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Applying Probability Determination to Refine Landslide-triggering Rainfall Thresholds Using an Empirical "Antecedent Daily Rainfall Model"

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Abstract—Rainfall-triggered landslides constitute a serious hazard and an important geomorphic process in many parts of the world. Attempts have been made at various scales in a number of countries to investigate triggering conditions in order to identify patterns in behaviour and, ultimately, to define or calculate landslide-triggering rainfall thresholds. This study was carried out in three landslide-prone regions in the North Island of New Zealand. Regional landslide-triggering rainfall thresholds were calculated using an empirical "Antecedent Daily Rainfall Model." In this model, first introduced by CROZIER and EYLES (1980), triggering rainfall conditions are represented by a combination of rainfall occurring in a period before the event (antecedent rainfall) and rainfall on the day of the event. A physically-based decay coefficient is derived for each region from the recessional behaviour of storm hydrographs and is used to produce an index for antecedent rainfall. Statistical techniques are employed to obtain the thresholds which best separate the rainfall conditions associated with landslide occurrence from those of non-occurrence or a given probability of occurrence.

The resultant regional models are able to represent the probability of occurrence of landsliding events on the basis of rainfall conditions. The calculated thresholds show regional differences in susceptibility of a given landscape to landslide-triggering rainfall. These differences relate to both the landslide database and the difference of existing physical conditions between the regions.

Key words: Landslides, probabilistic threshold determination, rainfall threshold, critical water content.

Introduction

Since the introduction of climatic recording in New Zealand, it has been possible to establish a broad relationship between rainfall input and erosional response. PAGE *et al.* (1994b) have shown that in the headwater catchments of New Zealand hill country, erosional response is driven more or less exclusively by the landslide process. Establishing a relationship between input and response over time

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makes it possible to differentiate between those input conditions which did not trigger landslides and those which triggered landslides. Thus, rainfall thresholds for landslide initiation can be established for specific regions. Clearly, thresholds will vary from region to region depending on the influence of inherent stability factors within each region.

Temporal changes of the climatic regime (e.g., increased storm frequency with higher magnitude of maximum daily rainfall in a given year) do not affect the threshold itself; they only affect the frequency with which the threshold is exceeded. This would result in a change of the frequency of landsliding and hence result in geomorphic changes such as less soil availability on slopes for failure, decreased slope gradients because of soil removal and colluvial deposition on footslopes, and reduced transport abilities of sediment filled valleys, which reduces incision rates and may reduce landslide occurrence. Early work by CAINE (1980) established rainfall duration-intensity thresholds. Since then numerous other research groups have worked on landslide-triggering rainfall thresholds (CAINE, 1980; CANNON and ELLEN, 1985, ELLEN and WIECZOREK, 1988; HARP *et al.*, 1997; KEEFER *et al.*, 1987; WILSON *et al.*, 1993; WILSON and WIECZOREK, 1995; WIECZOREK, 1987; CHURCH and MILES, 1987). A common finding of all studies is the realisation that determination of landslide-triggering rainfall thresholds is strongly dependent on a sound database, which ultimately controls the reliability of calculated thresholds.

In New Zealand, soil erosion, and specifically landsliding of various types and forms, was described and recognised as a nationwide problem over 50 years ago (CUMBERLAND, 1944). Since then, numerous case studies of specific landslide-triggering rainstorms have been carried out (e.g., CROZIER *et al.*, 1979; PAGE *et al.*, 1994a; PAIN, 1969; SELBY, 1976). Most of these studies deal with specific research questions, use different procedures, and produce results which are specific to the original research aim (GLADE and CROZIER, 1998). Thus, comparisons between these different studies are difficult. Some attempts have been made in the past to summarise available landslide information. These attempts were either focused on landslides of specific magnitude (IGNS, 1993) or highly damaging landslide-triggering rainstorms (HARMSWORTH and PAGE, 1991). More recently, a complete landslide bibliography summarising all available landslide literature related to rainfall as the triggering agent has been compiled for New Zealand (GLADE and CROZIER, 1997).

The information taken from this landslide bibliography has been transferred into a landslide database, providing the opportunity to carry out frequency and magnitude analysis of landslide-triggering rainstorms at both regional and national scales (GLADE, 1996) and to establish landslide-triggering rainfall thresholds.

Using this database as a starting point, it is our intention in this study to show the extent to which landslide-triggering rainfall thresholds may be established on a regional basis. Information on time and place of landslide occurrence contained in the database allows identification, from the existing meteorological record, of the rainfall conditions most closely associated with each event. The rainfall conditions used here are derived as a linear combination of antecedent rainfall and rainfall on the day of the event. Statistical techniques are employed to obtain the thresholds which best separate the rainfall conditions associated with landslide occurrence from those of non-occurrence or a given probability of occurrence.

