of locating a range of potential study sites, such a study needs the full cooperation of the New Zealand steepland forestry industry. Based on a wider sample size, it would be useful to determine if empirical “rule sets” or generalisations between study areas could be developed to enable a more general categorisation of buffer effectiveness, or for use in developing either rule-based decision frameworks or spatial models.

1 Introduction and background

Water quality from New Zealand plantation forests is generally very good, except during and following the harvest phase (Baillie & Heaphy 2011; Baillie & Neary 2015; Baillie & Rolando 2015; Quinn & Phillips 2016). The greatest risk to forested streams arises when harvesting coincides with intense rainfall that causes flooding and debris flows (Quinn & Phillips 2016). Best management practices have been shown to be effective in mitigating many of the effects of forest harvesting if implemented correctly and in adequate numbers (Cristan et al. 2016).

The generation and management of sediment within New Zealand plantation forests, particularly in steeplands[1], is becoming an issue for many communities (e.g. Baker et al. 2014). In other countries sediment is considered to be the most significant water pollutant associated with forest management (Yoho 1980; US EPA 2005). While sediment management is largely governed by Resource Management Act regulatory processes, it has yet to be included in the Ministry for the Environment's National Objective Framework for Freshwater Management, though it is only a matter of time before it is. As in other New Zealand land uses (intensive agriculture, dairying, etc.), attention is increasingly becoming focused on riparian buffers as a key tool to mitigate the effects of land use on stream-water quality.

Vegetated riparian buffers (also known as riparian buffer zones, buffers, buffer strips, setbacks, streamside management zones; Neary et al. 2011) are known to provide a range of benefits for protecting or enhancing stream-water quality in agricultural land uses, particularly on flatter terrain where sheet-flow erosion processes dominate (e.g. Norris 1993; Collier et al. 1995; Parkyn 2004; Mayer et al. 2006). Much of the evidence for this comes from international studies. Such buffers are seen as effective for mitigating a range of contaminants, from excess nitrogen, to phosphorous, micro-organisms and sediment.

The use of riparian buffers is based on experience, largely in the United States, where a sizeable body of literature supports such interventions. However, an examination of many of these overseas studies reveals that there is a wide range of 'effectiveness', and that many studies were conducted on relatively flat to gently sloping land dominated by unconcentrated or sheet flow sediment transport processes (e.g. Frasier et al. 1998; Pearce et al. 1998a,b; Helmers et al. 2005). There are fewer studies assessing the performance of riparian buffers to capture sediment and prevent water quality degradation in steeplands (in general), and more specifically in forested steeplands (e.g. Gilliam et al. 1992; Boothroyd et al. 2004; Broadmeadow & Nisbit 2004; Anderson & Lockaby 2011).

Riparian buffers have been promoted for decades as a means to mitigate sediment reaching streams from plantation forests, particularly during the harvest and post-harvest phases, but their effectiveness has not been fully investigated. In steeplands, where slopes mostly

[1] In the context of this report, 'steepland' means slopes greater than 25°, which equates to F and G slope classes in the New Zealand Land Resources Inventory.

grade directly to streams, the effectiveness of riparian vegetation to remove sediment from concentrated flow paths may be limited. In addition, there is the common case where landslides can be generated within stream-side or riparian zones by storm events (Marden & Rowan 1995). Landslides arising from such locations, or from the mid and upper slopes of forest cutovers, have the potential to become channelised debris flows, often with devastating downstream effects. Evidence for the ability of tall, woody riparian vegetation with limited ground cover to remove sediment generated by landslides is scant. While there have been studies on the overall benefits and effectiveness of riparian buffers in forestry (e.g. Davies & Nelson 1994; Boothroyd et al. 2004; Quinn et al. 2004; Parkyn 2004), the effectiveness of vegetated buffers in the forestry sector to remove sediment has not been quantitatively determined.

Considerable public and regulatory pressure for increased setbacks and the inclusion of riparian buffers in plantations potentially means additional costs to the forestry sector through loss of growing area and increased harvesting costs. However, it is unclear whether even if such interventions are implemented there would be any improvements in water quality or reduced sediment. Resolving the effectiveness of buffers for sediment removal is thus an important issue for the forest sector and regulators alike, and should be a high priority for investigation.

The National Environmental Standard for Plantation Forestry (NES-PF) has a permitted activity regulation relating to planting setbacks from streams, which with time will create opportunities for vegetation other than plantation forest trees to be within the riparian margin. Regulation 14 states that ‘afforestation must not occur within 5 m of a perennial river with a bankfull channel width of less than 3 m or within 10 m of a perennial river with a bankfull channel width of 3 m or more’. A further rule (Regulation 68, parts 1−6) deals with harvesting and disturbance of margins of water bodies (riparian zones). The permitted activity conditions vary but do allow for harvesting within or across riparian zones, with conditions. The primary aim of this rule is to minimise disturbance to the margins of water bodies

The authors’ considerable field experience in assessing storm impacts on sediment generation from steepland forests (e.g., Phillips & Marden 2005; Marden et al. 1991, 1995; Marden & Rowan 2015) suggests that slope steepness and slope form are key determinants that govern a vegetated riparian buffer’s effectiveness in trapping sediment, rather than the presence of the vegetation itself; i.e. the shape of the ‘valley’ profile and the presence and width of stream-side terraces (e.g. Phillips 2005, unpubl.). Our hypothesis is that slope steepness and form are primary drivers of connectivity of sediment sources to streams, and the presence of riparian buffers for removing or filtering sediment within plantation forests is secondary.

If our hypothesis is not supported by the evidence, the field information collected will still be of benefit because it will help to substantiate provisions made in the NES-PF for setbacks, and support the forest industry’s position on plantation forests providing a range of ecosystem services. If the hypothesis is supported, it will assist the industry in future discussions with regulators and with the public, who currently perceive that riparian buffers are necessary to mitigate the effects of forest-derived sediment on waterways. This project addresses an unmet need expressed in the NZFOA Science Plan 2015, *Improved Understanding of the Performance of Riparian Reserves in Reducing Sedimentation*.

This project is a preliminary assessment of the effectiveness of riparian buffers to trap sediment. It is limited in geographic scope and the number of sites assessed. However, it provides some evidence and recommendations for future work. The project focuses on sediment and does not address other 'benefits' of riparian buffers, such as shade, stream temperature (Gomi et al. 2006), and biodiversity corridors, for which there is a well-established literature.

2 Objectives

In this pilot project we aimed to determine, by desktop analysis and field assessment, the effectiveness of vegetated riparian buffers for trapping hillslope-derived sediment generated from landslides and surface erosion from reaching streams in recently harvested steepland plantation forests. We approached forestry companies to locate suitable study sites and then developed a reconnaissance-level methodology to assess the effectiveness of vegetated riparian buffers for trapping or mitigating sediment entering streams.

The aim was to assess combinations of slope steepness, slope profile, geology/soil type, width and composition of buffer to determine the buffer's sediment-trapping effect. Slope profile is defined as the shape of the contributory slope to a point on the stream channel. It may be planar, convex, concave or stepped. Of particular interest is the presence or absence of a change in slope, such as a terrace near the stream that might promote 'capture' of landslide-derived sediment and slash, or at least reduce its momentum sufficiently to minimise the amount of sediment entering a stream channel.

3 Methods

- Conduct a literature review on the effectiveness of riparian vegetation and buffers for preventing sediment reaching streams.
- Contact forest companies to find suitable study sites.
- Assess vegetated riparian buffer effectiveness for trapping sediment on sites harvested <2 years before undertaking this assessment by:
    - locating study sites across a range of geology, soil type, region, buffer width, buffer density, buffer composition, and time since harvesting
    - visual ground inspection of selected sites to determine evidence of sediment tracking through, or trapped within, the buffer
    - determine key contributing sediment processes.
- Use the Spatial Analyst/Slope tool in ArcInfo to derive slope maps, channel gradients, and buffer dimensions.

Riparian strips, where present, were mapped on-screen at a scale of 1:1,000 and stored as polygon shapefiles in ArcGIS. These shapefiles were then split into true left and true right using the stream centrelines supplied for each site. To obtain statistics describing the riparian margins in each watershed, transects were laid at 50 m intervals at approximate right angles to the stream lines and intersected with the riparian strip polygons. Transect lengths within riparian strips (from the stream centreline to the edge of the riparian strip, where present) were then calculated and extracted to Excel. Where no riparian strip was present, a zero length was entered.

Field surveys were completed by walking immediately adjacent to or within the stream channel and assessing evidence of sediment delivery to the stream channel and stream condition. In one case (Te Weiti Stream, Tairua Forest), stream cleaning had removed some evidence of the amount of sediment/debris contributed, but the evidence of delivery from upslope sources remained.

Key erosion processes and sediment sources documented included:

- concentrated runoff originating upslope of the buffer from either a road or landing, or from a heavily disturbed area of the cutover and following a channelised flow path (also known as 'sediment breakthroughs' – their connection point with a stream channel was recorded using GPS, and an assessment of their source made[2])
- sediment mobilised by sheet wash (also referred to as slope wash)
- a translational or rotational landslide
- a debris flow or debris avalanche (Figure 1)
- a lower slope adjacent to the stream collapse (riparian failure)
- channel scour, including bank erosion
- some unknown mix of several sources.

[2] Note: this assessment was not as detailed as the study of Brown and Visser (2017), in which flow paths were followed upslope to identify the erosion source.

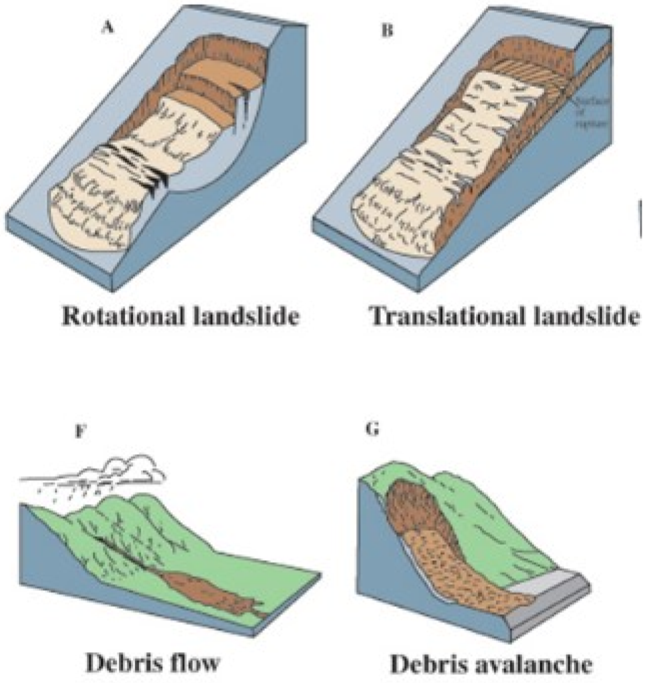

Figure 1 Schematics of common types of landslide movement observed in this study. (Source: https://www.pinterest.nz/pin/220324606746567527/)

4 Literature review

4.1 Sediment sources and delivery

General overview

When forests are harvested there are changes to the hydrogeomorphic and biogeochemical processes that confer high water quality to headwater streams. One of the primary changes is in relation to slope hydrology and response to rainfall, including reduced interception (more effective rainfall), increased runoff, and potentially reduced near-surface soil hydraulic conductivity), all of which tend to intensify the frequency and magnitude of surface runoff and potentially sheet-wash erosion. These changes also affect soil moisture and the duration of near-saturated soils, with soil moisture levels remaining higher for longer (Pearce et al. 1987), hence increasing landslide susceptibility. Responses to forest canopy removal appear to be similar around the world (Stott & Mount 2004; Croke & Hairsine 2006).

Forest harvesting can also affect hydrogeomorphic processes in steep, forested terrain and contribute to increasing incidences of slope failure and changing the sediment transport rate in stream channels (e.g. Imaizumi & Sidle 2012; Phillips et al. 2012; Brown & Visser 2017).

Increased water yields and peak flows can erode existing stream channels and significantly increase sediment loads, especially where substantial amounts of legacy sediment exist in streams from past activities (Thornton et al. 2000; Schoenholtz 2004). Mohr et al. (2013) studied the hydrologic response of soils to clearcutting using rainfall simulations, and suggested that harvest areas behave in a complex way, and may switch from being a sink of runoff and erosion to being a source, a fact previously disregarded in predictive models.

Much of the literature on the effects of forest harvesting is based on studies conducted several decades ago. Increased public awareness and pressure relating to the general effects of land-use activities on water has resulted in more recent attention being focused on the harvesting phase of plantation forestry. While the public perceive the value and benefits that forests provide in creating high water quality (natural and planted forests), this perception changes when those same forests are harvested for their timber. In some cases current impacts on water quality are inappropriately characterised by the results of past studies that examined management practices that are outdated or no longer in use. Further, undisturbed forests (natural or planted) are often perceived to have negligible erosion, but they do in fact contribute sediment (Zimmerman et al. 2012). Landslide erosion is also important in the New Zealand context, as some of the highest erosion rates occur in native forests, especially in steep mountainous areas (Marden & Rowan 2015).

Within a harvested catchment there is a wide variety of land forms and associated sediment sources. These include infrastructure-related sources (unsealed road sections and landings), hillslope sources (landslides, gullies, log-haul paths, general harvest area [cutover], bare areas created by machinery or by timber extraction), and channel sources (stream-side vegetated areas, stream bank or bank collapse). The probability of runoff from such sources reaching the stream reflects both the volume of water generated and the distance to the stream network. For example, sediment eroded from a particular source is often redeposited on-slope before it is delivered to a stream, and there are complex patterns of sediment storage, remobilisation and delivery even within relatively small areas of hillslope (Motha et al. 2003). Walling (1983) concluded that because only a fraction of the sediment eroded from the landscape actually leaves a catchment during the course of a monitoring study, estimates of on-site erosion alone are insufficient for developing management programmes for off-site practices. Sediment delivery thus encapsulates the dominant processes by which water resources are affected, and the processes that perhaps can best be managed to limit off-site impacts.

Brown and Visser (2017) studied ‘breakthroughs’ (where concentrated surface runoff and sediment reach streams) in New Zealand forests following harvesting. They found that breakthrough frequency on cutover harvested using a ground-based skidder was 1.9 times higher than that on cutover harvested by a cable yarder. In addition, 73% of breakthroughs were associated with concentrated runoff from roads, skid trails, stream crossing approaches, and ruts from machine tracks on hillslopes directed toward the stream.

Roads

Croke and Hairsine (2006) suggest that unsealed roads and logging tracks can be regarded as one of the most hydrologically active areas within a logged forest for the majority of low to moderate rainfall events, and are thus a major influence on runoff source strength. Adding roads to a forested landscape results in higher peak discharges, which occur earlier than for the same environment without roads (Wemple et al. 1996). Roads, even if well maintained, can produce large quantities of sediment, so careful consideration of their placement and management is paramount in order to reduce water quality impacts (Grayson et al. 1993).

Motha et al. (2003) found that unsealed roads contribute 20 to 60 times more sediment than undisturbed forest, and about 10 times more sediment than harvested areas on a per unit area basis. Harvested areas contribute 1 to 5 times greater sediment than the undisturbed forest. These results support other studies that identify unsealed roads (e.g. Fahey & Coker 1989; Fransen et al. 2001) as important sediment sources in forested catchments.

Cutover or general harvest area

General harvest areas or logged hillslopes typically represent the largest land surface area within a harvested catchment. In selectively logged or small-patch harvesting, runoff generation usually only develops on the bare or disturbed parts of the hillslope. As a result, and because there is often retention of some forest or understory vegetation, sediment transport in these areas is often limited, and channelised flow is rarely generated. However, in clear cuts, where the proportion of cutover to catchment area is large, the opportunity for runoff to be generated and potentially channelised increases, as does the erosion and sediment transport rates.

There have been several international (Garrison & Rummell 1951; Wooldridge 1960; Dyrness 1965) and local (McMahon 1995; Marden & Rowan 1997; Marden et al. 2006, 2007) studies of harvest-related site disturbance aimed at quantifying post-harvest sheet-wash erosion. However, there have been few studies on the contribution of the resultant sediment to stream sediment yield (Fahey & Marden 2000; Fahey et al. 2003; Phillips et al. 2005) or relative to that generated and delivered to streams by non-harvest-related erosion processes, particularly the ubiquitous storm-initiated shallow landslides typically associated with forest cutover (Marden et al. 2006, 2007).

Harvesting practices produce significant areas of ground disturbance. During the immediate post-harvest period sediment is generated through surface erosion processes (weathering), and subsequently mobilised downslope, predominantly during rainfall events (sheet wash). The rate at which sediment is generated is, however, dependent on the severity of ground disturbance and the time required for ground vegetation to recolonise these sites.

