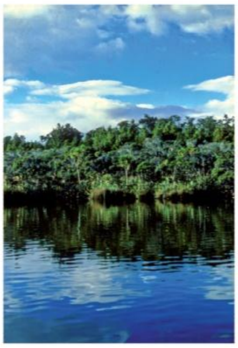
Sedimentation History of Waipaoa Catchment

Envirolink project 1015-GSDC95



Landcare Research
Manaaki Whenua

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Envirolink project 1015-GSDC95

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Contents

Summary

Project and Client

- Gisborne District Council requested a literature review of the pre- and post-human settlement erosion and sedimentation rates in Waipaoa catchment. By assessing the proportion of sediment derived by erosion processes considered to be part of the natural background erosion rates versus that induced essentially since the clearance of indigenous forest for pastoral farming, the Council seeks to better understand where and how improved land management and remediation practices could potentially result in a reduction in sedimentation. Information from this report will be provided to the Fresh Water Advisory Group and used to assess effective management strategies for managing sedimentation in the Waipaoa Catchment.
- The reports objectives are to:
- collate and review existing literature relevant to establishing sedimentation rates pre- and post-human settlement
- provide an account of the relative contributions of sediment derived by the different erosion processes identified in the Waipaoa catchment
- summarise the causal factors and scientific evidence explaining the increase in erosion and sedimentation following human settlement.
- provide an assessment of the effectiveness of past erosion control efforts in reducing sediment generation and delivery to streams
- provide modelling results showing potential future trends in sediment production with and without further erosion control treatment of erosion-prone parts of the landscape
- provide examples of best management practices that could be used to mitigate sediment input into Waipaoa River, their effectiveness and any associated benefits in overall stream health
- indicate the implications of climate change on erosion and sedimentation in Waipaoa catchment.

Conclusions

- The relative contributions of sediment derived from different sources have changed over time and in response to different drivers including tectonics, climate and more recently, deforestation. Prior to human settlement channel incision, shallow and deep-seated landslides were the major processes that delivered sediment to stream channels. Following deforestation, gully erosion and shallow landsliding dominate the present-day sediment budget of the Waipaoa River.
- The present day sedimentation problem in the Waipaoa catchment is of historical origin and can be attributed directly to the dramatic increase in hill slope erosion following clearance of the indigenous forest from erosion-prone terrain during the early European settlement period. The delivery of sediment to the main channels of the Waipaoa and Mangatu river's, primarily from gullies, exceeded the rate at which these rivers could transport the material and hence it accumulated in these channels. This legacy of stored

sediment together with ongoing sediment delivery from existing, untreated gullies and from shallow landslides during periodic storm events, has the greatest, long-term, on-site (loss of soil depth and productive capacity) and off-site (sedimentation and flooding) environmental impact. Although other sediment-generating processes, including earthflows, slumps, bank and cliff erosion and slopewash, can at times be significant sources they tend to be localised and ‘event driven’ and their contribution, relative to gullies and shallow landslides, is small and short term.

- Geology (rock type, induration, regolith composition, drainage and permeability), uplift rates, and climate (rainfall amounts and intensities, frequency of large storms) largely determine the landscape’s inherent susceptibility to erosion, including the response to vegetation change. Susceptibility to erosion is readily identifiable at a regional scale and increasingly tools and methods are becoming available that can be used at hillslope and farm scale. Large, high-magnitude, low-frequency storms or long wet periods drive mass movement erosion (landslide, earthflow) on hillslopes. For fluvial erosion (gullying, bank and channel erosion) the smaller more frequent storms are more important (i.e. low-magnitude, high-frequency events). Earthquakes are a significant driver for deep-seated mass movements and are much lower frequency events.
- Closed-canopy woody vegetation reduces rates of hillslope erosion by an order of magnitude on the most susceptible terrain. Past vegetative erosion control efforts through reforestation, reversion and pole planting have proved successful for controlling much erosion. However, the use of pole planting for the treatment of large and active mass movement features (earthflow and slump) and gully erosion, in the most highly erodible terrains, has had only limited success. Space-planted poles can provide protection against the initiation of shallow landslides if planted in sufficient numbers and in the appropriate position on slopes. The encouragement of natural reversion and/or the establishment of riparian vegetation ‘strips’ as a means of reducing sediment input into streams has its limitations in hill country terrain dominated by mass movement failures, as the mobilised and often ‘liquid-like’ sediment tends to be transported through all but the densest vegetation barriers. Nonetheless, streamside vegetation can be an effective barrier to sediment (derived either by mass movement or slopewash), nutrients and animal pathogens in situations where alluvial terraces act as a buffer between the stream and a hill slope and the terraces are elevated above high flood level.
- Further planting of all remaining gullies, earthflows and of terrain identified as having a high potential for shallow landsliding is required if further sediment input into Waipaoa river is to be minimised. The reforestation of gullies is the most practical and effective means of stabilising all but the largest gullies. If all remaining untreated gullies in each of the three major catchments were to be reforested before 2020, and no new gullies were initiated during this period, gully-derived sediment yield could be halved by 2030 and would remain constant thereafter. A modelled reforestation strategy aimed at prioritising land for reforestation according to landslide susceptibility could have a significant impact on fine sediment yields. With prioritisation, a 40% reduction in landslide-derived sediment could be achieved through reforestation of 8% of the Waipaoa River catchment, whereas 25% of the land would need to be reforested to achieve the same effect through random selection. Sediment yields from other sources, including earthflows, stream banks and reworked material in temporary storage as bedload could be considered as being of lesser concern.

- Following reforestation, streams within mature plantation forests have greater stability and lower water temperature than adjacent pastoral streams, resulting in improved overall stream ecological health approaching the condition of reference streams in native forest. Reductions in sediment input and improvements in stream health are possible at a localised scale and within a relatively short time frame but are unlikely to make a significant difference to the sediment load or water quality of the Waipaoa River as a whole for many decades, if not millennia. Without further erosion mitigation intervention and in the event of more severe storm events, erosion on unprotected hill slopes will increase and further exacerbate the current sedimentation issues of the Waipaoa catchment.
- For sediment management to be effective and sustainable the fundamental unit of management should be the whole river basin. This introduces some important issues. It is necessary to recognise the numerous environments within a river basin (including soils/hillslopes, rivers, floodplains, wetlands, lakes/reservoirs and the coastal zone), and the interconnectivity between these environments. The interconnection between land-use changes on hillslopes, sediment delivery and transport in rivers, and sediment deposition and flooding in downstream reaches has been demonstrated for the Waipaoa River (Owens et al. 2004). This study illustrated the potential for targeted management in headwater reaches to control downstream problems (i.e. controlling the source of the problem as opposed to downstream management). Second, there is a need for a greater understanding of how the processes that control sediment generation, delivery and transport within rivers operate at scales that are meaningful for management and based on this the means of identifying which remediation strategies could provide a reduction in sediment generation from hillslopes and where to apply them.
- The impacts of pre- and post-European deforestation have persisted for more than a century. Climate change is likely to exacerbate erosion problems and lead to increased sedimentation since it is predicted to cause heavier and/or more frequent extreme rainfalls.

Recommendations and future research needs

- In view of the potential worsening of hill slope erosion and its impact on sedimentation patterns within the Waipaoa River, it is recommended that the Gisborne District Council use Snelder et al.'s (2005) River Environmental Classification (REC) as a spatial framework for mapping and classifying rivers or reaches within the catchment into classes discriminated by variations in physical (land cover, geology, climate, topography) and biological (water chemistry, biological communities) characteristics at a range of scales. The REC classes can be treated as management units, each of which can be linked to a monitoring strategy and used as a framework for environmental assessment, management and reporting.
- Use existing data to establish the current 'base level' of suspended sediment yield from monitored sub-catchments, and based on this use prediction tools/models to prioritise sub-catchments/parts of sub-catchments according to where the greatest gains in sediment reduction might be possible if mitigation measures were to be implemented.
- Develop appropriate erosion mitigation implementation plans targeting existing, active sediment sources (e.g. gullies) first, then future proof vulnerable areas (e.g. steep hill slopes, stream banks) through further tree planting (poles, reversion and/or forestry).

- A survey of regional councils, industry, central government agencies and science providers identified a wide variety of research needs to assist improved management of hill country erosion and resultant sedimentation. Gaps identified by the greatest number of stakeholders included: (from Basher et al. 2008)
    - ability to measure regional/catchment rates of erosion and determine what is tolerable, including measuring the contribution from different land uses and land management practices, being able to distinguish natural and induced erosion, and the contribution of different processes
    - integrated research on sediment dynamics (connectivity and lags) within catchments and downstream effects, including slope–channel linkages
    - development of erosion prediction tools/models incorporating land use/management effects and able to distinguish different erosion processes
    - effectiveness of space-planted trees (including willows, poplars and natives) for erosion control and their management requirements, and other erosion control measures, over a range of event magnitudes
    - cost–benefit analysis of different mitigation techniques including co-benefits of erosion control on carbon storage, role of erosion in the carbon budget
    - effective community engagement processes for erosion and catchment management, and improved technology transfer.

1 Introduction

One of the most dramatic examples of landscape response to environmental disturbance by humans can be found in the East Coast Region, North Island, New Zealand. In the brief European settlement history of this region (from ~1860s) the greatest impact has been the widespread initiation and development of erosion following clearance of mature indigenous forest for pastoral farming (Allsop 1973; Gage & Black 1979). Concern over accelerated erosion induced by human activity has generated a substantial literature (Campbell 1946; NWASCO 1970; Jones & Howie1970; Eyles 1985). Several recent studies have highlighted the erosion response to land-use change, sediment generation processes and river channel sedimentation (Marutani et al. 2001; Owens et al. 2005; Liebault et al. 2005; Page et al. 2008; Hicks et al. 2011).

Equally dramatic has been the implementation of restorative efforts, principally reforestation, and other soil conservation strategies on eroding pastoral hill country and its success in effectively treating erosion and slowing the delivery of sediment to stream channels. There are few documented cases where land-use change from indigenous forest to pasture followed by the re-establishment of a forest cover for erosion control has occurred over such an extensive area and in a timeframe measurable in decades rather than in centuries.

This short but dramatic change in land use has left a legacy of problems associated with extensive sedimentation within river channels including increased risk of flooding, degraded stream ecology and water quality issues. Sediment has been identified as a major contaminant affecting freshwater (Parkyn et al. 2002; Davies-Colley et al. 2003) and is the single biggest stressor to the marine environment (Morrison et al. 2009). Managing the freshwater effects relies on managing sediment generation from the land.

A requirement of the National Policy Strategy for Freshwater Management is for Gisborne District Council to set appropriate water quality standards as part of a proposed Gisborne District Water Plan for the Waipaoa Catchment. In view of the susceptibility of the soft rock lithologies comprising this catchment, with consequent very high suspended sediment yields, it is important to establish a 'base level' for what could be considered 'natural' background (pre-human) yields. This requires an understanding of the history of erosion, the causal factors and processes that produce sediment, together with knowledge of those mitigation measures that afford effective restoration and thereby offer potential solutions to manage, if not to reduce, sedimentation levels.

With a focus on the Waipaoa River this report:

- collates and reviews existing literature relevant to establishing sedimentation rates pre- and post-human settlement
- provides an account of the relative contributions of sediment derived by the different erosion processes identified in the Waipaoa catchment
- summarises the causal factors and scientific evidence explaining the increase in erosion and sedimentation following human settlement.
- provides an assessment of the effectiveness of past erosion control efforts in reducing sediment generation and delivery to streams

- provides modelling results showing potential future trends in sediment production with and without further erosion control treatment of erosion-prone parts of the landscape
- provides examples of best management practices that could be used to mitigate sediment input into Waipaoa River, evidence of their effectiveness, and associated benefits in overall stream health
- indicates the implications of climate change on erosion and sedimentation in the Waipaoa catchment.

2 The Waipaoa River Catchment

The Waipaoa River (Fig. 1) drains an area of about 2205 km^2 on the North Island of New Zealand, flowing south-eastward from the Raukumara Range and discharging to Poverty Bay (Hicks et al. 2000). The watershed is located in the forearc region of the Hikurangi Margin, where the Pacific Plate is subducting obliquely westward beneath the Australian Plate. The river has incised into uplifted and variously deformed, jointed and clay-rich marine sedimentary rocks of Cretaceous to Pliocene age (Fig.2) (Mazengarb & Speden 2000) that are predisposed to mass movement, gullying and mechanical disintegration under the influence of water and to acid sulphate weathering (Pearce et al. 1981).