Study Areas

The three study areas (Wairarapa, Hawke's Bay, and Wellington) are all located in the North Island of New Zealand (Figs. 1, 2). These areas have aerial pho-

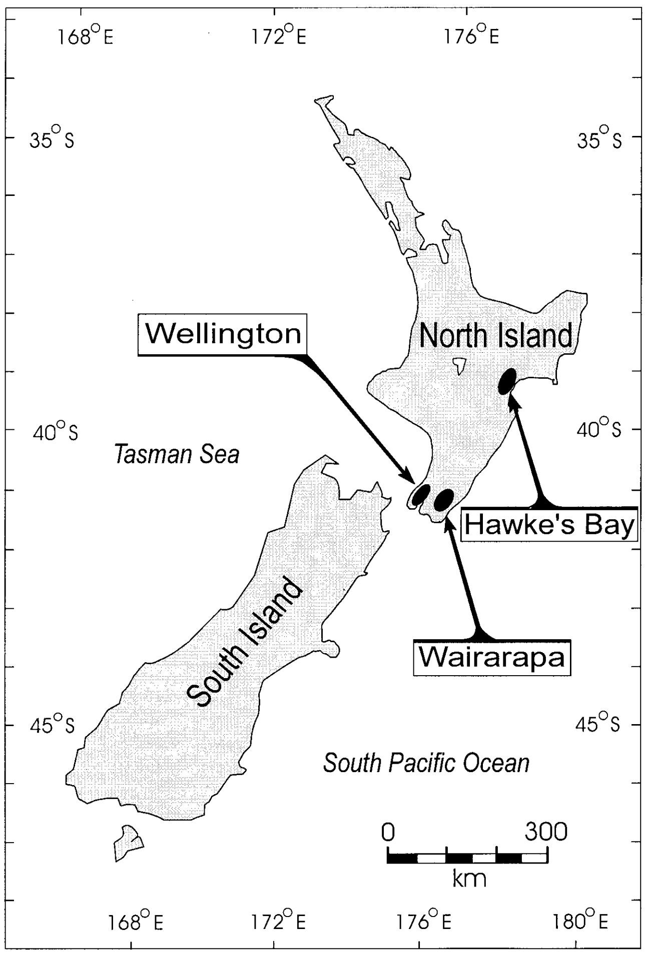


Figure 1
Locations of the study areas Hawke's Bay, Wairarapa, and Wellington in New Zealand. (*Note*: Marker is not related to the real study area size. It gives broad location only.)

(a)

(b)

(c)

Figure 2
Photographs of the study areas Foster's Hill in Wairarapa (a) and Northern Hawke's Bay (b) taken November 1977 and March 1988, respectively. Both photographs show widespread landslide occurrence with different landslide types and magnitudes involved. A typical slope failure in a suburban area of Wellington City after the December 1976 rainstorm is given in (c).

tograph coverage after landslide-triggering rainstorms, comprehensive records of landslide-triggering events, and records from a high density network of climatic stations over long periods. Their physical environments are distinctively different (Table 1).

The results of previous research on landslides in these areas, carried out by the Department of Geography, Victoria University of Wellington (CROZIER and EYLES, 1980; CROZIER *et al*., 1979; CROZIER, 1996; CROZIER and PRESTON, 1998; EYLES *et al*., 1978) and the Crown Research Institute Landcare Research Ltd (HARMSWORTH and PAGE, 1991; PAGE *et al*., 1994a,b) and its predecessors (IGNS, 1993), constitute a significant part of the established landslide database.

Methodology

The Landslide Database

Before any analysis could be carried out, the landslide information sources contained in the previously compiled bibliography had to be analysed and the relevant information listed using a standardised citation style. In this way a national-scale based landslide database was created, which included information on location of landslides, landslide characteristics, regional physiographic patterns, and triggering rainstorm events. Refer to GLADE (1996, 1997, 1998) for a comprehensive discussion of this inventory.

For this study, relevant regional data were extracted from this database. Previous research in all three regions had established a list of landslides causing major damage which was augmented, where possible, by a more detailed search for landslide information or general slope stability problems on the regional scale.

From the precipitation records, the largest daily totals for the entire recording period were ranked and newspaper archives for these and adjacent dates searched. These resulting regional landslide inventories provide the basis for the development of rainfall thresholds.

Table 1

Generalised physiographic settings of the study areas Hawke's Bay, Wairarapa, and Wellington in New Zealand

	Hawke's Bay	Wairarapa	Wellington
Approx. size	50 km^2	120 km^2	30 km^2
Geology	Dark blue-grey siltstones (silty mudstones) and sandstones, interbedded with conglomerates and very fossiliferous limestone bands	Limestone, siltstone-interrupted by various faults	Alternating dark grey argillite and greywacke sandstone, extensively faulted, tilted and folded
Tectonic uplift	0–2 mm/yr	2–4 mm/yr	$\sim$1 mm/yr
Soils	Volcanic ash beds	Loess	Colluvium, solifluxion deposits
Vegetation	Pasture, plantation forest	Pasture, plantation forest	Scrub, pasture
Relief	250–300 m	200–250 m	460 m
Geomorphology	Steep, dissected slopes with very flat ridges ephemeral channels	Short straight valley-side slopes with summit convexities, high drainage density	Steep, strongly dissected slopes, often along fault lines, drainage lines aligned along faults
Landuse history	Since 1870s, native forest converted to pasture, partially now plantation forest	Since 1840s native forest converted to pasture	Since 1840s native forest converted to pasture, increasing urbanisation

