Should detailed terrain stability or erosion susceptibility mapping be mandatory in erodible steep lands?

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Abstract

In 2012 an opinion piece in this journal on plantation forest harvesting and landscape response advocated a need to better manage the risk of high intensity, low frequency storms during the most vulnerable post-harvest period. With the expectation that there will be more storm damaging events associated with exotic forests we question:

- Whether sufficient resources are being directed towards identifying on-site and off-site values at risk, with a view to better management of adverse environmental effects of forest practices
- Whether more detailed mapping of terrain stability or erosion susceptibility, together with a risk analysis approach, would enable better preventative management at operational level rather than relying on corrective action as at present
- And, if so, could the Erosion Susceptibility Classification (ESC) developed for the National Environmental Standard (NES) for plantation forestry be used to decide if a reconnaissance-level or detailed-level of terrain stability mapping is required.

In posing these questions we provide a brief review of the international experience in assessing storm damage, re-introduce the concept of terrain stability mapping, promote the potential role of new technology in identifying site-specific areas susceptible to storm damage, and conclude with some recommendations.

Background

The usual response to a major storm event in New Zealand that affects a plantation forest is to undertake a storm damage assessment. These assessments are usually made by company personnel and consist of a file note containing photographs and a brief description of damage. In the past, a few more in-depth assessments attempted to relate the type and location of damage to site factors (including geology, slope and aspect), stand age and density, and to infrastructure using observational and photographic data only (e.g. Basher, 2010; Jelenik, 2010; Phillips & Marden, 2011; Page et al., 2012).

At present, however, the lack of quantitative data collected in a methodical and consistent way (e.g. Marden & Rowan, 1995; Hancox & Wright, 2005; Page, 2013) precludes establishing robust relationships between rainfall characteristics and on-site factors that may help alleviate, or conversely, has in the past exacerbated the severity of damage sustained to a forest during low frequency rainfall events. Our ability to provide both national and/or regional guidance on suitable mitigation methods for storm events with different recurrence intervals (10, 20, 50 years), and to decide what is an (un)acceptable level of risk, is thus limited.

The effects of climate change on New Zealand are likely to be more frequent floods, storms, landslides and droughts (MfE, 2008; 5th IPCC assessment for New Zealand). Thus we can expect more storm damage events in plantation forests. Further, in recent years we appear to have returned to a period of higher storminess not dissimilar to periods in the 1970s and 1980s that caused significant regional landsliding and flooding (Harmsworth & Page, 1991). These cyclic swings in storminess are not uncommon (e.g. Grant, 1977; Page et al., 2010) and may be why there has been more focus on post-harvesting issues around the country in recent years.

Each forest has a characteristic set of physical features such as geology, slope, altitude, soils and a different mix of species at varying stages of maturity; there are also different probabilities of storm frequency and associated rainfall intensity. For a plantation forest, the extent of harvesting and the time since harvesting at the time of a storm event will also be critical in determining the geomorphic or landscape response. It might seem reasonable then that a key aim for forest management is to design and implement approaches that will try to minimise the impact of storms, should they occur (Phillips et al., 2012).

Landslides are a common natural process on the steep forested landscapes in New Zealand (e.g. McSaveney et al., 2005; Bloomberg & Davies, 2012). They can also be expected to occur in steep land plantation forests at any time in the forest rotation, but especially in the few years post-harvest. A key issue for the forest industry is to understand this and to develop management practices that aim to minimise their on-site and off-site effects.

Lessons gained from retrospective assessments of storm-related impacts can undoubtedly assist in the identification of other areas where similar potential for slope failure associated with forest activities – not just harvesting – exists. In addition, lessons learned have value in either underpinning or re-evaluating existing best management practices and environmental standards, and in planning replanting or exclusion strategies. Ultimately their value is in reducing environmental, social and economic costs incurred following slope failures initiated within exotic forests.

As Ziemer (1981) states ‘prudent management should identify the values at risk and direct erosion control activities towards processes most likely to affect those values. Steep land erosion is controlled most effectively – both in physical and economic terms – by preventive land-use practices rather than corrective action. Management of steep land erosion is merely the appropriate application of varying levels of care and caution when dealing with terrain of varying erosional sensitivity.'

The international experience

Issues associated with managing forests – natural and planted – and their harvesting on steep erosion-prone lands are not unique to New Zealand. An extensive body of literature and experience exists on forest practices associated with erosion management, much of which originated in North America (e.g. Fannin et al., 2005), although historically similar experience also comes from Europe and Japan (Rickli & Graf, 2009; Imaizumi & Sidle, 2012). For example, the move of forest harvesting onto steep terrain in coastal forests of British Columbia in the 1960s and 1970s occurred without an appreciation of the potential response and downslope risks associated with forest harvesting, or a systematic method for identifying unstable terrain, with devastating results (Schwab, 1988; Hogan et al., 1998).

