

# Landslide occurrence as a response to land use change: a review of evidence from New Zealand

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## Abstract

Vegetation cover is an important factor influencing the occurrence and movement of rainfall-triggered landslides, and changes to vegetation cover often result in modified landslide behaviour. However, it is difficult to relate the occurrence of landslides directly to variations in land use, especially in some European countries. In contrast, New Zealand provides a good opportunity to investigate geomorphic responses to anthropogenic land cover changes. Before European settlers first arrived in the 1840s, hilly regions were only marginally influenced by human activity. The Maoris, New Zealand's first settlers, lived largely on coastal plains or near lakes and rivers. They influenced general vegetation cover only through localized burning practices. In contrast, European settlers moved into the back country and converted extensive hill areas from native forest and bush to pasture. This reduced the strength of the regolith and rendered the slopes more susceptible to landslides. Pulses of natural sedimentation in the pre-European period have been related to volcanic activity, climatic variability, including changes in frequency of cyclonic storms and wind erosion and fluvial erosion following forest fires initiated either by volcanic eruptions or lightning strikes. Since European deforestation began, sediment production has largely been determined by landslide events. On unstable slopes, thousands of landslides were triggered by high-magnitude/low-frequency climatic events during storms with estimated return periods in excess of 50 years. In contrast, low-magnitude/high-frequency rainfall events have caused gully and channel erosion. Examples from different parts of New Zealand indicate changes in sediment-generating processes following land use modifications. After deforestation, landslides have contributed significantly to sediment sequences in depositional basins such as lakes, swamps, estuaries, coastal wetlands and the nearshore and offshore zones of continental platforms.

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## 1. Introduction

Land use change has been recognized throughout the world as one of the most important factors influencing the occurrence of rainfall-triggered landslides. Following Cruden and Varnes (1996) and Dikau et al. (1996), the term landslide is used in this review for soil, debris and rock travelling by sliding, flow and complex movement.

Landslide occurrence as a response to land use changes has been studied over various time periods. In the late Holocene, humans converted large areas from native forest and bush into arable land in various areas throughout Europe. Increased activity of geomorphic processes resulted, including aeolian transport and flooding, accelerated sheet and rill erosion, open and tunnel gullying and landsliding. For Europe and other regions, Matthews et al. (1997) reviewed rapid mass movement as a source of palaeoclimatic evidence for the Holocene. Various contributing authors stressed the link between climatic and human impacts on landslide initiation. Examples for the Holocene were given for Germany (Grunert and Hardenbicker, 1997), Scotland (Innes, 1997), Great Britain (Ibsen and Brunnsden, 1997) and Italy (Rodolfi, 1997), to name only a few. However, this link is not an ancient phenomenon. Examples from Mt. Ichifusa, Japan (Marutani et al., 2000), Canada (Goff and Hicock, 1995; Goff et al., 1996) and those from New Zealand discussed later in this review demonstrate increased landslide occurrence and effects in downstream sediment sinks with continuing deforestation in recent periods.

When focusing on landslide response to past land use change, a major problem in agricultural areas is the removal of evidence by intense soil cultivation. Consequently, few remnants of older landslides can be recognized (Matthews et al., 1997). Even when they are identified, dating is imprecise, if it is possible at all (Lang et al., 1999), and it is even more difficult to relate landslide occurrence to vegetation changes. Of particular interest is the influence of human activity on vegetation changes. Often, large areas were changed in a short time, thus, influencing strongly the environmental factors, which control landscape stability. Changes should be related to the stratigraphy of colluvial and alluvial sediments, but it is usually impossible to relate these sediments to erosion processes such as sheet and rill erosion, open and tunnel gullying and landslides. Therefore, it is important to investigate in more detail regions such as New Zealand where it seems possible to relate sediment layers to landslide processes.

## 2. New Zealand setting

The vegetation of New Zealand developed during a long period of isolation from any other landmass. Over 85–90% of the country, the native vegetation developed over thousands of years to a dynamic climax around 3000 BP (McGlone, 1989). There is no simple relationship between vegetation cover and erosion processes. Even under forest regimes, landsliding can be the dominant erosion process (Crozier et al., 1992; Eden and Page, 1998). However, depletion of native vegetation tends to be followed by increased erosion (Trustrum et al., 1990; Page and Trustrum, 1997; Wilmshurst et al., 1999).