Climatic Data

New Zealand has daily rainfall records dating back to the 1860s on which empirical relationships between climatic events and landslide occurrence can be based. This study focusses solely on daily precipitation because of its long record and the availability of data in a similar form elsewhere in the world. In analysing the relationship between landslides and rainfall, earlier studies on similar scales have generally used mean annual rainfall totals (e.g., HICKS, 1989 for East Cape, New Zealand; SLOSSON and LARSON, 1995 for Southern California, USA), monthly values (e.g., JÄGER and DIKAU, 1994 for Rheinhessen, Germany), or storm totals (e.g., LARSEN and SIMON, 1993 for Puerto Rico).

Daily rainfall data were provided by NIWA (National Institute of Water and Atmospheric Research Ltd.) through their Climatic Database (CLIDB) (PENNEY, 1997). Two data sets were chosen: daily and monthly measures. As is standard practice with climatic data, observations relate to the 24 hours prior to 9 a.m. on the day of recording. As a consequence 62.5% of the recording time attributed to a given day occurs on the previous day, which introduces a 9 to 15-hours lag when defining thresholds. This is important to consider when defining landslide-triggering rainfall thresholds.

Antecedent Daily Rainfall Model and the Threshold Approach

In an earlier analysis, the relationship between landsliding and rainfall was explored using daily rainfall totals only, without taking into account antecedent conditions (GLADE, 1998). Using the threshold approach, two major thresholds can be defined the *minimum threshold* and the *maximum threshold*, which define the lower and upper boundaries of the *threshold probability range*. The minimum threshold is defined as the rainfall value below which there has been no recorded landslide activity. The maximum threshold is defined as the rainfall value above which landslides have always been recorded. Between these two boundaries, different probabilities of occurrence exist. In other words, not all of the rainfall values lying between the two thresholds will be associated with landslide occurrence. However, as values approach the maximum threshold there is greater probability that they will be associated with landslide activity.

This model is improved here by incorporation of an antecedent rainfall term, to give the relationship between antecedent rainfall conditions prior to an actual "rainstorm event" and the rainstorm magnitude itself. The model is referred to as the *Antecedent Daily Rainfall Model*. In this model, rainfall for each field area is represented by two factors: rainfall which occurs over a given period preceding a given day and the rainfall total on the given day. It uses only the maximum rainfall value of each day from all recording stations in the climate database for the whole region. This is based on the assumption that the maximum rainfall within the region on any day is the one most likely to have triggered the reported landslide.

The advantage of this model lies in the use of a simple surrogate measure of soil moisture using only daily rainfall. During dry conditions the amount of rainfall in a period preceding an event will give a general indication of soil moisture storage. During wet conditions it will indicate, in addition, the amount of gravitational water residing in or moving through the soil and slope drainage system. If antecedent rainfall has been of sufficient intensity to produce overland flow, calculated indices will overestimate the amount of moisture in the regolith. Therefore, the calculated antecedent rainfall can only be regarded as an index of antecedent soil moisture (CROZIER and EYLES, 1980).

The *Antecedent Daily Rainfall* model employed by CROZIER and EYLES (1980) uses the antecedent rainfall index (BRUCE and CLARK, 1966) calculated as follows:

$$r_{a_0} = kr_1 + k^2 r_2 + \cdots + k^n r_n \quad (1)$$

where r_{a_0} = antecedent daily precipitation, based on maximum regional precipitation values (mm) for day 0, k = constant representing the outflow of the regolith, and r_n = maximum regional precipitation (mm) on the nth day before 0.

CROZIER and EYLES (1980), following BRUCE and CLARK (1966), used $k = 0.84$, which comes from Ottawa (United States) streamflow data. The resulting relationship between antecedent daily rainfall and daily rainfall is shown in Figure 3. The assumptions in this model are constant rates of drainage and evaporation processes throughout the year.

Although setting $k = 0.84$ worked satisfactorily for some sites in New Zealand (Fig. 3) and has been used subsequently in landslide prediction (CROZIER, 1996), it has no physical basis in New Zealand conditions. Here, we derive values for k which reflect New Zealand soil moisture drainage more appropriately, based on the recession coeffecients of regional flood hydrographs. The rate of decrease is in fact dependent on a number of geomorphic factors such as catchment shape and size, relief, slope gradients, vegetation cover, soil type as well as the existence of natural or man-made lakes. The regional geomorphic factors in the respective regions are listed in Table 1.

This method, however, is appropriate because soils in the three regions do not have large long-term water storage capacity. This is related to the existence of steep slopes, soil texture, and the presence of shallow soils with a well-defined interface between regolith and bedrock. Rates of streamflow recession should, therefore, accurately reflect water outflow from the hillslope regolith.