The increase in incidence of shallow landslides associated with forest-related activities, and the need for a formal process to identify areas of greater and lesser risk, led to the development of terrain stability mapping and slope stability hazard analysis in Canada. Terrain stability mapping is a method to delineate areas of slope stability with respect to stable, potentially unstable, and unstable terrain within a particular landscape. The mapped terrain stability polygons indicate areas or zones of initiation of slope failure. The provision of terrain stability maps at the planning stage of forest activities has, through the awareness and avoidance of unstable terrain, been credited with improved forest practices on steep, potentially unstable terrain in British Columbia (Fannin et al., 2005).

The basic rule in the application of terrain stability mapping principles is that any forest management activity – not just harvesting – that increases the potential for groundwater or surface water to enter landslide-prone terrain or unstable slopes, and on material properties created by cut-and-fill (e.g. compaction, etc), increases the risk of slope failure or reactivation. The key therefore is to identify which parts of the landscape are landslide-prone or could potentially become unstable following site disturbance. A basic requirement of this approach was that the information needed to be presented in a form that could be easily interpreted for forest and environmental management planning.

Mapping can be at two levels – reconnaissance and detailed. Reconnaissance-level mapping is appropriate where there are only local occurrences of unstable and potentially unstable terrain within extensive areas of stable terrain. Conversely, detailed-level mapping is recommended for areas that have a large proportion of steep erosion-susceptible terrain, and where significant resources might be affected by slope failure. As many classes as are required to differentiate potential problem areas can be used, but they give no indication of the expected magnitude of failures or of potential downstream damage. In regions where landslides are the dominant form of slope instability, both approaches involve identifying individual landslides and stratifying them by 'activity levels' based on criteria including:

- Mapped drainage boundaries upslope of landslides
- Slope angle, aspect and changes in slope angle
- Position on slope
- Effects of other geomorphic processes, e.g. bank undercutting
- Nature of the regolith
- Bedrock geology.

Risk evaluations are then assigned to landslide 'activity levels', with landslides or concentrations of landslides with the highest risk (i.e. deemed to be active) being assigned to terrain with the most severe hazard level. Conversely, landslide areas at minimum risk of failing are assigned to the terrain with the least hazard level. Risk also takes into account the potential for activated landslides to affect off-forest assets or sensitive environments.

The evolution of legislative approaches to managing forestry activities in British Columbia has moved from voluntary guidelines and prescriptive regulations to professional judgement and due diligence in a mandatory results-based approach (Fannin et al., 2007). This shift towards a results-based approach arose because the prescriptive approach was found to be relatively complex and costly. However, although the requirements for terrain stability mapping and terrain stability assessments to underpin this approach were carried through, it was left to the forest companies and relied more on professional judgement and due diligence. That judgement was 'founded on a remarkably extensive body of specialist knowledge developed in British Columbia, and an understanding of landslide management in the forest sector that is based in world-class field research and monitoring' (Faninn et al., 2007).

The more recent development of high resolution aerial photography, Digital Elevation Models (DEMs), Light Detection and Ranging (LiDAR), multi-spectral satellite imagery, and Geographic Information Systems (GIS)-based analyses of landslide inventories has improved the data collection and mapping processes. In addition, these new techniques have led to considerable interest in the development of slope stability models that incorporate GIS technology, thereby quantifying topographic, hydrologic and soil attributes that control slope stability (Montgomery & Dietrich, 1994; Pack, 1995; Wu & Sidle, 1995). These approaches essentially fall into two groups. First, those that utilise a more traditional factor-of-safety stability analysis and, second, those that are more empirical or statistically based.

A common feature of the first group is the coupling of a hydrological model that describes the groundwater flow regime with the infinite-slope stability model that describes the factor of safety, e.g. SINMAP (Pack et al., 1998). Uncertainty can be incorporated through the use of probability density functions for the input parameters. However, such methods require calibration and are most confidently implemented in conjunction with other terrain stability mapping techniques. Ideally, the methods are suited to calibration against a set of data that captures known landslide activity, with the intent of then applying them to other areas of terrain where data on landslide activity are sparse or unavailable (Fannin et al., 2005).

