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Validation of a region-wide model of landslide susceptibility in the Manawatu–Wanganui region of New Zealand

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Abstract

Since European settlement 160 years ago, much of the indigenous forest in New Zealand hill country has been cleared for pastoral agriculture, resulting in increased erosion and sedimentation. To prioritise soil conservation work in the Manawatu–Wanganui region, we developed a model of landslide susceptibility. It assigns high susceptibility to steep land not protected by woody vegetation and low susceptibility everywhere else, following the commonly used approach for identifying inappropriate land use. A major storm on 15–16 February 2004 that produced many landslides was used to validate the model. The model predicted hills at risk to landsliding with moderate accuracy: 58% of erosion scars in the February storm occurred on hillsides considered to be susceptible. The model concept of slope thresholds, above which the probability of landsliding is high and below which the probability is low, is not adequate because below 30° the probability of landsliding is approximately linearly related to slope. Thus, reforestation of steep slopes will need to be combined with improved vegetation management for soil conservation on moderate slopes to significantly reduce future landsliding.

Keywords: Landslide susceptibility; Land cover; Digital terrain model; Landslide model; New Zealand

1. Introduction

Over 60% of New Zealand is steep land. Until European settlement c. 160 years ago, this steep land was largely covered in indigenous forest, but since then the forest has been dramatically reduced by burning and logging for pastoral farming. Consequently, landslide erosion, associated with large rainstorms, has increased (DeRose et al., 1993; Page and Trustrum, 1997; Glade, 2003). Repeated landsliding (Page et al., 1994a,b; Glade, 1998) is gradually decreasing the pastoral productivity of hill country (Douglas et al., 1986; Trustrum and DeRose, 1988; Lambert et al., 1993; DeRose et al., 1993, 1995), jeopardising the sustainability of hill country farming (Blaschke et al., 1992) and increasing sedimentation and its detrimental environmental effects in streams and rivers.

Landslides in New Zealand hill country are typically shallow (about 1 m deep) involving the soil horizon only (the terminology of Varnes (1978) would classify them as shallow rapid earthflows). When the gravitational force per unit area down the hillside exceeds the shear strength of the soil mass in any plane, the soil slips and flows rapidly (~3 m s^{-1}) downhill, leaving a debris-tail about 0.2 m thick. The gravitational force per unit area down the slope on a soil mass is given by $\rho gh \sin\theta$, where ρ is the density of the soil mass, g is

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acceleration due to gravity, h is the thickness of the soil mass, and θ is the slope angle. Hence, as slopes get steeper, the sheer force required to maintain stability also increases by $\sin\theta$. The strength of soil may be described by Terzaghi's modification of Coulomb's law (Johnson and Rodine, 1984):

$$\tau = C + (\sigma_n - u)\tan\beta \quad (1)$$

where τ is shear stress (N m^{-2}), C is cohesive strength, σ_n is normal stress on the shear surface, u is pore water pressure, and β is the angle of internal friction. C and β are constants for a given soil type. During storms, rainfall infiltrates the soil mass, creating and then increasing pore water pressure as infiltration continues, until a maximum of $gh/\cos\theta$ is reached at saturation. As pore water pressure increases, soil strength reduces and there is a risk of soil strength being exceeded by the shear force required for stability (Ekanayake and Phillips, 1999a). Where there is woody vegetation on the slope, roots, which are usually stronger than soil, increase the effective strength of the soil mass (Ekanayake and Phillips, 1999b). Thus, slope angle, storm rainfall, soil strength, and vegetation cover are all important factors in shallow landsliding.

These four physical factors have been recognised in several field-based studies of storm-triggered landslides in New Zealand (Pain, 1969; DeRose, 1996; Fransen, 1996; Crozier, 1996; Dymond et al., 1999). The influence of vegetation on landsliding is of special interest because vegetation cover is usually controlled by human activities. Hicks (1991) examined a transect through the East Coast hill country after a major storm (Cyclone Bola) and found that pasture had eight times more landslides than forested land (indigenous or exotic). Marden and Rowan (1993) examined nine study sites and found that pasture had sixteen times more landslides than forested land and four times more than scrub. Pain and Stephens (1990) examined five study sites and found that 10% of pasture was covered in landslides, whereas less than 1% of forested land and scrub was covered in landslides. The variability of these results reflects either site-specific processes due to the limited area of study sites or the combined influence of factors other than vegetation. Soil properties, slope, and vegetation are also commonly used in some GIS approaches for modelling susceptibility to shallow landsliding (Larsen and Torres-Sanchez, 1998) and to deep-seated landsliding (Carrara et al., 1982, 1991; Carrara, 1983; Gokceoglu and Aksoy, 1996; Turrini and Visintainer, 1998; Chung and Fabbri, 1999; Fernandez et al., 1999; Guzzetti et al., 1999; Lee and Min, 2001). Gritzner et al. (2001) observed that models are generally limited by the quality of input data.