In New Zealand three disturbance indices are readily recognised on cutover (McMahon 1995; Marden & Rowan 1997; Marden et al. 2006, 2007): undisturbed, shallow disturbance, and deep disturbance. Previous research has found that an order of magnitude more sediment is generated from sites that have been deeply disturbed (to depths sufficient to expose the mineral soil) than from sites of shallow disturbance, while undisturbed sites (where needle duff remained intact) generated no sediment (McMahon 1995; Marden & Rowan 1997, Marden et al. 2006, 2007). Also, the recolonisation by groundcover vegetation is rapid (more so if the setting has been oversown), and as a consequence the rate of sediment generation from all disturbance classes decreased to a negligible amount within 2 years of completion of harvesting (Marden & Rowan 1997; Marden et al. 2006, 2007). Although a significant proportion of the sediment generated during this period was mobilised from sites relocated on mid and upper slopes, the bulk of it was effectively entrapped by surviving groundcover vegetation, slash, and in microtopographic hollows immediately downslope of its source (Marden & Rowan 1997; Marden et al. 2006, 2007).

Marden and Rowan (1997) also found that the delivery of sheet-wash-generated sediment to streams was most likely to be from those sites of deep disturbance within close proximity, and connected to, a stream channel. These deep disturbance sites were predominantly created by dragging logs across watercourses, and therefore generally occurred within 10 m of the streambank. Log haul-paths resemble channels, where surface water tends to concentrate in sufficient volumes to mobilise, and deliver, all available sediment to the stream channel, whether a riparian buffer is present or not. The take-home message from this and later studies (Marden et al. 2006, 2007) is that although the volumes of sediment generated and delivered to streams by sheet wash erosion, relative to that generated by landslides, is small, the creation of sites of deep disturbance within 10 m or so of a stream channel will result in sediment delivery, regardless of the presence of a riparian buffer.

How riparian buffers affect surface erosion

The riparian buffer zone is generally regarded as the strip of land that separates an upland or hillslope area from streams, lakes or wetlands (Parkyn 2004). Forest management practices in many regions leave an undisturbed vegetated buffer strip immediately adjacent to the majority of streams and drainage lines. This buffer has a range of functions, including maintaining the stability of the stream channel, providing riparian habitat, long-term recruitment of woody debris, regulating light and water temperature in the stream, and acting as a filter for runoff between any areas of soil disturbance and the stream (Croke & Hairsine 2006). This last function can be considered the 'last line of defence' to filter contaminants such as sediment generated from within the catchment.

The general consensus from the scientific literature suggests that vegetated buffers are likely to be effective in reducing sediment derived from diffuse sources by surface processes such as unconcentrated sheet wash (Schlosser & Karr 1981; Cooper et al. 1987; Daniels & Gilliam 1996). However, their effectiveness is dependent on the erodibility of the soils, the density and type of groundcover vegetation, connectivity to the stream network, and land slope, and it diminishes as the ratio of unvegetated to vegetated area decreases, and as slope length and storm intensity increase. Importantly, poor land management practices within the buffers can also reduce their sediment trapping effectiveness (Dillaha et al. 1989; Magette et al. 1989).

Such buffers may include grass filter strips, shrubs and forests. In agricultural settings they have been shown to be effective for either trapping or reducing contaminants from entering streams, or by providing an environment that allows for the biogeochemical transformation of nutrients (e.g. nitrogen). However, studies that demonstrate such benefit are predominantly on flat to gently sloping land, where sheet flow or overland flow is the principal transport process. The literature indicates that buffers are really only effective in removing sediment from runoff on low slope angles, generally less than about 10°. The literature also suggests that thick grass is more effective than woody vegetation at filtering runoff. However, world-wide there is a dearth of studies on steep, dissected, headwater streams, so it remains unclear what the range of effectiveness of riparian buffers is for mitigating sediment (in particular) in such environments.

Slaney et al. (1977) showed riparian buffers to be ineffective when point sources such as roads transport sediment in channelised flow to the stream. In the same study the riparian treatments were effective at protecting stream banks from physical damage, but disruptions to the channel from windthrow may eventually contribute to the sediment supply (study site topography gentle to moderately sloping).

The width and placement of buffers in catchments is still a contentious issue (Croke & Hairsine 2006). Much of the variability in studies of nutrient and sediment removal efficiencies can be explained by site-specific differences in the characteristics of the buffer zone or of the surrounding land. These characteristics include width, vegetation type, slope, soils and drainage, topography, and longevity of the buffer. Phillips (1989) evaluated a number of factors that determine the effectiveness of water-quality buffer zones and found that for sediment, slope gradient is the most critical factor, followed by soil hydraulic conductivity. Studies conclude that buffers need to be wider when the slope is steep, generally to give more time for the velocity of surface runoff to decrease and water to infiltrate. The effectiveness of grass buffer filter strips as filters of sediment is less in steep or hilly terrain than in rolling or flat land, as overland flow is concentrated in flow lines, giving rise to high flow velocities.

Data from studies comparing multiple-width buffers in the same location have shown that sediment and total phosphorous removal rates (53 and 98%, respectively) increase with increasing buffer width (5 to 27 m) (see Parkyn 2004). Grass filter strips, in particular, have been shown to be effective at trapping sediment particles from sheet rather than channelised flow (McKergow et al. 2004). Soils and drainage are also factors that influence runoff generation and infiltration. Thus free-draining soils or those with high infiltration rates minimise the generation of runoff on the hillside. The effect of these factors on sediment removal is not primary but secondary, as they influence both runoff generation and runoff velocity.

There are also some indications that buffer zones may have a limited life span even where they are effective. For example, soil pores may become clogged with sediments and increase rather than reduce runoff.

Focusing on forest environments, a study by Lynch et al. (1985) found 75–80% removal of sediment transported by surface erosion resulting from logging activity where there was a 30 m wide buffer, although the slope was not given in this study. Ward and Jackson (2004) assessed and discussed the effectiveness of forestry stream-side management zones for trapping sediment and found trapping efficiencies of 71–99% of sediment carried by concentrated flow. However, their study sites were all on gentle slopes (8–20% or 5–11°). Clinnick (1985) reviewed the Australian experience of buffer strips in forest management for detaining sediment-contaminated water from entering streams. The review focused on the effectiveness of buffers to act as a physical barrier to the transport of displaced soil/sediment from roads and forest harvesting areas. It concluded that 30 m on either side of the stream would provide adequate protection to the stream environment, and that this could be reduced to 20 m for slopes less than 30% (17º). However, for slopes greater than 30%, wider buffers were recommended, particularly where the slopes were convex. Hairsine (1997) looked at buffer zones for managing sediment movement in forestry operations and found they reduce the effect of overland flow (velocity and amount), but that a uniform cover is required. Grass filter strips and forest cover had a similar ability to trap sediment.

Two New Zealand studies indicated that a 30 m wide buffer left along each bank of a stream was highly effective at reducing the effects of logging on the stream environment (Wylie 1975; Graynoth 1979). However, while the latter study assessed sediment, the amount of physical disturbance to the actual stream itself due to logging meant that it was impossible to separate out the effects.

Source to stream connectivity – delivery pathways

The concept of connectivity relates to the extent to which a runoff source is linked to the stream network (Wemple et al. 1996; Croke & Mockler 2001; Croke & Hairsine 2006). In the case of roads, as outlined above there is generally a high degree of connectivity, but where overland flow pathways are diffuse, the degree of connectivity depends on the relative runoff source strength and the available length of hillslope where infiltration can occur. Further, surface roughness and topographic variation, coupled with the presence of logging debris/slash, can affect both runoff and trapping of sediment. Within the harvested area each runoff-sediment source has its own specific delivery pattern, which is dependent on its spatial distribution and any management practices employed (Croke & Hairsine 2006). Roads, for example, have a delivery pattern largely determined by the arrangement of culverts and cutoffs. If there are no drainage structures, sediment delivery will be strongly influenced by the topography of the road and hillslope, as in the case of tracks, though if cross drains/banks are used they tend to disperse runoff. There are a number of studies that have also demonstrated the significance of concentrated flow paths at road outlets with respect to channel initiation, gully formation and sediment delivery (e.g. Croke & Mockler 2001).

Diffuse overland flow paths have received less attention, partly because of the difficulty of quantifying the attributes of overland flow during storm events. Often wide runoff plumes can be seen at the outlets of road drainage structures (where not incised), but descriptions of the fate of such pathways are rare (Croke & Hairsine 2006). Croke et al. (1999) found that in experiments generating overland flow, the plumes had infiltrated into the soil within 25 m of the outlets, even during rainfall intensities of 110 mm/h. Croke and Hairsine (2006) in their review suggest there is a general tendency for elevated sediment concentrations or turbidity following logging, roading or fire, but that there is a high degree of variability in both the magnitude and direction of response.

The same authors suggested a template for predicting the potential impacts of surface runoff and erosion following harvesting on water quality for a specific location, which required knowledge of soil characteristics, climate, topography, and local forest management practices. For example, where overland flow is concentrated in a channel or a gully that formed as a result of scour below a road drainage outlet, this type of pathway is characterised by high-energy flow, with little or no potential for the deposition of sediment. In such situations the buffering of the source area from the stream by the presence of vegetated areas adjacent to the stream is minimal. Such channels, gullies and flow lines effectively bypass the importance of vegetative filtering in reducing runoff and sediment fluxes.

Reid et al. (2010) demonstrated that fine sediment on stream beds in headwater Coromandel plantation forest streams increased with either upstream harvest exceeding 40% of total catchment areas or after riparian forest trees adjacent to the stream were harvested. However, there were no obvious post-harvest increases in fine sediment in the study reaches of the largest streams (>500 ha), where the proportion of upstream catchment harvest was usually relatively low. They also concluded that movement of sediment into streams is most likely when recent harvesting coincides with large storms, as occurred in 1995 at Whangapoua Forest. They also concluded that, ultimately, management of riparian vegetation involves compromises in terms of maximising the ecological benefits while minimising both the loss of area for timber production and the mobilisation of extra sediment from land cleared for forestry infrastructure, and considering hydrological and landscape constraints within each plantation.

Marden et al. (2006, 2007) concluded that sediment generated by sheet wash from bare areas of forest cutover does not travel far downslope from its source. Instead, it becomes trapped in micro-topographic hollows or accumulates behind woody debris (slash), and if generated >10 m from a stream channel it is unlikely to contribute to the stream sediment load. However, where sites of deep-disturbance such as haul paths traverse the riparian margin and across the stream network, they act as conduits for concentrated runoff and the delivery of sediment to the stream. Retention of riparian buffers does little to stop sediment from entering streams from the latter sources.

In contrast, in situations where landslides are generated, there are many factors that contribute to determining whether landslides will deliver sediment to a stream. During storm events, and depending on their magnitude, landslides generated upslope of a riparian buffer may be ‘captured’ or trapped by riparian vegetation. This is largely due to the physical barrier or ‘hedge’ effect of the vegetation, and its density and extent. As mentioned above, the effectiveness of this riparian vegetation to trap sediment will increase when there is a reduction of slope adjacent to the stream (largely because the kinetic energy of the mass is reduced when the gradient lessens). However, if the landslide is generated within the riparian margin, it will deliver sediment directly to the stream, and the likely scenario is for a debris avalanche or a debris flow to occur that will, if the stream gradient is steep enough, cause more riparian failures, resulting in a ‘reamed out’ channel (e.g. Figure 2). Further, debris flows generated by landslides are important processes for routing sediment and wood from hillslopes to alluvial channels downstream, and there is a complex interaction between hillslope processes, channel storage, and the occurrence of debris flows that can remove large amounts of sediment (Benda & Dunne 1988; May 2007).

Research has also shown that episodic, storm-initiated landslides are the single most important sediment-generating process, providing the primary mechanism for mobilising and delivering most sediment to the stream network. This was most evident during a storm in Whangapoua Forest in 1995, when c. 91% of debris avalanches and c. 51% of soil slips tracked sediment and debris through standing forest and into stream channels (Marden & Rowan 1995). As shown by earlier studies, this is not an uncommon occurrence. Salter et al. (1983) classified 40% of landslides initiated during the 1981 Thames–Te Aroha storm as connected to a stream channel, and Harmsworth et al. (1987) established that 50% of landslides initiated during an event in 1985 at Otoi were connected to a stream channel. Furthermore, storm events commonly initiate slope failures within riparian areas, and these also potentially contribute significant sediment and woody debris to the stream network (Marden & Rowan 1995).

Figure 2 Reamed-out tributary channel caused by debris flow in Opoutere Block, Tairua Forest.

Summary

In summary, much of the perception of the performance and effectiveness of vegetated riparian buffers to trap sediment, and thus mitigate the impacts of land use on sediment delivery to streams, arises from studies on agricultural lands, often with grassed filter strips and on low-sloped or flat land. In these situations the buffer slows and filters water flowing through it as sheet flow, resulting in some sediment removal and an increased ability to allow that water to infiltrate into the soil. There is a body of literature relating to this situation demonstrating that buffers are effective, although effectiveness varies depending on many factors.

In contrast, the literature on the effectiveness of woody riparian buffers in steepland forests to trap or prevent sediment entering the stream from land-use activities is sparse. That literature supports the view that riparian buffers are ineffective at trapping sediment generated by mass failures, such as occurs when there are debris avalanches during storm events, and as concentrated load delivered in highly connected flow paths (Dillaha et al. 1989; Daniels & Gilliam 1996).

5 Study sites

5.1 Introduction

Three North Island forests were selected to examine in detail (Figure 3). Details of imagery used to assess catchment attributes are listed in Appendix 1. Study site details and photographs from field inspections illustrating key points are listed in Appendix 2. (Two other potential sites in the Nelson–Marlborough region suggested by Nelson Forests Ltd were also considered but were not suitable.)

Figure 3 Location map of the three study sites.

5.2 Site 1: Paroa Forest, East Coast

Paroa Forest is located inland of Tolaga Bay (Figure 3). Two stream reaches were assessed in a tributary of the Tapuae Stream (Watersheds 1 and 3, Figures 4, 5 and 6). The slopes flanking the stream reaches surveyed in this report were planted in 1986/87, harvested in 2015, and replanted in 2016.

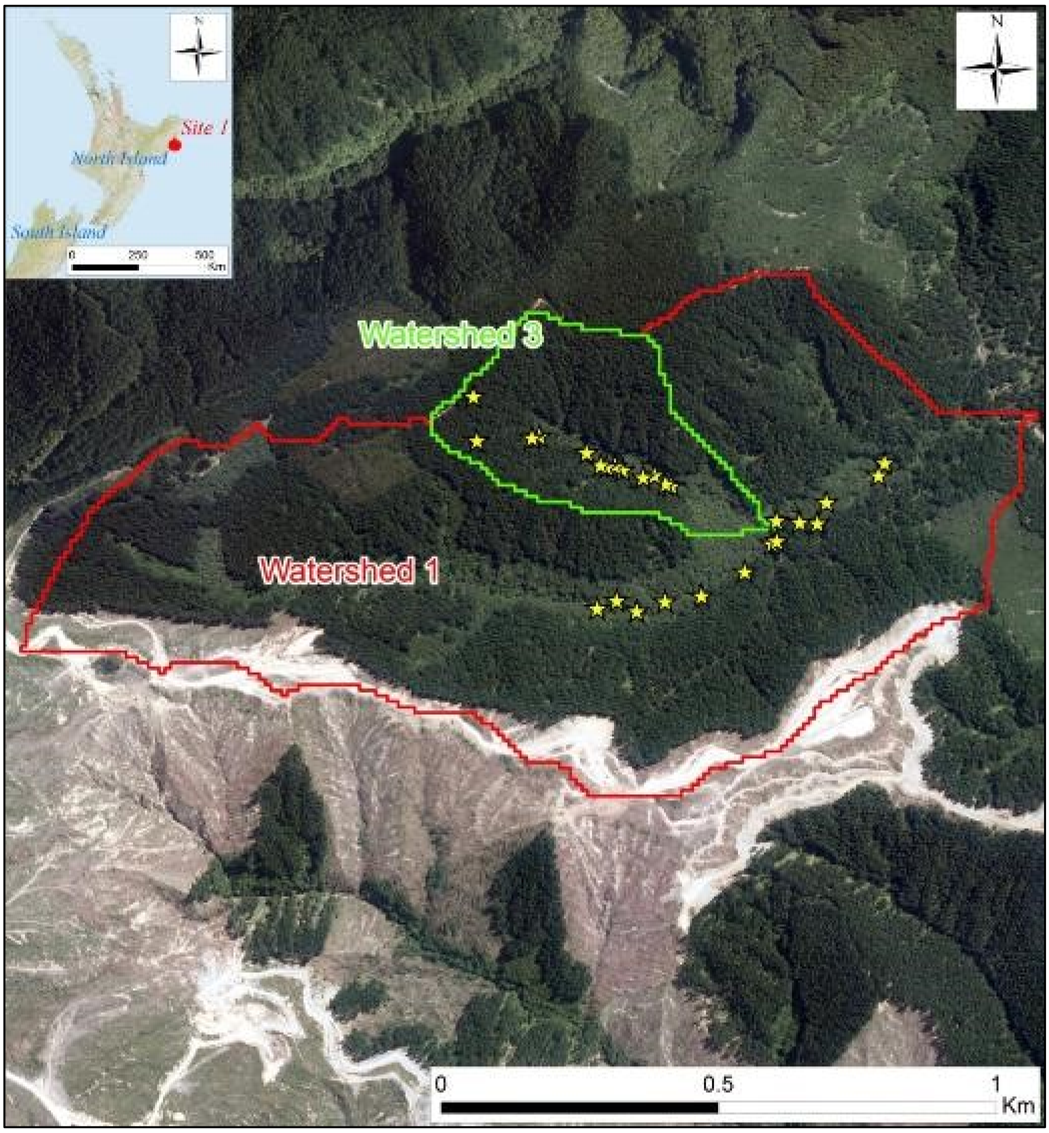

Figure 4 Paroa Forest sites before harvesting. Note the contrasting vegetation – darker green *Pinus radiata* and lighter green native riparian vegetation alongside the stream channel. Two watersheds (1 and 3) are defined for analysis. Yellow stars represent GPS locations of photos/specific locations recorded in the field. Total site area (defined by Watershed 1) is 99.3 ha.