In the second group that includes semi-quantitative slope instability screening tools (e.g. HAZONE) (Washington State Department of Natural Resources, 2010), a range of land 'information' is used together with landslide frequency data and landslide area to assess sediment delivery to streams. Other screening tools are GIS-based models of inherent landform characteristics that use slope geometry derived from DEMs and climate data. The authors of these types of models claim that the 'utilization of slope stability screening tools by geologists, land managers, and regulatory agencies can reduce the frequency and magnitude of landslides' (e.g. Whittaker & McShane, 2012).

However, while these approaches have had reasonable success in identifying areas of high landslide hazard, they were less successful in identifying incidences of landsliding in areas identified as low hazard. Importantly, the reasoning given was that landslides initiated in low-hazard areas may have resulted from:

- A variety of site-specific factors that deviated from assumed modelled values
- The inadequate identification of potentially unstable landforms due to low-resolution DEMs, or
- The inadequate implementation of forest practice rules.

Post-storm damage assessments provide much needed field-based data for model development and verification, but these empirical approaches on their own may be limited in application to new areas that differ from that used in model development. Further, while empirical techniques work best in simple terrain with shallow soils, they do not work well for deep-seated landslides or where the topography is significantly more complicated than captured on a DEM (Schwab & Geertsema, 2010).

Furthermore, as the reliability and efficiency of landslide mapping and analysis has improved with the introduction of new techniques their use has not, and nor in our view will not, diminish the requirement for detailed on-site verification of identified hazards by field inspections.

The New Zealand scene

The current challenge in New Zealand is managing exotic forests that were largely planted to control erosion. Many of these are on geologically complex terrain where forests were historically established to control mass movement (shallow landslides, earthflows and slumps), and gully erosion, and are often in areas where large storms are a regular occurrence. Retrospective assessments of storm damage in many of the more highly erodible areas of exotic forest suggest that historical factors (physical or policy) may also have contributed, at least in part, to an increase in erosion susceptibility. These include:

- A legacy of land clearance and stock incentive policies for marginal land introduced between 1979–82 (Chudleigh et al., 1983)
- Inherited sub-standard forest infrastructure (Phillips & Marden, 2011)
- Declining health of steep land indigenous forests, remnants of which remain within exotic forest estates, resulting from pre-European fires (Esler, 1963), burning and grazing (Cunningham & Stribling, 1978), increased storminess (Grant, 1977) and the influence of introduced animals (James, 1973)
- Inadequate consideration of forested landscape's inherent susceptibility to disturbance.

Landscape and terrain stability mapping

In terms of more general landscape assessments, the forest industry and regional councils have to date largely relied on the New Zealand Land Resource Inventory (NZLRI, NWSCO, 1975) to provide the necessary information to underpin consent conditions for the forestry sector. Developed between the 1970s and 1990s, this is the only nationally consistent mapping approach. It is helpful in identifying broad areas of landscape with similar physical attributes of slope, erosion potential and mix of failure types, but the scale of these maps is a major limiting factor when it comes to identifying site-specific hazards (see Figure 1a). This poses a question over its continued use at an operational scale when it is now possible with new techniques to produce more accurate site-specific information at a more appropriate scale (e.g. between 1:5,000 and 1:10,000).

Terrain zoning is not a new concept in this country's plantation forests. Historically, many of New Zealand's steep land forests were established as 'protection forests' (Poole, 1960) after pastoral farming had failed. Subsequent to their establishment a number of these forests were re-classified as 'protection-production' forests, raising concerns, largely anecdotal, over the probability that harvesting would reactivate erosion. As a consequence, in an attempt to give foresters an appreciation of the areal extent and distribution of different terrain types and their likely response to disturbance following harvesting, an adaptation of the British Columbia approach to terrain stability mapping was developed for the most highly erodible region of New Zealand, where deep-seated mass movements and gully erosion dominate the landscape.

Gage and Black (1979) devised a classification for Mangatu Forest consisting of a decreasing stability sequence from Types 1 to 6 for hill slopes, and an additional two Types 7 and 8 to embody aggrading alluvial fans and river bed, and 'older' terraces elevated above current river level (see Figure 1b). This classification is based on the underlying geology, the long-term (geological time-scale) processes that produced the landscape topography, and the extent, type and status of current erosion processes to all of which a relative stability rating was assigned. This style of mapping was modified in later years for use in areas of steeper terrain more prone to shallow landslides and gully erosion (Phillips & Pearce, 1984). However, with the sale of the state-owned exotic forests to international interests, and during a period of multiple ownership changes, these maps covering an approximate area of 30,000 hectares of the East Coast region remained largely forgotten and were not used for harvest planning (early 1990s).