In this paper, we present a simple GIS-based model of susceptibility to shallow landsliding (Fig. 1). It identifies steep land that does not have appropriate protective vegetation. This type of model regards land as either susceptible or not, and has been commonly used in New Zealand to identify inappropriate land use (O'Leary et al., 1996; Stephens et al., 1999; Young and McNeill, 1999). Our model advances existing approaches by using better quality data for input and covering a greater land area. The slope information came from a 15 m DEM (Landcare Research, 2004) and the vegetation information from topographically corrected Landsat ETM+ satellite imagery. Output was provided for the whole of the Manawatu–Wanganui region, some 21,200 km^2, at sufficient detail (15 m pixels) to guide priority setting for soil conservation work, as well as identifying inappropriate land use. A major rainstorm in February 2004 provided an opportunity to test the model's accuracy. We had provided the output from the model to the local environmental agency (the Manawatu–Wanganui Regional Council) six months before the February rainstorm; therefore, by testing the model with the storm data only, i.e. not further developing it on the basis of the data, we could generate a truly independent test of the model. Also, to understand better how land cover affects landslide occurrence, we analysed the spatial distribution of

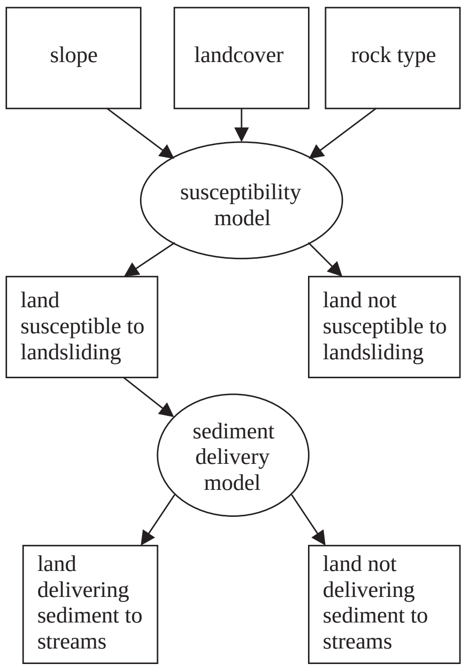

Fig. 1. Schema of the landslide susceptibility model.

the landslides to obtain a more complete picture than that presently available.

2. Study area

The hill country of the Manawatu–Wanganui region, in the North Island of New Zealand, comprises sedimentary rocks, varying in age from Jurassic/Triassic to present-day alluvial and marine deposits (Heerdegen and Shepherd, 1992). The Tararua and Ruahine ranges (Fig. 2a) that dominate the eastern margin have a fault-bounded origin and rise to over 1500 m. Fronting the range was a large basin of late Cenozoic sedimentation, which has deformed upon uplift and now appears as a deformed plain. Flowing across this deformed and elevated plain are rivers that have carved valleys and through orogenic uplift and downcutting have left dissected hills and terraces. Indigenous forest formerly covered the hills and lowlands, but has now been cleared (since European settlement c. 1840) for pastoral agriculture on the less steep slopes. This deforestation accelerated the existing erosion, leaving much evidence of slope failure and aggraded river beds.

The climate is temperate and maritime with prevailing westerly winds. Annual rainfall varies from 800 mm at the coast to more than 5000 mm at the top of the ranges. Landslide-triggering rainstorms occur about once every five years (Glade, 1998). A major rainstorm, with rainfall varying between 150 and 220 mm, deluged the Manawatu–Wanganui hill country on 15–16 February 2004, causing 62,000 landslides over an area of c. 10,000 km^2. The combined cost of damage from landsliding, flooding, and siltation was 170 million (NZ) dollars (Trafford, 2004). This rainstorm was used to test the accuracy of the model.