Figure 5 Looking up (left) and down (right) Watershed 3 to where it joins Watershed 1. Note the very steep slopes and high proportion of bare ground on slopes flanking the true right side of Watershed 1. Black arrows indicate small stands of *Pinus radiata* not harvested, also shown in Figure 6. Note the gentler slopes within the hanging valley upstream of a waterfall (white arrow) in Watershed 3.

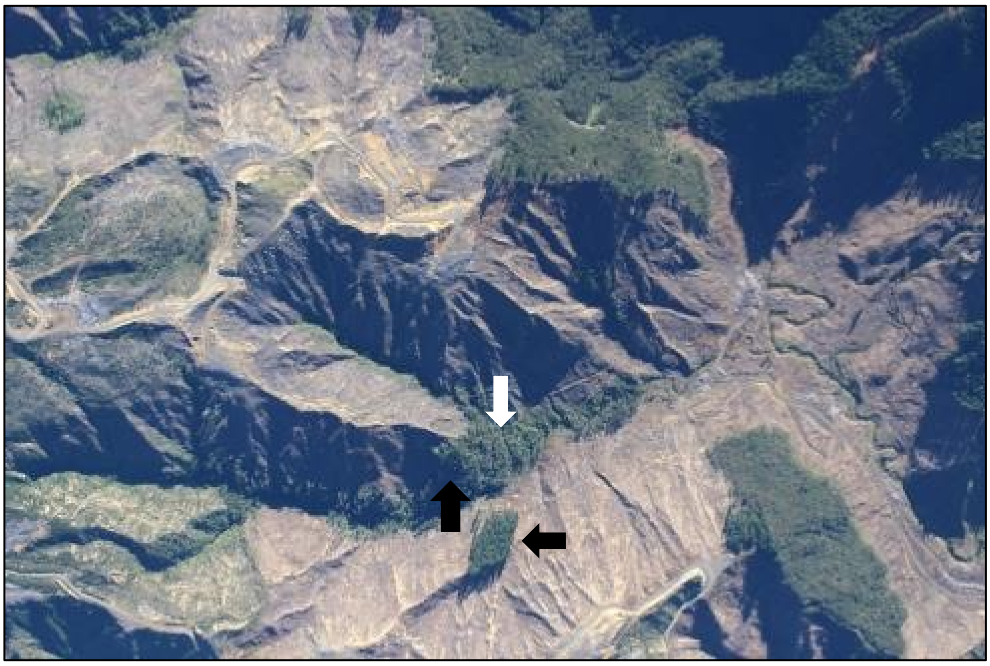

Figure 6 Aerial photograph showing Watershed 3 (centre left) and Watershed 1. Two small patches of unfelled *Pinus radiata* (black arrows) are the same as in Figure 5 above. The white arrow marks the knickpoint/waterfall at the bottom of Watershed 3.

The topography is steep (20–40°, mean 32˚, in places >40°) (Figure 5), has fairly long rectilinear slopes and occurs at an altitude of between 42 and 133 m above sea level. Lower slopes often connect with very steep, incised bedrock gorges in parts of the catchment.

Erosion is described in the New Zealand Land Resource Inventory (NZLRI, National Water and Soil Conservation Organisation 1975) as slight soil slip, and the vegetation cover before being cleared for the establishment of exotic forest was mānuka, kānuka and hardwood forest.

Mean annual rainfall varies from about 700 mm at the coast to 2,500 mm at higher altitudes (New Zealand Meteorological Service 1973). This region has a history of extreme rainfall events, often associated with storms of tropical origin (e.g. Cyclone Bola in 1988) and, together with more localised storm cells (e.g. 2005, 2009, 2014, 2015, 2017), these have been a major contributor to the unstable nature of the steep hill country. Since the completion of harvesting there has been one major storm event in 2017, but an assessment of the extent of post-storm damage was not undertaken at that time.

The bedrock consists of sedimentary mudstone with intercalated sandstone, conglomerate and tuff (Mazengarb & Speden 2000), overlain by varying thicknesses of volcanic tephra, and a thin (15 cm) forest topsoil. Soils are well drained and typical of those associated with land that has been eroded or has received sediment as a result of slope processes (Hewitt 2010).

At the time of forest establishment it is likely that decisions were made to retain a significant riparian buffer that consisted of mature, dense stands of tall (10 m) kānuka, and a diverse range of reverting native shrubby-hardwood understorey species. In the upper reach of Watershed 1 the grade of the lowermost slopes steepens significantly and descends into a narrow, steep-sided gorge. The planting boundary between the riparian buffer and exotic forest coincides with this change in slope. A significant riparian buffer clearly existed before the commencement of harvesting (Figure 4).

5.3 Site 2: Whangapoua Forest, Coromandel

Whangapoua forest (Figure 3) is located on the eastern side of the Coromandel Peninsula within the Thames–Coromandel district. Three watersheds (5, 3, 2 and part of 1) were assessed in the Otama Block at elevations of 40–120 m (Figure 7. The topography has short slopes between 26 and 35°, with a range of slope profiles (Figure 8. Erosion is described in the NZLRI as severe sheet wash and slight soil slip.

The Otama Block (Figure 7) was planted in 1983, predominantly with exotic *Pinus radiata*. Harvesting began in 2014 and continued through until 2016, and all cutover areas had been restocked by 2016.

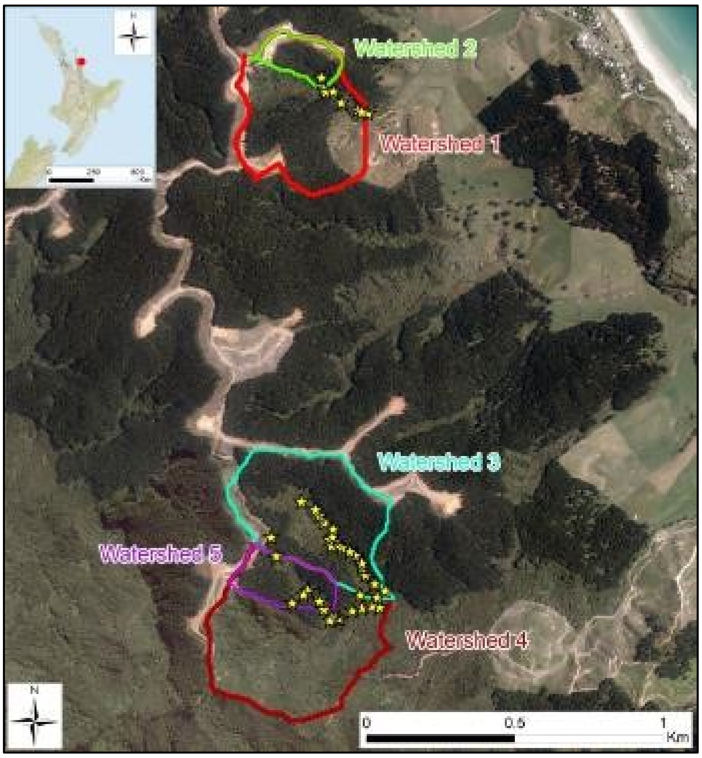

Figure 7 Otama Block of Whangapoua Forest, showing locations of catchments and streams assessed.

The basement geology of the area consists of hydrothermally altered Whangapoua and Matarangi andesites of Miocene age (Skinner 1976). The soils are highly variable, with soil types strongly related to parent materials, elevation and slope steepness. The weathered nature and high clay content of these soils predispose slopes to shallow, rapid slides (soil slip and debris avalanche) and flows involving soil and regolith. Soil slips typically have a small scar ≤1 m deep exposing a slip surface, with debris redeposited as a narrow debris tail downslope of the scar.

Though temperate, the climate at Whangapoua is known for its frequent, high-intensity localised storms, often of tropical origin, which frequently result in severe flooding. The average annual rainfall is 1,729 mm, with a distinct March to June ‘wet season’. The estimated 2-year return period rainfall is 127–133 mm in 24 hours (New Zealand Meteorological Service 1973).

Figure 8 Typical topography in the Otama Block with short, steep slopes and often native riparian buffers in valley bottoms. Note the incidence of small, shallow landslides.

Native riparian buffers, predominantly kānuka but with some kauri, and a diverse range of regenerating shrubby understory species have been retained as part of resource consent conditions and for specific purposes such as ecological corridors.

The eastern edge of the block was affected by a storm in March 2016, which caused several mass failures and distributed sediment and debris onto the adjacent farmer's land near Opito Bay. This storm delivered 160 mm of rainfall in less than 24 hours (Murray Eden's rain gauge – Norbert Klein, pers. comm). Rainfall records on 17 March show the following: Castle Rock: 67 mm; Whitianga airport: 109 mm; Opito Bay (Murray Eden's account) >160 mm.

5.4 Sites 3 and 4: Tairua Forest, Coromandel

Within Tairua Forest three watersheds were chosen as study sites. Site 3 (Figure 3, the Opoutere Block (Figure 9), consists of a single watershed (Watershed 1) on the western side of the road to Opoutere. At Site 4, in the Te Weiti Block, Watersheds 4 and 5 (Figure 12) are located upstream of the state highway on the northern outskirts of Whangamatā.

The topography is varied, with elevations ranging between 10 and 200 m and a range of slope forms and steepness.

The geology of the area consists largely of weathered volcanic rocks (Schofield 1967). Some large landslides have occurred in the past, as evidenced by remnant rockfall debris. Soil slip and debris flow/avalanche from the steeper upper slopes is the common mass movement erosion type, and sheet wash and surface erosion are common on exposed or bare surfaces. Opoutere Block Watershed 1 falls in LUC Class 7e 3, and Watersheds 4 and 5, Te Weiti Stream, are predominantly 6e 5, with some 6e 1 in the lower parts of Watershed 5.

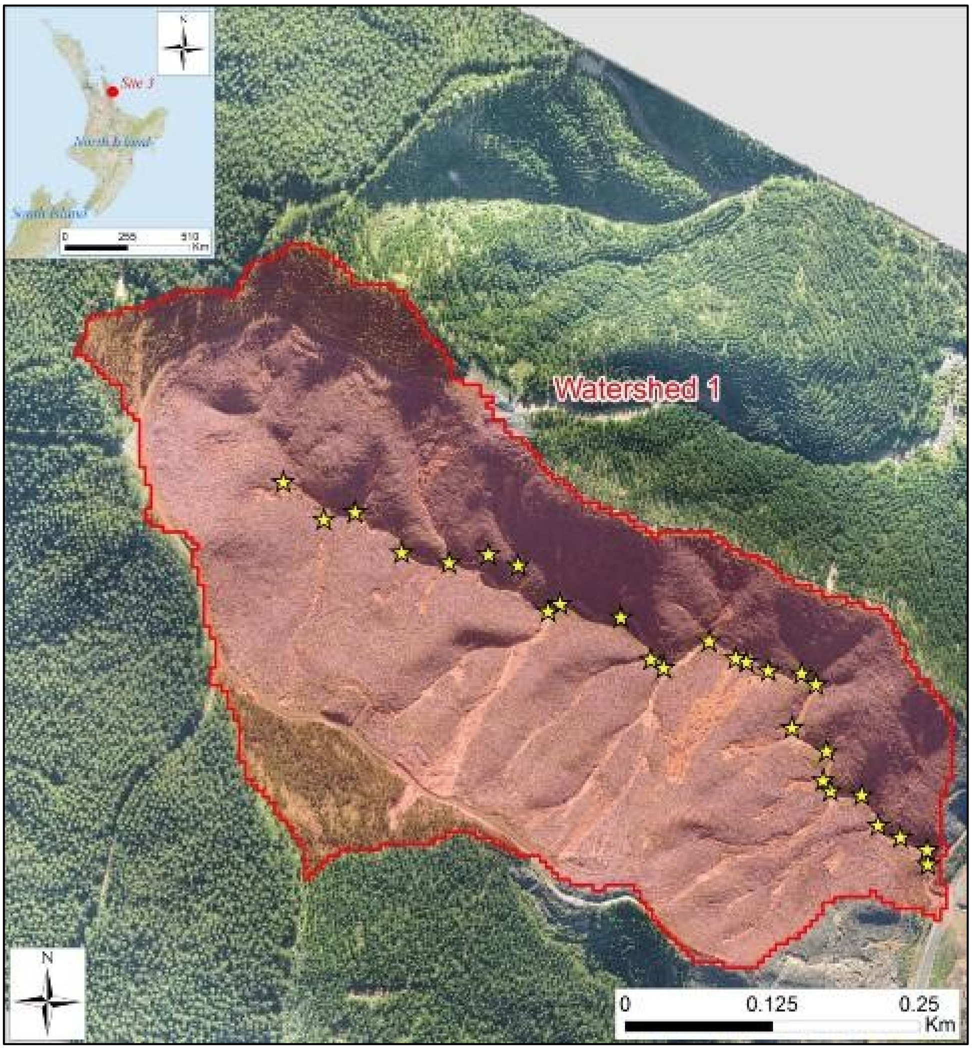

Figure 9 Tairua Forest, Opoutere Block, Watershed 1, eastern Coromandel Peninsula. A single watershed is defined for analysis. Yellow stars represent GPS locations of photos/locations in the field. Site area (Watershed 1) is 24.0 ha. Note the numerous landslides, debris flows, and degree of connectivity to the stream caused by the storm in March 2017.

The Opoutere Block (Watershed 1) was planted in *P. radiata* in 1989. Harvesting began in 2014 and continued through until 2015, and all cutover areas had been restocked by 2016.

The Te Weiti Block (Watersheds 4 and 5) was planted in *P. radiata* in 1990. Harvesting began in 2016 and continued through until 2017, and all cutover areas had been restocked by 2017. In both areas aerial photographs prior to harvesting did not reveal the presence of significant areas of riparian vegetation nor unplanted setbacks. Watershed 5 was the only one in which riparian vegetation was apparent in the upper part of the basin.

Annual rainfalls are in the order of 1,800–1,900 mm. The area is characterised by the occurrence of high-intensity rainfalls of extra-tropical origin, which often bring rainfalls in excess of 100 mm in a 24-hour period. Return period statistics calculated by Environment Waikato for the nearest gauges with long-term records give return periods of 2 to 5 years for 12-hour depths of 150–190 mm and 24-hour depths of 220–285 mm. Typical 10-year return periods are about 50 mm in 1 hour, 130 mm in 6 hours, 210 mm in 12 hours and 327 mm in 24 hours.

This area was affected by a significant storm in March 2017, which caused extensive damage to the forest and to neighbouring infrastructure (roads, fences, private property) (Figure 10). The storm rainfall recorded by the forestry company rain gauge indicated that rainfall really increased in intensity (48 mm in 1 hour at 1 am on 8 March 2017), and at this stage 108 mm had already fallen (Figure 11). High-intensity rain (>25 mm/hr) continued for another 3 hours, and by then 234 mm had fallen. It continued to rain lightly for about another 17 hours and by then just over 300 mm had fallen. These rainfall totals indicate an annual recurrence interval (ARI) of around 10 years (HIRDS-NIWA). A maximum 1-hour rainfall intensity as a result of Cyclone Cook a month later (13 April) was 23 mm.

Figure 10 Looking across Wharekawa Estuary from the outlet of Watershed 1, which spilled logging debris and sediment onto the road to Opoutere. Landslides are visible on cutover on the opposite side of the harbour.

Such rainfall intensities or durations are not unusual, and they cause considerable landslide damage and flooding across the region.