Some of the more common and avoidable mistakes that have arisen largely through lack of due diligence with respect to understanding the landscape and its response to disturbances, include:

- Road-related landslides associated with fill or inadequate drainage
- Road alignments and landing construction on or across terrain typically formed by previous episodes of slope failure, and
- The destabilisation of slope material uphill of bedrock-incised road cuts, particularly at locations where the dip slope of the bedrock is towards the cut face.

Where criticisms have been levelled at forest-related impacts it has been justified in some instances, but not all, and can often be attributed to less than adequate consideration of the geomorphology, the processes that formed the landscape, or the consequences of disturbance to that landscape.

In other cases, it can be argued that no manner of management would have been enough to avoid landslide failures or the occurrence of a debris flow, and that these situations were ‘natural’ and part of the continuing cycle of landscape adjustment (Bloomberg & Davies, 2012). However, forest owners need to learn from past events – or mistakes – and do more to identify hazards, particularly if the risk of initiating failures as a consequence of forest-related activities and their potential impact is high.

It is possible, using a combination of old (stereoscopic analysis of aerial photography that pre-dates planting) and new (LiDAR, GIS, slope stability tools) technology, that the type and location of geomorphic responses during and following major storm events can be anticipated with reasonable certainty. Access to such information would forewarn harvest planners with the knowledge required to design a harvest strategy that avoids, or is at least cognisant of, the most vulnerable areas at times of greatest risk from the impact of storms. This might involve a modelling (e.g. Harrison et al., 2012) or a geomorphological-based terrain zoning approach (e.g. Hancock Forest Management, 2010).

So why is there a general reluctance across the industry to adopt estate-wide detailed mapping to identify site-specific hazards? Reasons might include:

- It may not be a mandatory requirement of the consent application process
- Roading engineers and harvest planners have guidelines and systems in place that are considered adequate and compliant with best management practices (NZFOA, 2007, 2012)
- Inadequate training of foresters in basic geomorphic understanding and landscape mapping skills
- A lack of perceived value in employing or contracting skilled mappers/geoscientists in favour of paying for resultant damage, clean-up costs or consent breaches.

Furthermore, as foresters tasked with harvest planning and associated activities are often transient, i.e. moderately high staff turnover in some companies, many will lack the local knowledge and experience essential for identifying areas of differing stability and in assessing the associated on-site and off-site risks. Also, while forest inventories and associated databases (mostly spatial and in GIS) are regularly kept up to date, resource information on other forest attributes, much of which may be historical, can and often does remain under-utilised, especially where staff turnover is high. These resources may include:

- Maps and publications dismissed as ‘old’ and no longer relevant – their significance is not understood
- The existence of aerial photography flown before forest establishment or, if known, the inability of staff to use a stereoscope to identify areas of potential risk
- Relevant material in the form of internal reports but not consulted.

The way forward?

Using an example of a recently harvested area within Mangatu Forest, Figure 1 demonstrates the contrasting level of detail between different mapping approaches previously available in the form of the NZLRI (Jessen et al., 1999) (Figure 1a), Terrain Stability Zoning (Gage & Black, 1979) (Figure 1b), and that able to be captured by stereoscopic analysis of aerial photography – Landscape Resilience (Marden, unpublished) (Figure 1c) and/or by LiDAR.

Corresponding Tables 1a, 1b and 1c list attributes associated with mapped units identified by each mapping approach. These are criteria considered most useful for identifying associated hazards and potential risks related to forest management practices, with particular emphasis on the post-harvest period.

Each of the mapping approaches and accompanying tables clearly signal the potential for earthflow reactivation. However, only Figure 1c, derived solely from stereoscopic analysis of aerial photography, provides the level of on-the-ground detail required to avoid aligning roads or siting landings in the vicinity of a known site-specific hazard, where disturbance has the potential to trigger slope failure. For example, at the marked location (X) landing construction involved the importation of fill to extend the size of the landing, unknowingly onto the body of an existing but at that time ‘inactive’ earthflow. After harvesting, part of the landing failed, which reactivated the flow, referred to as top-loading, and resulted in the translocation of earth and slash 500 metres downslope to displace an access road to a second landing. Had 'detailed' mapping been undertaken before harvesting began, a number of post-harvest-related incidences involving forest infrastructure within this forest could have been avoided or at least significantly minimised.