3. Data and methods

3.1. Landslide susceptibility model

Our model identifies land susceptible to landsliding from three GIS layers: a land cover map; a slope map from a DEM (Landcare Research, 2004); and a rock type map (Fig. 1). The GIS layers are raster with 15 m pixels. For every pixel in a regional coverage, the slope is examined to see if it exceeds a threshold set for each rock type (Table 1). These slope thresholds are inferred from Crozier et al. (1980), Salter et al. (1983), and Trustrum and DeRose (1988). If a pixel does exceed the slope threshold and does not have woody vegetation in the land cover map, then it is identified as land susceptible to landsliding; in that case, the flow path down to the nearest stream is traversed in the DEM, using flow direction and flow accumulation, to decide whether the pixel can deliver sediment to the stream network. If the flow path encounters any significant flat land, that is, consecutive pixels below four degrees of slope, then the original susceptible pixel is tagged as “non-contributing”, because sediment will deposit on the flat land before it reaches a stream. Otherwise, the pixel is tagged as “contributing”.

The quality of the input land-cover map is important because the main purpose of the landslide susceptibility model is to identify where land cover needs to be changed. Therefore, the land-cover map was produced to high spatial detail from a mosaic of several Landsat ETM+ satellite images, acquired between September 1999 and November 2002, using the method described by Dymond and Shepherd (2004). The ETM+ imagery was pan-sharpened to 15 m pixels and ortho-rectified using the 15 m (pixel) DEM (Landcare Research, 2004). The effect of topography on radiance was then removed by processing the imagery to standardised spectral reflectance. Then a hierarchy of binary split rules was used to identify land cover. Indigenous forest, exotic forest, scrub, and unspecified woody classes were amalgamated to form a woody vegetation class. Similarly, a rock type map was produced to 15 m pixel resolution from an existing national database, the New Zealand Land Resource Inventory (Eyles and Newsome, 1990).

3.2. Landslide mapping

Six SPOT5 satellite images were acquired shortly after the storm to assess the area affected by landslides. SPOT5 was used because it covers a large area, giving cost-effectiveness, and it has a high spatial resolution of 10 m, necessary for identifying landslides. The pointing ability of the sensor also gives good revisit capability, helpful for obtaining a rapid coverage of cloud-free imagery. The imagery was ortho-rectified to 10 m using the DEM mentioned previously and then processed to standardised spectral reflectance to remove the effect of topography in the mountains and hill country. Landslides were then identified by applying a 20-class unsupervised classification. Bright classes corresponding to bare ground were considered landslides. Erosion scars (the site of failure) could not be separated from debris-tails (the trail of sediment deposition) as they are equally bright. To separate landslides from other bare ground, such as ploughed paddocks and siltation areas, which occurred mainly on flats, we used the DEM to permit landslides only on slopes greater than five degrees. Also, all large landslides, i.e. greater than 10,000 m^2, were visually checked for correct classification.

To validate the landslide susceptibility model, erosion scars must be separated from debris tails because the model predicts where erosion scars can occur, not where debris-tails occur. To do this we developed a separation algorithm. We lumped pixels classified as landslide into contiguous clumps; for each clump, the pixel with the highest elevation was identified and assumed to be the uppermost part of an erosion scar. The pixel with the lowest elevation was also identified and therefore the elevation range of the clump could be calculated. All other pixels in the clump within 25% of the elevation range from the uppermost pixel were also labelled as scar. When compared with aerial photographs, this percentage gave a conservative estimate

