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# Reprint of "A proposed cell model for multiple-occurrence regional landslide events: Implications for landslide susceptibility mapping"☆

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A B S T R A C T

Multiple-occurrence regional landslide events (MORLEs) consist of hundreds to thousands of shallow landslides occurring more or less simultaneously within defined areas, ranging from tens to thousands of square kilometres. While MORLEs can be triggered by rainstorms and earthquakes, this paper is confined to those landslide events triggered by rainstorms. Globally, MORLEs occur in a range of geological settings in areas of moderate to steep slopes subject to intense rainstorms. Individual landslides in rainstorm-triggered events are dominantly small, shallow debris and earth flows, and debris and earth slides involving regolith or weathered bedrock.

The model used to characterise these events assumes that energy distribution within the event area is represented on the land surface by a cell structure; with maximum energy expenditure within an identifiable core and rapid dissipation concentrically away from the centre. The version of the model presented here has been developed for rainfall-triggered landslide events. It proposes that rainfall intensity can be used to determine different critical landslide response zones within the cell (referred to as core, middle, and periphery zones). These zones are most readily distinguished by two conditions: the proportion of the slope that fails and the particular type of the slope stability factor that assumes dominance in determining specific sites of landslide occurrence. The latter condition means that the power of any slope stability factor to distinguish between stable and unstable sites varies throughout the affected area in accordance with the landslide response zones within the cell; certain factors critical for determining the location of landslide sites in one part of the event area have little influence in other parts of the event area. The implication is that landslide susceptibility maps (and subsequently derived mitigation measures) based on conventional slope stability factors may have only limited validity for many events. The overall ability to predict the impact of these events and consequently the development of effective mitigation measures is limited by the ability to predict the travel path, storm centre, and intensity range within the cell structure of extreme weather systems.

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## 1. Introduction

Multiple-occurrence regional landslide events (MORLEs) consist of hundreds to thousands of landslides occurring more or less simultaneously within defined areas, ranging from tens to thousands of square kilometres (Fig. 1). They occur in a range of geological settings in areas of moderate to steep slopes and are triggered by intense rainstorms and/or high intensity earthquakes. While they have been described from many parts of the world, they are particularly well represented in New Zealand as a result of the country's exposure to intense rainfall from tropical and mid-latitude weather systems and earthquakes generated from highly active tectonic plate convergence. Because there are differences in the failure mechanisms between rainstorm and earthquake triggering agents and because rainstorm events have been more frequently analysed, this paper has chosen to define discussion solely to rainfall-triggered events.

The largest rainfall-triggered event in New Zealand in recent years took place in the Wanganui-Manawatu region on 15–17 February 2004 (Fig. 2), resulting in approximately 80,000 landslides over an area of 16,000 $km^2$, with total storm rainfall in the centre of the cell in excess of 300 mm in 72 h (Hancox and Wright, 2005a, 2005b). Almost two decades earlier, Cyclone Bola had produced an event of similar magnitude with storm rainfall in parts of the region reaching 700–900 mm in 72 h (Marden and Rowan, 1994). Many other events of lesser magnitude bracket these landmark storms, the most recent being the Golden Bay event of 13–15 December 2011 that produced devastating landslides

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**Fig. 1.** A large, multiple-occurrence regional landslide event resulting from Cyclone Bola rainfall of 300–900 mm in 72 h, affecting an area of over 8300 $km^2$, March 1988, East Coast, North Island, New Zealand (photo: Noel Trustrum).

and debris flows in response to maximum 24-hour rainfalls of 454 mm and storm totals of 674 mm in 48 h (Page et al., 2012).

Individual landslides within these events are generally small (<1000 $m^3$ in volume), dominantly shallow debris and earth flows, and debris and earth slides (terminology: Cruden and Varnes, 1996) involving regolith or weathered bedrock.