Implications for forest management are obvious from the scale and size of mapping units (Figure 1). The finer resolution of the detailed mapping obtainable from aerial photography or LiDAR provides a much clearer picture of individual erosion forms and their activity. Thus a harvest planner or roading engineer is better equipped to identify potential hazards, and is therefore better able to evaluate their potential risk to forest management. Produced in a systematic way, such maps would provide a valuable resource on a forest company's GIS, in much the same way as compartment maps and stand records do now. The systematic recording of sites of storm-related damage and of site-specific incidents related to forest activities, and their proximity to mapped hazards, would also promote a greater understanding of cause and effect relationships between disturbances in that forest and the likely landscape response. It would also provide the necessary ongoing information needed to validate quantitative models and to reinforce any cost-benefit analysis that might be done.

The forest industry as a whole has therefore been relatively slow to develop terrain stability or erosion susceptibility mapping. It is clear from our conversations with the forest sector that many decisions are, and will continue to be, made without the use of the best available information or of an understanding of likely slope responses subsequent to site disturbance. Terrain stability mapping in conjunction with new screening tools (e.g. Pack et al., 1998) and slope stability models (e.g. Harrison et al., 2012) is fundamental to the development of more proactive approaches to hazard identification and risk assessment. While LiDAR is currently used by some forest companies for improved road and infrastructure planning it could also be used to identify site-specific hazards at a more detailed level than previously possible.

However, while LiDAR is an extremely valuable tool to aid infrastructure planning, perhaps its true value lies in the analysis and expert knowledge required to interpret the landscape from it, and to provide an increased level of understanding of the implications of any forest-related activities that may result in disturbance. Used in conjunction with aerial photography, maps could be produced with sufficient detail to be of more practical value at an operational level, and their use would likely contribute to reductions in the incidence of damage resulting from slope failures both within and beyond the forest boundary.

Such an approach requires site-specific description and delineation of attributes associated with surficial materials, landforms and geological processes within different landscapes to identify and differentiate areas of relative instability, the nature of the instability, and any potential on-site and off-site risks associated with each area. Interestingly, Pearce (1977) commented that a landscape zoning scheme needed to be developed urgently for all New Zealand plantation forests if it was to provide landslide hazard information at the planning stage of forest activities and at a scale suitable for use at the operational level. Thirty-five years later recent erosion events suggest the need remains (Amishev et al., 2013).

That said, some forestry companies and regional councils have taken up the challenge to develop management plans that include recommendations for managing at-risk sites (e.g. Hancock Forest Management, 2010). These include areas identified as being at greatest risk to high intensity, low frequency storms (Horner, 2012), and/or for particular issues such as the management of woody residue (Hancock Forest Management, undated).

In the eastern Bay of Plenty, storm-initiated erosion in the last five years provided the impetus for Hancock Forest Management to review its management practices, starting with improving their understanding of the land resources. This involved mapping the distribution of the soil, regolith, and geology at 1:5,000 scale, which identified significant variations to those shown in the NZLRI and regional geological mapping, and led to a better understanding of the differences in susceptibility of different soil/geological units to storm-initiated landslides and the potential for them to transport on-slope soil and woody debris downslope. With an improved understanding of the likely landscape response to future storm events, detailed risk maps of erosion-susceptibility and slash-mobilisation provide engineering and harvesting staff with a better framework for managing and improving the sustainability of their forests.

However, sector-wide, further work is required to develop improved quantitative hazard identification and risk management methods that can be widely applied across New Zealand. This is required at both a 'reconnaissance' scale (e.g. 1:50,000 or greater) for use at a national level to underpin for example further development of the NES for plantation forestry (Bloomberg et al., 2011), to more detailed mapping for use at an operational scale (e.g. 1:5,000 to 1:10,000) as a prerequisite for roading, harvesting and replanting operations.

The ESC developed for the NES for plantation forestry (Bloomberg et al., 2011) is a start, but it has a number of limitations including:

- The poor definition of potential erosion used as the metric for defining erosion susceptibility
- Misclassification of the potential erosion severity of some Land Use Capability Units
- A scale (1:50,000) unsuited for operational use and ESC errors that result from the scale limitations.

A possible way forward is to use the ESC to broadly identify areas of potential high erosion susceptibility, that then triggers the need for operational scale mapping in these areas to provide appropriate spatial detail and a closer look at erosion susceptibility class.