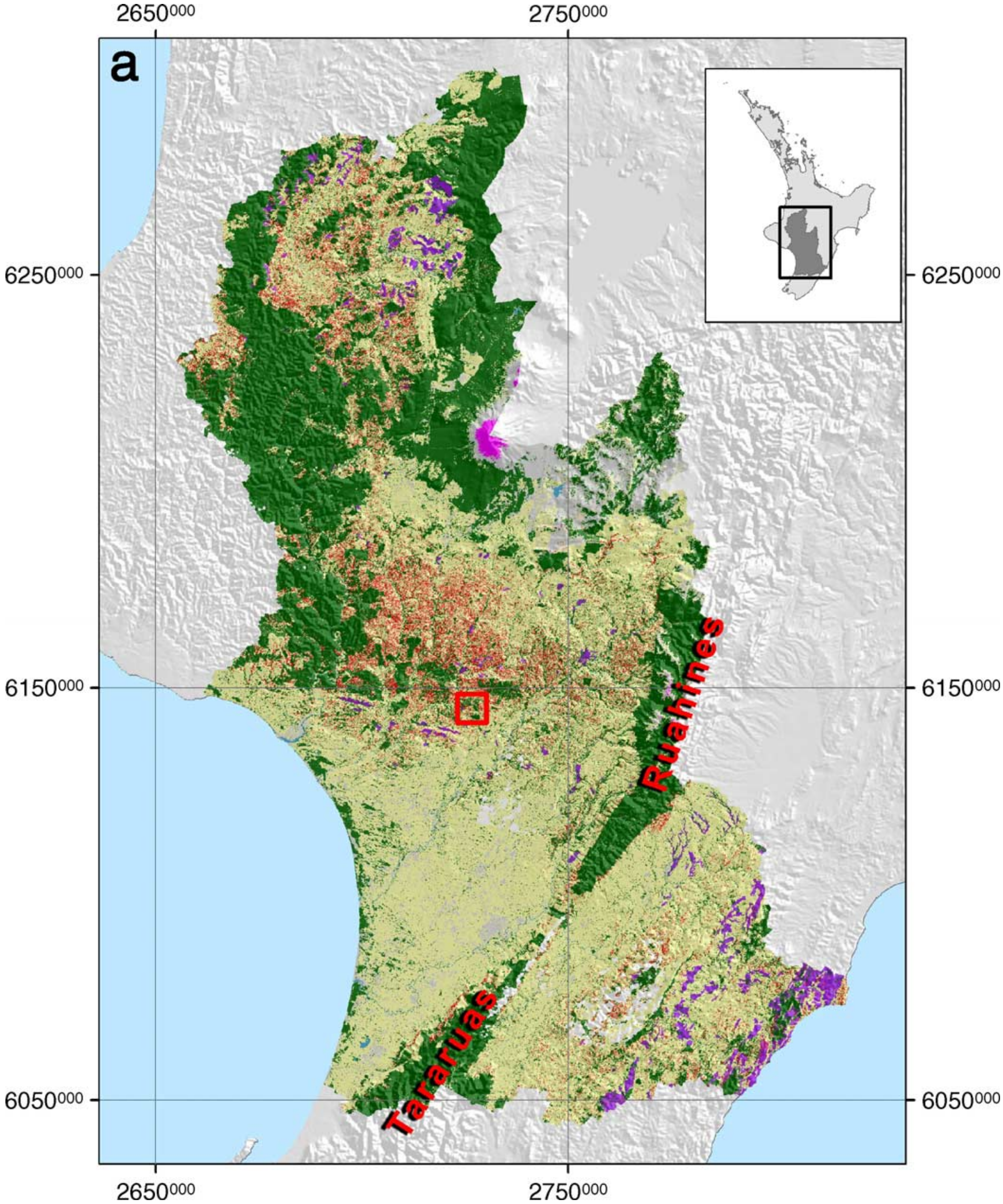

Fig. 2. Land susceptible to landsliding (red) in (a) the Manawatu–Wanganui region and (b) a part of the region, as predicted by the landslide susceptibility model. Purple is land susceptible to earthflow erosion (that is, slow creep of the order of centimetres per year). Other colours show land cover. Dark green is woody vegetation. Light green is pasture. Blue-grey is bare ground. Blue is water. Magenta is snow. Grey is undefined (due to cloud cover). Grid lines show constant easting and northing, 100 km apart, in the New Zealand metric grid. Red square in (a) shows extent of extract in (b).