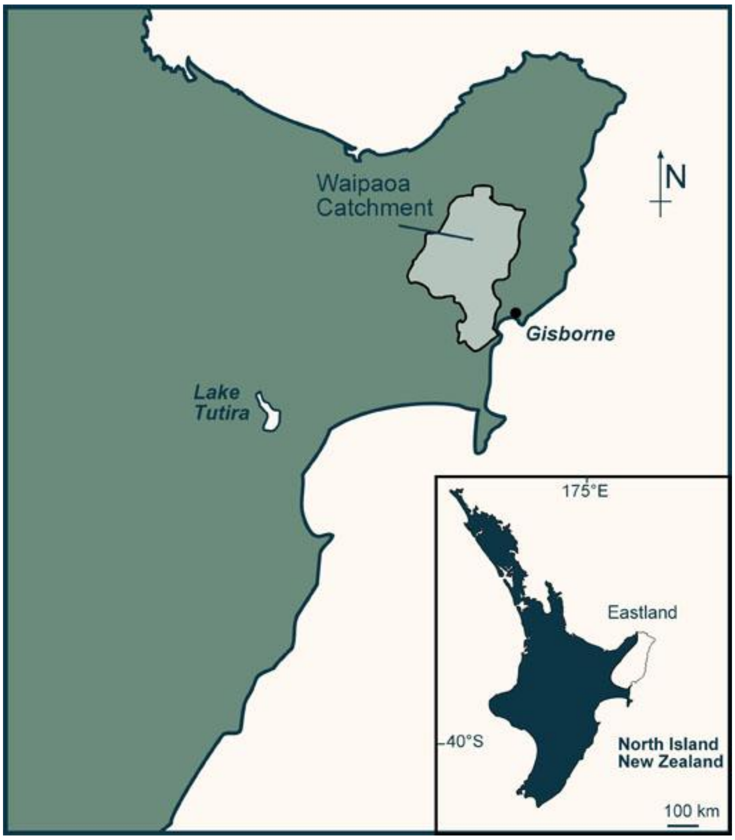

Figure 1 Location map of Waipaoa catchment

Superimposed on this bedrock base are remnants of four Quaternary-aged alluvial terraces, each of which represents floodplain aggradation during a cool glacial period (Berryman et al. 2000; Eden et al. 2001; Marden et al. 2008a) and seven levels of alluvial terrace that formed since the Last Glacial Maximum (Marden et al. 2010). Over the past ~18 000 years a mantle of volcanic ash, derived from the Taupo and Okataina Volcanic centres ~150 km to the west, has blanketed both the alluvium and sedimentary rocks of the Waipaoa catchment to several meters thickness, and serves as the foundation for many of its soils.

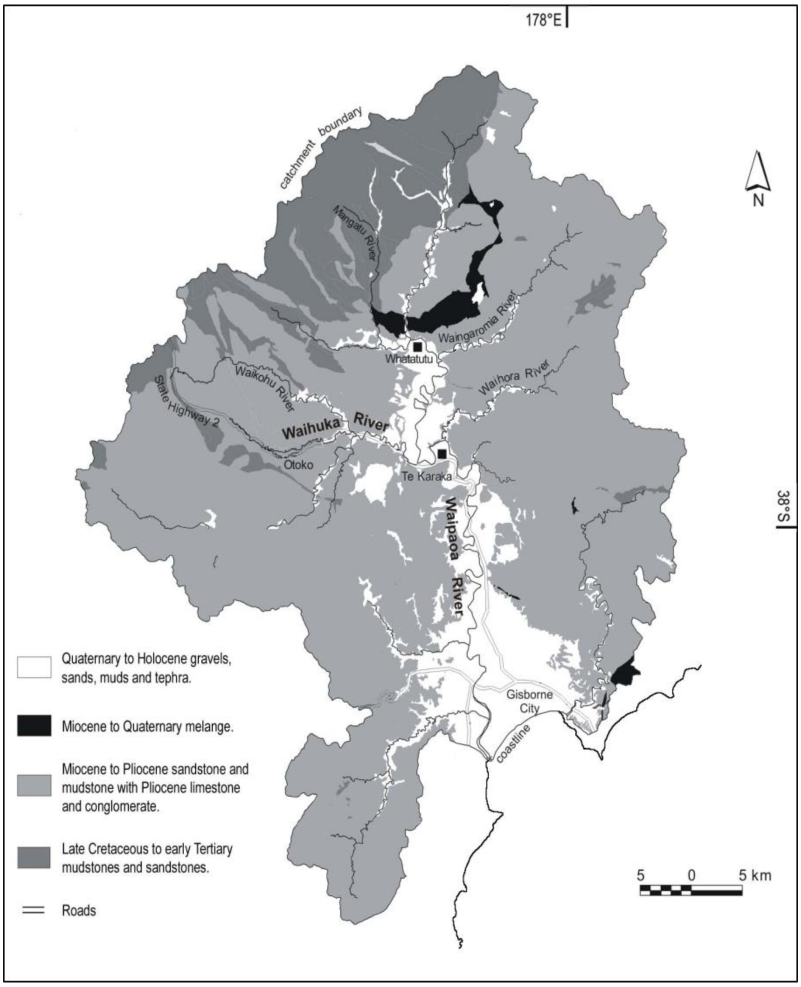

Figure 2 Distribution of lithologies within Waipaoa and Waimata catchments. The dark grey area in the headwater reaches (8% of catchment area) is underlain with Cretaceous-aged lithologies prone to mass movement (earthflow and slump) and gullying. The light grey area in the mid and lower reaches (78% of catchment area) is underlain with Miocene to Pliocene-aged lithologies more prone to shallow landsliding. Elsewhere in this document these areas are referred to as the Cretaceous and Tertiary terrains, respectively.

The climate is warm temperate maritime, with warm moist summers and cool wet winters. Rainfall gradients increase from the coast to inland areas. Mean annual rainfall for coastal areas in the south (Gisborne City) is 1200 mm, while inland areas receive ~2500 mm (Hessell 1980). The region's climate is strongly influenced by the El Niño/Southern Oscillation (ENSO), with an increase in major rainfall events during La Niña conditions and severe and prolonged droughts during El Niño years. Tropical cyclones during the summer months (November–March) have on occasion accelerated erosion, the last being in 1988 (Cyclone Bola). In the Waipaoa catchment there is a 29% chance of a major event every year, and a greater than 99% chance one will occur every 10 years (Kelliher et al. 1995). This volatile climate contributes to high erosion rates (Water and Soil Directorate 1987).

Current vegetation cover in hill country areas comprises pasture (70%), exotic forest (20%), indigenous forest (6%), and bare ground (4%). Before Maori (~600 yr BP) and European (commencing in the 1820s) settlement, the East Coast region was almost completely vegetated with podocarp/hardwood (mainly conifer) forest in the lowlands, *Nothofagus* forest at higher altitudes, and alpine-subalpine shrub land and grasslands on the highest parts of the axial ranges (McGlone 1988; Wilmshurst 1997).

Deforestation of the watershed, primarily by burning, commenced in its lower reaches with the arrival of Polynesian (Maori) settlers around 700 years ago and extended into the headwater reaches following European settlement (Pullar 1962; McGlone et al. 1994; McGlone & Wilmshurst, 1999 Wilmshurst et al. 2008). Much of the lowland had been deforested by 1875 (Murton 1968) and by the late 1920s 97.5 % of the old-growth native forests had been destroyed (Gomez et al. 1999).

Early photographs (c. 1903–1910) show that the landscape revealed by the clearance of forest had been subjected to mass movement in the past, a process that has continued since at least the end of the last glacial period and throughout the Holocene (~ 18 000 years). Accounts of the early onset of erosion in the Waipaoa catchment since settlement are obscure. Anecdotal evidence suggests it was likely initiated within a decade or two following the clearance of indigenous forest beginning in the late 1800s with early observations of extensive landsliding in the hill country during the winters of 1883 and 1894. During the first decade of the 20th century there followed a period of geomorphic slope adjustment in response to the removal of this forest (Hill 1895; Henderson & Ongley 1920), the most noticeable being the initiation of mass movement (earthflows and slumps) and associated gullying. Erosion was precipitated by changing soil moisture conditions, the pattern of hillslope runoff (from subsurface, diffuse drainage to surface runoff and its concentration along preferred drainage channels) and the loss of root strength that lowered the threshold for their development (O'Loughlin 1974a,b). Erosion, and gully erosion in particular, had a noticeable effect on river channel aggradation (Kennedy 1912; Allsop 1973; Gage & Black 1979), and in headwater streams the cobble-sized bed material had been replaced by fine gravel and sand (Kelman, undated; Laing-Meason 1914; Jones & Howie 1979; Black 1977) leading to an estimated 6.5-fold increase in suspended sediment discharge of the Waipaoa River (Kettner et al. 2007).

The combination of highly erodible, steep and jointed bedrock, tephric soils and alluvium, episodically intense precipitation, seismic activity, and human disturbance contribute to rapid erosion of the Waipaoa watershed, and one of the highest suspended sediment yields in the world (7216 tons km^{-2} yr^{-1}; Hicks et al. 2011).

3 Sediment sources

3.1 Shallow landslides

Shallow landsliding (Fig 3) is defined as the movement of soil/or subsoil to expose a slip surface that is approximately parallel to the original slope. It is the dominant mode of sediment generation and delivery over much of the middle and lower watershed, where more competent Miocene-Pliocene sandstone, mudstone, and minor limestone underlie the hill slopes (78% of catchment area) (Reid & Page 2003; Hicks et al. 2004; Marden et al. 2008b). Landsliding is triggered during lower-frequency, higher magnitude storms that occur with typical decadal return periods (Hicks et al. 2000; Reid & Page 2003; Hicks et al. 2004). Slope failure tends to occur at less than one metre, but where surficial coverbeds are thicker failure often occurs at the bedrock-soil interface at depths up to two metres and mobilizes generally sandy, pumiceous material (Preston & Crozier 1999).

Figure 3 Shallow landsides initiated on steep pasture slopes in the Ngatapa area following a storm in July 1985.

3.2 Earthflows

Earthflows (Fig 4) are described as the downslope movement of soil and rock, involving a large quantity of water. The ratio of soil to water causes the material to behave like a liquid. When soil moisture conditions become ‘wet’ and remain so for long periods (months) they mobilise at glacier–like pace interspersed with surge-like displacements in increments of metres to tens of metres in a day (Marden et al. 2008c). Displacement of material occurs through sliding along an internal and planar shear surface of depths between 0.5 and 6 m below ground surface. Most earthflows are associated with slopes of 5–25 degrees. During dry periods they remain stable for long periods of time (decades to centuries).

Figure 4. Wether Run earthflow, Mangatu Forest, before reforestation.

3.3 Gullies

Accelerated erosion by gullying (Fig. 5) is a major source of sediment in steepland catchments. Gully and associated mass movement erosion is most prevalent in crushed argillite and mudstone underlying the basin headwaters (~ 8% of the total catchment area) and is currently the primary source of fine-grained sediment to the system (Hicks et al. 2004; Marden et al. 2008b). Studies of the morphology and development of gullies (relatively deep and rapidly eroding channels) suggest they have a limited lifespan and rapidly evolve to a condition of relative stability. Some gullies appear to be a natural component of landscape evolution, but many contemporary gullies formed after native forests were cleared and agriculture intensified in the 19th and 20th centuries (Ireland et al. 1939). In either case, gully extension represents a major adjustment to the landscape that is imprinted on the drainage network and has a profound impact on basin sediment yield. As gullies are part of and thus directly connected with the drainage network, sediment supply from them dominates even during high-frequency, low magnitude rainfall events (<1 yr return period; Hicks et al. 2004).

Figure 5 Example of a gully that was already too active and large at the time of planting for reforestation to become an effective treatment. Sediment from this (Tarndale Gully) and all other gullies considered to be 'active' contribute sediment directly into the drainage system.