A comparison of the results obtained by using the conventional ($k = 0.84$) and runoff-derived recessions shows that the use of the exponent d (coefficient of the decay curve, see equation (2)) results in a shift of the distribution of the daily rainfall magnitudes to lower antecedent daily rainfall values (GLADE, 1997). This means less important antecedent rainfall for all regions, which seems appropriate

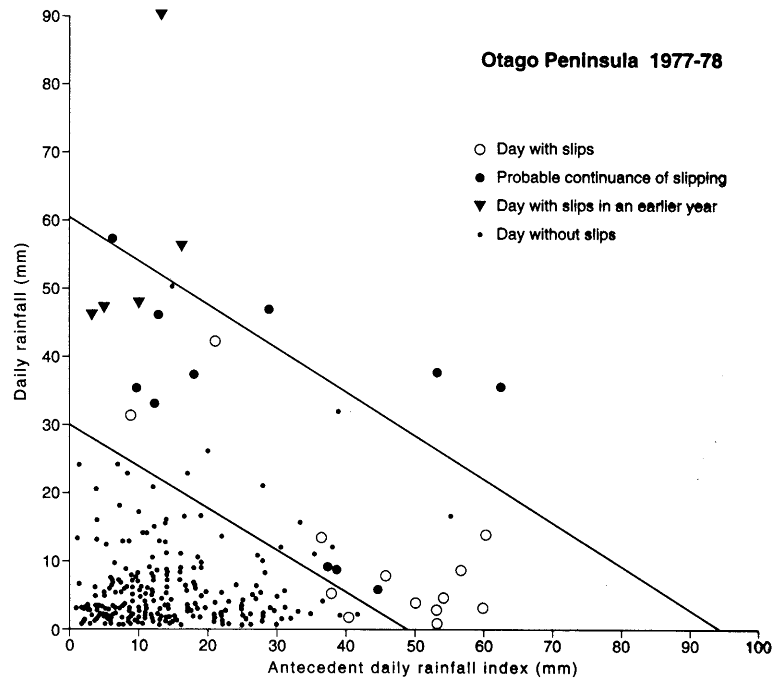


Figure 3
The *Antecedent Daily Rainfall Model* applied to landsliding episodes in Otago Peninsula, New Zealand (CROZIER and EYLES, 1980).

considering the fast drainage of soils. Consequently, the use of the runoff-derived decay factor has been adopted here and the method of its derivation is described below. Furthermore it was shown by GLADE (1997), that the appropriate length of antecedent period is 10 days ($n = 10$).

To obtain data recession rates of flood hydrographs, river flow records were analysed within each of the three regions. These hydrograph recession curves are best represented with a power trend line. The general power equation for these recession curves takes the form:

$$y = cn^d \tag{2}$$

where y = discharge at any point in the recession curve and c = peak of streamflow, n = time in days, and d = coefficient of the decay curve.

In order to ensure that rates of hydrograph recession accurately reflect drainage from the catchments, the analysis used only those hydrographs where precipitation ceased prior to recession. The hydrograph time units used in the curve-fitting exercise are the same as those used in the rainfall analysis, in this case days. Various recession curves with varying lengths, different total discharge volumes, and from several different catchment areas have been analysed. From these, an average value of the coefficient was calculated to represent a regional drainage rate. Table 2 gives the different resulting regional coefficients of the decay curve (d) used in subsequent calculation of the antecedent rainfall index.

Introducing this runoff characteristic to equation (1), the *Antecedent Daily Rainfall* index becomes:

$$r_{a_0} = r_1 + 2^d r_2 + 3^d r_3 + \cdots + n^d r_n \quad (3)$$

where d = derived from the hydrograph recession curve coefficient d (refer to equation (2), and n = number of days before the day 0 (this study uses $n = 10$ days. Refer to GLADE (1997) for comprehensive discussion).

Calculation of Probability Thresholds

All rainfall days since records began have been categorised as days coincident with landslide occurrence, and days associated with no record of landsliding. There is, however, a third category possible: "probably induced landslides." This latter category is applied to days preceding and following instances of recorded landslide occurrence with similar or larger landslide-triggering rainfall magnitude—keeping in mind that the landslide record will not have included all landslides that actually occurred. For reasons offered above relating to the quality of landslide record, it cannot be assumed that landsliding did not occur on these days.

In the following calculations both days with landslides and days of probable landslides are treated as landslide events providing a binary variable corresponding to the presence or absence of a landslide event which may be analysed by logistic regression, which is a common tool for studying binary data. The objective is to model the probability of landslide occurrence P at all possible combinations of

Table 2

Comparison of the conventional k-factor used to decay antecedent rainfall conditions (CROZIER and EYLES, 1980, CROZIER, 1989) and the calculated exponential d-factor derived from hydrograph recession curves applied within this study (n = time, here days)

Scale	Parameter	Hawke's Bay			Wairarapa*	Wellington
Scale independent	Conventional k-factor				0.84	0.84
Catchment scale	Size [km^2]	1	18	253	1	16
	Exponential d-factor	−2.84	−1.71	−2.05	−1.19	−1.52
	Standard deviation of d-factor	0.35	0.24	0.37	0.10	0.52
Regional scale	Exponential d-factor		$n^{-1.99}$		$n^{-1.19}$	$n^{-1.52}$
	Standard deviation of d-factor		0.47		0.10	0.52

* Streamflow data available for one catchment only.

daily precipitation r and *antecedent daily precipitation* r_a. Traditional regression methods might model $P(r, r_a)$ as a linear combination of powers of r, r_a and cross products. Since the linear combination can fall outside [0, 1], it is of limited use in modelling probabilities. For this reason the expression:

$$\log\left(\frac{P}{1-P}\right) \tag{4}$$

is modelled as the linear combination discussed above. This new expression has a range $(-\infty, \infty)$ rather than [0, 1]. Consequently, any linear combination might be meaningful.