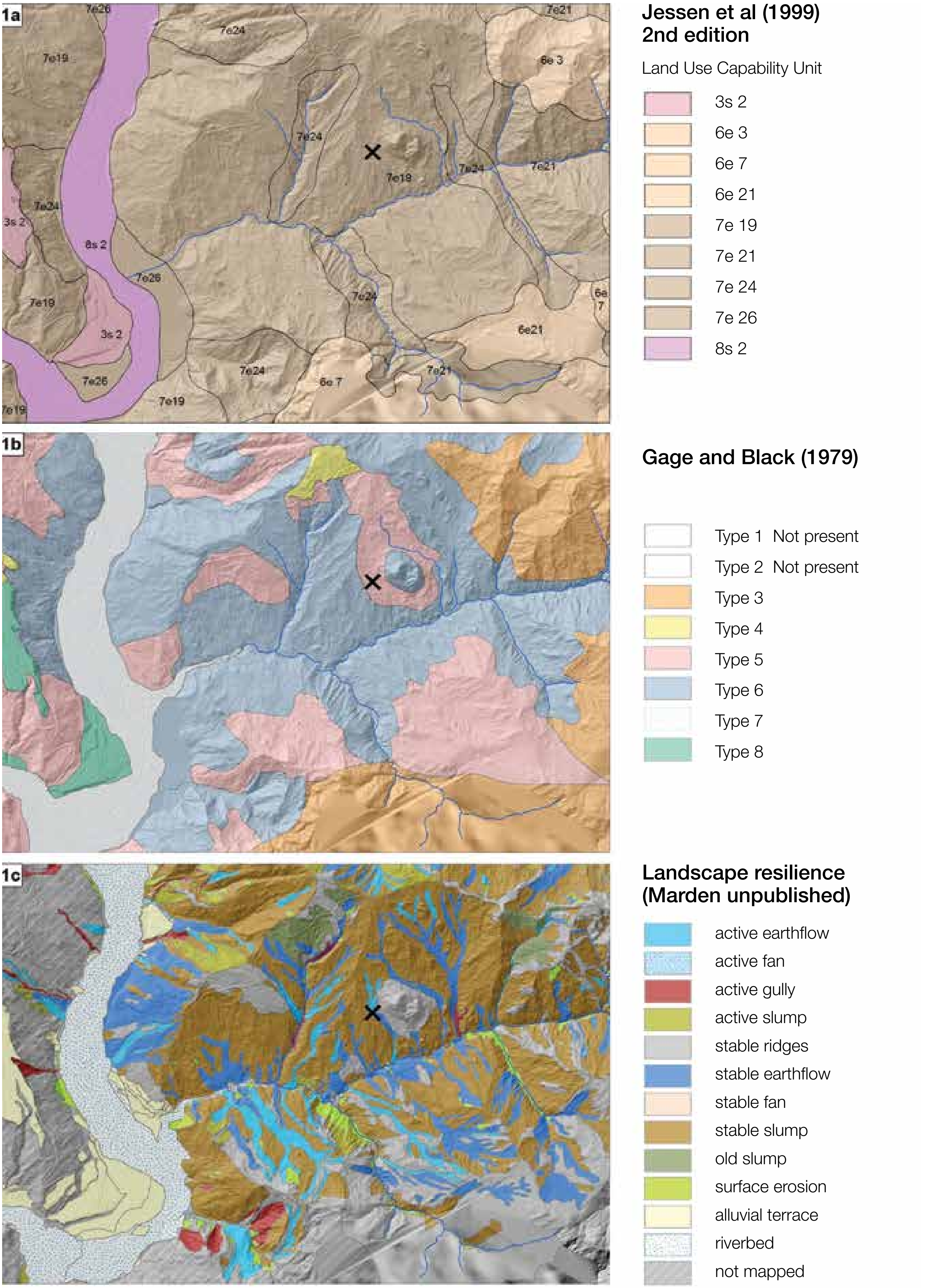

Figure 1: Different mapping approaches for an area of Mangatu Forest. Figure 1a: Land use capability (Jessen et al., 1999); Figure 1b: Terrain stability zoning (Gage & Black, 1979); and Figure 1c: Landscape resilience (Marden, unpublished). Definition of units is given in Table 1