3.4 Cliffs and river banks

Cliff and bank erosion is the removal of material along a permanent course by the action of flowing water. This normally involves the undercutting of the bank (generally unconsolidated alluvium) or cliff (generally more consolidated bedrock) resulting in the collapse of blocks of material directly into the river (e.g., Fig. 6). Lateral and vertical erosion of cliffs and banks occurs mainly during high peak flows (floods).

Figure 6 Undercut bedrock cliff resulting in the slumping of sediment directly to the channel (photograph courtesy of Gisborne District Council).

Bank collapse also occurs after flood waters have receded when saturated and unconsolidated alluvium (silt, sand, gravel mix) fails by slumping (Fig. 7).

Figure 7 Bank consisting of unconsolidated alluvium that likely failed after flood waters receded (photograph courtesy of Gisborne District Council).

3.5 Aggraded riverbeds

Significant amounts of sediment are stored within the stream system as bed load. In the headwater reach of Mangatu and Waipaoa river aggradation has appreciably raised and widened their respective channels, burying terraces which used to be former homestead sites. In catchments draining soft rock that is mudstone dominated the bed load is overwhelmingly dominated by smaller particle sized material (e.g. fine gravel, sand and silt). In other catchments where the lithologies comprise harder material such as sandstone and limestone their bed load comprises mainly cobble and boulder sized material with minor sand and silt. Bed load, irrespective of its composition, breaks down into smaller particles as a consequence of in-situ weathering processes (heating, cooling, wetting, drying etc) and attrition/abrasion as it is transported along the streambed. These finer particles (silt and clay) are transported as suspended sediment and during high flows is a significant component of total sediment load Fig. 8).

Figure 8 An actively aggrading river bed in the headwater reach of the Waipaoa River. The pre-settlement bed level is thought to lie ~20 m below the current bed level.

3.6 Slumps

These are rotational failures where displacement occurs at depth along a surface of rupture that is curved concavely upward. Slumps (Fig. 9) combined with other types of slope failure in the Waipaoa catchment have at one time or another over the past 18 000 years affected ~ 18.5% of the hill slopes present in this and Waimata catchment (Page and Lukovic, 2011). Extensive slumping occurred during the early settlement period, particularly in the headwater areas now occupied by Mangatu Forest. More recently, slump failures have tended to occur as temporally and spatially separated features with failure usually associated with heavy rainfall events or earthquakes. Although slumping is currently uncommon in this catchment, when they do fail they tend to connect with and hence deliver an initial and significant volume of sediment to a stream channel. Slumps can result in the temporary blocking of a channel. With time the channel cuts through the slump and often continues to deliver sediment to the stream years after the initial failure.

Figure 9 Isolated slump with stream undercutting along the toe slope contributing a small amount of sediment to the stream channel with most of the displaced material remaining on-slope.

3.7 Slopewash

Slopewash sediment is derived from diffuse areas of bare ground within the pasture sward, especially from steep areas where the pasture is heavily grazed or affected by drought. Farm tracks, landslide scars, and debris tails are also sources of slopewash sediment. Slopewash occurs by a combination of splash and surface water movement downhill. It usually occurs when intense rainfall exceeds the infiltration capacity of the soil. Slopewash is less common in standing forest than in areas of pasture and cleared forest. Slopewash can result in the redistribution and delivery of organic matter, fine sediment, forest slash, nutrients, and faecal microbes to stream channels.

4 Evolution of the Waipaoa catchment and sedimentation history of Poverty Bay

Since the late Quaternary there have been ten identifiable periods of extensive floodplain aggradation. The cessation of each phase of aggradation was brought about when drainage channels began to incise into their floodplain in response to variations in climate and regional uplift (Berryman et al. 2000; Eden et al. 2001; Marden et al. 2008a. Thus periods of floodplain aggradation alternated with periods of channel incision to leave abandoned remnants of former floodplains as alluvial terraces. Seven of the alluvial terrace surfaces identified in Waipaoa catchment have formed in the last 27 000 years, that is, since the Last Glacial Maximum (Marden et al. 2010).

Sediment generated during periods of channel incision and by subsequent hill slope failures, in response to a lowering of stream base level, formed the Poverty Bay floodplain. Channel incision is thought to have primed hillslopes for failure through the oversteepening and removal of slope support to produce12.1 cubic kilometres of sediment since the Last Glacial Maximum (Marden et al. 2008a). This is about 42% of the estimated 28.6 km^3 of sediment stored in depositional sinks (Poverty Bay floodplain and offshore) with shallow landslides producing 21%, deep-seated landslides (slumps) 8%, slopewash 3% and lake sediments released by dam breaching 1% (Page and Lukovic,2011).

Over the entire Holocene period (~last 10 000 years) up until extensive deforestation in the 19th century the influx of suspended sediment to the coastal plain remained roughly constant at ~2.7 Mt/year (Wolinsky et al. 2010); ~ 5 times less than the 15Mt /year at present. From the distribution of dated tephra (volcanic ash) and palaeo-shorelines (Fig. 10), Pullar and Penhale (1970) and Brown (1995) estimated that the shoreline has advanced seaward from its maximum inland extent 7000–6000 years ago to its position 5000 years ago at a rate of 4 m/year, and during the period 5000–2000 years ago the rate of advance slowed to 1.3 m/year. Over the last 2000 years this decreased further to 0.6 m/year (Gibb 1995). Wolinsky et al. (2010) demonstrate that the slowing in coastal progradation is not the result of decreasing sediment supply or increased subsidence of the Poverty Bay floodplain but rather is due to an increase in accommodation space as the area of floodplain increased. This suggests that baseline sedimentary processes (sediment supply, coastal subsidence, regional uplift) were relatively constant prior to recent anthropogenic disturbance in the Waipaoa catchment. For the post-deforestation period it is estimated that of the sediment stored in depositional sinks (floodplain and offshore) since the Last Glacial Maximum, gullies have contributed 1%, shallow landslides 1%, slopewash 0.2% and other processes combined (earthflow and streambank erosion) 0.5% (Page and Lukovic,2011). Based on the high suspended sediment yield currently discharged from Waipaoa River it is expected that the shoreline will continue to advance well into the next century and beyond (Gibb 1995).

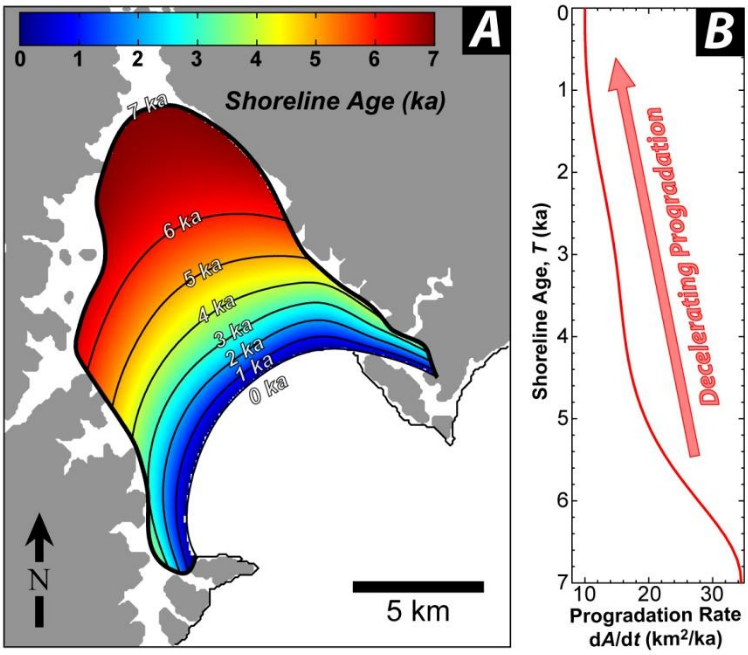

Figure 10 Evolution of the Poverty Bay shoreline over the last 7000 years (From Wolinski et al. 2010).

5 Post-settlement erosion and sediment contribution to sediment yield

Estimates suggest that there has been at least an order-of–magnitude increase in erosion within Waipaoa River as a consequence of anthropogenic deforestation and land use change. For example, before deforestation the incidence of gully erosion within areas of indigenous forest was low but soon became a pervasive feature on farmland with 99.5% of the total composite area of all gullies present in 1957 being associated with areas of cleared land. It is likely therefore that the majority of gullies were initiated subsequent to, and in response to, forest clearance. The relative contribution of sediment derived by gully erosion is the equivalent of ~ 43% of the annual suspended sediment yield of Waipaoa River (Marden et al. 2008b).

Similarly, the incidence of shallow landsliding before deforestation was likely negligible, as it is today within remaining forested and reforested areas. Since deforestation the frequency and extent of shallow landsliding have increased dramatically, with landslides contributing ~60% of the sediment yield of the Waipaoa river during floods but 10–20% overall (Reid & Page 2003).

There has been no appreciable change in rates of cliff erosion over the past 18 000 years. Bank and cliff erosion processes were likely relatively more important as a source of sediment before widespread land-use conversion from native forest to pasture. In an essentially pastoral land-use regime the contribution of sediment from bank and cliff erosion (74.3 and 23.3 kt a^{-1}, respectively) to suspended sediment load is low (<2%) because the Waipaoa river has a high specific load dominated by mass movement erosion (De Rose & Basher 2011). Although Rosser (2007) found that bank-derived sediment from a 21-km floodplain reach of Waikohu River during the 1952–2002 equated to ~8% of the total annual suspended sediment yield of Waipaoa River most of it was generated during a single event on Labour Weekend 2005. In contrast, the long-term records show that the entire Waikohu catchment produces just 1.4% of the total annual suspended sediment of the Waipaoa River.

The contribution of sediment derived by slopewash has not been quantified for Waipaoa catchment. Page et al. (2004) estimated that the slopewash component of sediment derived from pastoral hillslopes and delivered to Lake Tutira following Cyclone Bola was in the order of 7% of the total sediment mobilised from all sources (predominantly landslides) during this event. Given the extreme nature of this event, the longer term average annual contribution would be less than this. Studies on slopewash derived from harvested forests indicate that the bulk of sediment generated occurs within a year of the completion of harvesting and that most of this remains on the slope. The general consensus is that slopewash from harvested forests is short term and does not contribute in a significant way to the overall long term sediment yield of streams draining the forested areas studied (Marden et al. 2006, 2007). In view of the currently high average annual suspended sediment yield of the Waipaoa river slopewash-derived sediment from pasture and harvested forest slopes combined, is likely to be one of the least important sediment generating processes in this catchment.

Contributions of sediment from other sources within Waipaoa catchment such as large landslides and earthflows have not been quantified but are probably in the range of between 2 and 5%. The proportion of suspended sediment derived by the breakdown of bedload material from the broad expanses of aggraded river bed, though unknown, is likely to be significant.

The extent to which the total sediment yield of the Waipaoa River has been increased by anthropogenic deforestation and land use change has not been determined. Page and Trustrum (1997) observed a ~10-fold increase in sedimentation rates after European settlement, in cores from Lake Tutira (Hawke's Bay). Similarly, Kettner et al. (2007), using a simulation model that incorporated the effects of land cover on runoff and sediment yield, estimated that the suspended sediment yield of the Waipaoa River had increased by 350% after European arrival, when pastoral farming began on the coastal lowland of Poverty Bay, and by 660% once the catchment headwaters were deforested. Increases in river sediment yield following European settlement are evident in cores from the Waipaoa floodplain and from the continental shelf off the Waipaoa river mouth (Gomez et al. 2007).

In recent times, in coastal Hawke's Bay hill country, a pasture catchment produced about 4 times more suspended sediment than a forested catchment (Fahey & Marden, 2000; Fahey et al. 2003).

The scant availability of bedload estimates makes it difficult to derive a total sediment load delivered to the coast. Nonetheless, because of the high abrasion rates for the relatively soft mudstone and sheared argillite found in its catchment and also simply because of the very high generation rate of muddy suspended load at source (Trustrum et al. 1999; Hicks et al. 2000) the Waipaoa River is considered to have a low bedload equivalent (<1% of its suspended load (Gomez et al. 2009).

