

Assessing the Probability of Rapid Mass Movement

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SUMMARY Threshold conditions required to induce landsliding on Otago Peninsula and in Wellington City are identified by employing water balance calculations and antecedent rainfall indices to define the soil water status preceding each daily rainfall. These thresholds are used to compare terrain sensitivity and to assess the probability of landslide occurrence.

1 INTRODUCTION

While mass movement is one of the most important erosive processes on much of New Zealand's hill country, very little quantitative data is available; this is particularly true for the time of occurrence of mass movements because of the obvious difficulties of observing an extreme event which is discontinuous in both time and space. This paper, then, draws on information of variable quality compiled over a period of 12 years for three areas: Otago Peninsula, Wellington City and the Wairarapa.

As Selby (1979) has noted, 'nearly all examples of regional landsliding in recent years have occurred during individual storms or as a result of prolonged wet periods'. It is therefore reasonable to assume as a starting point that there is a rainfall threshold above which landslides will occur, and below which the input of rainfall to slopes is insufficient to trigger mass movements.

An examination of daily rainfall records shows that, instead of the presence of a distinct threshold, there is a wide range of rainfall values associated with landslide events. During 1974, landslides were reported to the Wellington City Corporation or in local newspapers on 20 individual days with rainfalls ranging from 3 to 88 mm. If the 20 December 1976 storm is included, Wellington City, since 1974, has experienced landslides on days with recorded rainfalls ranging from 3 to 236 mm. Similarly, landslide-triggering rainfalls on Otago Peninsula during 1977 and 1978 ranged from 6 to 57 mm. The 6 mm value was exceeded on no less than 79 days which were apparently free from slipping. It is therefore clear that no distinct threshold can be defined solely in terms of total rainfall on the day of landslide occurrence.

2 ANTECEDENT RAINFALL

The inability of daily rainfall amounts to define a consistent triggering threshold has been attributed in general terms to the variability of pre-existing soil moisture conditions. As direct measurements of soil moisture have only rarely been made immediately prior to a landslide event (e.g. Crozier, 1968) some other means of estimating antecedent conditions is generally required.

Of the four conventional methods of estimating antecedent moisture conditions: baseflow in rivers, well levels, climatic water balance and antecedent rainfall, the first two can be discount-

ed because of insufficient regional data and their inability to reflect conditions in the uppermost metre of soil where most landsliding occurs. The climatic water balance and antecedent rainfall methods overcome both these problems, the latter having the advantage of being simple to calculate.

During dry conditions the amount of rainfall in a period preceding an event will give a general indication of soil moisture storage and during wet conditions will indicate in addition the amount of gravitational water in the soil system. If antecedent rainfall is sufficient to produce overland flow, a rare situation in temperate environments, antecedent rainfall values will over-estimate the amount of moisture in the soil. Inaccuracies will also occur as a result of variation in evapotranspiration rates throughout the year.

For these reasons and because of the unknown variability in soil and site properties throughout the areas studied, the amount of antecedent rainfall can be considered only as an index to antecedent soil moisture.

A measure of antecedent rainfall is used in Figure 1 in an attempt to define landslide triggering rainfall conditions for the Otago Peninsula during 1977 and 1978. Antecedent rainfall was determined for a 10 day period immediately prior to an event using the method outlined by Kohler and Linsley (1951).

$$Pa_o = KP_1 + K^2P_2 + \dots + K^nP_n \quad (1)$$

where Pa_o is the antecedent daily rainfall for day 0,

and P_n is precipitation on the n'th day before day 0.

The value of 0.84 used for K is close to that used in hydrological studies in North America (Bruce and Clark, 1966) and has been chosen for its ability to delineate a threshold between landslide and non-landslide producing conditions. The K factor is decayed by an exponential function so that past rainfall exerts progressively less influence on the index as time elapses. Values derived from the equation should only be considered as an index as their power to depict actual soil moisture levels is unknown. The decay rate employed therefore represents only an approximation of outflow from the soil as a result of drainage and

evaporation processes assumed to be operating at a constant rate throughout the year. The index does however allow for greater absolute outflows with higher soil moisture levels, in recognition of the lower soil tensions and greater hydrostatic heads that prevail under such conditions.