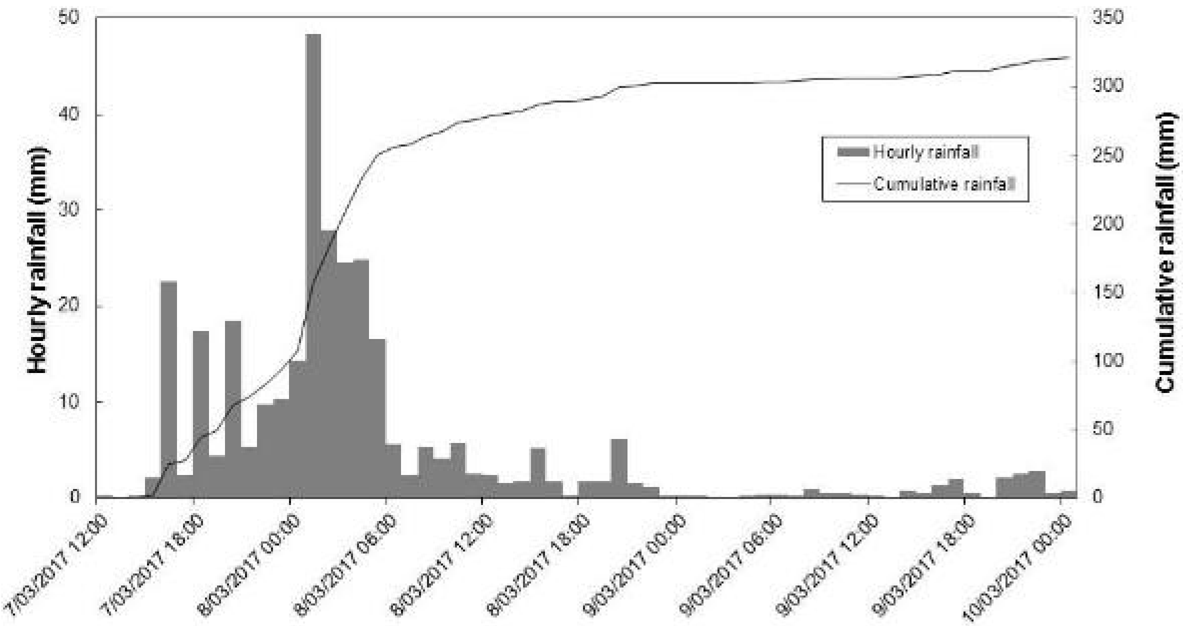

Figure 11 Rainfall 7 March 2017 to 10 March 2017 at Whangamata Fire Station.

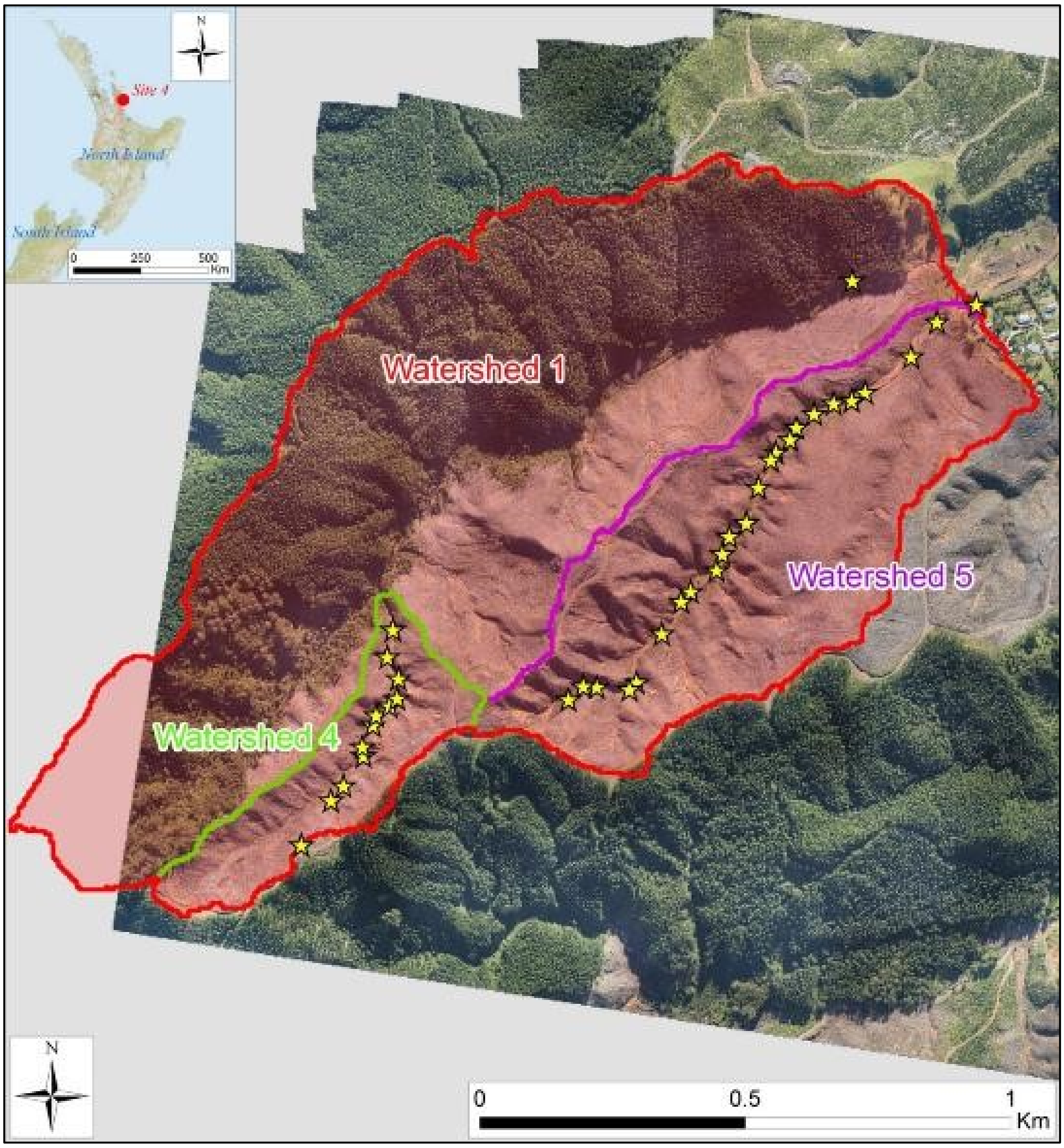

Figure 12 Tairua Forest, Te Weiti Stream, Area 4, eastern Coromandel Peninsula. Three watersheds are defined for analysis. Yellow stars represent GPS locations of photos taken in the field. Total site area (defined by Watershed 1 – Te Weiti Stream) is 144.4 ha

6 Results

6.1 Desktop analyses

6.1.1 Slope

Digital elevation model (DEM)-derived slope layers are shown in Figures 13 to 15. Of particular note are the very steep slopes (>35°) adjacent to the channels at Paroa (Figure 13).

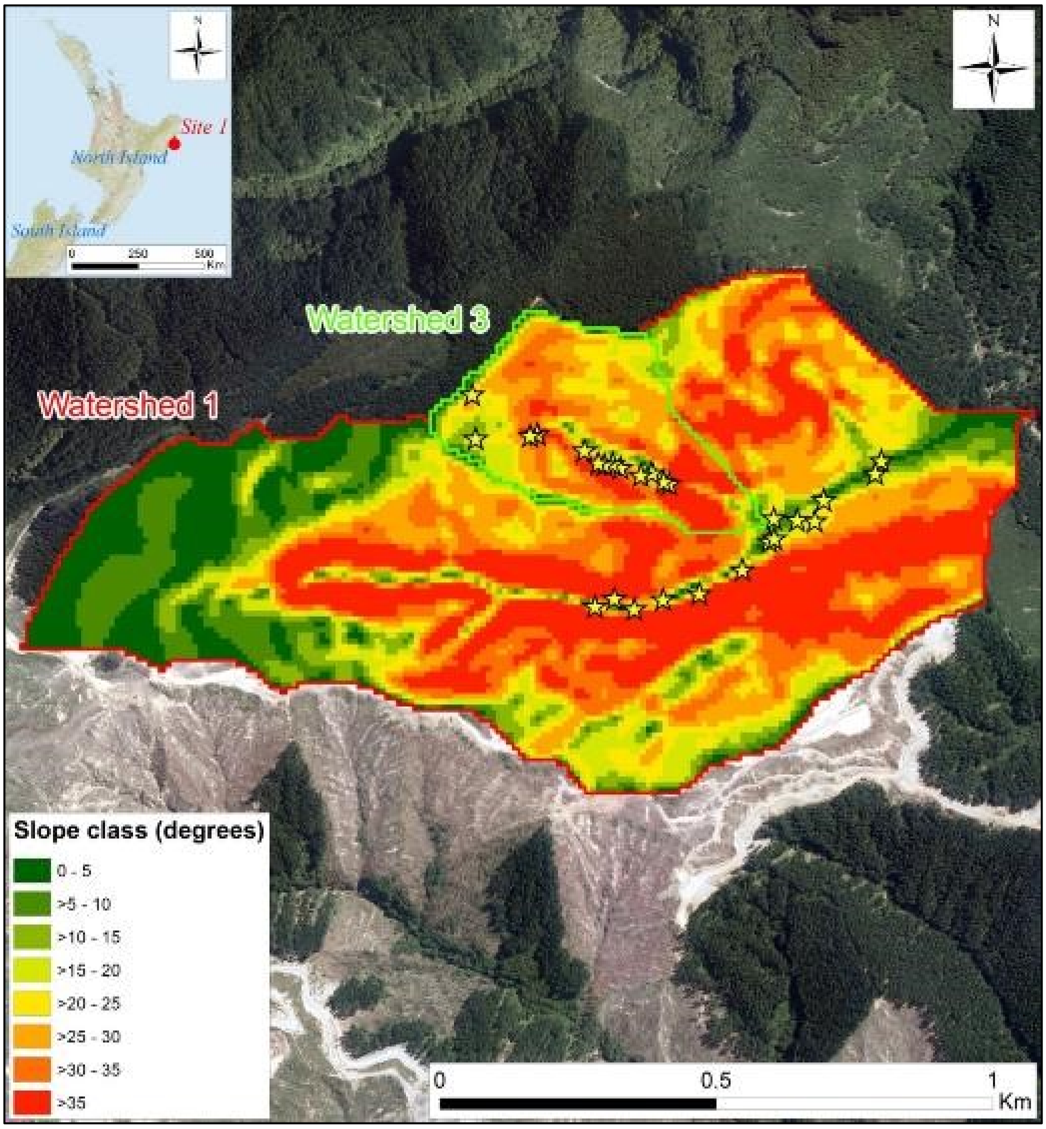

Figure 13 Slope distribution for Paroa Forest. Yellow stars represent GPS locations of photos/locations in the field.

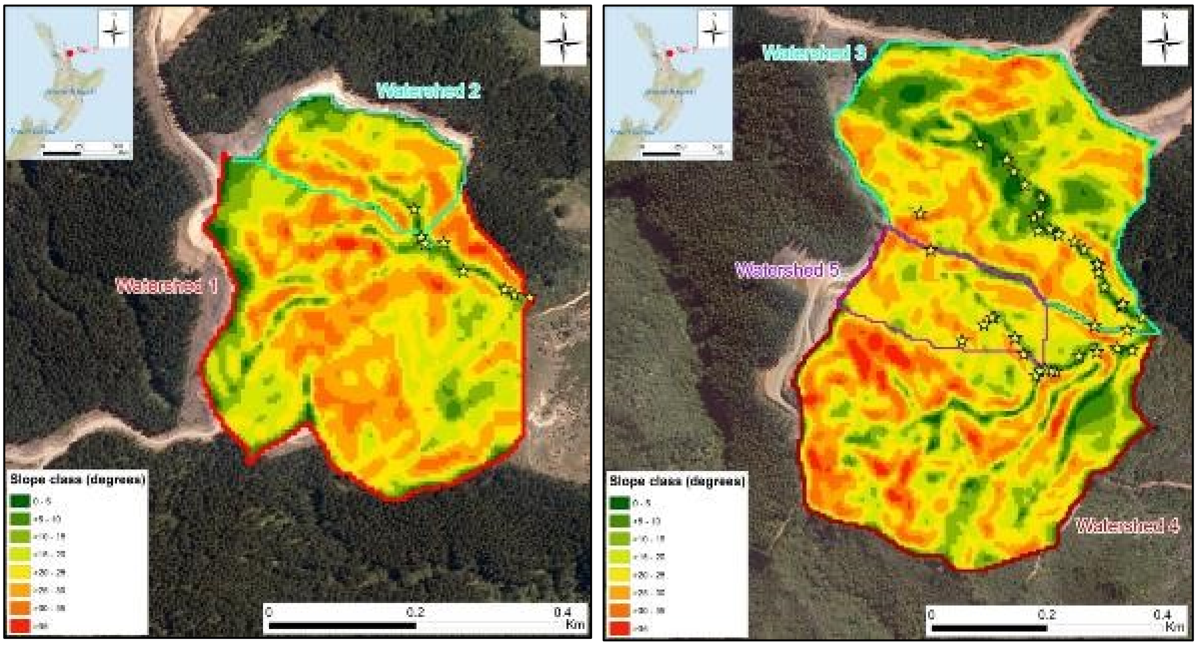

Figure 14 Slope distribution for Otama Blocks (Whangapoua Forest). Yellow stars represent GPS locations of photos/locations in the field.

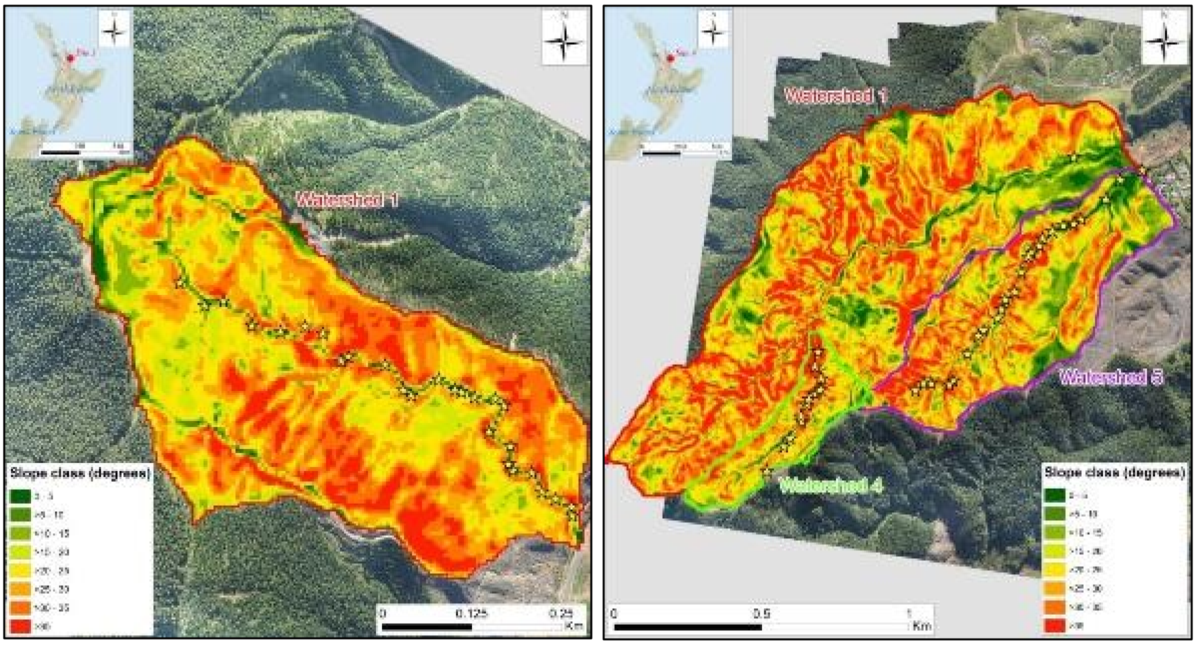

Figure 15 Slope distribution for Opoutere (left image) and Te Weiti Block (Tairua Forest). Yellow stars represent GPS locations of photos/locations in the field.

Of the three study sites, those within Paroa Forest have the highest proportion of the steepest slope classes, where the dominant slope class is 26–30° and where 20% or more of watershed slopes are greater than 35°.

Slope classes in the Otama Blocks are generally the gentlest of the three study sites, with many slopes in the <20º classes in Watersheds 3 and 5. Watershed 2 slopes contain a mix of gentle and steeper slope classes.

The dominant slope class in Opoutere and Te Weiti Blocks, combined, is 21–25°, and overall 20% or more of watershed slopes are greater than 35°.

The greatest proportion of the total stream length bounded by the steepest slope class (>35°), and therefore where slope/channel connectivity is highest, is in Watersheds 1 and 3 in Paroa Forest (Figure 13), and in Te Weiti Block (Tairua Forest, Figure 15). Conversely, in Opoutere Block, slopes >35° are less well connected to a stream channel because they are located on the uppermost parts of watershed slopes and are separated from the stream by slopes of lesser gradient (Figure 15).

In the Otama Blocks (Whangapoua Forest) slopes >35° are less prevalent than at the other sites, and are distant from, and therefore generally not well connected to, a stream channel (Figure 14.

6.1.2 Relief ratio

Relief ratio is the ratio of the maximum elevation range within a catchment divided by the distance (via a stream) from the highest elevation point to the lowest. This gives the average drop in elevation per unit length of river (i.e. an expression of the average grade of a stream).

Table 1 Relief ratios for watersheds across the three study forests

Site	Watershed	Max elevation (m)	Elevation range (m)	Relief ratio
Paroa	1	305.35	285.45	0.14
Paroa	3	291.07	238.51	0.82
Otama	2	145.97	81.61	0.25
Otama	3	161.42	118.90	0.21
Otama	5	177.67	118.70	0.26
Tairua	1 (Opoutere)	179.66	173.86	0.19
Tairua	1 (Te Weiti)	221.26	210.08	0.08
Tairua	4 (Upper)	195.52	136.76	0.16
Tairua	5 (S. branch)	150.34	139.10	0.09

In Paroa Forest the steep stream grade in Watershed 3 is due to the presence of multiple waterfalls (knickpoints) over a short stream reach. Conversely, the low grade of the stream in Watershed 1 suggests that in the absence of lithological controls (knickpoints), this larger stream has had sufficient stream power to incise into the bedrock to form a deeply incised gorge and maintain a low grade.