Table 1a: Land use capability unit descriptors

Land use capability units	Description	Slope	Rock type	Present erosion	Potential erosion	Implications for forest management
3s 2	Undulating terrace	4–8	Alluvium	Negligible	Slight sheet	
6e 3	Moderately steep to steep slopes in stable hill country	16–25	Tephra overlying stable Tertiary-age sedimentary rocks	Negligible to moderate soil slip, slight gully	Moderate soil slip, slight gully	
6e 7	Strongly rolling to moderately steep slopes in stable hill country	16–25	Tephra overlying stable Tertiary-age sedimentary rocks	Negligible to moderate soil slip, slight gully	Moderate soil slip, slight gully	Establish groundcover on eroded areas
6e 21	Strongly rolling to moderately steep slopes in hill country mainly on crushed argillite and sheared mixed lithologies	16–25	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene rocks	Slight to moderate gully, earthflow, slight soil slip	Moderate gully, earthflow, soil slip	Potential for large-scale gully erosion even if risk is presently slight
7e 19	Strongly rolling to moderately steep slopes in hill country on crushed argillite and shared mixed lithologies (melange)	16–35	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene rocks	Slight to very severe earthflow, slight to severe gully, negligible slump and soil slip	Very severe earthflow, severe gully, moderate slump, slight soil slip	Potential to reactivate severe earthflow, severe gully, moderate slump slight soil slip
7e 21	Strongly rolling to moderately steep slopes in unstable, loose-jointed Tertiary mudstone hill country	16–35	Frittered mudstone, sheared mixed lithologies	Slight to very severe gully and soil slip, slight to severe earthflow	Very severe gully and soil slip, severe earthflow and slump, moderate sheet	Management is best directed at stopping new gullies forming
7e 24	Steep to moderately steep and very steep slopes in hill country on crushed argillite and associated lithogies	26–35	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene rocks	Moderate to very severe gully, slight to severe earthflow, negligible soil slip	Very severe gully, severe earthflow, slump and moderate slip	Maintain ground cover, site-specific control measures required for earthworks
7e 26	Flat to undulating low river terraces subject to flooding	0–7	Alluvial gravels	Slight to very severe deposition and stream bank erosion, negligible gully	Very severe deposition and stream bank erosion, slight gully	Stream bank protection
8s 2	Active river beds	0–3	Alluvial gravels	Very severe to extreme deposition	Extreme deposition and severe streambank	

Table 1b: Terrain stability descriptors

Terrain stability types	Description	Rock type	Present erosion	Potential erosion	Implications for forest management
Type 1	Stable surfaces on Tertiary strata	Tephra overlying stable Tertiary-age sedimentary strata	Negligible to moderate soil slip, slight gully	Negligible to moderate soil slip, slight gully	Re-initiation of deep-seated failures and gullying unlikely but minor surficial slips likely following harvesting
Type 2	Stable surfaces on Cretaceous-Palaeocene strata	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	Slight earthflow and slump, negligible soil slip	Slight earthflow and slump, negligible soil slip	Initiation of deep-seated failures likely around margins with less stable Type 5 and 6
Type 3	Very deep slumps in Tertiary strata	Tephra overlying Tertiary-age sedimentary strata	Negligible to slight soil slip, slight gully	Slight to moderate soil slip, gully	Less stable than Type 1, therefore more sensitive to forest-related disturbances but unlikely to affect the rate of deep-seated movements
Type 4	Older moderately deep flows and slumps on Cretaceous-Palaeocene strata	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	Negligible to slight earthflow, slump and soil slip	Slight to moderate earthflow, slump and soil slip	Mantled by Waiohau Tephra but recent slumping, earthflow and gully erosion initiated within adjacent less stable terrain is eroding into Type 4 terrain. Unless Type 4 terrain is protected, it has the potential to develop into Type 6 terrain
Type 5	Younger moderately deep flows and slumps on Cretaceous-Palaeocene strata	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	Very severe earthflow, gully, slump, negligible soil slip	Very severe earthflow and slump, extreme gully and slump, negligible soil slip	At risk of reactivating slope movement through stresses associated with forest practices
Type 6	Active flows, slumps and gullies	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	Moderate to very severe gully, slight to severe earthflow, negligible soil slip	Very severe to extreme gully, severe earthflow, slump and moderate soil slip	The least stable of slopes with currently active gullies and slow moving slumps and earthflows. High risk of escalating the rate of erosion processes
Type 7	River flood-plain accumulations, and debris fans	Alluvial gravels	Very severe to extreme deposition	Extreme deposition and severe stream bank	The most unstable of the terrain types due to the high risk of continual inundation
Type 8	Stream terraces, dissected fans	Alluvial gravels	Elevated terraces – negligible erosion. Lowermost terraces and fans – slight to very severe deposition and stream bank erosion	Elevated terraces – negligible sheet erosion. Lowermost terraces – very severe deposition and stream bank erosion	Older (Holocene age), near horizontal terraces not in danger of inundation. Margins prone to slight gullying if drainage is not controlled