Choosing the appropriate logistic regression model is done by hierarchical model building where the fit of a more complicated model is compared to the previous simpler ones. When significant improvement in fit is achieved, the more complex model is accepted. If not, the simpler model is used. The decision of best fit uses the measure of residual deviance as a criterion (McCullagh and Nelder, 1983). Generally, the smaller the deviance, the better the fit of the model. The question is, however, if the improvement is significant. This is particularly true with respect to the more complicated nature of the model which produces smaller residual deviances.

In fact, model building is complicated by three effects. First, the data are sparse in the sense that relatively few landslide events are present in the two-dimensional space of (r, r_a). Second, since there are many thousands of non-landslide events, the total data set is large and in such situations it is well known that using standard significance tests may lead to complex models which may not be physically meaningful. Third, there is the inherent uncertainty in the probable continuance of landslides. To counter these problems, a combination of significance tests coupled with a preference for simple, robust models which are physically reasonable are used. Hence the models chosen below are proposed on a wider basis than simple hypothesis testing.

Results

The *Antecedent Daily Rainfall* model has been applied to three regions. The different exponential decay factors k are summarised in Table 2. These decay factors strongly influence the magnitude of antecedent daily rainfall. The larger the exponents, the faster water drains from the soil, thus lowering the time interval of effective antecedent rainfall influence to the critical water content required to trigger landslides.

For each region, different logistic regression analyses were performed and the resulting model used to calculate the respective curve for the landslide probability

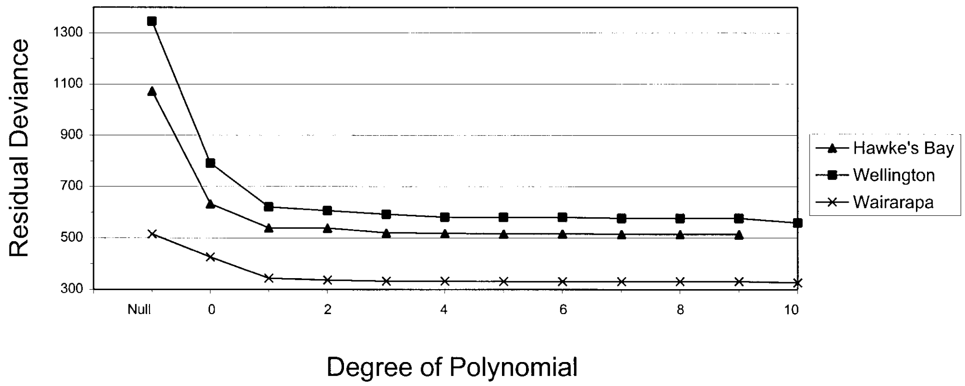


Figure 4
Screeplots showing Residual Deviance against Degree of Polynomial Model for the three New Zealand regions Wairarapa, Hawke's Bay, and Wellington. (*Note*: Refer to text for differences in degree of polynomial.)

P. Screeplots of each of the regions clearly show most of the savings in residual deviance (i.e., improvement in fit) occur within the first few terms (Fig. 4).

The degree of polynomial refers to the complexity of the model measured by the maximum power of r_a included in the logistic regression. The NULL model is the simplest and refers to the model in which the probability of a landslide is assumed to be constant. When the degree is n the model uses a linear combination consisting of a constant, a linear term in r and all powers of r_a up to the degree n.

The adequacy of any model is assessed in three ways. Firstly, screeplots in Figure 4 show visually the decreasing improvements in model fit gained by using more complicated models. Secondly, a chi-squared test is used (summarised in Table 3) to see if the decrease in residual deviance is significant using more complex models. Lastly, any postulated models are plotted to check that they are physically reasonable. A combination of all three methods is used to produce the regional models which are given in Table 4.

Applying these equations to the respective region results in regional figures which illustrate how the combination of antecedent daily rainfall and the magnitude of daily rainfall influence landslide occurrence. The resulting regional figures are shown in Figure 5. Although the results here are different from region to region, the nature of the conclusions remains the same.

Confidence intervals have been calculated for all three regional models (Chambers and Hastie, 1993). The width of the intervals depends on the position (r, r_a). 95% confidence intervals using the respective regional model are plotted for $P = 0.1$, $P = 0.5$, and $P = 0.9$ in Figure 5.

Depending on the model used, envelopes indicating given probability levels have different shapes (Fig. 5). All of the envelopes show a generally negative relationship between antecedent conditions and daily rainfall, indicating that with increasingly wet antecedent conditions, less rainfall is required to trigger landslides on a given day. This interpretation is consistent among the three regions and with the results of other authors.