In the absence of knickpoints in Watersheds 2, 3 and 5 in Otama Block, their stream gradients are low and similar, as are the stream gradients at Tairua Forest, particularly in the Te Weiti watershed.

6.1.3 Riparian strip widths

At Paroa, the main channel (Watershed 1) has the widest pre-harvest buffer widths (70–100 m), and these tend to coincide either with the older kānuka stands on terraces near the bottom of the catchment or are related to the change of slope creating the 'gorgy' nature of parts of the catchment (Figure 13). Mean riparian pre-harvesting buffer widths are 19–34 m for Watershed 1 and 20–27 m for Watershed 3.

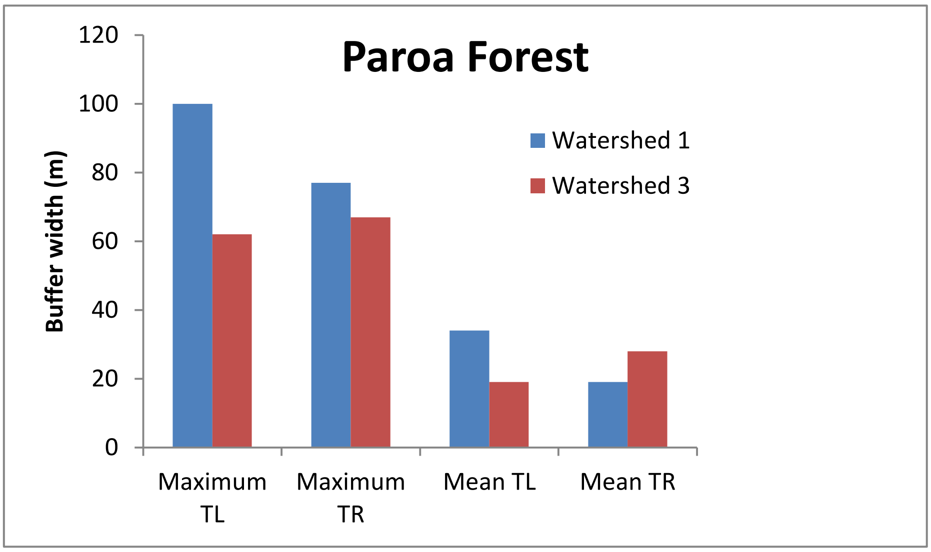

Figure 16 Maximum and mean pre-harvest buffer widths for true left (TL) and true right (TR) banks of Watersheds 1 and 3 at Paroa Forest.

In the Otama Block of Whangapoua Forest, mean buffer widths for Watershed 5 were about 25 m, but they were larger on Watershed 3 because of the reserve with larger emergent native trees (15–50 m).

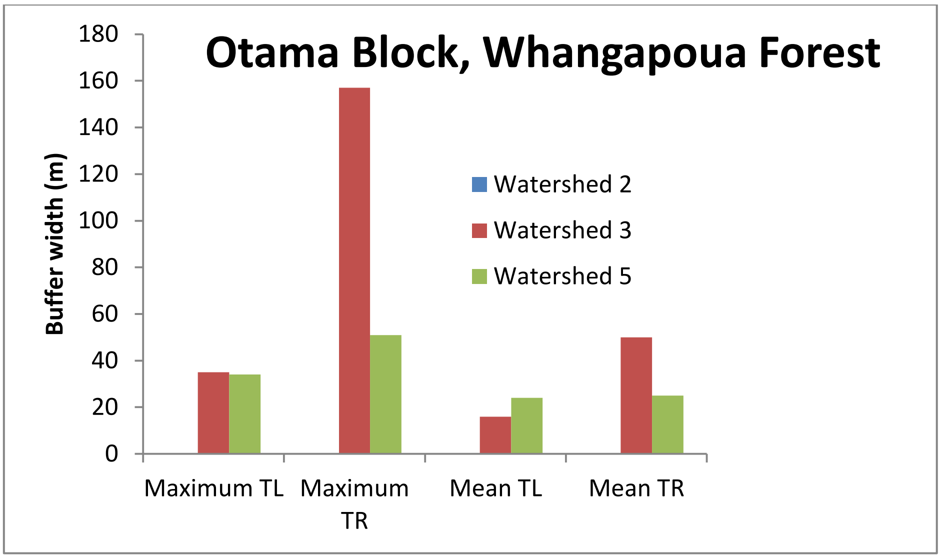

Figure 17 Maximum and mean pre-harvest buffer widths for true left (TL) and true right (TR) banks of Watersheds 2 (no significant buffer), 3 and 5 at Otama Block, Whangapoua Forest.

Mean pre-harvest buffer widths in Tairua forest were about 5 m (Figure 18), and maximum buffers widths were highly variable.

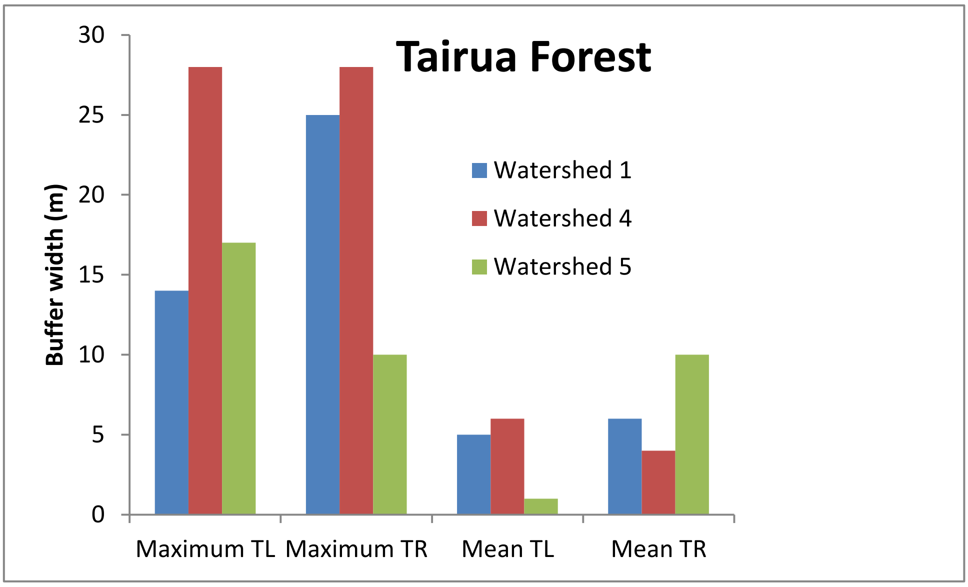

Figure 18 Maximum and mean pre-harvest buffer widths for true left (TL) and true right (TR) banks of Watersheds 1 (Opoutere), 4 and 5 (S. branch Te Weiti stream) at Tairua Forest.

In summary, all sites had variable-width riparian buffers, largely reflecting earlier planting patterns, slope changes, and/or the presence of remnant patches of native vegetation.

6.2 Field visits

6.2.1 Paroa

Cutover areas were characterised by having a high proportion of bare ground resulting from either shallow landslides (both past and recent) or disturbance during harvesting. The severity and extent of soil disturbance, combined with the skeletal nature of soils on steep slopes (often >35°), provided little opportunity for runoff generated from roads or cutover to disperse. Instead, runoff concentrated in incised flow paths that pass through the buffer and deposit entrained sediment directly into the stream channel. In places a lessening of the slope angle, as is often found at the base of many slopes where sediment has in the past been deposited to form an alluvial fan (e.g. in the lower part of Watershed 1, Figure 12), or where there are streamside terraces or benches present, means these landscape features often retain significant amounts of slope-derived sediment. In a cutover setting, ground cover vegetation, slash and the micro-topography further promote sediment capture.

A further feature of this site was the excessive slash and large woody debris retained within the stream channel. In many cases this caused log jams and sediment build-up behind them, resulting in a change of stream gradient profile. Log jams were particularly prevalent within a steep-sided gorge in the mid-reaches of Watershed 1, where trees felled on >35° slopes slid into the gorge and were not able to be retrieved. Landsliding initiated during Cyclone Cook in April 2017 probably delivered additional woody debris from cutover areas to the channel.

Most of these landslides originated in the cutover upslope of the riparian buffer. Where there was a buffer, sediment and wood often went through it (with some minor trapping) and reached the stream. Sediment delivery, either from landslides or from gullies, was down steep slopes, often directly on bedrock. There was a tendency for landslides to be more predominant on north-facing slopes, backing up earlier work (in ’t Veld & de Graaf 1990), but as this project was not focused on this aspect it cannot be verified. A lot of surface drainage originating from slopes high in the landscape infiltrated into the thin but porous colluvium, then emerged further downslope as subsurface flow emanating at the bedrock–soil interface. The point at which subsurface flow emerged from the slope often coincided with the head scarp of a shallow translational landslide, indicating that subsurface flows almost certainly initiated some landslides and resulted in the delivery of soil and woody debris to the stream.

There was extensive evidence of fresh landslide-derived sediment being redeposited on existing colluvial fan surfaces at the base of steep slopes and on small streamside terracettes. Nonetheless, it was equally apparent that some of the mobilised sediment reached the stream channel. This was particularly evident where runoff flow paths developed and became entrenched within colluvial fan deposits. The re-eroded sediments were then transported further downslope, across low gradient terraces and into the stream channel. Sites that afforded potential short-term sediment storage were limited to the lower reaches of Watershed 1.

The impact of the 2017 storm was probably relatively minor. Though there was evidence of small pockets of sediment accumulation within stream channels, there was no visible evidence in support of a possible post-harvest debris flow or extreme flood flow in the channel. Moss was growing on boulders within the stream channel, and there was little evidence of bank undercutting or channel scour as only a few small ‘riparian’ failures were observed, but the volumes of sediment generated by them would have been minor.

From photographs taken before commencement of harvesting there was an obvious and reasonably wide stream-side corridor of closed-canopy indigenous vegetation (Figures 4 and 13). Post-harvest observations suggest that the intact riparian buffer was essentially two-tiered and predominantly comprised mature, tall (10 m) kānuka and an understorey of shrubby species, nīkau palms and tree fern (punga). The riparian corridor was severely damaged during harvesting, leaving only a few standing (but broken) kānuka forming a sparse canopy, and a lower tier of recovering understory species.

In places where there was riparian vegetation on a slope that graded into the stream, any sediment derived either from outside or within the buffer would have made its way into the stream (e.g. Figure 5). Where there was a change in gradient at the base of the slope (as discussed above), and if there had been dense riparian vegetation comprising woody species, it is likely it would have provided some degree of sediment trapping or filtering, particularly if the vegetation was dense grasses rather than woody vegetation.

Photographs of examples of key field observations, processes and impacts from Paroa Forest Watersheds 1 and 3 are shown in Appendix 2, Figures A1 and A2).

6.2.2 Whangapoua: Otama Block

The Whangapoua watersheds (Figures 3, 7 and 8) characteristically have short, gentle slopes separated by intervening broad, flat ridge crests. During the post-harvest period a large storm event in March 2016 produced increased stream flows and resulted in significant channel scour and bank collapse. Field evidence included accumulations of fresh sediment, exposed tree roots, channel deepening and/or widening (particularly on outside bends), and undercutting resulting in bank collapse. Episodes of increased stream flow, particularly during the post-harvest period, are likely therefore to be significant both in terms of increasing sediment generation and modifying channel morphology.

Observations in Watershed 5 confirmed that bank undercutting leading to bank failures (small rotational slumps) was the main source of sediment. There was also evidence of sub-surface flow emanating from stream-side banks, leading to small-scale riparian bank failures. While the incidence of scouring of the channel bed and banks was significant along the length of the stream, it did not always result in bank collapse, and is thus unlikely to have generated as much sediment as bank failures.

Figure 19 Confluence of stream into which Watershed 5 drains (left side) and Watershed 3 drains (right side). Note the cloudy stream water, the evidence of some high flows (clean banks, and recovering moss), and fresh sediment on the left.

There were examples of landslides reaching the stream, and others that did not. In one case the momentum of failed material from a large rotational landslide/slump arising off a broad-crested ridge was slowed by a dense stand of tall kānuka and understorey. Here the presence of a change in slope at the base near the stream was likely to have contributed to the high degree of sediment retention. A brief assessment of this landslide and its deposit suggested it was a fairly 'dry failure', because if it had been more fluid sediment would have moved through the vegetation and reached the stream. Because the vertical relief was not great and the distance between the ridge and stream not large, it meant the bulk of the failed material didn't gain enough momentum to travel far, which improved the retention of sediment in the riparian vegetation and prevented sediment from overwhelming the stream channel (Figure 20).

Figure 20 Large landslide partially held up by a mature stand of tall kānuka and dense understorey vegetation. The momentum of the slump was also slowed when the material came to rest on a flattish terrace remnant.

Where landslides occurred and there were no buffers or flat lower slope areas, failed material in all cases entered the stream (e.g. Otama North, Watershed 2). The proportion of failed material for each landslide that entered the stream was not assessed and was highly variable, with some material retained on the slope.

Evidence of surface sheet wash or concentrated flow paths (deep rills or gullies) bringing sediment through a buffer into the stream from the cutover was not particularly obvious in Watersheds 5 and 3. While not assessed directly, the amount of slash cover on slopes, trashed ‘outer riparian vegetation’, and other vegetation would have provided some opportunity for any slope-wash sediment to be retained before it reached the top of the buffer. Further, post-harvest desiccant spraying around the margins of existing riparian vegetation (i.e. established natives or reserves, as defined on the forest maps) resulted in an additional 10–20 m of non-planted setback from the upper edge (i.e. a helicopter boom width as part of a resource consent condition). Rapid regrowth resulted in a dense growth of mostly native regeneration, which created an additional filter strip for any slope-derived sediment.

Figure 21 Post-harvest regeneration on outer (up-slope) margins of existing riparian buffers in Watershed 5.

The nature of the local topography, with many humps and hollows, would also have resulted in sediment deposition. Possibly because of shorter slopes and highly permeable soils, the development of rills and gullies connecting upslope areas with streams was not common.

Photographs of examples of key field observations, processes and impacts from Whangapoua Forest Watersheds 2, 3 and 5 are shown in Appendix 2, Figures A3, A4 and A5.

6.2.3 Tairua Forest

No significant areas of standing riparian vegetation were observed in any of the three harvested catchments, though in places native shrubs and grasses were growing where radiata were not present. One area of scrub/native regrowth was observed in the upper part of Watershed 5, but this had been desiccated as part of forest re-establishment practice. Where riparian vegetation was present, there was evidence of damage by logging and or subsequent landslide activity in all three catchments.

Landslides and stream scour were the main erosion processes observed. Stream scour caused significant removal of channel sediment and often contributed to riparian or basal slope failures of varying sizes and depths. Unlike Whangapoua, where this was also seen, the magnitude of channel adjustment was significantly greater because the storm of March 2017 was an order of magnitude larger. One interesting observation, particularly in Watershed 5 but also seen in the other two assessed watersheds, was the removal of large amounts of legacy sediment and readjustment of the channel. In Watershed 5, old valley infills and deep peat with remnants of burnt native vegetation were eroded and removed, suggesting that the channel had not been active for many decades or centuries. In other parts of the stream system, channel scour completely exposed bedrock. This indicates a high likelihood of channelised debris flows.

All surveyed catchments in Tairua had landslides attributed to the March 2017 event. These varied in size from small, shallow riparian failures to large, deep failures (slumps) in a range of slope positions. Landslides at Tairua were deeper than those observed at other study localities (other than the large failure in Watershed 5 at Whangapoua). In Watershed 5 at

Tairua, near the top of the catchment, there were a number of quite large but shallow translational landslides on very steep slopes. In all three Tairua watersheds, landslide material found its way into the stream either directly, or via delivery into tributary streams which then transported sediment. Many of these tributary streams also exhibited severe scour, often to bedrock. The inference from such observations was that if riparian buffers had been present, then landslides would have traversed these, likely causing damage and delivering material to the stream. If buffers had existed, the landslides above the buffer as well as those originating at the base of the slope adjacent to the stream would have resulted in additional debris being removed and transported.

Figure 22 Looking down Watershed 5 towards lower Te Weiti Stream and the outskirts of Whangamatā. Note the number of landslides and the lack of standing riparian vegetation.

In terms of the sequence of events during the March 2017 event, it is a story that is hard to unravel. There was clear evidence of landslides becoming debris flows on slopes and in tributaries as well as within the main channels of Watersheds 1 and 5. However, in the deposition zone downstream, where much of the logging slash and sediment ended up, any evidence of debris flow lobes or levees − if they had reached the lower floodplain − had disappeared prior to field assessment as part of the general clean-up of neighbouring properties. The presence of significant amounts of large, woody debris possibly implies some transport by debris flows, with later re-working by flood flows.

Figure 23 Deposited woody debris and sediment on Ludo Heylen's front lawn from the south branch of Te Weiti Stream (left) and looking upstream towards the house in the background. Taken the day after the March 2017 storm. Photos: Ludo Heylen.