The relative contributions of sediment derived from different sources have changed over time and in response to different drivers including tectonics, climate and more recently, deforestation. Prior to human settlement channel incision, shallow and deep-seated landslides were the major processes that delivered sediment to stream channels. Following deforestation, gully erosion and shallow landsliding dominate the present-day sediment budget of the Waipaoa River.

6 The role of forest vegetation in mitigating erosion processes

The understanding of how vegetation contributes to slope stability and erosion control is relatively well advanced. In general terms, the above-ground components of vegetation (canopy) reduce the ability of rainfall to initiate slope failure through the processes of interception and evapotranspiration, while the below-ground components (roots) provide mechanical reinforcement and are the means by which trees extract soil moisture from the soil to reduce pore water pressures. These processes become most effective when canopy closure (canopies of individual trees touch) and full root occupancy (lateral roots of adjacent trees overlap) first occur. Factors affecting the rate at which canopy closure and root occupancy occur include plant spacing and growth rate. Within a reforested area any measured reduction in 'active' eroded area of individual shallow landslides, earthflows, and gullies is attributed to increasing tree canopy size over time. A closed canopy (i.e. the erosion feature is no longer visible on aerial photography) by inference, implies the erosion feature has stabilised. Conversely, an increase in 'active' eroded area over time is interpreted as a reactivation of the erosion feature. The size of individual erosion scars and any change in size over time are able to be measured from sequential aerial photography and captured in a Geographic Information System (GIS).

The development of models to predict the rate of canopy closure are time-dependent and rely on the measurement of the size of individual erosion scars before reforestation, knowledge of the date of planting and the duration (years) since planting, and the remeasurement of each feature at the end of the study period. Our current understanding of the role and modelling of canopy closure and root occupancy with respect to shallow landslides, gully erosion and earthflows stabilised by exotic forest (predominantly pine) is largely based on studies initiated in the East Coast Region, North Island, following Cyclone Bola in 1988.

7 Effectiveness of past erosion mitigation efforts

On account of the scale and rapidity of the onset of erosion many of the initial on-farm attempts to stabilise riverbeds and gullies by check-dams or tree planting were largely ineffective as these became rapidly overwhelmed with sediment. Increasing costs associated with on-farm conservation efforts for the protection of downstream infrastructure and utilities led the Government to purchase large tracts of eroding farmland for reforestation. The principal tree species included radiata pine (*Pinus radiata*), Douglas fir (*Pseudotsuga menziesii*), and assorted minor species. Reforestation started in this region in 1961, and by 1985 in excess of 14 000 hectares of exotic forest had been established, creating Mangatu Forest. Following extensive damage sustained to large tracts of pastoral hill country during successive storms in 1980, 1982 and 1988 (Cyclone Bola) there was a second wave of forest plantings commencing ~1990, mainly in Waihora, Te Arai, and Waingaromia catchments, and by 1997 a total of ~20 000 ha of eroding pastoral hill country had been replanted in exotic forest.

7.1 Shallow landslides

Researchers have attempted to quantify the effectiveness of different vegetation types in mitigating the impact of relatively infrequent but large magnitude storms against landslide initiation. Much of this research focused on *P. radiata* (radiata pine) and kanuka *(Kunzea ericoides var. ericoides)*, the two species used most widely for erosion control in this region. The effectiveness of *P. radiata* for protection against shallow landslides in New Zealand is well documented (O'Loughlin 1984; Phillips et al. 1991; Marden & Rowan 1993; Marden 2004). Less well-known is the role that kānuka, a species endemic to New Zealand and an early coloniser of harsh sites, plays in soil conservation and erosion prevention (Marden & Rowan 1993; Bergin et al. 1995; Rowe et al. 1999) and that of native forest (Marden & Rowan 1993; Parkner et al. 2007) . The following is a summary of those findings.

Comparisons of storm-initiated landslide densities and different vegetation types showed that there is little difference in the protective value between different closed-canopy evergreen forest species but that forest age has a significant effect on the number of landslides initiated. For example, areas under indigenous forest and exotic plantations > 8 years old were 16 times less susceptible than pasture and exotic pines < 6 years old, and 4 times less susceptible than regenerating scrub and exotic pines 6–8 years old to landsliding during Cyclone Bola (Marden & Rowan 1993). In another East Coast study of landslide damage to fully stocked stands of reverting kānuka and mānuka scrub of known age, damage to 10-year-old stands was estimated to be 65% less than that sustained by pasture and 90% less in 20-year-old stands (Bergin et al. 1993, 1995). Similarly, following the Manawatu storm in 2004, landsliding under forest was 90% less than that under pasture and 80% less under scrub

(Dymond et al. 2006). These figures show that a forest cover affords considerable protection against the initiation of landslides and is consistent with process-based research showing little difference in the magnitude of interception loss, as a percentage of rainfall, across different, closed-canopy vegetation communities (Rowe et al. 1999). Soils under a forest cover will therefore be less prone to rainfall-induced landslides than similar soils under pasture (Fig. 11) or soils with an open or partial vegetation cover such as young stands of pines < 5-years old and scattered, regenerating scrub that sustain a similar level of landslide damage (Marden & Rowan 1993).

Figure 11 Contrasting incidence of shallow landsliding on pasture and a closed-canopy stand of native forest following Cyclone Bola in March 1988.

Within forested areas, and particularly during extreme rainfall events, factors additional to the soil-water regime are also likely to influence landslide initiation. These include stand density, root-system dimensions, and the magnitude of root-soil reinforcement. Comparisons of excavated root systems of kānuka and *P. radiata* revealed that, although the roots of *individual* kānuka were smaller than those of *P. radiata* at all stages of growth, the difference in total root mass was more than compensated for by the higher stand densities of the kānuka. Thus, the annual rate of root production of stands of regenerating kānuka exceeds that of *P. radiata* for the first 9 years of growth (Watson et al. 1995). As a consequence, the calculation of slope safety factors (a measure of a slope's resistance to failure) showed that slopes with a dense stand of regenerating kānuka were less likely to fail than similar slopes in *P. radiata*, at least for the first 9 years after establishment. Thereafter, older aged stands of both species afforded a high and comparable level of slope resistance against landslide initiation (Ekanayake et al. 1997).

A study of the relationship between soil erosion and farm conservation plantings (predominantly deciduous poplar and willow) concluded that the effectiveness of these plantings was contingent on correct planting and maintenance. Appropriately planted and maintained trees reduced erosion by 75% compared with similar unplanted slopes, whereas if improperly installed and not maintained their effectiveness declined to 10%. The same study concluded that properly installed farm conservation trees (planting density unspecified), close afforestation with pines, and reversion to native scrub all reduced erosion (erosion type not specified) by about the same amount (Hicks 1991).

7.2 Earthflows

There can be little doubt that the removal of the original indigenous forest cover increased the risk of earthflow initiation and that the absence of a forest canopy and lack of a dense network of intertwining roots in the subsoil is directly related to today's accelerated rates of earthflow movement on pastoral hill country (Marden et al. 1992).

Surface-movement studies of a grassed earthflow complex (Fig. 12) showed that surface-displacement rates were fastest during wet periods and were moderately correlated with monthly rainfall (Zhang et al. 1993). In an earlier study it was shown that the difference in movement rates between reforested and grassed earthflows represents an order of magnitude reduction in erosion rate by earthflows after reforestation, with interception loss by the forest canopy being the principal contributing factor (Pearce et al. 1987). Depending on planting density and growth rate, canopy closure in this area occurs within 8–10 years of planting pines. Thereafter, the soil water content of forested earthflows is dryer for longer periods than grassed earthflows and as a consequence surface displacement slows appreciably (Pearce et al. 1987). Surface displacement of the earthflow depicted in Figure 4 (this report) slowed within 4 years of planting and by 2000 the earthflow had stabilised.

Figure 12 Actively moving earthflow under pasture (left) stabilised following establishment of a closed canopy of exotic pines.

In addition, and at about the time of canopy closure, the root systems of 8–10-year-old pines are known to develop both strong lateral structural roots, which may extend up to 5 m from the root bole, and vertical sinker roots up to 2.1 m deep (Watson et al. 1999). Given that most earthflow displacement occurs along a basal shear plane typically 5–7 m below the ground surface and at a depth exceeding that of the maximum root penetration of most forest tree species, it has been suggested that where trees are planted close enough, the roots of individual trees interlock to form a large raft. The interlocking roots constitute a reinforced, semi-rigid layer that floats on the more mobile material beneath (Zhang et al. 1993).

Through its superior interception function, a closed-canopy of evergreen forest affords the best option for stabilising mobile earthflows. However, earthflows can be stabilised by space-planted trees and afforestation, along with the use of subsurface drains and diversion banks. Tree spacings recommended vary depending on attributes such as the extent of the earthflow, its movement, and stage of development, and depth to the failure plane. On intermittently moving or creeping earthflows, tree spacing of < 12 m may enable adequate erosion control and satisfactory pasture production, whereas for more active, continuously moving earthflows, spacings < 5 m are recommended to encourage development of a denser root network. Deep earthflows (e.g., several metres deep) are much more difficult to control with vegetation and dewatering with fast-growing evergreen species and subsurface drains are recommended.

7.3 Gullies

Gully erosion is prevalent in many East Coast catchments with most gullies forming after the indigenous forest was cleared and the land converted to pasture in the first quarter of the 20th century. Within three or four decades after deforestation the headwater reaches of the Waipaoa catchment had become severely degraded with gullies occupying ~2% of a 14-km^2 study area. By the early 1960s the area affected by gullies increased to a maximum of ~4%, but 24 years after reforestation with exotic species this had decreased by ~64%, to 1.5% of the study area (Marden et al. 2005).

Canopy closure models (Marden et al. 2005, 2011) developed to measure the effectiveness of exotic forest in stabilising gullies showed that the time required to 'shut down' gullies was strongly associated with gully size and the duration (years) since planting and, for gullies of equivalent size, the duration since planting is similar in both geological terrains. Also, linear gullies are likely to stabilise earlier than their amphitheatre-shaped counterparts. Physical evidence that reforestation has been effective in stabilising gullies include channel narrowing and incision as an initial response to the decrease in sediment yield. A similar response to reforestation has been widely documented, notably in Europe where major reforestation occurred a century ago (Garcia-Ruiz et al. 1997; Liébault & Piégay 2001; Surian & Rinaldi 2003, Piégay et al. 2004). Additional indicators are the survival of forest plantings within a once-active and open gully, channel incision into depositional fans emanating from them, and the subsequent stabilisation of these fans (Fig. 13).

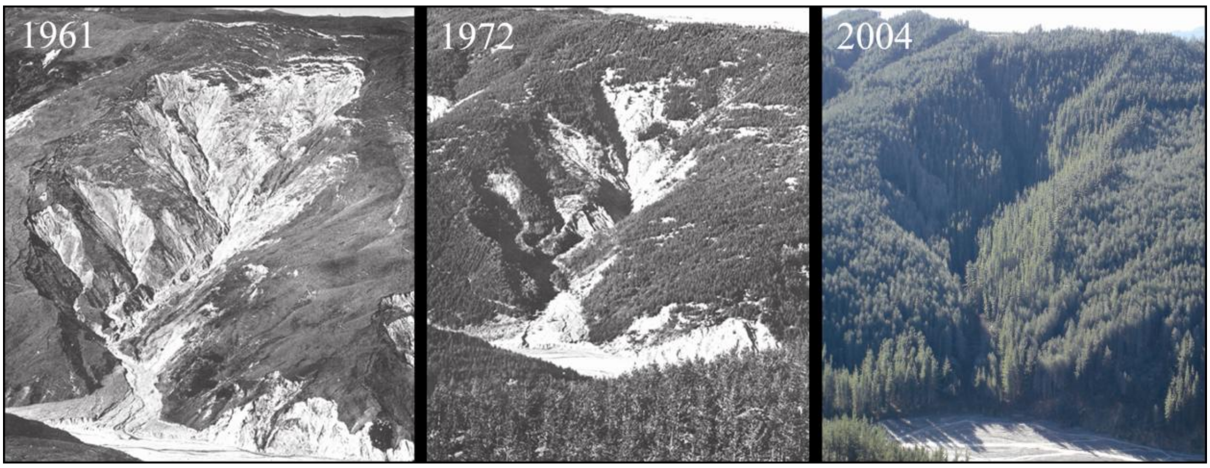

Figure 13 A medium-sized gully (7.6 ha) before reforestation (1961) and post-reforestation (1972, 2004). Within 10 years (1972) the planting of pines had effectively reduced sediment input into the channel and the channel responded by incising below the level of the fan at the mouth of the gully. The latest photograph shows

that in spite of a major cyclonic event in 1988 (Cyclone Bola) this and similarly reforested gullies of equivalent size have remained stable.