Rainstorm-triggered events are the most common mode of landsliding in New Zealand, occurring somewhere in the country two or three times a year on average and are the principal agent of soil erosion, reduction of primary productivity, and downstream sedimentation problems (Page et al., 2000; Crozier, 2005). The aim of the paper is to examine the range of landslide impacts prevalent within these events and to analyse which factors are exerting dominant control over the specific location of landslides within the affected area. The method used to achieve this aim involves examining data from published reports and photographic records of events. This material is analysed to extract reported relationships between rainfall gradients, the degree of landslide impact, and preferred location of landslide occurrence, with respect to: the type of vegetation cover, topographic features that influence runoff distribution, and availability of susceptible material. In an attempt to represent the patterns that emerge, a model is presented based on 40 years of field observation by the author, backed up by data from a range of published reports. While trends and patterns represented within the model are established empirically, they are supported and explained by a number of studies by the author and others that provide a physical basis of explanation – these are referred to throughout the body of this paper.

**Fig. 2.** Landslides resulting from the Wanganui-Manawatu event of February 2004; rainfall exceeded 300 mm in 72 h in the worst affected areas. Landslide locations are aligned to drainage lines and to ridge crests (photo: Graham Hancox).

## 2. Measures of landslide impact

Spatial variation in landslide impact throughout the storm cell has been an important aspect of this study and a fundamental component of the model presented in this paper. For this reason, it is important to recognise that landslide impact data have been represented in many different ways throughout the literature. The term 'impact' is used here to refer to the extent to which a given area of land surface is affected by landslides. A range of different parameters has been used to represent impact. The broadest and most subjective measure is the magnitude of 'affected area' or 'event area'. This term refers to the land area envelope within which landslides associated with the storm event have been identified. Not only is the determination of the event area subject to the resolution of imaging used to identify landslides but it is also affected by the extent to which peripheral outliers have been taken into account. In erosion and sediment budgeting studies, a fundamental measure of impact is the cumulative volume or mass represented by the landslide scars (the total amount of displaced material) expressed per unit of land surface of the study area or event area (e.g., $m^3$/ha or tonnes/ha). This measure can be converted to an event denudation or surface lowering (mm) or a denudation rate when combined with other events of known age, on the assumption that all displaced material leaves the study area. Because of the difficulty in determining the depth of scars from remote sensing (in some cases involving thousands of landslides) in place of scar volume, the cumulative scar area alone is used to provide an indication of the extent of erosion, often expressed as a percentage of the study area. Pre-established regressions between measured scar area and measured volumes can be used to estimate volume from scar area. Whereas today, topographic surface difference analysis of 'before' and 'after' LiDAR imagery can be used to determine scar volume, many valuable older investigations have relied on two-dimensional imagery or field sampling for event assessment; thus comparison of impact studies from different periods needs to recognise and adjust for the different levels of precision underlying the data sets.

At the reconnaissance level, landslide impact may be represented simply by landslide density (the number of landslides/$km^2$) or by the cumulative area of the entire landslide footprint, i.e., scar and runout (transport zone and deposit) represented as a percentage of the study area. In their characterisation of the Wanganui-Manawatu event, Hancox and Wright (2005b) used landslide density and landslide footprint (scar and runout), noting that the average ratio of runout length to scar length was between 2.5 and 3.1:1.

Landslide impact resulting from an event can also be measured by sediment delivery ratios (SDRs) by comparing the mass of material displaced by landslides with the mass of material leaving the catchment. This approach was used successfully in one of New Zealand's largest MORLEs on record, the Cyclone Bola event of 1988. In the Tutira catchment affected by this event, Page et al. (1994) employed lake sediment analysis to measure the magnitude and frequency of landslides based on the delivery of landslide-derived sediment to the lake. In the latter part of this record they were able to correlate magnitude of events with catchment rainfall, providing a measure of the minimum landslide triggering rainfall and an indication of the exponential increase in landslide event magnitude with increasing rainfall (Fig. 3).

## 3. Susceptibility factors

Observation indicates that most slopes are stable most of the time and even when a multiple-occurrence regional landslide event is initiated, only certain parts of the terrain succumb to landsliding, while

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