The role of knickpoints (sharp changes in stream gradient, such as waterfalls) was observed to be important in controlling deposition and scour across the streams we assessed. Each stream possessed a range of geomorphic conditions, including depositional zones, intact valley fills, erosional zones, knickpoints and scoured channels. However, as mentioned above, the size of the March 2017 storm was such that complete channel segments had been scoured to bedrock and bedrock waterfalls 'cleaned up'.

Logging debris retained on slopes was observed to have retained most hillside-derived sediment arising from both sheet wash and some landslides, except within tributary flow lines. However, changes in slope also contributed to significant retention of sediment on the slopes. A noticeable feature of the Tairua streams was that there was generally not much large wood left in the channels, nor remnants of log jams. Any large wood that was delivered by landslides and debris flows during the storm had been removed and deposited downstream. This was in contrast to Paroa Forest and also points to the occurrence of debris flows. Further, the deep vertical scour in stream channels and valley bottoms is a further indicator of debris flow activity. Some evidence of super-elevation around stream bends is another indicator.

The Tairua example is an extreme end-member of our small sample, and our assessment indicates that even if substantial riparian buffers were in place they would have been unlikely to have prevented any landslide material from entering the stream. They may have been partially effective if they were well established and on flatter terrain, such as in the valley bottom or on a terrace. For example, on the lower flood plain, where significant logging debris and sediment ended up, the kānuka adjacent to the stream opposite Ludo Heylen's place acted as a fence and held up material. It should be noted, though, that the channel gradient was fairly gentle and the flood plain wide. In other words, we are suggesting that slope is a bigger determinant on deposition and woody debris capture than a riparian buffer. However, in some places, particularly in the upper basins, we did see some log jams trapping sediment, but again these tended to be on wider, gentler valley floors.

Photographs of examples of key field observations, processes, and impacts from Tairua Forest Watersheds 1, 4, and 5 are shown in Appendix 2, Figures A6, A7 and A8.

6.2.4 Summary of findings across the study sites

Looking across the three forests there are some similarities in terms of the landscape response to tree removal, the type and magnitude of erosion process, and how vegetated streamside buffers behaved. Firstly, there was clear evidence for the following.

- Event magnitude controlled the scale of landscape response. In other words, the severity of the response to a storm – both on the hill slopes (initiation of landslides) and in the channels (elevated flows, resulting in bank failures and channel scour) – is reflected in elevated levels of sediment generation and discharge, in keeping with the severity of the storm.
- Where buffers were present, their sediment-trapping efficiency depended on the density, maturity and type of vegetation, the size and type of sediment-generating process, whether sediment was generated upslope or within the buffer itself, and the slope within the buffer itself.
- In general, sediment entrained within concentrated flow paths traversed directly through the buffers and entered the nearest stream channel.
- Similarly, the larger translational landslides initiated upslope of, or within, the buffer generally contributed sediment to the channel.
- The more porous volcanic soils observed in Whangapoua and Tairua also suggested that the generation of surface-wash-derived sediment would only occur when the infiltration capacity was exceeded or soils were saturated. Further, the porous soils indicated that subsurface lateral flow in the slope was probably responsible for the initiation of landslides and slope instability in many localities.
- The water content of the sediment at the time of failure was a significant factor in determining the mobility of the material and the distance it travelled downslope of its origin. Sediment generated by the initiation of shallow translational landslides was generally saturated at the time of failure, which meant it travelled considerable distances downslope and more often than not reached a stream channel. Conversely, the failed materials comprising the larger-sized and deeper-seated rotational slumps tended to be drier, and although some such failures occurred in close proximity to a channel, few reached or contributed sediment to the channel.
- At Whangapoua and Tairua, where the weathered volcanic soils are thick and porous, the generation of sediment from bare (unvegetated) areas of cutover by sheet wash probably only occurred when the infiltration capacity of the soil was exceeded or after the soil became saturated. Furthermore, the infiltration of rainwater through these porous soils to a depth where it became concentrated as subsurface lateral flow was probably responsible for the initiation of small landslides, and streambank failures at the point where this flow exited from streamside banks.
- Assessing the extent of sediment sources and the relative proportion of sediment that probably entered a stream some months or years after a storm event proved difficult,

because sites of sediment generation initiated at the time of a storm (landslides) or as a consequence of harvesting (bare ground disturbed during harvesting) had become recolonised by vegetation, obscuring much of the evidence of sediment mobility and its connectivity to streams. However, from our observations, and based on experience documenting the impacts of previous storm events on cutover in landscapes typical of these three forests, we concluded that:

- shallow translational landslides generate significantly more sediment than deeper-seated rotational failures (including riparian bank failures)
- channel and bank scour can be a significant source of sediment
- sheet wash generates the least by several orders of magnitude.

Also, the probability of shallow translational landslides, small-scale slumping proximal to channel banks, and channel and bank scour delivering sediment to a stream channel is greater than it is for more distal, deeper-seated failures, and least for sediment generated from areas of bare ground by sheet wash. Thus, in areas of steepland forest at times when the rainfall intensity and/or magnitude is sufficient to initiate landslides and high flood flows, the relative contributions of sediment delivered to the stream load and suspended sediment yield are likely to be greatest from shallow landslides, channel and bank scour, small-scale rotational bank failures and distal rotational slumps, and least from sheet wash.

- The type and extent of erosion processes, their connectivity to stream channels, and their relative contribution to the sediment load will vary across forests in different regions due to differing combinations of site factors, including geology (lithology), physiography (slope, aspect, soil type porosity and depth), vegetation cover (density and maturity of forest and scrub type, including buffers), time since harvesting, and storm frequency and magnitude.

7 Discussion and conclusions

This pilot project aimed to assess the effectiveness of vegetated riparian buffers for trapping hillslope-derived sediment from reaching streams in recently harvested plantation forests. The work has added to our understanding of the role and effectiveness of riparian buffers in plantation forestry in New Zealand for removing sediment. However, because of the limited number of localities investigated, it has failed to confirm that slope steepness and form are the primary drivers of connectivity of sediment sources to streams, and that the presence of vegetated riparian buffers for removing or filtering sediment within steep plantation catchments is secondary.

Our findings largely support those of previous work in other countries but do not provide definitive evidence either way to suggest that vegetated riparian buffers in steepland forests are necessary to mitigate sediment delivery to streams. In the absence of large rainstorm events, the effect of tree removal on increasing runoff generation results in increased scour and re-distribution of sediment within, and potentially out of, harvested catchments. The increased runoff coupled with longer periods of increased soil moisture also leads to conditions (exfiltration, seepages / high pore-water pressures) that can promote slope instability. While this may or may not translate to a higher incidence of slope failures (landslides), it appears there may be an increase in basal slope or riparian failures. Without a detailed longitudinal study of slopes pre- and post-harvest, determining the importance of this mechanism is difficult.

Croke and Hairsine (2006) suggest focusing on managing runoff or managing sediment delivery pathway as the principal ways in which sediment might be managed within forests (see their Table 1). Many of the practices they suggest are also recommended in guidelines, codes of practice or regulations in many countries. While sediment is generated from a range of different sources in a harvested forest and is transported by different processes, roads, tracks and bare soil surfaces are universally important, as are mass movements (landslides).

Part of the sediment generated from these sources is delivered to the stream, and this proportion is determined by characteristics of the flow pathway, among other factors. This is termed the 'sediment delivery ratio', or SDR. For all sources, a combined approach of reducing the source strength and enabling the delivery pathway to trap or intercept sediment, thereby reducing connectivity, is a sound approach to managing the problem (Croke & Hairsine 2006). Conceptually, separating runoff source strength and the delivery processes is useful for guiding the management of forest landscapes. However, where slopes are very steep and grade directly into streams or concentrated flow paths, the ability of flatter areas to retain sediment is limited. In these situations it is better to ensure that sediment generation is minimised at source rather than trying to intercept it along the flow path. In the case of landslides on steep slopes, it is impossible to know where and when a piece of slope will fail, so managing these is effectively impossible, as is managing any delivery pathway.

Brown and Visser (2017), in their study of breakthroughs in recently harvested plantation forests in New Zealand, found that three-quarters of breakthroughs were associated with sediment sources such as roads, skid trails, stream-crossing approaches, and ruts from machine tracks on hillslopes directed towards the stream. They suggested that it will not be possible to eliminate all sediment generation and delivery from these sources and identified two areas for improved best management practices to either reduce road-to-stream connectivity or lessen the severity of water quality impacts from breakthroughs. The first is to locate road-stream crossings to avoid steep approaches, and the second is to ensure that temporary stream crossings are closed properly.

While our findings have been inconclusive in terms of quantifying the direct benefit of vegetated riparian buffers to mitigate sediment delivery to streams in steepland forests, they do support a range of findings from earlier work.

- Sediment yields rise and the harvested slopes are at their most vulnerable in the post-harvest period.
- If large, infrequent rain events coincide with steep harvested catchments in the years following harvesting, the combination of increased runoff, increased sub-surface lateral flow, and the generation of hillslope and riparian landslides can lead to the development of debris flows that can have significant effects on channel morphology and sediment delivery downstream (Phillips et al. 2012). If such events occur before

canopy closure of the new crop, the increased runoff causes re-distribution of sediment between temporary sediment stores, increases channel scour and leads to small riparian mass failures, all of which contribute to elevated sediment yields.

- Once sediment sources are exhausted and vegetation cover post-desiccation recovers, sediment yields tend to reduce to pre-harvesting levels. This usually occurs within 2 years (Quinn & Phillips 2016).

This study focused on the role of riparian buffers and setbacks for mitigating sediment input to stream channels. The other values and benefits (shade, biodiversity, ecological corridors, etc.) that riparian buffers might confer were not considered in this pilot study, and our conclusions need to be considered in this wider context.

8 Recommendations for future research

8.1 General needs identified from the literature

The focus of the current study was to determine the effectiveness of riparian buffers to mitigate sediment delivery to streams. However, this research sits within a wider set of questions concerned with understanding catchment response to harvesting and related sediment generation. Future research needs based on our findings largely support the recommendations of earlier work from other countries. Some of these relate to general forest hydrology (e.g. Williams et al. 2016), while others are focused more on sediment in forested catchments.

For example, Anderson and Lockaby (2011) suggested there are four categories of research gaps, based on a literature review of forest operations and sedimentation of streams. These are:

1. timber harvesting effects on water yield and water quality:
   - determining stream sediment from in-channel versus overland sources
   - influence of catchment size on sediment yield
2. temporal and spatial scale of sediment delivery:
   - cumulative watershed effects of forest operations on sediment yield
3. sediment/water yield from roads:
   - tracking sediment produced from roads (and landings and cutover) and its delivery to streams
4. assessing the effectiveness of best management practices (or mitigation):
   - optimising best management practice applications for sediment reduction
   - quantifying the effectiveness of different best management practices.

There is evidence that increased water yields and peak flows can erode existing stream channels and significantly increase sediment loads, especially where there are substantial amounts of legacy sediment in streams from past activities (Thornton et al. 2000; Schoenholtz 2004). However, Mohr et al. (2013) have suggested there are unanswered questions if harvest areas act as sources or sinks for runoff and soil erosion.

For streams where sediment loads rise during or following harvesting, it is important to know if the sediment concentration increases come from in-stream or out-of-stream sources. If most material originates from within the channel and is being moved as a result of a higher water yield/discharge, the use of best management practices such as riparian buffers to reduce overland flow of sediment may only have a marginal effect on the sediment load. Incorporating tracer studies (radionuclides) in future studies could greatly improve understanding of in-channel and other potential sediment sources. We suggest investigating these techniques would be valuable. However, our experience over many decades suggests that in regions subject to intense rainfalls where landslides are common, better characterisation of regional landslide–rainfall thresholds might be more useful.

Temporal and spatial variability of different erosion processes is still an area with many unresolved research questions. Major storms have been suggested as the primary factor responsible for sediment movement, but many study durations are too short to determine the temporal variability of sediment generation and delivery. Often they are conducted in a period where there is no storm (underestimate) or coincide with a major storm (overestimate). Another factor to be assessed is that forest operations today are very different from in the past, and long-term studies that capture the full range of 'normal' precipitation events, while accounting for current operational practices, are needed to adequately address the current impact on water quality.

Catchment scale and stream order are also important spatial factors to consider. Some studies suggest that smaller catchments (<10 km^2) have greater increases in peak flow after harvest compared to larger catchments (Grant et al. 2008).

Forest roads and landings are often seen as the primary sources of sediment related to forestry operations (excluding mass wasting). Distinguishing road-generated sediment yield from other sources (cutover/harvest area, landings) can be difficult because sediment is often generated concurrently. The variability of activities associated with forest management can make it difficult to unpick the contribution of any one activity to sediment yield.

Croke and Hairsine (2006) in their review suggested that to accurately predict the potential impacts of accelerated surface runoff and erosion processes due to harvesting on stream water quality, three key areas need to be understood:

1. the major sources of runoff and sediment, and their spatial distribution with respect to streams
2. the delivery pathway of each of these sources and its effect on sediment fluxes as runoff moves through the landscape from source to stream
3. the effectiveness of best management practices with respect to sediment production and delivery.

They provided a template for considering these components, which requires specific location knowledge of soil characteristics, climate, topography, and local forest management practices.

8.2 Specific needs identified from field study assessments

The contention that vegetated riparian buffers mitigate sediment delivery to steepland forest streams in New Zealand has not been proven in this study. We believe a larger study (incorporating a range of parameters and regional variations) is required to determine the importance of riparian buffers for mitigating sediment delivery to streams, and to support their inclusion as primary mitigating mechanisms in regional council plans. Such a study should determine the relative importance of a buffer versus changes in slope gradient for reducing sediment delivery to streams.

If future studies were to be conducted, strong industry support is needed to promote site selection across different regions, as we found there is a high transaction cost in locating suitable sites for this pilot study. A further need is to identify sites so that assessments can be carried out within 6 months and/or within 12 months of cessation of harvesting to capture an average year's rainfall and catchment response. This means finding a balance between seeing enough evidence of sediment breakthroughs (such as assessed by Brown and Visser 2017) and streamside zones where new vegetation potentially hides or covers evidence of sediment pathways or sites of sediment deposition.

If a larger study were contemplated, then better geographic coverage is needed, including some South Island sites. Better coverage of a range of buffer widths and density and composition would be ideal, but it might not be possible to undertake a full multivariate study. Conversely, there may be value in doing further reconnaissance-level assessments, such as in this study. If a second pilot found contradictory results, then a larger multi-parameter study would be required to gather sufficient information in order to support or reject the contention that riparian buffers do or do not mitigate sediment delivery in forested catchments.

Our pilot study suggested that in undertaking stream assessments, high-resolution imagery is valuable. Undertaking this before harvesting would be of value to stream assessment. High-resolution imagery, such as provided for the study catchments at Tairua Forest, would assist in greater geo-referencing of sediment sources outside the buffer, and the fate of material could then be confirmed by ground assessment in terms of delivery to the stream.

In terms of future methodology, can a technique be found to quickly provide a reconnaissance-level assessment of the sources to assist sampling or within-site descriptions, such as with drones or high-resolution remote sensing? Is it possible to do a longitudinal study of a few chosen sites to assess the short and longer-term changes in stream and slope process contributions and revegetation regrowth, etc. (taking into account the presence or absence of large storms)? This could include setting up 'plots', photo points, and/or measurement sites in a before-and-after experiment.

Lastly, a related need that has previously been pointed out (e.g. Phillips et al. 2012) is to formalise a national network of forestry companies that are willing to share information about the incidence of rain events that cause erosion, landslides and debris flows, so that local threshold conditions for landsliding can be determined along with any driving factors. Currently it is difficult to determine if issues arising following harvesting are exceptional or typical.

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10 References

Anderson CJ, Lockaby BG 2011. Research gaps related to forest management and stream sediment in the United States. Environmental Management 47(2): 303–313.

Baillie BR, Heaphy M 2011. Water quality monitoring and water quality indicators for plantation forests. FFR Report No. ES005. Rotorua, New Zealand, Scion.

Baillie B, Neary DG 2015. Water quality in New Zealand’s planted forests: a review. New Zealand Journal of Forestry Science 45(7): 1–18.

Baillie BR, Rolando CA 2015. Long-term management of stream in planted forest steeplands. New Zealand Journal of Forestry 60(2): 21–24.

Baker J 2014. The environmental effects of plantation forestry - the Ngunguru catchment, Northland, New Zealand: a discussion document. 1–73 p.

Benda L, Dunne T 1988. Sediment routing by debris flow. Erosion and sedimentation in the Pacific Rim: proceedings of an international symposium held at Oregon State University, Corvallis, Oregon, USA. International Association of Hydrological Sciences Publication. Pp. 213–223.

Boothroyd IKG, Quinn JM, Langer ER, Costley KJ, Steward G 2004. Riparian buffers mitigate effects of pine plantation logging on New Zealand streams: 1. Riparian vegetation structure, stream geomorphology and periphyton. Forest Ecology and Management 194(1–3): 199–213.

Broadmeadow S, Nisbet TR 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practise. Hydrology and Earth System Sciences 8(3): 286–305.