Holocene disturbance of sediments has been related to volcanic activity, climatic variability (Eden and Page, 1998; Page and Trustrum, 2000), wind erosion (Basher and Webb, 1997) and erosion following forest fires initiated by volcanic eruptions (McGlone, 1981; Wilmshurst and McGlone, 1996) or lightning (Burrows, 1996; Wilmshurst et al., 1999). Eden et al. (1994), Trustrum et al. (1999) and Page and Trustrum (2000) have noted pulses of sediment activity that can be related to increased frequency of rainfall and other natural disturbances like fire and volcanic effects.

The environment was relatively undisturbed by human activity until the middle of the 19th century. Before this, the first settlers, Polynesians from the South Pacific Islands, arrived around 1250 AD and became the native inhabitants of New Zealand, the Maoris. Although few in number, they were the first to influence the natural system through slashing and burning the indigenous vegetation over wide areas. About half the forest and scrubland was burned (Poole and Adams, 1994). Although this caused a long-term change of vegetation and irreversible damage (McGlone, 1983; McGlone and Basher, 1995), Maoris were principally active on flat landscapes such as valley floors, plains, coastal regions and forelands (Newnham et al., 1998a). Some sheet erosion, rill erosion and gully erosion did increase on gentle slopes and degraded the soil, but this occurred only locally, and most slopes remained stable. A Polynesian-induced increase in landslide occurrence is not clearly identifiable from hillslope studies (DeRose et al., 1993), although a 60% increase in sedimentation rates in one lake basin has been attributed to Polynesian deforestation (Page and Trustrum, 1997). This situation changed suddenly with the arrival of the first European settlers in New Zealand. Within a few years, the Maoris had become a minority (Glade, 1998) and their agricultural practices and influence on the landscape was overshadowed by extensive European forest clearance and conversion to pasture.

Of particular interest for relating landslide occurrence to vegetation change are sedimentary sinks within the landscape such as colluvial bodies, floodplains, lakes and nearshore marine environments. Recent studies of river discharge and suspended sediment load suggest that most of the sediment transported by streams and deposited in these sinks during and following rainstorms has come from landslides and landslide–gully complexes in headwater catchments (Hicks et al., 2000). Ultimately, these sediment stores can be used to disentangle the different transport processes. Although nearshore and coastal wetland sinks are also prone to changes from sea-level variations or catastrophic events such as tsunamis, these can be distinguished in the sediment record from human-induced sedimentation (Goff and Chagué-Goff, 1999; Chagué-Goff et al., 2000).

Within a sediment body, deforestation effects can be clearly distinguished from natural impacts by pollen analysis, which shows the introduction of exotic European trees, herbs and pasture by European settlers (Wilmshurst et al., 1997, 1999). This gives a more detailed view of increased erosion resulting from human settlement.

In this review, landslides triggered by rainstorms are distinguished from long-term erosion resulting from other processes in order to filter human activity from natural erosion conditions. The study is based on the hypothesis that deforestation led to increased slope instability. The first large rainstorm following deforestation was able to trigger landslide activity, resulting in higher sedimentation rates.

### 3. Methods

There have been many case studies relating landslide activity in New Zealand to human interference and the influence of vegetation cover. However, they have been based on a range of different methods, so any conclusions based upon them can only indicate possible linkages between landslide occurrence and land use change. Another problem with using case studies is that different authors have worked on different time scales, in significantly varying environmental settings, using methods specifically designed for their respective aims. Nevertheless, a preliminary review based on analogous interpretations is considered useful in providing perspectives for future investigations.

Information about prehistoric periods is based on pollen analyses of colluvium, floodplain, limnic and coastal deposits (e.g. Newnham et al., 1998b; McGlone and Wilmshurst, 1999; Wilmshurst et al., 1999),  $^{14}\text{C}$  dating (e.g. Lowe et al., 1998) and tephrochronology (e.g. Eden and Froggatt, 1996; Lowe et al., 1998; Newnham et al., 1998a).

Historical data were compiled from written documents, drawings and photographs. Sources included archives, newspapers, reports, scientific publications and vertical and oblique aerial photography. The number of historical records increased with population density and with event magnitude (Glade, 1996, 1998). Although this was a general drawback of the inventory, it does not mean that only greater magnitude landslide events are known. Vegetation data since the 19th century were obtained from the New Zealand Statistics yearbooks.

The locations of all study sites are shown in Fig. 1.