At catchment scale, the magnitude in the reduction in gully-derived sediment yield reflects the timing and area of land reforested. In the Waipaoa catchment, the early establishment (1960s to 1980s) of exotic forest in the most gully-prone part of this catchment resulted in a 33% decrease in gully-derived sediment yield. The benefits of later plantings (1990s) have yet to be realised.

7.4 River banks and cliffs

Although the planting of streambanks, largely with poplars and willows, as a means of slowing streambank erosion is a widespread practice, there is little documentation of its effectiveness. Similarly, the benefits of the establishment of native riparian strips or encouragement of natural reversion along waterways as a means of trapping sediment derived from mass movement processes is largely unproven. There are documented cases where mass movement failures (landslides) originating upslope of existing riparian buffers have passed through the buffer with little or no sediment trapped by the buffer. However, their value in filtering pathogens and chemicals from agricultural land has been documented (Collins et al. 2007).

7.5 Aggraded river beds

Attempts to revegetate actively aggrading reaches of river beds as a means of slowing the rate of sediment mobility within a river channel have met with mixed success. While some accounts indicate that the revegetation of river bars slows sediment mobility, thereby retaining the sediment in headwater catchments, others actively remove vegetation to increase sediment transport rates through the river channels so that aggradation does not occur.

7.6 Slopewash

Maintenance of a complete, healthy ground cover is essential for effective prevention or control (Hicks 1991; Hicks & Anthony 2001). This can be achieved through pasture improvement using cultivars of grasses and legumes that are persistent and adapted to drought, wet, cold, and variable intensities of grazing pressure. Associated with this are management options such as subdivision of large blocks (e.g., sunny vs shady aspects) and improved stock grazing practices (e.g., destocking paddocks at particular times of the year, more rotational grazing), and maintenance of soil fertility through strategic topdressing and animal transfer. Cover of unimproved pasture swards can also be maintained using some of these management options, but pasture growth responses are not generally as large as when applied to swards comprising improved pasture cultivars.

8 Modelled reductions in sediment yield following reforestation

In degrading catchments dominated by hill country (e.g. Waipaoa catchment), shallow landslides are often perceived to be the most important source of sediment. While shallow landslides supply as much as 60% of the suspended sediment transported during high flow events they overall generate only 10 to 20% of the Waipaoa River's annual suspended yield (Page et al. 2000; Reid & Page 2003). A modelled reforestation strategy (Fig. 14) aimed at prioritising land for reforestation according to landslide susceptibility could have a significant impact on fine sediment yields. With prioritisation, a 40% reduction in landslide-derived sediment could be achieved through reforestation of 8% of the Waipaoa River basin, whereas 25% of the land would need to be reforested to achieve the same effect through random selection (Reid & Page 2003).

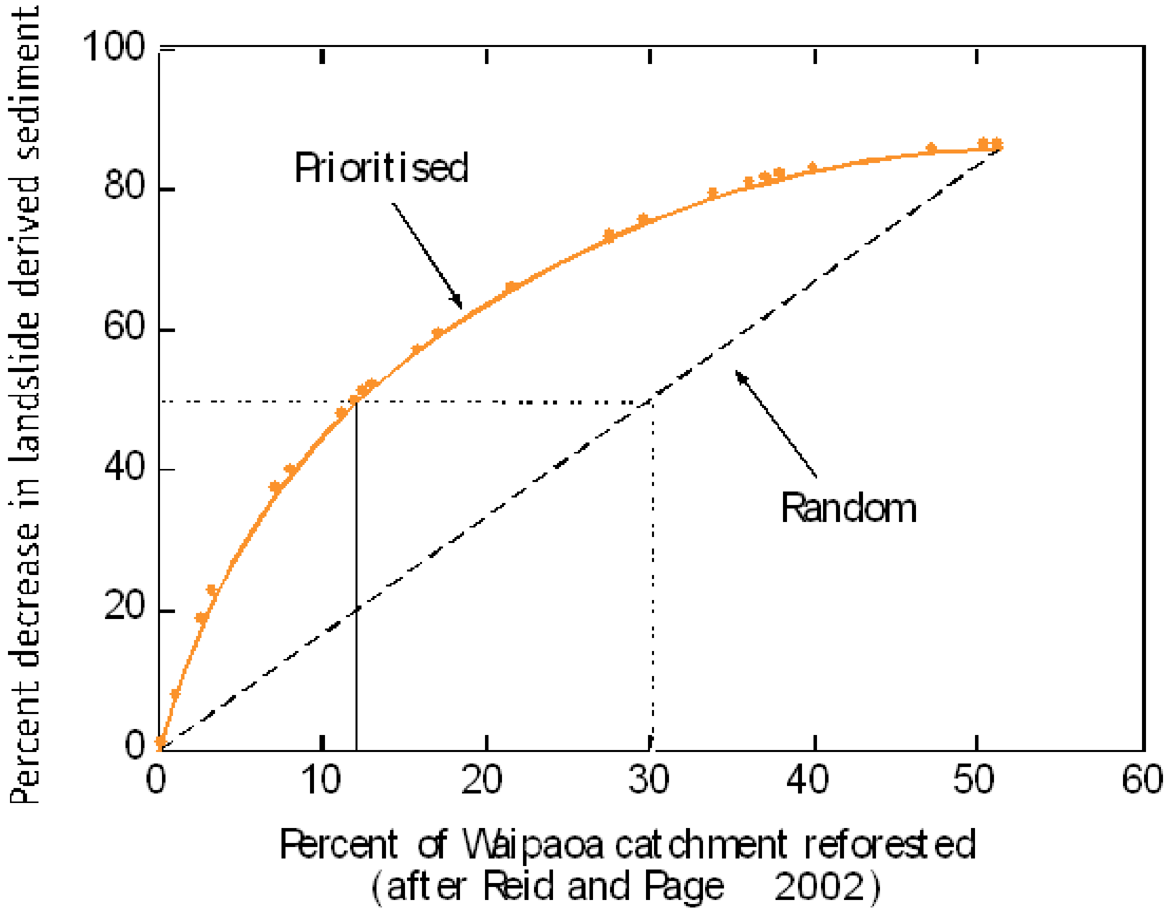

Figure 14 Percentage change in landslide-derived sediment for different levels of reforestation for two reforestation strategies.

In contrast, gullies are the dominant sediment source in each of the major river systems in this region. For the period since reforestation began gullies have generated the equivalent of 43% of the average annual suspended sediment yield of the Waipaoa catchment (Marden et al. 2008b).

Based on the gully degradation model presented in Marden et al. (2008b) and gully stabilisation models in Marden et al. (2005, 2011), further models have been developed specifically to forecast potential reductions in sediment yields from remaining untreated gullies, including those already considered too large to stabilise through reforestation (Herzig et al. 2011). Several practical reforestation scenarios were considered (see Table 2 in Herzig et al. 2011). The results show that reforestation would be most effective if all remaining gullies in the Waipaoa catchments were to be planted before 2020, and providing no new gullies developed during this period, the annual sediment yield could be halved by 2030 and remain constant thereafter (Fig. 15). Within Waipaoa catchment if the remaining 413 untreated gullies were to be treated and if no new gullies formed before 2050 it is expected that sediment yield would decline to ~2 Mt/year by the end of the modelling period (Fig. 15). Conversely, if new gullies were to form and remained untreated during this period, the annual sediment yield as at 2050 would be approximately twice that if no new gullies were initiated (Herzig et al. 2011).

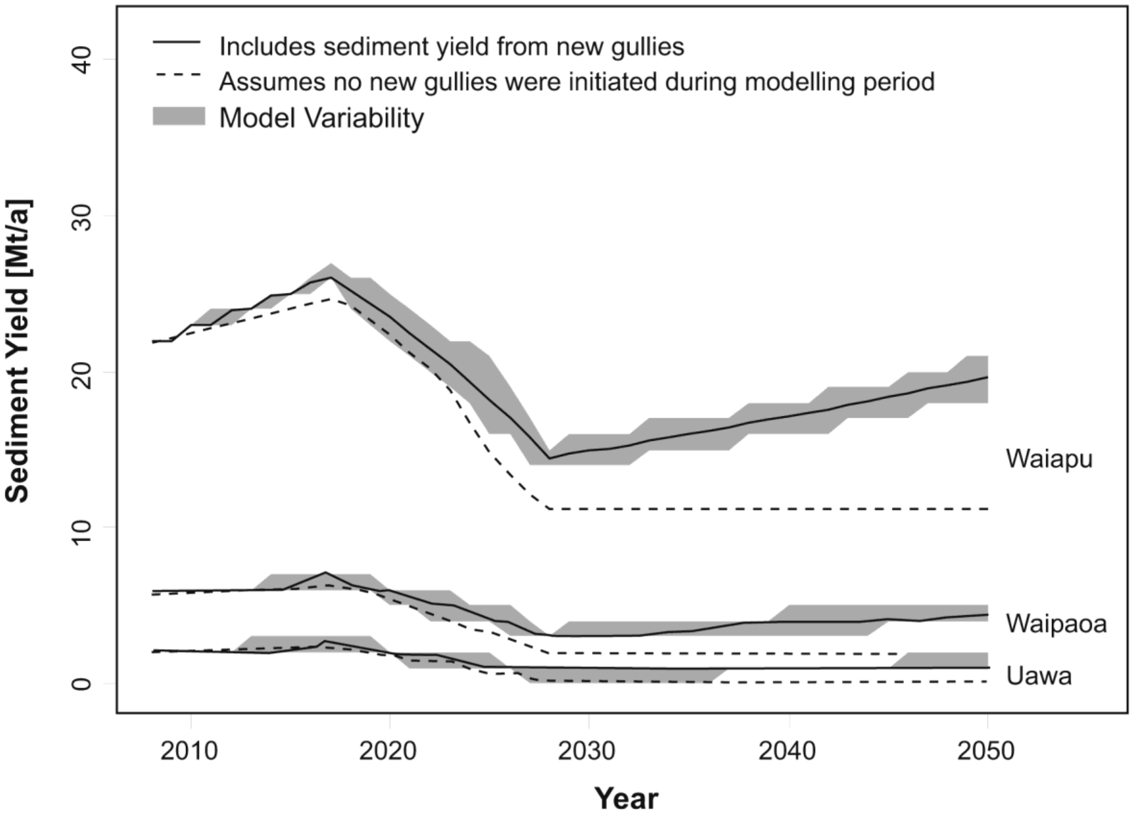

Figure 15. Modelled reductions in gully-derived sediment yield (Million tons per year) if all remaining gullies within the respective catchments were to be reforested by year 2020. Solid line includes sediment yield from new gullies initiated but not treated during the modelling period. Dashed line assumes that no new gullies were initiated during the modelling period.

8.1 Sediment from harvested areas of exotic forest

It is well documented that forests in general terms result in a reduction of sediment generated from eroding hill slopes and improve overall stream health (Parkyn et al.2006). However, Fahey and Marden (2000) and Fahey et al. (2003) showed that during the harvesting phase there is a sharp increase in suspended sediment yield but this declined over a 2-year period and within 5 years had returned to pre-harvest levels. In other studies of slopewash-derived sediment on harvested slopes the largest proportion of sediment generated occurred within a few months of clearfelling and within less than 2 years had declined to almost zero. The same study showed that a single landslide contributed the equivalent of ~6000 times more sediment than was delivered to the stream by slopewash from a 38-ha area of clearfelled forest (Marden et al. 2007). Within the Waipaoa catchment the progressive harvesting of exotic forest began in 1990 and will continue henceforth. The size of the area harvested at any one time is small relative to the size of the catchment as a whole and any resultant increase in the amount of sediment generated during the harvest phase will not be detectable at the catchment scale. Nonetheless, there have been increasing instances when large volumes of sediment have been generated from forests. This usually occurs when a storm event coincides with the location of an area of recently harvested forest and/or areas replanted in pines younger than about 8-years old, that is, before replanted areas have attained canopy closure (Marden & Rowan 1995; Phillips & Marden 1996; Basher 2010). During these storms sediment is generated from natural slope failures (landslides) and failures associated with forestry infrastructure such as landings and roads. Sediment, when combined with logs, logging waste (slash) and flood waters, produce debris flows that often result in severe scouring of ephemeral stream channels. The runoff and entrained debris can bring about serious on- and off-site damage to roads, cause washouts, block culverts and bridges, and trigger the flooding of low lying land. During such events debris-laden sediment often reaches the coast, resulting in off-shore sedimentation and the accumulation of woody debris on beaches.