Brown K, Visser R 2017. Erosion sources and sediment pathways to stream associated with forest harvesting activities in New Zealand. 19th Biennial Southern Silvicultural Research Conference, Blacksburg, Virginia, US.

Clinnick PF 1985. Buffer strip management in forest operations: a review. Australian Forestry 48(1): 34–45.

Clutter JL, Forston JC, Pieenar LV, Brister GH, Bailey RL 1983. Timber management: a quantitative approach (reprint ed.). Malabar, Florida, USA, Krieger Publishing.

Collier KJ, Cooper AB, Davies-Colley RJ, Rutherford JC, Smith CM, Williamson RB, Clelland L 1995. Managing riparian zones: a contribution to protecting New Zealand's rivers and streams. Wellington, Department of Conservation.

Cooper JR, Gilliam JW, Daniels RB, Robarge WP 1987. Riparian areas as filters for agricultural sediment. Soil Science Society of America Journal 51: 416–420.

Cristan R, Aust WM, Bolding MC, Barrett SM, Munsell JF, Schilling E 2016. Effectiveness of forestry best management practices in the United States: literature review. Forest Ecology and Management 360: 133–151.

Croke J, Hairsine P, Fogarty P 1999. Runoff generation and re-distribution in logged eucalyptus forests, south-eastern Australia. Journal of Hydrology 216: 56–77.

Croke JC, Hairsine PB 2006. Sediment delivery in managed forests: a review. Environmental Reviews 14(1): 59–87.

Croke J, Mockler S 2001. Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. Earth Surface Processes and Landforms 26(2): 205–217.

Daniels RB, Gilliam JW 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Science Society of America Journal 60: 416–420.

Davies PE, Nelson M 1994. Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. Australian Journal of Marine and Freshwater Research 45: 1289–305.

Dillaha TA, Sherrard JH, Lee D 1989. Long-term effectiveness of vegetation filter strips. Water Environment and Technology 1(3): 419–421.

Dyrness CT 1965. Soil surface disturbance following tractor and high-lead logging in the Oregon Cascades. Journal of Forestry 63: 272–275.

Eyles GO 1985. The New Zealand Land Resource Inventory Erosion Classification. Water and Soil Miscellaneous Publication 85. Wellington, National Water and Soil Conservation Authority.

Fahey BD, Coker RJ 1989. Forest road erosion in the granite terrain of Southwest Nelson, New Zealand. Journal of Hydrology (N.Z.) 28(2): 123–141.

Fahey BD, Marden M 2000. Sediment yields from a forested and a pasture catchment, coastal Hawke's Bay, North Island, New Zealand. Journal of Hydrology (N.Z.) 39(1): 49–63.

Fahey BD, Marden M, Phillips CJ 2003. Sediment yields associated with plantation forestry, coastal Hawkes Bay, north Island, New Zealand. Journal of Hydrology (NZ) 42(1): 27–38.

Fransen P, Phillips C, Fahey B 2001. Forest road erosion in New Zealand: overview. Earth Surface Processes and Landforms 26(2): 165–174.

Frasier GW, Trlica MJ, Leininger WC, Pearce RA, Fernald A 1998. Runoff from simulated rainfall in 2 montane riparian communities. Journal of Range Management 51(3): 315–322.

Garrison GA, Rummell RS 1951. First-year effects of logging on ponderosa pine forest range lands of Oregon and Washington. Journal of Forestry 49(10): 708–713.

Gilliam JW, Schipper LA, Beets PN, McConchie M 1992. Riparian buffers in New Zealand forestry. New Zealand Forestry (August): 21–25.

Gomi T, Moore RD, Dhakal AS 2006. Headwater stream responses to clearcut harvesting with different riparian treatments, coastal British Columbia, Canada. Water Resources Research 42. doi: 10.1029/2005WR004162 (Art. No. W08437).

Grant GE, Lewis SL, Swanson FJ, Cissel JH, McDonnell JJ 2008. Effects of Forest Practices on Peak Flows and Consequent Channel Response: A State-of- Science Report for Western Oregon and Washington. General Technical Report. Pacific Northwest Research Station. PNW-GTR-760.

Graynoth E 1979. Effects of logging on stream environments and faunas in Nelson. New Zealand Journal of Marine and Freshwater Research 13(1): 79–109.

Grayson RB, Haydon SR, Jayasuriya MDA, Finlayson BL 1993. Water quality in mountain ash forests: separating the impacts of roads from those of logging operations. Journal of Hydrology 150(2): 459–480.

Hairsine PB 1997. Buffer zones for managing sediment movement in forestry operations. Erosion in Forests: Proceedings of the Forest Erosion Workshop March 1997. Pp. 19–21.

Harmsworth GR 1987. An assessment of storm damage at Otoi in Northern Hawke’s Bay. Publication 10, Soil Conservation Centre, Aokautere. National Water and Soil Conservation Authority, 76pp.

Helmers MJ, Eisenhauer DE, Dosskey MG, Franti TG, Brothers JM, McCoullough MC 2005. Flow pathways and sediment trapping in a field-scale vegetative filter. Transactions of the American Society of Agricultural Engineers 48: 955–968.

Hewitt AE 2010. New Zealand Soil Classification. Landcare Research Science Series No. 1.

Hockey M, Page M 1983. Site index data for the Gisborne-East Coast region. Collated 1981 and partially revised in 1983. Unpublished Internal New Zealand Forest Service Report, New Zealand Forest Service, Wellington, New Zealand.

Imaizumi F, Sidle RC 2012. Effect of forest harvesting on hydrogeomorphic processes in steep terrain of central Japan. Geomorphology 169: 109–122.

in 't Veld GJ, de Graaf F 1990. Erosion damage as a result of Cyclone Bola: an assessment on Arai Matawai and Emerald Hills properties East Coast Region, North Island, New Zealand. Gisborne, New Zealand, Forest Research Institute, Ministry of Forestry.

Lynch JE, Corbett, Mussallem K 1985. Best management practices for controlling nonpoint source pollution of forested watersheds. Journal of Soil and Water Conservation 1: 164–167.

Maclaren JP 1993. Radiata pine growers' manual. Forest Research Institute Bulletin 184. Rotorua, New Zealand, Forest Research Institute.

Magette WL, Brinsfield RB, Palmer RE, Wood JD 1989. Nutrient and sediment removal by vegetated filter strips. Transactions of the ASAE 32(2): 663–667.

Marden M, Phillips C, Rowan D 1991. Declining soil loss with increasing age of plantation forests in the Uawa catchment, East Coast Region, North Island, New Zealand. In: Proceedings of the International Conference on Sustainable Land Management, Napier, New Zealand. Pp. 358–361.

Marden M, Rowan D 1995. Assessment of storm damage to Whangapoua Forest and its environs following the storm of March 1995. Landcare Research Contract Report LC9495 / 172. Prepared for Ernslaw One Ltd.

Marden M, Rowan D 1997. Vegetation recovery and indicative sediment generation rates by sheetwash erosion from hauler-logged settings at Mangatu Forest. New Zealand Forestry (August): 29–34.

Marden M, Rowan D 2015. The effect of land use on slope failure and sediment generation in the Coromandel region of New Zealand following a major storm in 1995. New Zealand Journal of Forestry Science 45: 10. doi: 10.1186/s40490-015-0036-9.

Marden M, Rowan D, Phillips C 1995. Impact of cyclone-induced landsliding on plantation forests and farmland in the East Coast Region of New Zealand: a lesson in risk management? In: Proceedings of the XX IUFRO World Congress, Tampere Finland. Technical session on natural disasters in mountainous areas. Pp. 133–145.

Marden M, Rowan D, Phillips C 2006. Sediment sources and delivery following plantation harvesting in a weathered volcanic terrain, Coromandel Peninsula, North Island, New Zealand. Australian Journal of Soil Research 44: 219–232.

Marden M, Rowe L, Rowan D 2007. Slopewash erosion following plantation harvesting in pumice terrain and its contribution to stream sedimentation, Pokairoa Catchment, North Island, New Zealand. Journal of Forestry (NZ) 46: 73–90.

May C 2007. Sediment and wood routing in steep headwater streams: an overview of geomorphic processes and their topographic signatures. Forest Science 53(2): 119–130.

Mayer PM, Reynolds SK, McCutchen MD, Canfield TJ 2006. Riparian buffer width, vegetative cover, and nitrogen removal effectiveness: a review of current science and regulations. EPA/600/R-05/118. Cincinnati, Ohio, US Environmental Protection Agency.

Mazengarb C, Speden IG 2000. Geology of the Raukumara area. Institute of Geological and Nuclear Sciences 1:250 000 geological map 6. Institute of Geological and Nuclear Sciences, Lower Hutt, NZ. 1 sheet + 60 p.

McLaren JP 1993. Radiata Pine Growers' Manual. Forest Research Institute Bulletin, 184. Rotorua, New Zealand, Forest Research Institute.

McLaren, JP 1996. Environmental effects of planted forests in New Zealand, New Zealand Forest Research Institute, Rotorua. 180p.

McCraw JD, Bell JL 1975. Soils of the Coromandel–Thames counties. In: Land Inventory Survey of Coromandel-Thames Counties. Department of Lands and Survey.

McKergow LA, Prosser IP, Grayson RB, Heiner D 2004. Performance of grass and rainforest riparian buffers in the wet tropics, Far North Queensland. 2: Water quality. Australian Journal of Soil Research 42: 485–498.

McMahon S 1995. Cable logging disturbance on an unstable slope: a case study. Rotorua, New Zealand, Logging Industry Research Organisation. 1–9 p.

Mohr CH, Coppus R, Iroume A, Huber A, Bronstert A 2013. Runoff generation and soil erosion processes after clear cutting. Journal of Geophysical Research − Earth Surface 118(2): 814–831.

Motha JA, Wallbrink PJ, Hairsine PB, Grayson RB 2003. Harvested areas and unsealed roads as sources of suspended sediment in a forested water supply catchment in south-eastern Australia. Water Resources Research 39(3): 1056–1075. doi: 10.1029/2001WR000794.

National Water and Soil Conservation Organisation [NWASCO] 1975. New Zealand Land Resource Inventory Worksheets. Wellington, New Zealand Government Printer.

Neary DG, Smethurst PJ, Baillie B, Petron KC 2011. Water quality, biodiversity, and codes of practice in relation to harvesting forest plantations in Streamside Management Zones. National Research Flagships Sustainable Agriculture Report August 2011.

New Zealand Meteorological Service 1973. Rainfall normals for New Zealand 1941–1970. New Zealand Meteorological Service Miscellaneous Publication no. 145. Wellington, New Zealand Meteorological Service.

Norris V 1993. The use of buffer zones to protect water quality: a review. Water Resources Management 7(4): 257–272.

Parkyn S 2004. Review of riparian buffer zone effectiveness. MAF Technical Paper.

Pearce AJ, O'Loughlin CL, Jackson RJ, Zhang XB 1987. Reforestation: on-site effects on hydrology and erosion, eastern Raukumara Range, New Zealand. Forest Hydrology and Watershed Management, Proceedings Vancouver Symposium. International Association of Hydrological Sciences Publication 167: 489–497.

Pearce RA, Frasier GW, Trlica MJ, Leininger WC, Stednick JD, Smith JL 1998a. Sediment filtration in a montane riparian zone under simulated rainfall. Journal of Range Management 51(3): 309–314.

Pearce RA, Trlica MJ, Leininger WC, Mergen DE, Frasier GW 1998b. Sediment movement through riparian vegetation under simulated rainfall and overland flow. Journal of Range Management 51(3): 301–308.

Phillips C, Marden M, Basher L 2012. Plantation forest harvesting and landscape response – what we know and what we need to know. New Zealand Journal of Forestry 56: 4–12.

Phillips C, Marden M, Rowan D 2005. Sediment yield following plantation forest harvesting, Coromandel Peninsula, North Island, New Zealand. Journal of Hydrology (NZ) 44(1): 29–44.

Phillips J 2005. Evidence in chief to the Environment Court, Auckland, pursuant to an RMA application for resource consent for harvesting, roading, earthworks and minor crossings at Whangapoua Forest, Coromandel.

Phillips JD 1989. An evaluation of the factors determining the effectiveness of water quality buffer zones. Journal of Hydrology 107: 133–145.

Quinn JM, Boothroyd IKG, Smith BJ 2004. Riparian buffers mitigate effects of pine plantation logging on New Zealand streams. 2: Invertebrate communities. Forest Ecology and Management 191(1–3): 129–146.

Quinn JM, Phillips CJ 2016. Production forestry. In: Jellyman PG, Davie TJA, Pearson CP, Harding JS eds. Advances in New Zealand freshwater science. New Zealand Hydrological Society & New Zealand Freshwater Sciences Society. Pp. 469–481.

Reid DJ, Quinn, JM, Wright-Stow, AE 2010. Responses of stream macroinvertebrate communities to progressive forest harvesting: influences of harvest intensity, stream size and riparian buffers. Forest Ecology and Management 260: 1804–1815.

Roy B, Popay I, Champion P, James T, Rahman A 1998. An illustrated guide to common weeds of New Zealand. New Zealand Plant Protection Society (Inc.) ISBN 0 473 09760 5.

Salter RT, Crippen TF, Noble KE 1983. Storm damage assessment of the Thames-Te Aroha area following the storm of April 1981. 1–54 p.

Schlosser IJ, Karr JR 1981. Water quality in agricultural watersheds: impact of riparian vegetation on base flow. Water Resources Bulletin 17(2): 233–1240.

Schoenholtz SH 2004. Impacts of forest management on water quality. In: Burley J, Evans J, Youngquist J eds. Encyclopedia of forest sciences. Oxford, United Kingdom, Elsevier Ltd. Pp. 377–388

Schofield JC 1967. Geological map of New Zealand. Sheet 3: Auckland. New Zealand Geological Survey, Department of Scientific and Industrial research.

Skinner DNB 1976. Geological map of New Zealand 1:63360. Sheets N40 and part sheets N35, N36 and N39. Northern Coromandel. Wellington, New Zealand Geological Survey.

Slaney PA, Halsey TG, Smith HA 1977. Some effects of forest harvesting on salmonid rearing habitat in two stream in the central interior of British Columbia. Fisheries Management Report 71, 26pp. British Columbia Ministry of Recreation and Conservation.

Soil Survey Staff 1992. Keys to Soil Taxonomy. SMSS Technical Monograph 19.

Stott T, Mount N 2004. Plantation forestry impacts on sediment yields and downstream channel dynamics in the UK: a review. Progress in Physical Geography 28(2): 197–240.

Thornton KW, Holbrook SP, Stolte KL, Landy RB 2000. Effects of forest management practices on Mid-Atlantic streams. Environmental Monitoring and Assessment 63: 31–41.

US EPA 2005. National management measures to control nonpoint source pollution from forestry. United State Environmental Protection Agency, Washington DC.

Walling DE 1983. The sediment delivery problem. Journal of Hydrology 65: 209–237.

Ward JM, Jackson CR 2004. Sediment trapping within forestry streamside management zones: Georgia Piedmont, USA. Journal of the American Water Resources Association 40(6): 1421–1431.

Wardle P 1991. Vegetation of New Zealand. Caldwell, New Jersey, USA, The Blackwell Press.

Water and Soil Directorate 1987. East Coast Project review. Wellington, Water and Soil Directorate, Ministry of Works and Development.

Wemple BC, Jones JA, Grant GE 1996. Channel network extension by logging roads in two basins, Western Cascades, Oregon. Water Resources Bulletin 32(6): 1195–1207.

Williams TM, Amatya DM, Bren L, de Jong C, Nettles JE 2016. Future directions in forest hydrology. In: Amatya DM, Williams TM, Bren L, de Jong C eds. Forest hydrology: processes, management and assessment. CAB International, Wallingford, Oxfordshire, UK.

Woolridge DD 1960. Water disturbance from tractor and skyline crane loading. Journal of Forestry 58: 369–372.

Wylie REJ 1975. Forest operations to safeguard water and soil resources. National Water and Soil Conservation Organisation. Proceedings of Water and Soils Division, Course No. 2, Rotorua, New Zealand.

Yoho NS 1980. Forest management and sediment production in the South: a review. Southern Journal of Applied Forestry 4(1): 27–36.

Zimmermann A, Francke T, Elsenbeer H 2012. Forests and erosion: insights from a study of suspended-sediment dynamics in an overland flow-prone rainforest catchment. Journal of Hydrology 428/429: 170–181.

Appendix 1 – Details of imagery supplied by forestry companies

Site	DEM received	Processed DEM resolution (m)	Imagery	Stream lines	Road lines	Boundaries	Forest owner
1. Paroa forest	10 m contour data	10	Orthos for 2012 (obtained from LINZ)	Yes	Yes	No	PF Olsen
2. Whangapoua forest	5 m contour data	5	0.5 m orthos for 2002 and 2012	Yes	Yes	Yes	Ernslaw One
3. Opoutere Block, Tairua Forest 4. Te Weiti Stream, Tairua Forest	AAM-supplied Lidar (1 m bare-earth DEM)	5	UAV orthos (c. 0.09 m resolution)	Yes	No	No	Rayonier NZ

Appendix 2 – Study site details and photographs from field inspection, illustrating key points

Paroa Forest

Paroa Forest (178°13´21"E, 38°19´20"S) is located inland of Tolaga Bay (Figure 3). The slopes flanking the stream reaches surveyed in this report were planted in 1986/87. Roadlining and road and landing construction occurred in 2011. The upper part of Watershed 1 was harvested in 2012 and replanted in 2014. The lower part of this watershed was harvested in late 2015 and replanted in 2016. Watershed 3 was harvested in 2014 and replanted in 2015.