### 4. Results

#### 4.1. Hawke Bay

Lake Tutira and adjacent Lake Waikapiro (Fig. 2) have acted as sediment sinks since their formation about 6000 years ago (Trustrum and Page, 1992; Page et al., 1994a; Page and Trustrum, 1997; Eden and Page, 1998). Prior to the commencement of European farming activity, finely laminated sediments accumulated in Lake Tutira at rates of  $1.5\text{--}2.4\text{ mm year}^{-1}$ , which increased by about 60% following Polynesian settlement (Page and Trustrum, 1997). However, based on hillslope studies, DeRose et al. (1993) were unable to find any Polynesian influence, so landslides or other processes such as streambank erosion could have delivered the sediment to the lake.

Since the 1880s, the sedimentation rate in Lake Tutira has increased to approximately  $13\text{ mm year}^{-1}$  (Page and Trustrum, 1997). Historical sources have documented the large

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Fig. 1. Location of study sites. Circled numbers refer to locations mentioned in the text: (1) Whangape harbour estuary (Nichol et al., 2000); (2) Repongaere swamp (Wilmshurst et al., 1999); (3) Continental shelf (Wilmshurst et al., 1999); (4) Waipaoa valley floors (Gomez et al., 1998; Marutani et al., 1999; Hicks et al., 2000); (5) Lake Waikaremoana (Newnham et al., 1998b); (6) Lake Tutira (Page et al., 1994a; Trustrum et al., 1999); (7) Wellington harbour (Goff, 1997); (8) Abel Tasman coastal wetlands (Goff and Chagué-Goff, 1999).

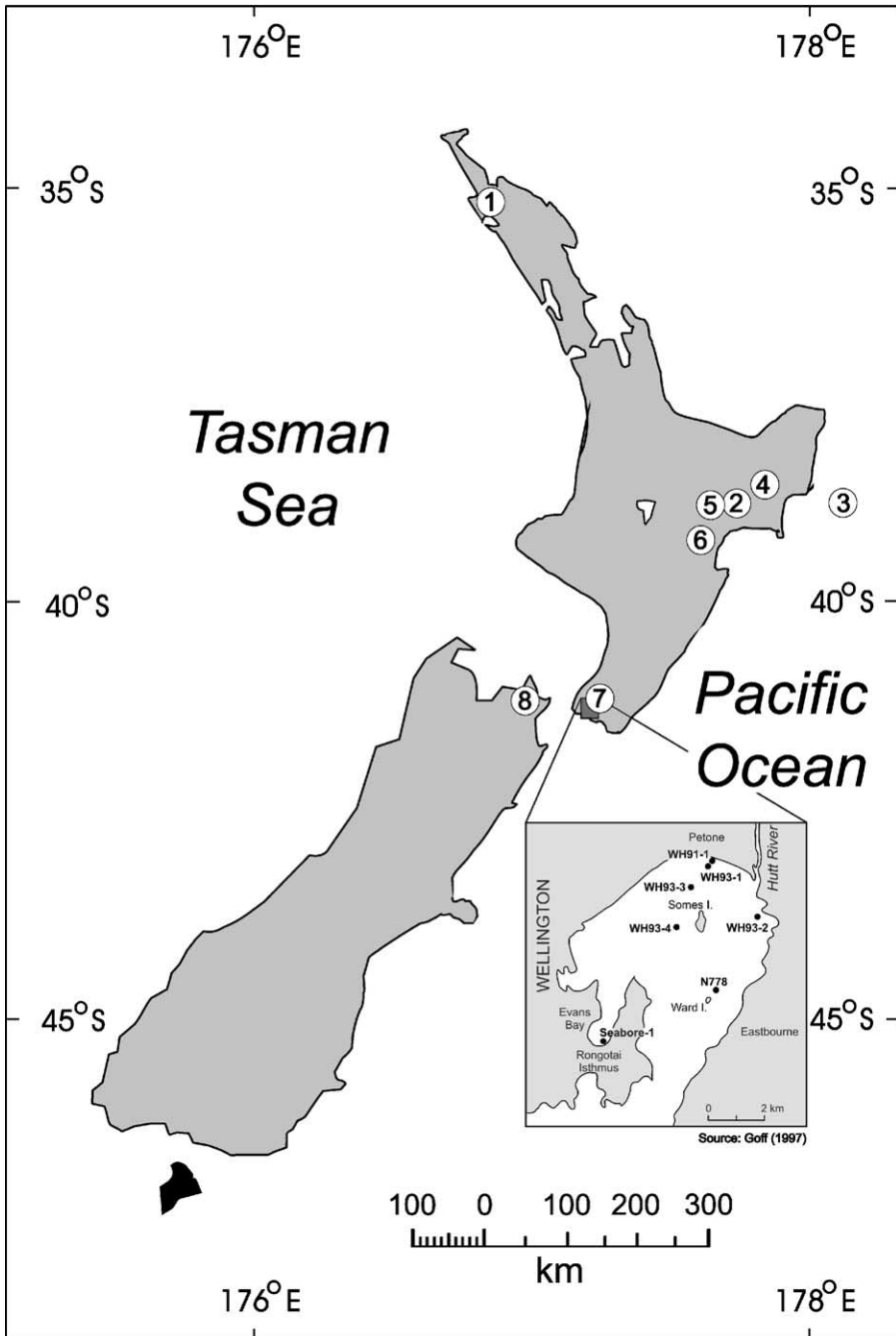




Fig. 2. Freshwater Lake Waikapiro in Hawke Bay, North Island, view towards southwest.