9 Off-site benefits of sediment reduction

9.1 Protection of infrastructure

In the Waipaoa catchment the continued sediment generation from large gully complexes that have remained ‘active’ within reforested areas, together with sediment derived from untreated gullies and shallow landslides on farmland, has led to an increase in the rate at which alluvium has accumulated on the Poverty Bay flats. Overbank deposition periodically continues to increase the elevation of the active floodplain and reduce the standard of flood protection. This off-site impact suggests that remediation efforts should focus on the benefits of on-site management strategies and conservation measures, previously shown to be effective in reducing the supply of sediment, by targeting remaining untreated gullies (Marden et al. 2011) and land classes most susceptible to shallow landsliding (Reid and Page 2003) for reforestation. The contribution to the overall budget of the Waipaoa River derived from earthflows is unknown. As not all earthflows are necessarily active at any one time, and given the low periodicity and slow pace of activity, the amount of sediment earthflows deliver to the Waipaoa River may be minor. Banks and cliffs probably generate < 2% of the sediment budget (DeRose & Basher 2010) and slopewash < 1%.

Prevention of sediment entering the drainage network, particularly from gullies and shallow landslides, probably represents the most sustainable management option. Attempting to retain sediment in aggraded reaches of channels is likely to be high risk and the least effective management option.

In the longer term, as a consequence of an expected reduction in sediment generation from hill slopes following reforestation, bed load aggradation rates will decline (Peacock & Turner 2003; Peacock & Marden 2004). This will in turn result in additional benefits, namely: 1) a reduction in the cost of bridge replacement and road repair; 2) obviation of the need for expensive channel excavation, realignment and /or stopbank construction; and 3) likely reduction in the risk and clean-up costs associated with the flooding of low-lying, high-value farmland.

9.2 Stream health

Parkyn et al. (2006), in comparing the water quality and stream ecological ‘health’ of streams in pasture, pine plantation, and native forest in catchments that were characterised by differing forms of erosion, concluded that streams in mature pine plantations had generally better water quality (lower faecal contamination and nutrient concentrations) than in pasture, and tended to approach the condition of reference streams in native forest. Visual clarity and turbidity and particulate forms of nutrients, however, remained degraded in pine plantations where deeply incised gullies continued to yield large amounts of fine sediment and were therefore more strongly associated with geological differences than land use. Nonetheless, given that invertebrate community metrics of stream health were more degraded in pasture streams than in streams draining mature pine and native forest, the conclusion drawn was that a pine plantation established on degraded pastoral hill country in soft rock terrain appeared, in time, to improve water quality and stream health toward conditions found in streams draining native forest.

This study is of importance to the Waipaoa Catchment as one of the sites studied included an area of native bush, an exotic forest and a pasture sub-catchment located in the Te Arai River catchment. The waterworks bush reserve is the only significant area of in-tact native forest remaining in Waipaoa catchment and from which a substantial proportion of Gisborne City’s water supply is drawn. This then potentially becomes the reference stream (Fig. 16) with which to compare water quality and stream ecological ‘health’ of other streams elsewhere throughout Waipaoa catchment.

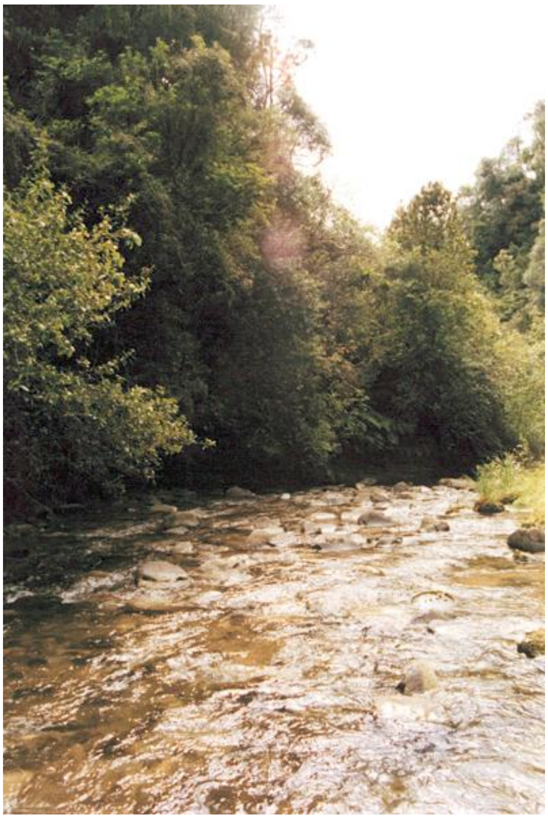

Figure 16 Section of Te Arai River upstream of Gisborne water uptake. Note the predominance of cobble- and boulder-sized material and lack of 'fines' comprising the bedload. Presumably most of the riverbeds within the Waipaoa catchment looked like this in pre-settlement times when the catchment was fully forested.

The results from the area of exotic forest indicate how quickly stream health can return to an acceptable standard and those from the pasture catchment could be considered as the current norm for all remaining areas of pastoral hill country and requiring improvement.

9.3 Best Management Options

Best management practices are practical mitigation measures that can prevent or reduce the movement of sediment, microbes, nutrients and other pollutants from the land to streams or to groundwater. These practices are generally site specific and are developed to achieve a balance between water quality protection and economically viable agricultural activities (Ballantine & Davies-Colley 2009).

9.4 Fencing waterways and establishing riparian plantings

Grazing animals in hill country areas migrate to waterways and can severely damage streambanks adding both sediment and faecal matter to streams. While fencing and the establishment of vegetation may prevent livestock access to streams and greatly reduce faecal pollution, sediment runoff and damage to stream banks, it is only practical where river terraces flank a stream and occur above the maximum flood level (Fig. 17). Fencing and establishment of riparian 'strips' as a means of reducing sediment input into streams has limitations in hill country terrain dominated by mass movement failures where slopes descend directly into streams as the mobilised and often 'liquid-like' sediment tends to be transported through all but the densest vegetation barriers. Nonetheless, streamside vegetation can be an effective barrier to sediment (derived either by mass movement or slopewash), nutrients and animal pathogens in situations where alluvial terraces act as a buffer between the stream and a hill slope and the terraces are above high flood level. It is often not an appropriate bank erosion control method on low lying floodplains subjected to regular flooding.

Figure 17 Fenced and planted (with some reversion) terrace edges well above high flood level, Wharekopae River.

9.5 Reversion

Reversion is defined as either unassisted (natural) reversion (Fig. 18) ,where it is considered this will occur within a reasonable time, or actively managed (enhanced) regeneration by planting indigenous species. As with the establishment of riparian plantings, reversion requires fencing and is not practical in many situations for the same reasons listed above. A subsidy is available through the East Coast Forestry Project for 'natural' reversion. Estimates for establishing areas of 'enhanced' regeneration are ~$15,000–25,000/ha (MacGibbon 2011).

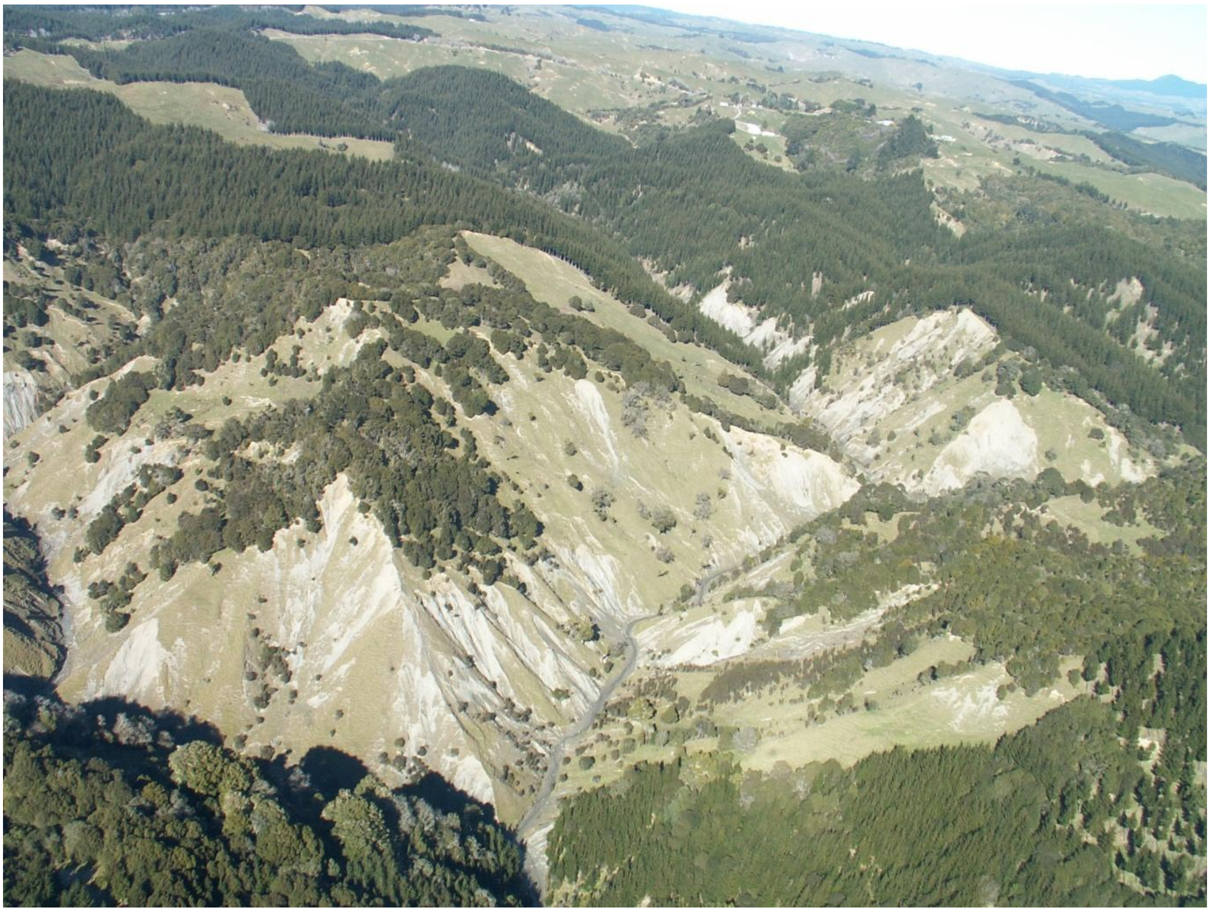

Figure 18 Natural reversion on severely eroding East Coast hill country.

9.6 Natural and constructed wetlands

Wetlands (Fig. 19) are natural traps of slopewash sediment, nutrients and faecal matter but require fencing and, in cases, enhanced plantings. Depending on their location within the catchment, wetlands will only trap localised sources of contaminants.

Figure 19 Reinstating a previously drained wetland, Nicks Head Station.

9.7 Debris dams/stock ponds

The construction of debris dams in combination with pole plantings in small streams and gullies has been used for years to prevent small streams from incising and thereby reduce their potential to generate sediment. While debris dams are useful for trapping mostly sediment from localised sources, they are costly and labour intensive, and the technique proved unsuccessful in retaining sediment derived from large and active gullies. Without subsidies very few debris dams are currently being built.

9.8 Culverts/bridging of stream crossings

The construction of bridges and culverts aimed at keeping stock out of waterways has improved water quality in the Sherry Catchment (Ballantine & Colley 2011).