Table 1c: Landscape resilience descriptors

Landscape resilience	Description	Rock type	Present erosion	Potential erosion	Implications for forest management
Active earthflow	Earthflows with signs of post-deforestation (indigenous) activity	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	Severe	Very severe	Very high risk of increased rates of localised displacement at any time. Risk increases during and after road and landing construction and for six to eight years after the completion of harvesting. Side-casting material from roads and landings onto earthflows increases the risk of reactivation and potential damage to forest infrastructure
Active fan	Alluvial fan aggradation since European settlement	Alluvial gravels	Severe	Very severe	High risk of flooding and debris flow accumulation following harvesting. Can be stabilised by plantings but only after the sediment source area has been stabilised
Active gully	Gullies initiated since European settlement	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	Very severe	Extreme	Unplanted and deforested gullies have a very high probability of expanding in size. Small gullies stabilise quickly following reforestation, larger gullies require decades to stabilise
Active slump	Active slumps initiated since European settlement	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	Severe	Very severe	Very high risk of increased rates of localised displacement at any point in time. Roads and landings increase the risk and rate of localised activity with potential damage to infrastructure
Stable ridges	Tephra covered ridges	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	None to negligible sheet erosion	Negligible sheet, slight soil slip	No significant stability problems exist. Protected by Waiohau and older Tephra but ongoing slumping, earthflow and gully erosion initiated on lower slopes is destabilising the margins of these ridges. Machine disturbance during harvesting likely to result in minor increase in soil slip with the concentration of water run-off resulting in rilling
Stable earthflow	Earthflow that has not reactivated within European settlement times	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	Negligible	Slight to moderate increase	Moderate risk of reactivating slope movement but poor water control can give rise to significant scouring. Side-casting material from roads and landings onto earthflows increases the risk of reactivation and potential damage to forest infrastructure
Stable fan	Alluvial fan stabilised following planting	Alluvial gravel	Negligible sheet, rill	Slight to moderate sheet and rill	Moderate to low potential for inundation or scouring following harvesting of watershed area upstream of fan
Stable slump	Slump that has failed within European settlement times but subsequently stabilised	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	Negligible	Negligible to slight	Moderate to low risk of reactivating slope movement but poor water control on roads and landings can give rise to significant scouring
Old slump	Slump that pre-dates European settlement times	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	None	None to negligible	No significant stability problems. Very low risk of reactivation
Surface erosion	Sheet erosion on bare rock outcrops	Crushed argillite associated with allochthonous terrain of Cretaceous-Palaeocene strata	Severe sheet, rill	Severe sheet, rill	Processes likely to remain severe as long as site remains un-vegetated. Small scale and not a significant source of sediment
Alluvial terrace	Alluvial terraces elevated above current river level	Alluvial gravels	Negligible sheet	Negligible sheet	Stable sites, often poorly drained and waterlogged in winter. Inappropriate water control can lead to slight gullying around fringes of terrace
River bed	Active aggrading river channel	Alluvial gravels	Extreme aggradation	Extreme aggradation	Extremely high likelihood of ongoing and unmanageable flooding and aggradation issues
Unmapped areas	N/A	N/A			

Conclusions

A major challenge in New Zealand is managing exotic forests established for erosion control on steep erodible terrain in environments where storm-initiated slope failures are a regular occurrence and where such events are the greatest contributor of sediment to streams. The way forward for the New Zealand forest industry is to consult with, and come to some agreement with, regulatory authorities on a standard of detailed erosion susceptibility mapping for forest estates. More specifically, the need is to identify areas of potential risk in landscapes where forest activities could likely result in an increase in the supply of sediment and woody debris with significant resultant damage to infrastructure beyond the forest boundary. As has been shown in recent years, with the incidence of isolated weather 'bombs' causing extensive damage to forested areas, there is also the potential for such events to result in loss of life, thus exposing forest companies to wider risks beyond environmental and infrastructure damage.

Some forestry companies and regional councils have in recent years dedicated resources to identifying areas at greatest risk to damage from high intensity, low frequency storms, and towards developing improved management approaches. However, and particularly in the area of terrain stability or erosion susceptibility mapping, further effort is required to provide maps that are sufficiently detailed to be of use in developing improved quantitative hazard identification and risk management strategies that can be widely applied across New Zealand. This will require greater use of available resources, technologies and expert knowledge.

The true value of detailed terrain stability/erosion susceptibility mapping lies in identifying and underpinning the need to modify existing management practices, and to reduce environmental, social and economic costs incurred as a consequence of damage to forests by not repeating past mistakes. To achieve this, however, will require improved mapping at varying levels of detail from national scale to underpin, for example, further development of an NES for plantation forestry (Bloomberg et al., 2011), to 'detailed' mapping needed at the operational scale for roading, harvesting and replanting operations. In doing so, some of the risks associated with infrequent large magnitude storms and forest-related activities may be avoided or significantly reduced.

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