extent of landsliding in this area since the 1880s, particularly in 1938, 1945, 1963, 1965 and 1988. The most active years of landsliding were 1938 and 1988. [Page et al. \(1994b\)](#) were able to correlate sediment thickness with landslide events, and [Turner \(1997\)](#) suggested that low concentrations of magnetic minerals in sediments deposited prior to European settlement indicate that erosion processes in the catchments did not remove strongly minerogenic sediments. Since the arrival of the Europeans, each major rainstorm has produced identifiable pulses of minerogenic sediment, which must be a result of processes mobilizing the regolith. This result strongly suggests increased soil erosion after deforestation. Although sediment pulses triggered by rainstorm events have rapidly infilled the lake basin, no simple relationship between storm magnitude and sediment thickness exists. For example, although rainfall event magnitude was larger in 1988 than in 1938, total sediment delivery was less. This could be explained by:

- The 1938 storm removed much of the sediment that had previously accumulated on the hillside, foot slopes and alluvial plains under native forest and scrub cover ([Page et al., 1994b](#)).
- Until 1988, hillside sediments were removed by previous events, thus, sediment sources have been emptied by progressive failures and not enough time had elapsed for soil recovery ([Page et al., 1994b](#); [Crozier and Preston, 1999](#)).

Despite this problem, a sediment budget for the Lake Tutira catchment was established for the widespread landslide-triggering rainfall event of March 1988 by [Page et al. \(1994a\)](#). They quantified the amounts of sediment stored on different terrains (e.g.

hillslopes, floodplains) and compared them to the sediment delivered to the lake. They showed that landslides contributed 89% to the sediment flux (Table 1); 43% of the mobilised sediment was stored on foot slopes and valley floors; and 51% was deposited in the lake.

The transition in landscape sensitivity from stable to potentially unstable conditions following conversion of native forest to farm land by European settlers has been addressed conceptually by Preston (1999) and Preston and Crozier (1999). If the native vegetation cover had still been in place, a similar rainfall event to that of March 1988 would have led to only minor effects on the landscape (Trustrum et al., 1999). Although the effect of climate change cannot be excluded in this region, the changing type or magnitude of geomorphic processes following land use change is apparent, and suggests that land use change is the most important factor leading to increased landslide initiation in this region (Eden and Page, 1998).

#### 4.2. Wellington

Wellington Harbour is a natural nearshore sink for sediment inputs from rivers draining a basin area of approximately 85 km<sup>2</sup>. The Harbour has a mean depth of 14 m with the Hutt River flowing into the northern end. Disturbance of sediment by ocean currents is minor because the Harbour has just one outlet to the south. Flows follow a clockwise path in the Harbour during flood tides and anticlockwise at ebb, but the effects on sediment dispersal are unknown. Goff (1997) used seven sediment cores to establish a Holocene sedimentation chronology, which shows the impact of colonisation since 1855 (Table 2). Rapid large-scale deforestation began with the arrival of the first European settlers in 1840 (Dunbar et al., 1997). In subsequent rainstorm events, the exposed soil cover was highly susceptible to erosion, resulting in an increase in sediment accumulation rates. Although sedimentation rates can be influenced by earthquakes and related uplift and the Holocene marine transgression, as well as by anthropogenic influences, Goff (1997) concluded that high-magnitude earthquake events only affect the harbour sediments near the area of uplift, and that anthropogenic influences have a far more significant effect on sediment accumulations. These conclusions are supported by increases in trace metal contents in the

Table 1  
Sediment budget of an erosion-inducing rainstorm (Cyclone Bola, 8–11 March, 1988) in Lake Tutira catchment, Hawke Bay

Budget component	Location	Process	Sediment flux (%)	Total (%)
Input	Hillslopes	Landslide	89	
		Sheet erosion	7	
		Tunnel gully	2	
Storage	Valley floors	Channel	2	100
	Hillslopes	Deposition	21	
Output	Valley floors	Deposition	22	
	Lake bed	Sedimentation	51	
	Lake outlet	Stream/channel transport	6	100

From Page et al. (1994a,b).