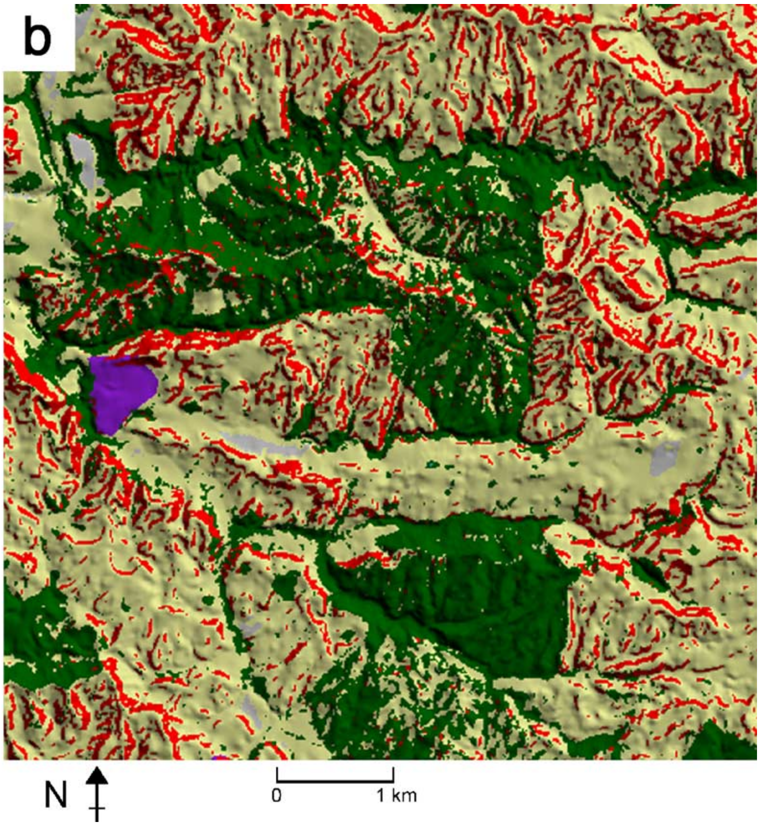

Fig. 2 (*continued*).

of the mapped distribution of scars. A lower limit of 25 m was set for the erosion scar length. A clump of landslide pixels often contains debris from several coalescing erosion scars and it is necessary to identify these erosion scars as well. We developed a region-growing algorithm that seeds from the top pixel in the clump and grows down the landslide. If the region on the landslide has finished growing and a significant proportion of the clump remains outside that region, then another erosion scar is assumed to exist. The algorithm is then repeated for the remainder of the clump, as often as necessary to separate all the coalescing scars from debris.

Table 1
Slope thresholds for rock types in the Manawatu–Wanganui region

Rock/regolith type	Slope threshold (degrees)
Loess	26
Tephra	26
Mudstone	24
Crushed mudstone/argillite	24
Sandstone/limestone	28
Greywake/argillite	28
Volcanic rocks	28

Above each slope threshold there is a high susceptibility to landsliding during an extreme rainstorm if the vegetation cover is not woody.

3.3. Validation methodology

The accuracy and utility of the landslide susceptibility model were assessed by comparing the map of susceptible land, produced by the model, with the map of actual erosion scars, produced from classification of the SPOT5 satellite imagery. The proportion of erosion scars on susceptible land (i.e. area of erosion scars in susceptible land/total area of erosion scars) gives the accuracy of the model, while the proportion of susceptible land with erosion scars (i.e. area of erosion scars in susceptible land/total area of susceptible land) measures the utility of the model, because it

Table 2
Area of land-cover classes in the Manawatu–Wanganui region

Land cover	Area (km^2)
Woody vegetation	8153
Herbaceous vegetation	12109
Bare ground	577
Water	60
Snow	47
Undefined	311
	Total = 21257

gives the proportion of land that could have been protected from landsliding in the February storm if it had been planted in trees. To validate the slope thresholds used in the model, we constructed graphs of percentage of land in erosion scar versus slope angle for each rock type. We produced separate graphs for indigenous forest, planted (i.e. exotic) forest, scrub, and herbaceous vegetation to check whether woody vegetation prevents landsliding, as the model assumes.

4. Results

4.1. Output of landslide susceptibility model

Table 2 shows the area of woody vegetation and other major land covers in the Manawatu–Wanganui region based on the land-cover map. Woody vegetation covers 38% of the region. Then, to identify land susceptible to landsliding, the slope thresholds in Table 1