9.9 Reforestation/soil conservation planting

Hill slopes with mature cover of native or exotic forestry have the lowest incidence of erosion and this appears largely independent of species (Phillips et al. 1991; Brown 1991; Hicks 1991, 1995; Marden & Rowan 1993; Hicks & Crippen 2004). The major considerations for erosion management in tree plantations focus on establishment and harvesting activities, where vegetation removal and mechanical earthworks temporarily increase soil movement and the risk of significant soil loss. The forestry industry and government agencies have thus developed extensive guidelines (NWASCO 1978; Vaughan 1984; Spiers 1987) and a code of practice (Vaughan et al. 1993; New Zealand Forest Owners Association 2007) to guide operational planning and maintain soil and water values through mitigation of erosion and sedimentation. These focus heavily on the practices that have been shown to contribute most to sediment generation, particularly management of roads, landings, and stream crossings.

Shallow landslides:

Areas prone to shallow landslides can be identified from the remains of previous slip scars and from knowledge of the soil type, slope, existing vegetation cover, and total rainfall and its distribution. Landsliding can be reduced or prevented by:

- ensuring a dense, healthy pasture sward coupled with establishment of wide-spaced trees, e.g. *Populus* spp., to provide deeper root-reinforcement of the substrate, and transpiration to reduce soil pore water pressure
- changing land use to regenerating scrub – indigenous forest, or
- establishing exotic forest for commercial timber production

(see Hathaway 1986; Lambrechtsen 1986; Pollock 1986; Brown 1991; Hicks 1995; Hicks & Anthony 2001; Quinn et al. 2007).

Revegetation of slip scars occurs naturally through seed dispersal from vegetation on neighbouring uneroded ground and stock defecation, and can take 20+ years for full coverage. The process can be hastened by oversowing with appropriate grasses, legumes, and herbs and seed mixtures are often tailored to site conditions to accommodate variation in such attributes as aspect (sunny vs shady), soil pH, and soil type (Lambrechtsen 1986; Lambert etal. 1993; Quilter et al. 1993). Opinion varies on the best time to oversow slips, ranging from as soon as possible after landsliding, while the sites are still moist, to autumn or spring in line with the timing of normal oversowing practice. Total sowing rates of 60–100 kg/ha or even higher have been used, but for general practice, they are uneconomic. Litherland et al. (2005a, b) describe experiences with regrassing slips and silt-covered areas following the 2004 Manawatu storm and suggest recommendations for best practice. Vegetation (both pasture and primary succession to natives) and soil recovery rates are described in Lambert et al. (1993), DeRose et al. (1995), Smale et al. (1997), and Sparling et al. (2003). These studies indicate landslide erosion causes a permanent reduction in mean herbage production and soil depth on hillslopes.

Trees for slope stabilisation should be planted at 5 × 5 m to 15 × 15 m (Hathaway 1986a) depending on the severity of landsliding, and it is recommended that planting be extended beyond the slipped land onto relatively stable ground. Lateral roots of broadleaved trees interlock for distances of up to 12 m from the trunk, and form very dense networks within 5–6 m of the trunk (Hicks 1995). Trees can be planted on slipped sites but it is recommended that they be planted on sites with potential to slip (Hicks and Anthony 2001), rather than for remediation.

Gully erosion

Most control of this erosion type aims to reduce further deepening and undercutting in the gully and its consequent effects on surrounding slope stability and reducing sediment discharge (Hathaway 1986b). The severity of the gully often dictates the type of treatment. For shallow (<2 m deep) gullies, spaced planting of *Populus* spp. or *Salix* spp., in combination with engineering structures (e.g. debris dams) while the trees establish, is recommended. For moderate (2–5 m deep) gullies the outcome of this type of treatment is less certain.

Tree planting patterns and spacings vary depending on the severity of erosion; with the most successful system being ‘pair planting’ up the watercourse at spacings of 2–10 m between pairs. Each pair comprises a tree on opposite sides of the watercourse, frequently between 1 and 2 m apart, or alternate planting in a ‘zigzag’ fashion along opposite sides of the watercourse (Hathaway 1986b; Hicks 1995; Hicks & Anthony 2001). The main treatment options for controlling gully erosion were presented in a hierarchical structure by Thompson and Luckman (1993), and although somewhat arbitrary, the classification is useful in the context of land management. They summarised the techniques commonly used to control gullying in soft rock terrain as debris retention dams, channel (or pair) planting, gully wall planting, and afforestation.

Severely eroded gullies should be retired from grazing and closed-planted with trees (Hathaway 1986b; Hicks 1995; Hicks & Anthony 2001). Considerable experience has been gained with plantings of *Pinus radiata* but other species may also be used (e.g. *Populus* spp.). The land stabilisation role of the trees is paramount and therefore they should generally not be harvested for timber, although currently many gullies that have previously been afforested are being harvested (e.g. at Mangatu Forest). Succession to indigenous scrub and forest should be a long-term objective. There has been some success with retirement, planting *Salix* spp., and then selectively removing the trees to encourage establishment and growth of indigenous species. Depending on the severity and distribution of gully erosion in a catchment, treatment may range from individual gullies and their perimeters being planted, to afforestation of most or all of the catchment.

Earthflow erosion

There is a range of vegetation techniques to control earthflows including options such as space-planted trees and afforestation; non-biological options include subsurface drains and diversion banks (Thompson & Luckman 1993). Tree spacings recommended vary depending on attributes such as the extent of the earthflow, its movement and stage of development, and depth to the failure plane. On intermittently moving or creeping earthflows, tree spacing of >8 m may enable adequate erosion control and satisfactory pasture production. When using broadleaved tree species for control of mass movement such as earthflows, Hicks (1995) recommended that trees should be 12 m apart or closer to ensure some interlocking of roots from adjacent trees. For more active, continuously moving earthflows, spacings < 5 m (400+ stems per hectare) are recommended to encourage development of a denser root network.

Recommendations on appropriate control techniques vary with site geomorphology (Hicks & Anthony 2001). On crushed argillite, options are erosion control forestry, dewatering, and construction of debris dams, whereas on other sedimentary rocks, pole planting and dewatering are recommended. Successful control of shallow earthflows (< 3 m deep) has been achieved using various plantings of *Populus* spp. and *Salix* spp. Deep earthflows (e.g. several metres deep) are much more difficult to control with vegetation, and dewatering with fast-growing evergreen species is recommended (Hicks & Anthony 2001). Reforestation at > 1200 stems per hectare affords the quickest and cheapest means of stabilising deep earthflows.

Slump erosion

Mitigation options are similar to those used to manage earthflow erosion. Spaced planting of trees in pasture is an effective preventative technique for potentially active sites or those with limited movement, and may offer some control on more active terrain. Depth of the failure plane is an important influence on how effective spaced-tree planting will be, and at depths greater than 5 m, additional control methods such as drainage will probably be necessary. Engineering methods have been used (Hicks 1995) to stabilise large, deep-seated slumps in bedrock where erosion threatens valuable infrastructure (e.g. roads, buildings) but their high cost precludes general applicability.

Severe slumping may require retirement from grazing and afforestation (close spacing) with species such as *Populus*, *Salix*, and *Pinus radiata* and other conifers (Hicks & Anthony 2001). The priority should be to retain the forest long-term. Harvesting for timber may be considered but care should be taken in deciding which trees are harvested. Replanting is recommended as soon as possible after harvesting to enable a new root system to develop before the previous system decays significantly. Encouraging the development of indigenous forest may offer better long-term stability.

9.10 Floodplains and estuaries as sediment traps

Floodplains and estuaries are considered to intercept only a small percentage of the total sediment delivered to the coast (Hicks et al. 2011). For example, Gomez et al. (1999) found that the Waipaoa floodplain intercepted only 5% of the 15Mt/year of its suspended sediment load over an 11-year period (1979–1990). More particularly, floodplain sequestration amounted to only 16% of the suspended load carried during events that exceeded the bankfull discharge, which included the 70-year return period flood of March 1988 associated with Cyclone Bola (Peacock & Philpott 2009). Supporting this, Hicks et al. (2000, 2002) used an extensive set of suspended sediment gaugings to show that 86% of the Waipaoa River's suspended load was carried at sub-bankful flows. The most effective strategy for sediment entrapment is to intercept it near source rather than sequestering it on the floodplain.

10 Prioritisation of areas for best management options (BMPs)

Priority areas will need to be selected at varying scales (sub-catchment, single reach of a major river, swampy part of a small stream, existing wetland or create new ones, etc.) and matched with BMPs where remediation would be expected to produce a beneficial outcome, i.e. a reduction in sediment yield and/or improved stream health.

Realistically, sediment reduction is more likely in parts of catchments where sediment is generally produced by surficial erosion processes such as slopewash and periodic shallow landsliding but less likely in catchments where erosion is dominated by mass movement processes and /or gullying. It would also be possible to make a difference at a localised scale (on-farm) but unrealistic to expect a measureable difference in suspended sediment yield in the bigger rivers, especially those with large volumes of sediment storage in their channels (e.g. Mangatu, headwater reach of Waipaoa River) or those rivers with extensive areas of floodplain where stream banks comprise unconsolidated sands and silt (e.g. lower reaches of Te Arai, Wharekopae, Totangi, Waikohu, Waingaromia and Waihora).

Positive outcomes are more likely to be achieved in sub-catchments with a ‘low’ base sediment yield (e.g. Wharekopae, Waikohu and Waihuka) with extensive channel incised between banks of bedrock rather than alluvium (unconsolidated silt and sand). Typically, the stream beds of these reaches comprise cobble- and boulder-sized material with little stored sand and silt, indicating that hill slope erosion upstream of these reaches produces little fine material, most of which is able to be mobilised down the channel rather that stored as bedload.

11 Impact of climate change on hill country erosion

The main features of the New Zealand climate projections for the 2030s and 2080s include:

- Mean temperature is projected to increase (mid-scenario) 0.6–0.7°C by 2030s and 1.6–2.0°C by 2080s, with the strongest warming in winter, and a tendency for slightly more warming in the east and north.
- Daily temperature extremes will increase with fewer cold temperatures and frosts and more high temperature episodes projected.
- Mean rainfall impacts will vary around the country, with a tendency for annual rainfall to decrease in the north and east and increase in the south and west, associated with a stronger west-east rainfall gradient. Changes of the order of −5 to +5% by the 2030s and −10 to +15% by the 2080s are expected.
- Heavier and/or more frequent extreme rainfalls are expected, especially where mean rainfall increases are predicted, since a warmer atmosphere can hold more moisture (about 8% more for every 1ºC increase in temperature). There may be up to a four-fold reduction in storm return period by the 2080s, although there is little quantitative information available[1]. The frequency of extra tropical cyclones (which bring large storm events to the north and east of New Zealand) is predicted to decrease but their intensity is expected to increase.
- An increase in both mean annual westerly windflow and severe winds that cause wind erosion.

The impact of climate change on soils and landscape processes has been reviewed by Basher (1990) using earlier estimates of likely climate change scenarios.[2] The direct effect of climate change on erosion is likely to be reflected in changes to the rates of erosion processes rather than the types of erosion occurring. The greatest effects are likely to occur through changes to precipitation processes and regimes, which will affect rates of erosion processes and recovery of vegetation following erosion. The pattern of erosion would be similar to the present, but the rates of individual erosion processes would be determined by changes in the frequency and magnitude of rain and wind storms. Annual rainfall is the dominant control on rates of erosion, as measured by suspended sediment yields (Griffiths 1981, 1982; Hicks et al. 1996), and if rainfall increases as predicted for many parts of the country, then erosion rates can be

[1] Gray et al. (2005) provide guidance on how to assess likely changes in extreme rainfall

[2] The 2007 IPCC estimates of climate change alter the magnitude of likely temperature rise but provide little more detail on impacts on rainfall amounts, intensities or frequency of large storms.

expected to increase substantially. Since most erosion occurs in large storm events, and these are predicted to increase even in areas where annual rainfall decreases, further information on likely changes in their patterns, frequency, and intensity is needed to assess quantitatively the likely impact of climate change on hill country erosion. Climate scenarios suggest that for many areas there would be an increase in high-intensity storms (i.e. more rain on fewer days) and an increase in intensity of cyclonic storms of tropical origin, especially in the North Island. Tropical cyclonic storms tend to cause mass movement erosion and flooding over wide areas as experienced during Cyclones Alison (Bell 1976) and Bola (Trotter 1988). Likely changes in their frequency and magnitude are currently poorly known.