Table 2

Estimated sedimentation rates ( $\text{mm year}^{-1}$ ) of specific periods for various cores in Wellington Harbour

Period	WH92-1	WH93-1	WH93-2	WH93-3	WH93-4	SB-1	N778
Surface	23.5–26.5	60.0–61.0	150	160	60	205	11.0–12.5
To 1963/1964 <sup>a</sup>							
To 1952/1953 <sup>a</sup>					34.5–41.5		
To 1910 <sup>b</sup>		95	40		28	550	
To 1890 <sup>c</sup>		17.0–20.5		75	55	2.1–6.5	
To 1855 <sup>d</sup>	370	285	0.11–0.52	0.7–1.25	4		
Pre-1855 <sup>e</sup>	0.5–0.7	0.5–0.7					

Data summarized from Goff (1997).

<sup>a</sup> <sup>137</sup>Cs.<sup>b</sup> Pollutants.<sup>c</sup> Pinus.<sup>d</sup> Earthquake.<sup>e</sup> <sup>14</sup>C.

harbour sediments, which provide an accurate historical baseline to determine minimum sedimentation rates since the 1920s (Dickinson et al., 1996; Pilotto et al., 1998).

A sediment budget differentiating sediment sources and sinks and associated processes, similar to that for Lake Tutira, has yet to be developed for the Wellington region. However, a study of geomorphic and hydrological effects of a rainstorm event in December 1976 documented that 78 landslides with a total volume of 33,500 m<sup>3</sup> contributed significantly to the sediment loads of rivers (McConchie, 1977, 1980). This storm produced 250–300 mm rainfall in 12 h and had a return period in excess of 100 years (Tomlinson, 1977). McConchie (1980) stated that, ‘Seventy of the landslides provided debris directly to the drainage system producing a highly loaded torrent which caused severe flooding downstream’. Thus, landslides contributed significantly to river sediment load and were dominantly responsible for sediment accumulation in Wellington Harbour. This conclusion is supported by other landslide studies in the Wellington region, which have indicated a relationship between land cover and landslide occurrence (e.g. Eyles et al., 1974a,b; Crozier et al., 1978; Kingsbury, 1994).

#### 4.3. Further indicators

In addition to the local studies of Lake Tutira in Hawke Bay and Wellington Harbour, there are further indications from environments throughout New Zealand that land use change was accompanied by an increase in landslide occurrence, which contributed significantly to sediment deposition. Data are summarized by sink types.

##### 4.3.1. Estuary

Whangape Harbour is on the western coast of Northland, North Island (Location 1 in Fig. 1). The coastal landscape here was heavily influenced by Polynesian settlers (Nichol et al., 2000). Europeans continued forest burning and introduced logging and grazing. Processes such as river bank collapse, gully erosion and landslides resulting from deforestation have contributed to sedimentation in the estuary, leading to an expansion



of mangrove forests and deterioration in the quality and quantity of sea food stocks. [Nichol et al. \(2000\)](#) stated: ‘The hillslopes of Whangape Harbour catchment are scarred by the effects of rill scour, gully erosion and mass movements, covering an area of approximately 80 km<sup>2</sup>. In an event in 1999, numerous landslips and boulder debris flows extended onto mangroves in the harbour. Although [Nichol et al. \(2000\)](#) did not quantify the contribution of individual erosional processes to sediment deposition, landslides were of major importance.

Sedimentation rates of 0.1–0.5 mm year<sup>-1</sup> in forested landscapes of Polynesian times increased to 1.7–4.6 mm year<sup>-1</sup> following deforestation in the European period ([Nichol et al., 2000](#)). Because of recent disturbance and drainage, most pollen profiles in Northland unfortunately do not record approximately the last 1500 years of history ([Newnham, 1999](#)) and, thus, do not detail geomorphic response to European disturbance to native forest cover. However, human impact is visible in increased sedimentation and as shown by changes in magnetic susceptibility of the sediment, can be attributed particularly to landslide processes ([Nichol et al., 2000](#)).