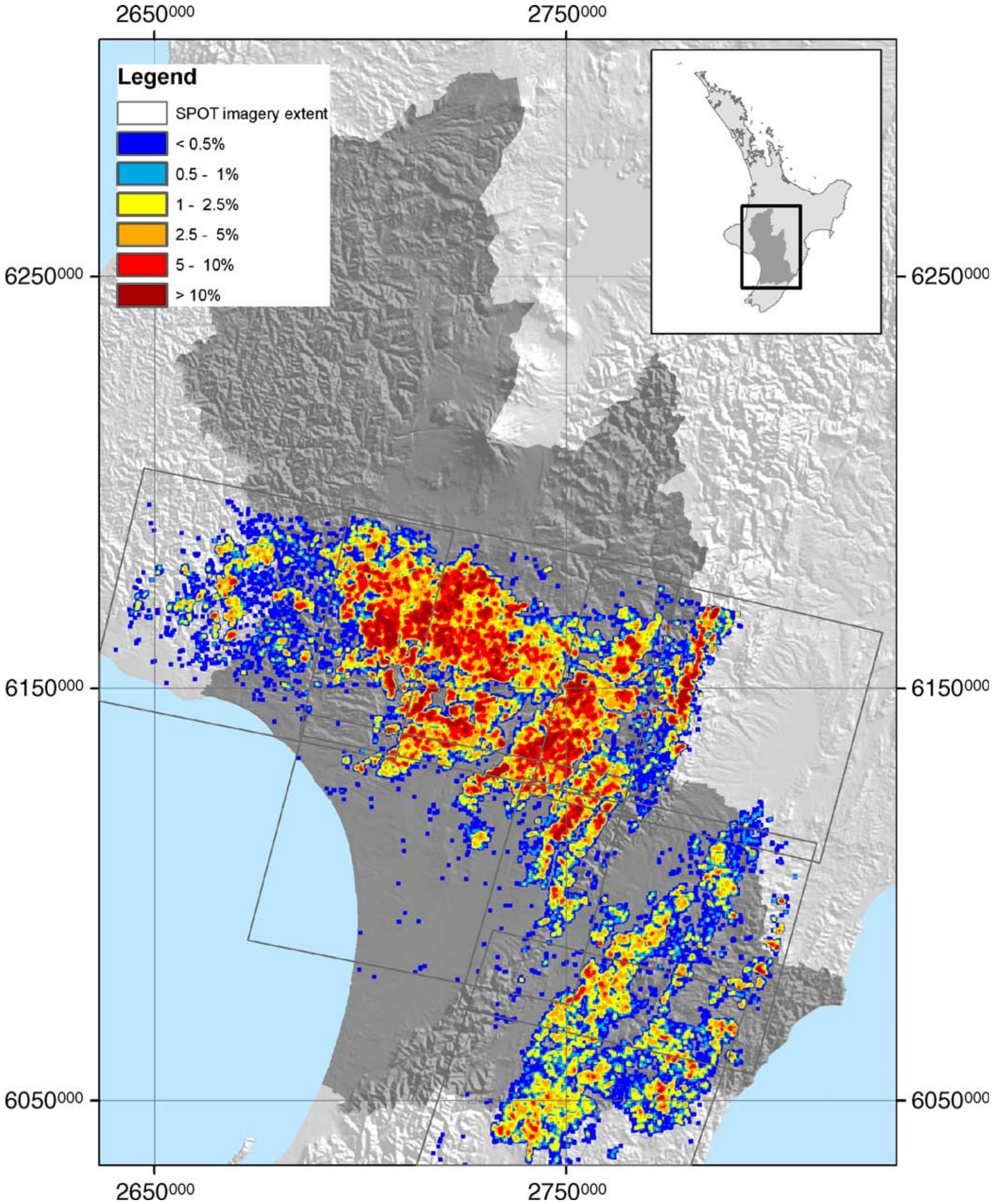

Fig. 3. Summary map of landsliding in the 15–16 February storm, lower North Island. Colours show the percentage of land in a kilometre square covered in either erosion scar (i.e. the exposed slip surface) or debris-tail. Grid lines show constant easting and northing, 100 km apart, in the New Zealand metric grid.

were applied to all the land not in woody vegetation (Fig. 2). According to the model, 1240 km^2 of land is susceptible to landsliding; this is over 5% of the region. Most of that land is north-east of Wanganui, between the Wanganui river and the Ruahine ranges, and south of Taumaranui down to Tongariro national park. According to the sediment delivery part of the model, 60% of the susceptible land can contribute sediment to the stream network.

4.2. Landslide map

The digital map of landslides, produced from the satellite imagery, identified over 62,000 individual landslides covering an area of 190 km^2. The spatial distribution of landslides is summarised graphically in Fig. 3. The map identified landslides with an accuracy of 80% (from visual assessment of the satellite imagery at a random sample of 6000 points) and overestimated total landslide area by just 2%.

4.3. Model validation

The proportion of landslide pixels that occurred in land susceptible to landsliding was 26%: a rather low accuracy. However, visual interpretation of the landslide map revealed that much of the landsliding was near susceptible land. Therefore, we developed an alternative accuracy assessment based on a whole hillside approach rather than a pixel approach. For all flow lines from ridge to stream, the proportion of the flow line that was susceptible was calculated, and if it exceeded 25% then the whole flow line was assumed to be susceptible. The hillside-based susceptibility map had an accuracy of 58%, compared to 26% for the pixel-based susceptibility map. The utility of the hillside-based susceptibility map was also higher than that of the pixel-based susceptibility map, increasing from 2.0% to 2.5%. Hence, if forest had been planted on hillsides susceptible to landsliding, then 0.025 km^2 of land would have been saved from slip erosion for every one km^2 of forest planted. This is only a moderate model utility. On susceptible land classified as “contributing” sediment, approximately 1 in 10 debris-tails reached first-order streams, while on “non-contributing” land fewer than 1 in 100 debris-tails reached first-order streams.