In the Wairarapa, the best model is linear in r and r_a and is relatively robust (Fig. 5a). Adding in r and r_a reduces residual deviance by 89.7 and 82, respectively (see Table 3). Thus linear models reduce residual deviance by 171.7. Adding 8 more terms only saves 17.4 more. Thus higher order terms in the regression (e.g.,

Table 3

Tests of significance of change in residual deviance with higher order models in Wairarapa (a), Hawke's Bay (b), and Wellington (c). Order of polynomial refers to the complexity of the models, Test Stat to the change in residual deviance from order before to new order model, and p to the significance value given by a chi-squared test of the respective change. (Note: Due to missing improvements in either residual deviance or significance, not all models are listed for the respective regions.)

Region	Order of polynomial	Test stat	P
Wairarapa	0	89.7	0.00
	1	82.0	0.00
	2	7.1	0.01
	3	3.7	0.05
	4	0.3	0.58
	5	1.5	0.22
	7	0.3	0.86
	10	4.5	0.21
Hawke's Bay	0	440.0	0.00
	1	94.3	0.00
	2	0.5	0.48
	3	18.8	0.00
	4	1.9	0.16
	5	2.4	0.12
	7	1.7	0.43
	9	0.7	0.70
Wellington	0	554.2	0.0
	1	170.8	0.0
	2	15.4	$8.7 * 10^{-5}$
	3	13.5	$2.4 * 10^{-4}$
	4	11.0	$9.1 * 10^{-4}$
	5	1.4	0.23
	7	4.0	0.14
	10	17.2	$6.4 * 10^{-4}$

Table 4

Regional equations for calculation of thresholds with different probabilities of occurrence (with P = probability of landslide occurrence at a given value of r and r_a: r = daily rainfall; r_a = antecedent daily rainfall).

Region	Threshold probability equation
Wairarapaa	$\log\left(\frac{P}{1-P}\right) = -8.45 + 0.033 * r + 0.036 * r_a$
Hawke's Bay	$\log\left(\frac{P}{1-P}\right) = -8.82 + 0.033 * r + 0.75 * r_a - 0.0052 * r_a^2 + 0.00000012 * r_a^3$
Wellington	$\log\left(\frac{P}{1-P}\right) = -8.08 + 0.072 * r + 0.00036 * r_a^2$

quadratic or cubic models) were either non-significant or led to physically unreasonable models. Note that it is quite easy to observe wild behaviour in a model in the high (r, r_a) region since here there are no data to suggest any given shape. Hence we require a model which fits in the bulk of the data well and does not become erratic where fewer data are available.

In addition, tests have been performed to investigate the influence of the very high magnitude events on the form of the model. In the Wairarapa region, analysis excluding the two highest daily rainfall magnitudes (190 mm and 155 mm) from the total data set has shown that the linear logistic regression model is still the best one. Removal of these two points results in only a slight shift of the probability lines towards zero, thus only the intercept changes. Thus the linear model is adopted.

The Hawke's Bay data set exhibits different behaviour (Fig. 5b). From Table 3 a cubic model is significantly better than linear or quadratic and higher complexity models, which do not offer significant improvements. Also the screeplot shows that most of the improvement in fit has occurred by degree 3. Finally raw contour plots of the landslide intensity show curved contours and therefore the cubic model is used.

However caution is needed here. The data are quite sparse close to the vertical axis (at low r_a values) and therefore the upturn in the cubic probability curve may be an artifact of the need for the rest of the curve to fit in areas where there is more data rather than a genuine physical feature.

Nevertheless, such a shape does have a logical explanation. At low r_a values a small additional amount of antecedent rain primes the soil and makes it far more receptive to landslides following moderate to heavy rain on the following day. Hence the curves exhibit a sharp drop near $r_a = 0$. After a certain amount of antecedent rain, the rate decreasing shear strength becomes less noticeable and the curves flatten out. Eventually however the porewater pressure builds up continuously with more antecedent rain until it reaches the levels where in the worst scenario no triggering rainfall is necessary to induce the movement. Consequently the curves steepen again.

The influence of antecedent rainfall conditions on actual daily triggering rainfall for the Wellington region is seen in Figure 5c. The choice for a quadratic model is based on three main arguments. First, contour plots clearly show the relationship is a curve. Second, the significance of the test of the quadratic model versus the