#### 4.3.2. Swamps

In Repongaere Swamp, located in northern Hawke Bay, North Island (Location 2 in [Fig. 1](#)), the vegetation was disturbed by volcanism (e.g. the post-Taupo forest disturbance) and lightning strike fires (e.g. [Wilmshurst et al., 1999](#)). Although an increased storminess is indicated ca. 2090–1855 years BP by sediment analysis ([Wilmshurst et al., 1999](#)), an increase of sediment input can be attributed to Polynesian deforestation AD 1350 ([Lowe et al., 1998](#)). However, the highest sedimentation rates followed European pastoralism ([Wilmshurst et al., 1999](#)). Although it is not quantified, fluvial sheet wash and in particular landslides may have strongly influenced sediment delivered to Repongaere Swamp. This hypothesis is strengthened by observations on late Holocene lake sediments in the same region by [Eden and Page \(1998\)](#). They concluded that storm sediment pulses identified in lake sediment cores are mainly derived from landslides.

#### 4.3.3. Continental shelf

East of Poverty Bay, northeastern North Island (Location 3 in [Fig. 1](#)), a marine core from the continental shelf showed from sediment and pollen analysis that sedimentation rates increased by an order of magnitude after European conversion of native scrub and forest to pasture ([Wilmshurst et al., 1999](#)). Although the core location was susceptible to sediment disturbance, increased sedimentation after deforestation of the eastern Hawke Bay Region, Gisborne and East Cape was confirmed in the core. [Foster and Carter \(1997\)](#) concluded that the Holocene sedimentation rate on the continental shelf was nearly five times less than the rate since European deforestation.

Detailed studies in the Waipaoa catchment, the largest tributary to Poverty Bay and New Zealand’s fourth largest river in terms of sediment supply, indicate that gully–mass movement complexes have been a major contributor to sediment delivery ([Marutani et al., 1999](#); [Reid and Page, 2003](#)) ([Fig. 3](#)). During intense rainstorms such as Cyclone Bola in 1988, sediments generated by landslides may contribute about half of the total suspended sediment load, as [Page et al. \(1999\)](#) and [Trustrum et al. \(1999\)](#) have shown for of the Kakanai River, a major tributary to the Waipaoa River. The large gully–mass move-



Fig. 3. Tardale gully complex with aggregated river bed in the Waipaoa catchment, Gisborne, North Island.

ment complexes in this catchment are different from the landslides of other regions, where the dominant landslide types are shallow translational earth and debris slides and flows.

#### 4.3.4. Valley floors

Sediment sources, pathways and sinks have been extensively investigated in the Waipaoa catchment (Location 4 in Fig. 1, Fig. 4). Gomez et al. (1998) and Marutani et al. (1999) measured river discharge and sediment concentrations, and surveyed cross-sections to determine changes of sediment storage for the Matakonekone and Oil Springs streams. In these catchments, heavy storms instantaneously aggrade river terraces, but the stored sediments are then gradually excavated by fluvial transport.

DeRose et al. (1998) and Reid and Page (2003) noted that for the period of investigation, large amounts of fine sediments are delivered to stream channels by gullies and shallow landslides. However, they recognized the importance of frequency and magnitude of triggering rainstorm events with respect to the geomorphic processes that generate sediment. Small frequent rainstorms activate gully erosion, but high-magnitude, infrequent rainstorms trigger shallow landslides in particular (Page et al., 1999; Trustrum et al., 1999). Besides the immediate input, the landslide scars and tails generate sediment for a 1–2-year period following heavy storms. Thereafter, both scars and tails are stabilized and revegetated (Hicks et al., 2000). In contrast, during high-magnitude rainstorms in subcatchments other than Matakonekone and Oil Springs valleys, existing gullies are enlarged and additional landslides generate further sediment, thus, increasing sediment availability. Hicks et al. (2000) measured enhanced suspended sediment load from these subcatchments for a period of approximately 3 years after such storms. Thus,



Fig. 4. Coastal wetland in the Marlborough Sounds, Northwest South Island.

heavy rainstorms in all the subcatchments have a longer term geomorphic impact than that during the event itself, and sediment generated by landslides during a single storm remains available for continuing erosion in high-frequency, low-magnitude events. This material contributes significantly to suspended sediment loads following large events.

Sediment from landslides contributes on average 10–19% of the suspended sediment loads of the Waipaoa River at Kanakanaia. However, this proportion can increase to 50% during large magnitude rainstorms (Reid and Page, 2003). Therefore, in the Waipaoa catchment, landslides and gully erosion provide most of the suspended sediment, which may be restored on alluvial plains (Marutani et al., 1999).

In addition to the long-term effect of secondary storage, DeRose et al. (1998, p. 1053) conclude that ‘... the amount of sediment contributed to the river system from extensive mass movements (e.g. earthflows and slumps) and from surface erosion processes in other parts of the catchment, though unquantified, is thought to be considerable’. In summary, Waipaoa studies show that both gully and landslide erosion have accelerated after human deforestation of catchments. However, the contribution of each erosion process to sediment mobilisation and deposition could have changed over time.