Fig. 4 shows how the probability of landsliding on pasture varies with slope angle for the four common rock types in Manawatu–Wanganui hill country. Between 0° and 40° landsliding probability generally increases linearly with increasing slope; it then stays constant until 55°, and then declines slightly. The gradual and linear rise of landsliding probability contravenes the concept of a threshold slope below which there is negligible probability of landsliding and above which there is a high probability of landsliding (Crozier et al., 1980; Salter et al., 1983; Trustrum and DeRose, 1988). Our results (Fig. 4) suggest all sandstone and mudstone hill country, no matter what the slope, is susceptible to landsliding. Fig. 5 shows how land cover affects the probability of landsliding for each of the rock types other than greywacke. Forest generally reduces landsliding probability by 90%, and scrub reduces it by 80%.

5. Discussion

Processing the SPOT5 satellite imagery to standardised reflectance removed the effect of topography so

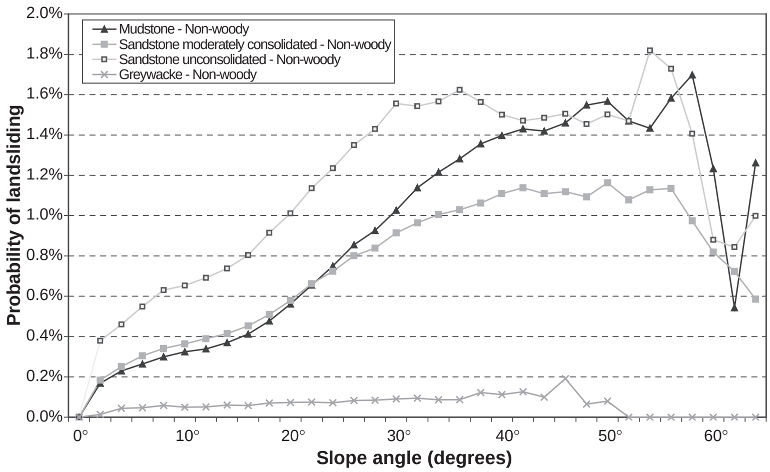

Fig. 4. Graph of landslide probability under non-woody vegetation versus slope angle for the four main rock types in Manawatu–Wanganui hill country. Landslide probability is calculated as the proportion of land in erosion scar.