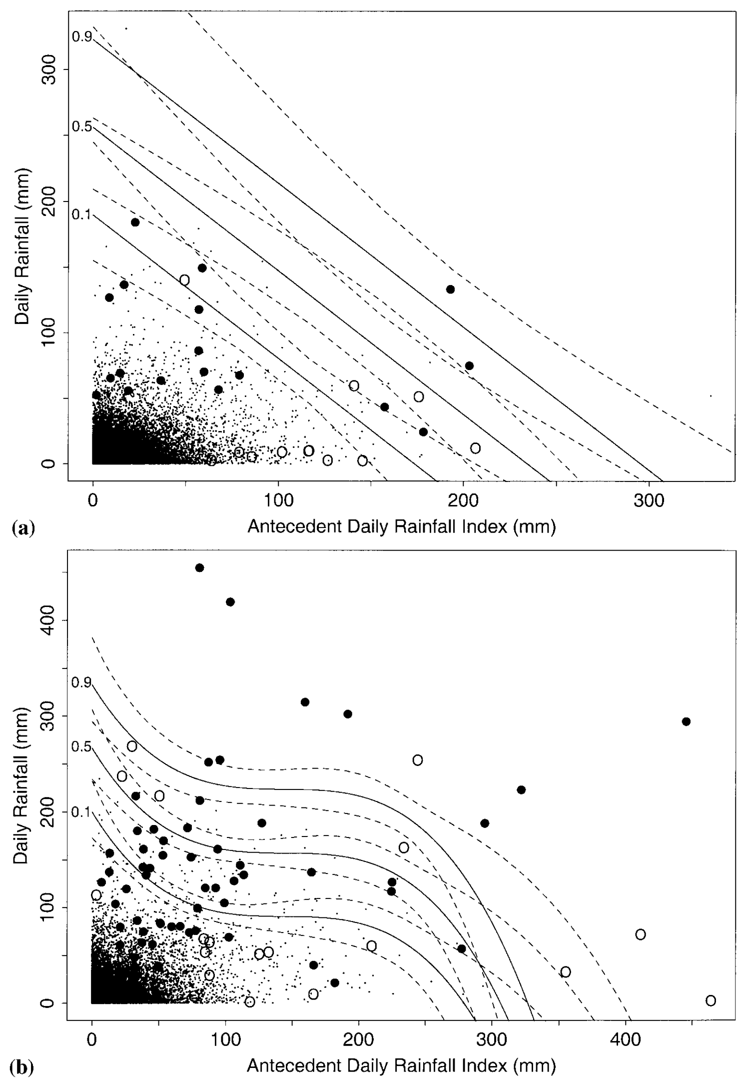
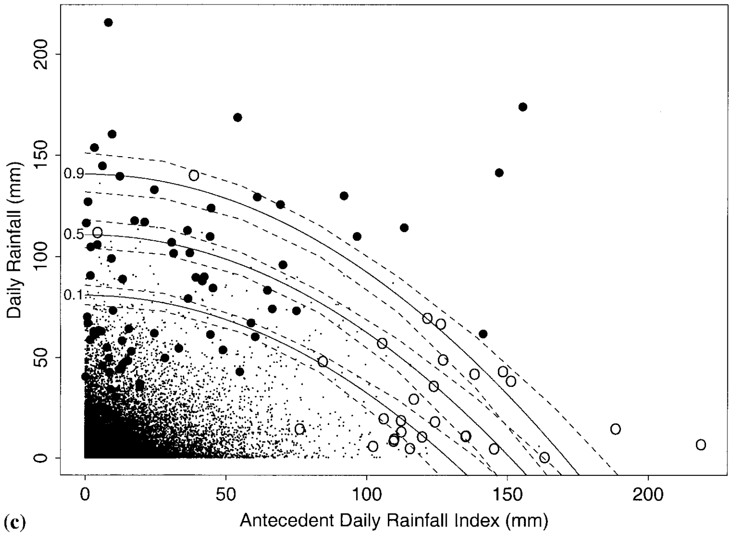


Fig. 5.



(c)

Figure 5
The *Antecedent Daily Rainfall Model* applied to the three regions in New Zealand (a) Wairarapa (Period 1883–1995, 40,576 observations/24,395 raindays), (b) Hawke's Bay (Period 1870–1995, 45,625 observations/24,106 raindays), and (c) Wellington (Period 1862–1995, 48,514 observations/26,109 raindays). *Note*: Calculation is based on raindays (>0.1 mm) only. Large dots relate to rainfall which triggered landslides, open circles relate to rainfall with probable landslide occurrence, and small dots relate to rainfalls which did *not* trigger landslides. Graphs have different scales. Confidence intervals are indicated for each probability curve by dashed lines. See equations from Table 4 for calculation of the probability curves in respective regions.

linear model is $8.7 * 10^{-5}$. Third, the screeplot shows that most of the increase in fit is supplied by the quadratic model. Further significant improvements are possible, even at an order 10 polynomial, however these models are complicated and results show physically nonintuitive or even unreasonable curves (i.e., non-convex).

Calculations were performed for 26,109 days with rainfall equal to or greater than 0.1 mm. Figure 5c suggests that the actual daily rainfall magnitude is particularly important for landslide initiation: landslides triggered by rainfall magnitudes less than 40 mm are grouped in two areas. One group is associated with high antecedent daily rainfall exceeding 100 mm while the second group shows only a minor importance of antecedent daily rainfall. The latter failures may be associated with other causes such as road cuts or building development on steep slopes, which is more common in the urbanised Wellington region rather than in the other two rural areas of Hawke's Bay and Wairarapa. On the other hand, even days with <20 mm of rainfall experience landsliding (lower right of Fig. 5c) which indicates that even very low rainfall may be able to trigger landslides after periods of sufficient antecedent precipitation.