The topography is steep (mean 32˚), is predominantly Class VIIe9 (National Water and Soil Conservation Organisation [NWASCO] 1975) land, and occurs at an altitude of between 42 and 133 m above sea level. Slopes are between 26° and 35°, and in places >35°. Erosion is described as slight soil slip, and the vegetation cover before being cleared for the establishment of exotic forest was mānuka, kānuka and hardwood forest. The forest has a site index of 30-35 (Hockey and Page 1983). Site index refers to the timber potential for a site for a particular species, usually at a fixed age somewhere near the expected rotation length for the species. In forestry, the usual method to develop site index is from stand height records, as good site quality is often reflected in good height growth (Clutter et al. 1983; McLaren 1993).

The climate is warm temperate maritime, with moist summers and cool, wet winters. Mean annual rainfall varies from about 700 mm at the coast to 2,500 mm at higher altitudes (New Zealand Meteorological Service 1973). Lengthy periods of little or no rainfall are common during January to April (mid-summer to late autumn). This region has a history of extreme rainfall events, often associated with storms of tropical origin (e.g. Cyclone Bola in 1988) and, together with more localised storm cells (e.g. 2005, 2009, 2014, 2015, 2017), these have been a major feature contributing to the unstable nature of steep hill country. The volatile climate contributes to high erosion rates (Water and Soil Directorate 1987).

The geology consists of fossiliferous mudstone with intercalations of sandstone, conglomerate and tuff of late Miocene age (Mazengarb & Speden 2000). Coverbed materials consist of layered volcanic tephra, predominantly Taupo Ash and Waimihia Lapilli, though older tephras may also be present, overlain by a thin (15 cm) organic forest soil. The thickness of these coverbeds varies from metres on ridgetops and on gentler topography to less than 0.5 m on the steeper slopes, and in places slope failures (landslides) have completely stripped this material to expose the underlying bedrock. Soils are well drained Typic Orthic Recent Soil, typically associated with land that has been eroded or has received sediment as a result of slope processes (Hewitt 2010). The soils correlate with the Inceptisols of the Soil Taxonomy (Soil Survey Staff 1992).

Watershed 3 looking upstream, showing general slope characteristics and riparian buffer.

Watershed 3 looking downstream, showing general slope characteristics and riparian buffer.

Riparian vegetation within the channel.

Example of shallow landsides on very steep slopes. Failure to bedrock.

TR landslide and deposit entering buffer

Landslide deposit entering stream, going over break in slope into gorge

Figure A1 Paroa Forest Watershed 3: photographs illustrating key points.

Watershed 1 looking downstream, showing general slope characteristics and riparian buffer of the lower catchment.

Sediment accumulation on terrace, concentrated runoff, sparse buffer.

Riparian vegetation within the channel. Tall kānuka older than 50 years.

Two-tier riparian vegetation: taller, older kānuka and smaller-stature native regrowth.

Figure A2 Paroa Watershed 1 (con’t next two pages)

Logging debris in channel. Channel shows little signs of any debris flow activity but does show sediment and wood deposition. Person for scale (white arrow).

This landslide, sourced above the buffer, traversed the buffer picking up native vegetation and depositing it and sediment in the channel. Note very steep slope.

TR landslide and deposit entering bedrock gorge. Note person for scale (white arrow).

Narrow bedrock gorge: limit of assessed reach.

Figure A2 con't.

Landslide and gully depositing material on terrace. Only fine sediment reached the stream via a concentrated flow pathway across the terrace.

Looking up Watershed 1 from the valley floor. Note the sediment build-up and the valley floor terraces on the left, which intercepted a lot of slope-derived material. Note person for scale.

Figure A2 con’t.

Whangapoua Forest

The Whangapoua forest study area (Figure 3) is located on the eastern side of the Coromandel Peninsula within the Thames–Coromandel district. Two sites were chosen in the Otama Block: Otama North (Compartment 502, 175°46´59"S, 36°42´53"S), at an elevation of between 42 and 133 m, and Otama South (Compartment 501, 175°47´02"N, 36°43´47"S), at an elevation of 39 to 104 m. The topography is classed as VIIe7 (NWASCO 1975) with slopes between 26° and 35°. Erosion is described as severe sheet wash and slight soil slip. Before exotic forest was planted the vegetation was predominantly mānuka and kānuka.

The sites selected for assessment are located in the Otama Block, which is at the eastern edge of the forest. Here, following scrub clearance (by root raking and roller crushing), substantial areas of secondary indigenous vegetation were preserved as riparian strips adjacent to stream channels. Native riparian buffers are retained as part of resource consent conditions and for specific purposes such as ecological corridors. Resource consent conditions for harvesting allow some damage to riparian vegetation if trees cannot be pulled away from the streams. In some cases corridors are ‘sacrificed’ to allow haul paths to pass through the buffers. Pastoral farming is currently restricted to rolling hill country located in the lowermost parts of these catchment, and to the coastal floodplain.

A storm in March 2016 coincided with the early establishment phase of the second rotation, during which several mass failures distributed sediment and debris onto the adjacent farmer’s land near Opito Bay, raising a number of issues of concern to residents, regional authorities, recreationists, and the forest owners. These included the likelihood of impacts resulting from on-site forestry activities (road and landing construction, harvesting, logging traffic) and their potential off-site effects, particularly on streams and associated estuaries. These estuaries are noted habitats for estuarine birds and shellfish, while the surrounding sea is internationally renowned for its game fishing. In addition, the Coromandel area is a popular tourist destination for both land- and sea-based recreation.

The sites selected for assessment are located in the Otama Block, which is at the eastern edge of the forest. The Otama forest block was first planted in 1983, predominantly with exotic *Pinus radiata*. Roadlining (ground-based harvesting) commenced in November 2011 and was completed by April 2012. Upgrading of the forest’s road infrastructure and landing construction in preparation for harvesting began in 2013, with clearfell harvesting (hauler) commencing in July 2014, and was completed by February 2016. To control competition from regenerating indigenous and wilding exotic pines, cutover areas were then aerially desiccated with herbicides on 10 March. This was followed by oversowing on 1 July 2016 with a mix of introduced grasses (Yorkshire fog, *Holcus lanatus*; Punawai browntop*, Agrostis capillaris*) (Wardle 1991), and legumes (white clover, *Trifolium repens*; birdsfoot trefoil, *Lotus angustissimus*) (Roy et al. 1998). Oversowing was undertaken to minimise surface erosion, predominantly by slope wash, during the post-harvest period. Cutover in the Otama Block was restocked with *P. radiata* between 28 July and 8 August 2016.

The basement geology of the area consists of hydrothermally altered Whangapoua and Matarangi andesites of Miocene age (Skinner 1976). The soils are highly variable, with soil types strongly related to parent materials, elevation and slope steepness. They have developed from deeply weathered andesite. Steep land soils, including Aroha (As) and Te Kie (Tks), occur in steep to very steep terrain in the uppermost parts of the major river catchments, where exposed bluffs of weathered andesite are common. At lower elevations, on moderately steep to steep terrain, Waitakere and Rangiuru hill soils predominate (McCraw & Bell 1975); that is, Typic Orthic Brown Soils and Mottled Orthic Brown Soils (Hewitt 2010), respectively. Soils on easy to rolling terrain include Whitianga Silt loam and Waitekere Clay loam (McCraw & Bell 1975). The weathered nature and high clay content of these soils predispose slopes to shallow, rapid slides (soil slip and debris avalanche) and flows involving soil and regolith. Soil slips typically have a small scar ≤1 m deep exposing a slip surface, with debris deposited as a narrow debris tail downslope of the scar. A debris avalanche is a similar type of failure but tends to be larger, the scar is deeper (2–5 m), and hence the depositional debris tail tends to occupy a significant length of the slope (Eyles 1985).

Though temperate, the climate at Whangapoua is known for its frequent, high-intensity localised storms, often of tropical origin, which frequently result in severe flooding. The average annual rainfall is 1,729 mm, with a distinct March to June ‘wet season’. The estimated 2-year return period rainfall is 127–133 mm in 24 hours (New Zealand

Meteorological Service 1980). High-intensity storms such as occurred in 1995 delivered 94 mm of rainfall (1.3-year return period), half fell within a 2-hour period at an intensity of 25 mm/hour while the maximum hourly rainfall intensity reached 37 mm/hour (return period 1.8 years). A storm in March 2017 delivered 160 mm of rainfall in less than 24 hours (duration 4 hours?) (Murray Eden's rain gauge – Norbert Klein, pers. comm). Rainfall records on 17 March show the following: Castle Rock: 67 mm; Whitianga airport: 109 mm; Opito Bay (Murray Eden's account) >160 mm.

Looking down Watershed 5. Note the gentle slopes and the riparian buffer.

Large landslide on TL of Watershed 5 (see below).

Streambank scour on both sides of stream. Note cloudy water.

Small riparian collapse/failure – lower slope, sediment directly in the stream – within buffer, exposed roots.

Riparian failure – exposed roots, within buffer, sediment into the stream.

A large landslide deposited material into the riparian buffer on a change of slope. Little material reached the stream. Note person standing on deposit (white arrow).

Figure A3 South Otama Block – Watershed 5

Example of channel scour – exposed sediment and vegetation roots.

Deposited sediment

Riparian failure, slump, tension cracks, into stream.

A combination of channel scour and bank failure at a knickpoint (step in channel). The channel has scoured down to hard bedrock. Above this point the channel is narrower and slotted into older deposits (see below).

Figure A4 South Otama Block – Watershed 3 (con't next page)

Above the knick point, the channel becomes entrenched in old sediment deposits.

Further upstream the channel disappears under a large amount of sediment deposited in a shallow basin.

Figure A4 con’t.

Looking down into the stream from a landing failure. Note landslides on slopes in background.

Examples of similar shallow landslides resulting from the March 2016 event in pasture in similar slope positions adjacent to the Otama Block.

Figure A5 North Otama block − Watershed 2 and part of Watershed 1 (con’t next page)

Looking upstream to the head of Watershed 2. Note landslides and channel scour.

Looking downstream. Note channel scour into old valley infills, causing lateral spread and collapse of banks and exposing old buried soils.

Landslide within buffer or just outside, traversing the buffer, damaging vegetation and delivering material to stream – low retention.

Channel scour to bedrock. Exposed side walls indicate high flows and/or possibly debris flows likely to have occurred in response to the March 2016 event.

Figure A5 con’t.

Tairua Forest

Two blocks of recent cutover were chosen within Tairua Forest, Opoutere Block (175°51´36"E, 37°06´56"S, elevation range 10−122 m above sea level) and Te Weiti Block (175°50´49"E, 37°11´36"S, elevation range 18−199 m). The Opoutere Block (Watershed 1) was planted in *P. radiata* in 1989, roadlined in spring 2014, with harvesting starting in November 2014. Harvesting was finished in November 2015 and the block was replanted in 2016.

The Te Weiti Block (Watersheds 4 and 5) was planted in *P. radiata* in 1990, roadlined in autumn 2016, with harvesting starting June 2016. Harvesting finished in December 2017 and the catchments were replanted in 2017. Both areas were aerially desiccated prior to replanting. In both areas, aerial photographs prior to harvesting did not reveal the presence of significant areas of riparian vegetation nor unplanted setbacks. Watershed 5 was the only one in which riparian vegetation was apparent in the upper part of the basin.

The climate can be classified as warm temperate maritime. Annual rainfalls are of the order of 1,800−1,900 mm. The area is characterised by the occurrence of high-intensity rainfall of extra-tropical origin, which often bring rainfall in excess of 100 mm in a 24-hour period. Return period statistics calculated by Environment Waikato for the nearest gauges with long-term records give return periods of 2−5 years for 12-hour depths of 150−190 mm and 24-hour depths of 220−285 mm. Typical 10-year return periods are about 50 mm in 1 hour, 130 mm in 6 hours, 210 mm in 12 hours, and 327 mm in 24 hours.

The geology of the area consists largely of weathered volcanic rocks of Minden rhyolite, undifferentiated Whitianga Group, and Omahia andesite (Schofield 1967). The deep weathering of these volcanic materials results in thick regoliths on gentle slopes but with a relatively impermeable subsoil the soils are mainly yellow-brown loam. On the steeper hill country the soils are often much thinner and are yellow-brown earth and brown granular clay. Some large landslides have occurred in the past, as evidenced by remnant rockfall debris. Soil slip and debris flow/avalanche from the steeper upper slopes is the common mass movement erosion type, and sheet wash and surface erosion are common on exposed or bare surfaces.

Experimental weir near road completely filled with sediment. Note the riparian failure upstream, and woody debris in channel.

Riparian or basal slope failure. Note channel scoured to bedrock by debris flow.

Scour in ephemeral channel. Scoured through old forest soil to bedrock exposing radiata roots.

Riparian and lower slope failures exposing bedrock. Note scour in channel to bedrock and 'flow' line RHS.

Figure A6 Watershed 1 − Opoutere Block (con't next two pages)

Lower slope failure through remnants of native riparian vegetation. Note degree of scour of lower slopes.

Upper-slope landslide arising from a roadside fill slope and subsequent debris flow track scouring tributary channel to bedrock and delivering material directly to stream.

Upper slope failure showing material flowing down into the stream.

Slope failure to bedrock delivered material directly to stream. Note darker forest soil.

Figure A6 con't

Upper-slope landslides forming debris flow that scoured tributary channel to bedrock. Note scoured channel to bedrock. Person for scale opposite tributary (white arrow).

Flatter upper part of catchment, exposed forest soils, deposition of sediment and logs from small riparian failures and slope failures, but volume of flow or scour activity less up here. Person for scale (white arrow)

Figure A6 con't.

Confluence of Te Weiti south and north branches, scoured and cleaned by digger, debris pile on flats opposite Heylen's place.

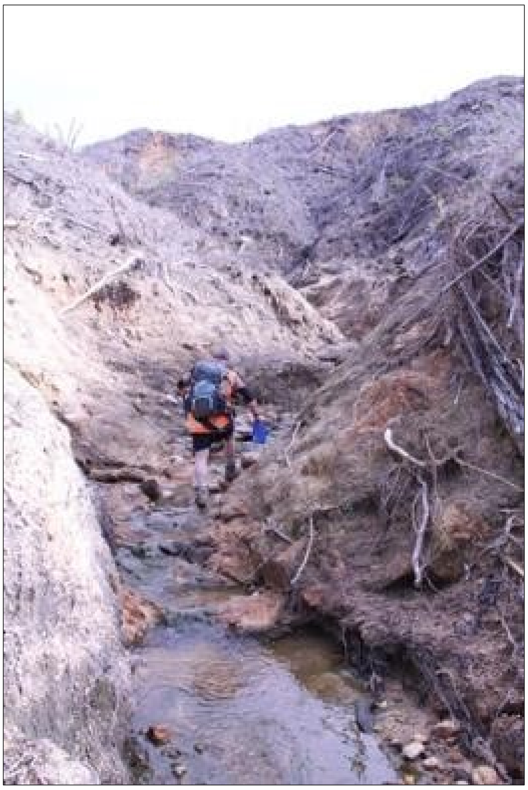
Looking up south branch, Heylen's reinstated garden. North branch of Te Weiti stream is along edge of radiata on right. Orange landslides in distance.

Figure A7 Watershed 5 – south branch of Te Weiti Stream (con't next page)

Channel incision caused by debris flow leaving tree stumps behind and scoured to bedrock. Original channel likely to have been 1 metre higher.

Channel incision into old deposits. Note the layers of sediment and buried soils. On LHS sediment has been removed, resulting in some lower-slope collapses. Stump in foreground would have been growing on the valley bottom several metres above the current stream channel.

Deep failure delivered sediment to valley bottom, rafted tree, with exposed roots.



Channel scour to bedrock. Note 'clean' lower slopes, suggesting erosion by debris flow.

Figure A7 con't.

Large mid-slope landslide, with deep material deposited in wider, gently sloping upper-slope basin. Material in foreground comes from a landing failure to the bottom left.

Failure below or from landing. Material ended up in valley floor. Directly opposite the photo on left.

Upper part of basin – gentle sloping valley infill, small landslides.

Upper part of Watershed 4 showing landslides, gently sloping upper basin. and deposition zone for major landslides.

Figure A8 Watershed 4 – upper part of tributary of north branch of Te Weiti Stream (con't next page)

Looking upstream – bottom of the sediment wedge from the landslide and landing failure. Note peaty valley floor and wide valley bottom. Knickpoint (photo to right) in peaty soil just downstream of this.

Knickpoint in peaty infill scoured to bedrock.

Channel scoured to bedrock, plus evidence of high flows and/or debris flow.

Very steep side slopes. The channel is scoured to bedrock and beyond this point drops over two 5-metre-plus waterfalls.

Figure A8 con't.