#### 4.3.5. Lake sedimentation

From sediment cores derived from Lake Waikaremoana (Location 5 in Fig. 1), located in northern Hawke Bay, North Island, Newnham et al. (1998b) delineated a 1850-year tephropalynological record indicating that anthropogenic forest clearance occurred 375  $^{14}\text{C}$  years BP (ca. AD 1523–1631). This date is later than Polynesian inputs elsewhere, but the region is remote, and has never been extensively cleared in historic time, so the

clearance was probably localized. Newnham et al. (1998b) suggested that around 1150  $^{14}\text{C}$  years BP (ca. AD 1025–977), there was a short-lived change in sediment supply, from shoreline erosion to stream input. They suggested that storms, snowfall damage, landslides and even recent tephra fall have also been responsible for short-term episodic interruption of the forest cover throughout the history of the lake. Although the effect of landslides was not quantified, they suggested that landslides were an important sediment-delivering process.

#### 4.3.6. Coastal wetlands

Goff and Chagué-Goff (1999) took three cores from adjacent coastal wetlands in Abel Tasman National Park (Location 6 in Fig. 1; a similar environment is shown in Fig. 4). They determined pre-European sedimentation rates of 0.5–1.7  $\text{mm year}^{-1}$  and post-European rates of 1.6–2.7  $\text{mm year}^{-1}$ , rising to 2.3–3.3  $\text{mm year}^{-1}$  in the last 30 years. They did not investigate the origin of the sediment nor did they assess a sediment budget. However, assuming a similar catchment response to removal of an originally dense native forest (O’Loughlin, 1974; Montgomery et al., 2000), it is suggested that landslides contributed significantly to these increased sedimentation rates. This interpretation is supported by Goff (personal communication, 2001).

## 5. Discussion and conclusions

All studies discussed in this review demonstrate increased sedimentation after the arrival of European settlers and farmers in New Zealand. However, climate variability can also influence sedimentation rates. As Eden and Page (1998) pointed out, some Holocene erosion periods for the Lake Tutira region (Page and Trustrum, 1997) are not represented in the nationwide sequence of distinct and synchronous periods of increased sedimentation recognized by Grant (1985, 1989, 1994) and McFadgen (1985, 1989, 1994). Eden and Page (1998) argue that this is because the fine resolution of the local Lake Tutira chronology shows shorter erosion periods over the last approximately 2250 years than the more coarsely resolved chronologies based on geographically widespread data extending back to the Taupo Tephra (1718 cal. years BP). Nevertheless, all chronologies attribute increased erosion in headwaters to climatic episodes such as increased frequency of tropical and extratropical cyclonic storms. Under native forest, bracken, fern and scrub, landslides were not so common because of protection by the dense native vegetation cover. This is supported by the early investigations of O’Loughlin (1984), which demonstrated enhanced slope stability through the mechanical reinforcement provided by tree root systems. Similar findings were documented by Phillips and Watson (1994), and are supported by observations of different landslide density in areas of different vegetation cover areas following two distinct rainstorm events (Phillips et al., 1990).

Polynesian and Maori culture changed the vegetation, but only near coasts, rivers and inland lakes and swamps. Although Page and Trustrum (1997) demonstrated the influence of Maori activity on hillslope stability, these effects were limited to areas surrounding their settlements. Maori activity did not significantly affect general slope stability. With the

arrival of European settlers and farmers about 1850, not only the flat plains but also the steep slopes were cleared of native forest for farming purposes. In 1991, only 6.2 M ha of forest (including exotic and plantation forests) remained (Poole and Adams, 1994) from the 16.2 M ha of native forest cover of the pre-European period (Newsome, 1987). The environmental change brought about by this deforestation is recognizable in increased sedimentation rates in swamp, lake, coastal and marine environments (Table 3). To compare the different environments, the change from the pre-European to the European period is expressed by the factor of increase, defined as the ratio between post-European and pre-European sedimentation rates. Although the factor ranges between 1.6 and 18.2, it demonstrates an increased sediment accumulation through deforestation for all sinks and environments.