Concept of Critical Water Content

The general negative behaviour relationship of antecedent conditions and daily rainfall concluded from Figure 5 conforms to the concept of a critical water content (CROZIER, 1997). This concept consists of two components: pre-existing water within the slope and triggering rain received on the day of landslide occurrence.

For a given probability of occurrence the critical water content can be obtained by summing the intercepts on the y and x axes from any point on the probability threshold. Theoretically then, if critical water content is a physical constant for a region, these values should always sum to the same amount. However, because of the wide range of controlling preconditions which exist in each region, as well as the statistical uncertainty of historical data, it is unlikely that such a theoretical relationship could be achieved.

The linear relationship for Wairarapa data most closely approximates the theoretical condition. For example, the 0.1 probability envelope yields a critical water content of 190 mm when antecedent rainfall is zero and 175 mm when daily rainfall is zero. The curved envelopes for Hawke's Bay and Wellington show a steepening gradient with increasing antecedent daily rainfall. This may suggest that under continued wet antecedent conditions there is a decrease in the critical water content required for landslide initiation. If this is the case, the rate of application of water rather than the total water content, may be important in lowering shear strength. It is possible that antecedent rainfall accumulating over a relatively long period progressively weakens the slope, making it more susceptible to triggering rainfall.

Assuming that the basic flood recession coefficient fits well for the hillslopes in each region, the overall gradients of the Hawke's Bay and Wellington curves indicate, in general, that more water is required to initiate landsliding if it is derived from antecedent rainfall than if it is derived simply from rainfall on the day of occurrence. For example, the 0.1 probability envelope yields a critical water content at zero antecedent conditions of 82 mm and a value of 128 mm at zero daily rain for Wellington; the corresponding values for Hawke's Bay are 285 mm and 201 mm.

The critical water content as indicated by the probability envelopes is also a measure of a region's overall susceptibility to landsliding. From these results Wellington stands out as the most susceptible region by having the lowest thresholds. Susceptibility however should not be confused with probability of occurrence or frequency with which landslides could be expected. Probability of occurrence is a function of both susceptibility and climatic conditions; i.e., the frequency with which rainfall exceeds the threshold curve. Although there is no evidence in recession coefficient, the relatively high susceptibility of Wellington may be a function of the amount of slope modification and drainage interference that has accompanied urban development in the region.

The increase of susceptibility due to urbanisation has been clearly demonstrated for given events in Wellington City by EYLES *et al.* (1978). That introduces yet another artefact: with greater population density, it is likely that many more small landslides are reported and used in analysis compared to the two rural areas (GLADE, 1998).

Discussion

Graphs such as these which define landslide probability thresholds may be useful for organisations which have to deal with landslides. Institutions such as insurance companies or regional government may be able to use these probability figures to define the appropriate level of either preparedness or, combined with risk analysis, to estimate the possible average costs resulting from landslide damage. The introduced model could be enhanced and even more useful for affected parties by including landslide type and, in particular, landslide magnitude into the analysis.

From an applied point of view, however, an index of antecedent daily rainfall is easily calculated on a day-to-day basis (Equation (3)). Thus, with a known antecedent daily rainfall value, the regional model provides the probabilities of landslides occurring somewhere in the region, assuming that the daily rainfall values required for threshold exceedence actually occur. To this probability has to be added the probability of the daily rainfall exceeding the threshold. This can be estimated by using empirical distributions of the probability distribution of daily rainfalls calculated from the meteorological record for the region (CROZIER, 1996), which is, to some extent, covered by traditional weather forecasting.

A more general question of probability of occurrence is: what is the probability of landslides occurring in a region in any year? To answer this, information is required regarding the frequency with which the combination of daily rainfall index and daily rainfall exceed the model threshold. As yet calculations on this basis have not been made.

Although the general use of these probability graphs is useful at the regional scale, there are problems associated with this modelling approach which have to be clearly addressed:

- The derived thresholds and calculated probabilities are regionally based and scale dependent. Extrapolation to different temporal and spatial scales must be done with care. It can be assumed that a given threshold varies in space and time with changing landslide-controlling factors (e.g., vegetation, geology, soils, topography, etc.) (CROZIER and PRESTON, 1998).
- The established thresholds give no distinction between different land use types, although land use has been shown to be a critical factor determining landslide occurrence in many settings (SIDLE *et al.*, 1985).

- Regional characteristics are important, but the definition of one value for an entire region is very problematic. This is a common result of generalisation. On the other hand, it is also a strength of this analysis because many land management decisions are made on a regional basis.
- The uncertainty in model building is due to three factors: sparse data on actual landslides, very large data sets which make formal significant tests of limited value, and the uncertainty over probable and actual landslide data.
- The effect of magnitude of landslide event or landslide type is not considered.
- Quality of landslide records may affect the reliability of the calculated thresholds and associated probabilities.
- Loss of water from the soil is not only through drainage. Water is also lost to the atmosphere by evapotranspiration, which is of course partly reflected in the decay factor. This flux of water between soil and atmosphere however has to be considered in more detail. One way of doing this is through the *Antecedent Soil Water Status Model*. This model will be addressed in the future.

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