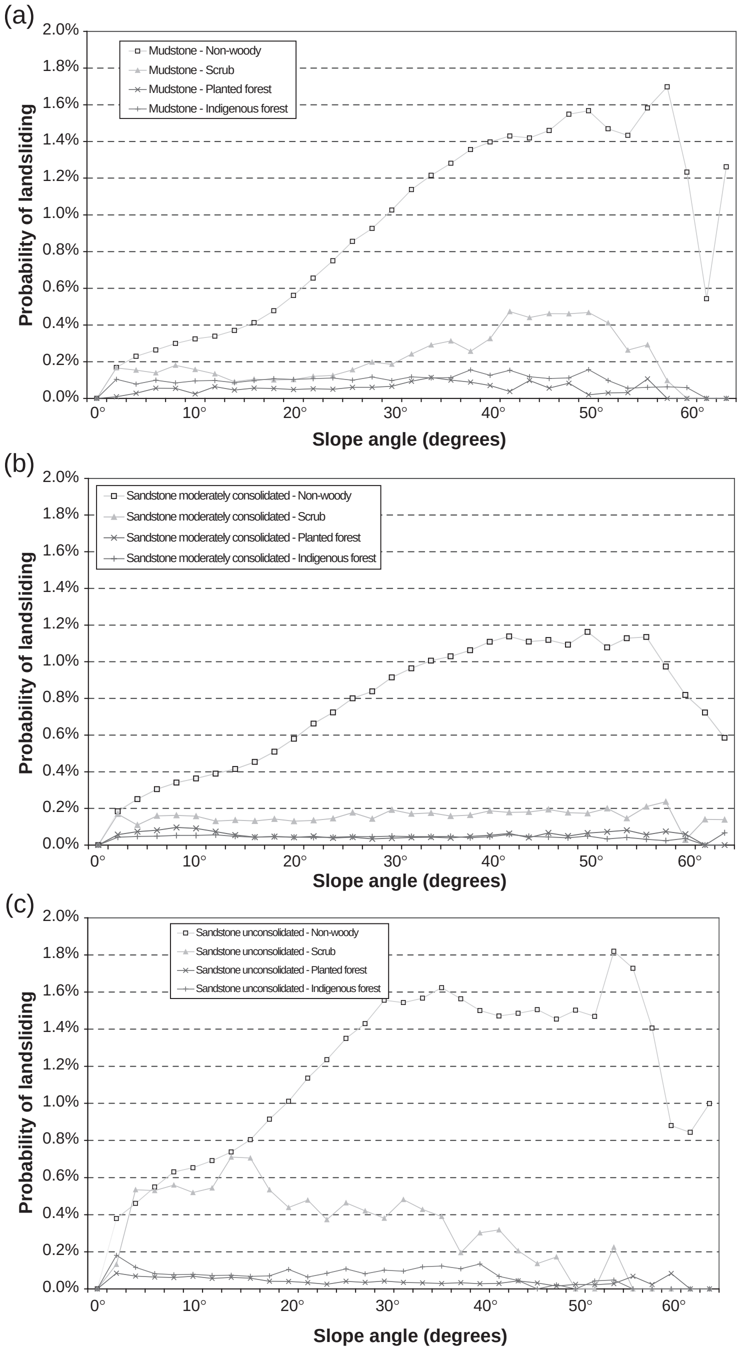

Fig. 5. Graph of landslide probability versus slope angle for four different land covers (indigenous forest, planted forest, scrub, and non-woody vegetation) on (a) mudstone, (b) moderately consolidated sandstone, and (c) unconsolidated sandstone. Landslide probability is calculated as the proportion of land in erosion scar.

that landslides could be mapped automatically. This method permits many landslides to be mapped over a large area in a short time (i.e. one week) and provides the basis for rapidly assessing storm damage. Because the data are digital, results can be distributed widely and quickly to assist the recovery process. While actual delivery of the February storm damage assessment (landslide only) into the public domain took approximately 2 months, this delay arose from institutional and organisational difficulties (such as securing finance before requesting imagery acquisition), not from technical difficulties.

The landslide susceptibility model presented in this paper assumes all land with woody vegetation is not susceptible. Fig. 5 confirms this assumption as a good approximation. Although some land under woody vegetation is still susceptible to landsliding, the susceptibility is much lower than under pasture. However, the assumption that there is a slope threshold, above which the susceptibility to landsliding significantly increases, is not a good approximation: Fig. 4 indicates that below 30° the probability of landsliding is linearly related to slope. There are many moderate slopes between 10° and 20° in the Manawatu–Wanganui hill country and their landsliding probability is almost one third of that for the slopes greater than 30°. This is the primary reason the landslide susceptibility model predicted slopes susceptible to landsliding with an accuracy of only 58%. This result differs from previous research in New Zealand (Crozier et al., 1980; Salter et al., 1983; Trustrum and DeRose, 1988) and requires validation with field data. It also suggests that the output of the landslide susceptibility model would be better expressed as a continuous variable rather than a binary "high" or "low".

For these reasons, using the model to target land susceptible to landsliding for afforestation or soil conservation work is only part of the solution for significantly reducing landslide erosion. Certainly, steep slopes tend to be more susceptible to landsliding and are more efficient in delivering sediment to the stream network, but because there are so many moderate to low slopes, significant sediment from those slopes still reaches streams. Therefore, a catchment-wide approach is required to reduce the loss of soil. This would entail managing slopes through their vegetation cover. Tools for vegetation management could include reforestation, farm forestry, space-planted trees, riparian planting or retirement, gully wall planting, or channel planting. These soil conservation techniques have been applied on various farms in the Manawatu–Wanganui hill country, but what is needed is a more comprehensive and catchment-wide approach, guided by a continuous-variable model of landslide susceptibility.

6. Conclusions

SPOT5 satellite imagery has sufficient spatial resolution to permit the identification of shallow landsliding in New Zealand hill country. The imagery may be topographically corrected for automatic mapping over large areas with moderate accuracy (80%). The landslide susceptibility model presented in this paper predicted hills susceptible to landsliding with moderate accuracy: 58% of erosion scars in the February storm occurred on hillsides considered susceptible to landsliding. The moderate accuracy arose because the model incorporated a concept of slope thresholds (above which the probability of landsliding is high and below which the probability is low). This concept is inadequate; in fact, below 30° the relationship between slope and the probability of landsliding is approximately linear. In future, we plan to develop a continuous-variable model of landslide susceptibility based on the data in Figs. 4 and 5, and to use the model in a catchment-wide approach to vegetation management.

Acknowledgements

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