Sediment pulses during historic and Holocene times suggest that sediment generation in New Zealand is particularly related to landslide erosion (e.g. Page et al., 1994a; Eden and Page, 1998). Landslides contribute significantly to sediment accretion rates on lake beds (e.g. Page et al., 1994b) and in fluvial environments (Marutani et al., 1999). However, most recent studies suggest the need to differentiate between low-magnitude/high-frequency and high-magnitude/low-frequency events. In the Waipaoa catchment, for example, high-magnitude/low-frequency events seem to be less important for total sediment yield than the cumulative influence of low-magnitude/high-frequency events. Although landslides contribute to the high-magnitude events, lower magnitude storms generate more sediment through erosional processes such as gully and stream bank erosion (Page et al., 1999; Trustrum et al., 1999; Reid and Page, 2003).

Contemporary landscapes reflect, to differing degrees, the impacts of prior erosional processes. Landsliding was probably not the dominant initial erosional process in the Waipaoa catchment. However, over time, the contribution of each erosional process changed. For example, large slow-moving mudslides and earthflows are known to have occurred in the past, with histories of movement and accumulation that probably span

Table 3  
Evidence of increased sediment accretion rates following human settlement

	European (pasture) rate (mm year <sup>-1</sup> )	Polynesian (scrub-fern) or pre-Polynesian (forest) rate (mm year <sup>-1</sup> )	Factor of increase
Whangape Harbour (estuary) <sup>a</sup>	1.7–4.6	0.1–0.5	9.2–17
Repongaere (swamp) <sup>b</sup>	3.6	0.3	12
Poverty Bay (continental shelf) <sup>b</sup>	3.7	0.3	12.3
Lake Tutira (freshwater lake) <sup>c</sup>	14.0	2.1	6.7
Wellington Harbour (near coast) <sup>d</sup>	38.2	2.1	18.2
Abel Tasman (coastal wetland) <sup>e</sup>	1.6–2.7	0.5–1.7	1.6–3.2

Factor of increase = post-European sedimentation rate/pre-European sedimentation rate.

<sup>a</sup> Nichol et al. (2000).

<sup>b</sup> Wilmshurst et al. (1999).

<sup>c</sup> Page et al. (1994a,b); Trustrum and Page (1992).

<sup>d</sup> Goff (1997).

<sup>e</sup> Chagué-Goff et al. (2000).

thousands of years. On the other hand, initially small landslides evolved into large gully complexes, which now dominate the sediment supply to the rivers. Sediment exhaustion is an additional key control on landslide activity.

The temporal and spatial response of erosional processes, particularly landsliding, to climatic impacts may vary greatly within and especially between catchments. With each triggering rainfall, landslide locations change within a given catchment. Also landslide responses to the same rainfall event vary significantly in different catchments. As the Lake Tutira catchment shows, smaller frequent rainstorms result in a greater volume of deposits than the few large magnitude events (e.g. Page et al., 1994b). Depositional response may be buffered by:

1. temporary storage on foot slopes or alluvial plains;
2. timing of processes (e.g. landslides following peak discharges may be followed by processes with lower transport capacities, which slowly remove the landslide material);
3. the general temporal and spatial variability of triggering storms and of the distribution of erosional processes; and
4. variation of land use and vegetation type.

Given the greater sensitivity of landscapes to disturbance following vegetation clearance, tropical cyclones of a relatively small magnitude probably affect larger areas than before land use change.

From the case studies reviewed here, the response to forest clearance seems to have been manifested primarily through increased rates of landslide activity, which have contributed to sediment accumulations downstream (e.g. Page et al., 1994a; Hicks et al., 2000). Although there is some temptation to accept this hypothesis, further investigations are necessary to confirm it. The case studies that have demonstrated the influence of landslides on depositional regimes following deforestation in the Hawke Bay and East Cape region need to be supported by parallel studies in other depositional environments such as coastal and inland swamps, estuaries, nearshore and offshore areas. Further studies might include:

1. detailed analysis of aerial photo sequences to detect land use changes and erosion response with particular focus on landslide occurrences;
2. coring colluvial foot slopes and alluvial plains in order to determine storage capacity and transport rates between slopes and sinks;
3. assessments of sediment budgets following both low-magnitude/high-frequency and high-magnitude/low-frequency landslide-triggering rainstorm events (Trustrum et al., 1999), and extrapolation of these local results to longer time periods (>50 years);
4. linkage of sediment sources, pathways and sinks to determine the most important factors for sediment generation and distribution throughout a catchment (Trustrum et al., 1999) and between catchments of various sizes (Wilmshurst, 1997);
5. temporal analysis of how erosion processes evolve in response to land use change; and
6. determination of the current sensitivity of various landscapes to landsliding (Thomas, 2001), particularly with respect to the relationship between single landslide events and specific event sequences (Brunsden, 2001).

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