Temperature changes will modify water balance. With the projected increases in erosion rates, water storage and retention capability of hillslopes will be severely reduced because the storage capacity provided by the porous regolith will be depleted with removal leading to increased droughtiness especially in eastern regions. As a consequence, more land will be exposed to sheet and wind erosion with drought effecting vegetation cover and re-establishment.

The newly exposed slip surfaces will also rapidly shed runoff water. Downstream channels will be affected by the increased frequency and magnitude of storm flows and consequently may become destabilised. Where there is a high degree of coupling between erosion processes and the drainage system, sediment supply will be enhanced. Low-gradient watercourses will consequently aggrade, reducing channel capacity and promoting overbank flooding.

The impacts of climate change on soils and landscape processes on the hill country in the Gisborne region can be summarised as follows:

This area is likely to become drier overall. However, there is likely to be a significant increase in landslide erosion on the steep Tertiary soft rock hill country, especially on deforested slopes, with predicted higher-intensity rainfalls and intensity of extra-tropical cyclones (i.e. more ‘Bola’-like storms with major effects on the hill country) (after Basher 1990).

11.1 Implications from process studies

Several key findings have come out of the extensive literature on erosion processes:

- Geology (rock type, induration, regolith composition, drainage, and permeability), uplift rates, and climate (rainfall amounts, intensities) largely determine the landscape’s inherent susceptibility to erosion. Susceptibility to erosion is readily identifiable at a regional scale and increasingly at hillslope and farm scale.
- Shallow landslides affect the greatest proportion of hill country terrain; earthflow, slumps, and gully erosion are far less extensive and frequent. The relative impact of sheetwash erosion and its contribution to the sediment budget in pastoral hillcountry areas (farm scale/catchments/erosion terrains/regions/nationally) is poorly known. Sheetwash is the least important of the sediment-generating processes on forest cutover, with shallow landsliding, roads, and landings generating the most sediment. Shallow landslides and gully erosion result in the greatest long-term, on-site (soil loss) and off-site (sedimentation and flooding) environmental degradation.

- In all terrains, but particularly in terrains identified as highly erodible, gully erosion needs to be identified and treated early. Untreated gullies increase in size and activity over time, lessening the chance of treatment being successful.
- Large storms, or long wet periods, drive mass movement (landslide, earthflow, slump) on hillslopes. These are high-magnitude events that occur at low frequency. In catchments where these features dominate the landscape, sediment production from mass movements dominates catchment sediment budgets during, and for a short time after, storm events.
- For fluvial erosion (gullying, bank and channel erosion) the smaller more frequent storms are more important (i.e. low-magnitude, high-frequency events) because they are directly connected to the stream network. A substantial proportion of the sediment generated between large climatic events can be generated by these processes, and in at least some landscapes they can dominate overall sediment generation. Recovery of river networks from the impacts of gully-derived sedimentation is slower (decades to millennia) than for rivers periodically impacted by other sediment-producing processes (annual to decade).
- Earthquakes are a significant driver for deep-seated mass movements but are far less frequent.
- Closed-canopy woody vegetation (evergreen species) reduces rates of hillslope erosion by an order of magnitude on the most susceptible terrain. On other less susceptible terrains hillslope erosion is reduced but the degree of reduction is not as well quantified, especially for space-planted poles.
- The impacts of pre- or post-European deforestation have persisted for more than a century especially in those landscapes with thick regoliths and/or soft rocks.
- Harvesting of forests in highly erodible terrain increases erosion rates in the short term, but over the length of a forest rotation (c. 27–30 years) pasture produces four times more sediment than forestry.
- Across all terrains, vegetative erosion control through reforestation, reversion, and pole planting has proven successful for controlling much of the erosion. However, the use of pole planting for the treatment of large and active mass movement features (earthflow and slump) and gully erosion, in the most highly erodible terrains, has had only limited success. Space-planted poles can provide protection against the initiation of shallow landslides if planted in sufficient numbers and in the appropriate position on slopes. Failure to recognise this has resulted in a poor outcome for many past soil conservation efforts.
- Storm-initiated landslides deplete the soil resource on hill country. Soil loss as a consequence of recurrent storm events is cumulative. Soil recovery on landslide scars is slow. Productivity after 20 years is 80% of that for stable sites unaffected by landsliding.
- Climate change is likely to exacerbate erosion problems in the worst affected areas since it is predicted to cause heavier and/or more frequent extreme rainfalls. This will result in a higher incidence of landsliding, and gullying in some areas where rainfall increases, and further depletion of the soil resource. Continued soil loss combined with slow soil recovery will ultimately impact the economic viability of hill country farms, particularly small farms in the more highly erodible terrains (from Basher et al. 2008).

12 Conclusions

The relative contributions of sediment derived from different sources have changed over time and in response to different drivers including tectonics, climate and more recently, deforestation. Prior to human settlement channel incision, shallow and deep-seated landslides were the major processes that delivered sediment to stream channels. Following deforestation, gully erosion and shallow landsliding dominate the present-day sediment budget of the Waipaoa River.

The present day sedimentation problem in the Waipaoa catchment is of historical origin and can be attributed directly to the dramatic increase in hill slope erosion following clearance of the indigenous forest from erosion-prone terrain during the early European settlement period. The delivery of sediment to the main channels of the Waipaoa and Mangatu Rivers, primarily from gullies, exceeded the rate at which these rivers could transport the material; hence it accumulated in these channels. This legacy of stored sediment, together with ongoing sediment delivery from existing, untreated gullies as well as that derived from shallow landslides during periodic storm events, has the greatest, long-term, on-site (loss of soil depth and productive capacity) and off-site (sedimentation and flooding) environmental impact. Although other sediment-generating processes, including earthflows, slumps, bank and cliff erosion and slopewash, can at times be significant sources, they tend to be localised and ‘event driven’, and their contribution, relative to gullies and shallow landslides, is small and short term.

Geology (rock type, induration, regolith composition, drainage and permeability), uplift rates, and climate (rainfall amounts and intensities, frequency of large storms) largely determine the landscape’s inherent susceptibility to erosion, including the response to vegetation change. Susceptibility to erosion is readily identifiable at a regional scale and increasingly tools and methods are becoming available that can be used at hillslope and farm scale. Large storms, or long wet periods, drive mass movement (landslide, earthflow) on hillslopes. These are high-magnitude events that occur at low frequency. For fluvial erosion (gullying, bank and channel erosion) the smaller more frequent storms are more important (i.e. low-magnitude, high-frequency events). Earthquakes are a significant driver for deep-seated mass movements and are much lower frequency events.

Closed-canopy woody vegetation reduces rates of hillslope erosion by an order of magnitude on the most susceptible terrain. Past vegetative erosion control efforts through reforestation, reversion and pole planting has proven successful for controlling much erosion. However, the use of pole planting for the treatment of large and active mass movement features (earthflow and slump) and gully erosion, in the most highly erodible terrains, has had only limited success. Space-planted poles can provide protection against the initiation of shallow landslides if planted in sufficient numbers and in the appropriate position on slopes. The encouragement of natural reversion and/or the establishment of riparian vegetation ‘strips’ as a means of reducing sediment input into streams has its limitations in hill-country terrain dominated by mass movement failures as the mobilised and often ‘liquid-like’ sediment tends to be transported through all but the densest vegetation barriers. Nonetheless, streamside vegetation can be an effective barrier to sediment (derived either by mass movement or slopewash), nutrients and animal pathogens in situations where alluvial terraces act as a buffer between the stream and a hill slope and the terraces are elevated above high flood level.

Further planting of all remaining gullies, earthflows and of terrain identified as having a high potential for shallow landsliding is required if further sediment input into the Waipaoa River is to be minimised. The reforestation of gullies is the most practical and effective means of stabilising all but the largest of them, and if all remaining untreated gullies were to be reforested before 2020, and no new gullies were initiated during this period, gully-derived sediment yield could be halved by 2030 and remain constant thereafter. A modelled reforestation strategy aimed at prioritising land for reforestation according to landslide susceptibility could have a significant impact on fine sediment yields. With prioritisation, a 40% reduction in landslide-derived sediment could be achieved through reforestation of 8% of the Waipaoa River basin, whereas 25% of the land would need to be reforested to achieve the same effect through random selection Sediment yields from other sources, including earthflows, stream banks and reworked material in temporary storage as bedload could be considered as being of lesser concern.

Following reforestation, streams within mature plantation forests have greater stability and lower water temperature than adjacent pastoral streams, resulting in improved overall stream ecological health approaching the condition of reference streams in native forest. Reductions in sediment input and improvements in stream health are possible at a localised scale and within a relatively short time frame but are unlikely to make a significant difference to the sediment load or water quality of the Waipaoa River as a whole for many decades, if not millennia. Without further erosion mitigation intervention and in the event of more severe storm events, erosion on unprotected hill slopes will increase and further exacerbate the current sedimentation issues of the Waipaoa catchment.

For sediment management to be effective and sustainable, the fundamental unit of management should be the river basin. The use of the river basin, as the scale of water and sediment management, introduces some important issues. First, it is necessary to recognise the numerous environments within a river basin (including soils/hillslopes, rivers, floodplains, wetlands, lakes/reservoirs, and the coastal zone) and the interconnectivity between these environments. The study by Owens et al. (2005) demonstrated the interconnection between land-use changes on hillslopes, sediment delivery and transport in rivers, and sediment deposition and flooding in downstream reaches for the Waipaoa River. This study illustrated the potential for targeted management in headwater reaches to control downstream problems (i.e. controlling the source of the problem as opposed to downstream management). Second, there is a need for greater understanding of how the processes that control sediment generation, delivery, and transport within rivers operate at scales that are meaningful for management and, based on this, there is also a need to identify which remediation strategies could provide a reduction in sediment generation from hillslopes and where to apply them.

The impacts of pre- or post-European deforestation have persisted for more than a century. Climate change is likely to exacerbate erosion problems and lead to increased sedimentation since it is predicted to cause heavier and/or more frequent extreme rainfalls.

13 Recommendations and future research needs

In view of the potential worsening of hill slope erosion and its impact on sedimentation patterns within the Waipaoa River, it is recommended that Gisborne District Council use NIWA's River Environmental Classification (REC) by Snelder et al. (2005) as a spatial framework for mapping and classifying rivers or parts of rivers within the Waipaoa catchment into REC classes discriminated by variations in physical (land cover, geology, climate, topography) and biological (water chemistry, biological communities) characteristics at a range of scales. Classes can be treated as management units, each of which can be linked to a monitoring strategy and used as a framework for environmental assessment, management, and reporting.

- Use existing data to establish the current 'base level' of suspended sediment yield from monitored sub-catchments and, based on this, use prediction tools/models to prioritise sub-catchments/parts of sub-catchments according to where greatest gains in sediment reduction might be possible if mitigation measures were to be implemented.
- Develop appropriate erosion mitigation implementation plans targeting existing, active sediment sources (e.g. gullies) first, then future proof vulnerable areas (e.g. steep hill slopes, stream banks) through further tree planting (poles, reversion and/or forestry)
- A survey of regional councils, industry, central government agencies and science providers identified a wide variety of research needs to assist improved management of hill country erosion and resultant sedimentation. Gaps identified by the greatest number of stakeholders included (from Basher et al. 2008):
    - ability to measure regional/catchment rates of erosion and determine what is tolerable, including measuring the contribution from different land uses and land management practices, being able to distinguish natural and induced erosion, and the contribution of different processes
    - integrated research on sediment dynamics (connectivity and lags) within catchments and downstream effects, including slope–channel linkages
    - development of erosion prediction tools/models incorporating land use/management effects and able to distinguish different erosion processes
    - effectiveness of space-planted trees (including willows, poplars and natives) for erosion control and their management requirements, and other erosion control measures, over a range of event magnitudes
    - cost–benefit analysis of different mitigation techniques including co-benefits of erosion control on carbon storage, role of erosion in the carbon budget
    - effective community engagement processes for erosion and catchment management, and improved technology transfer.

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