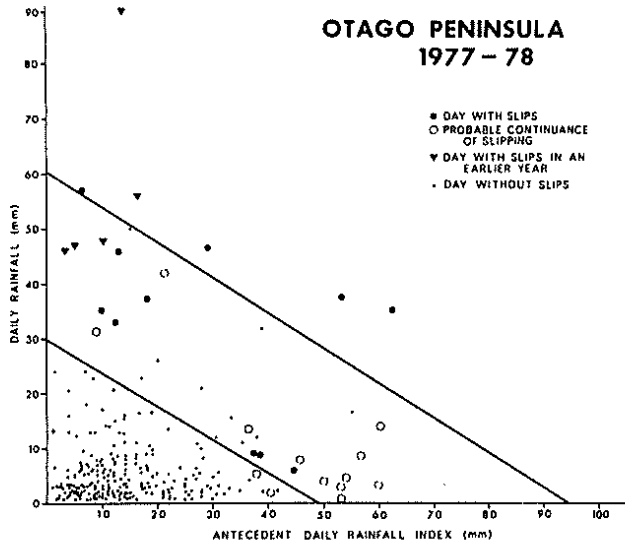


Figure 1 Landsliding episodes related to rainfall

Two principal envelope lines can be drawn on Figure 1 separating conditions with different probabilities of landsliding. As expected, the envelopes indicate that progressively smaller amounts of rainfall are able to trigger landslides as the antecedent rainfall index increases. The upper line is a well defined threshold indicating conditions which when exceeded invariably produced landslides during 1977 and 1978. The lower line represented the conditions above which there was some probability of slipping.

3 SOIL MOISTURE BALANCE

Antecedent conditions are more clearly defined in terms of soil moisture storage levels which depend, in addition to rainfall inputs, on loss of water to the atmosphere through evapotranspiration and the ability of the regolith to hold water. These factors are incorporated in a soil moisture balance model adapted by the New Zealand Meteorological Service from the theory of Penman (1948). Estimates of potential evapotranspiration are derived from mean temperature, vapour pressure, windspeed and sunshine hours, all of which are measured at official climatological stations. Available soil moisture capacity is defined as the amount of water that can be held in the top 76 cm of the regolith between tensions representing field capacity (the maximum moisture that can be held against gravity) and permanent wilting point (the level below which plant roots cannot extract water).

The model is used by the Meteorological Service to monitor soil moisture levels for pastoral and arable productivity, the 76 cm soil depth being an estimate of grass and crop rooting zones. This depth is, however, also appropriate for the shallow debris falls, slides, or flows which are the most common types of slope failure in New Zealand. While the soil moisture capacity of the top 76 cm varies considerably with soil type, a single value of 120 mm, an approximate mean of the values quoted by Gradwell (1974) for yellow brown and yellow grey

earths in central and southern New Zealand, is adopted in this study. Deficit soil moisture storage (DS) is recorded in the water balance programme on every fifth day but its value on any one day can be readily derived by the equation:

$$DS_0 = DS_1 - (P_0 - PE_0) \quad (2)$$

where DS_0 is deficit storage on day 0,

DS_1 is deficit storage for the day before day 0,

P_0 is precipitation on day 0,

PE_0 is the potential evapotranspiration for day 0

The computer printout, giving soil moisture deficits at 5-day intervals, can be used together with daily rainfall values to plot graphs such as Figure 2. Zero on the soil moisture storage scale signifies field capacity, and a deficit of 120 mm implies that the regolith has dried out to wilting point; it is assumed that no further drying out takes place. When a rainfall event occurs of sufficient magnitude to recharge soil moisture storage to field capacity, any additional precipitation is termed 'excess' and is shown as a vertical line on the graph. Excess water generates positive pore water pressures which may trigger landsliding. 'Excess' rainfall is equivalent to 'runoff' in the Meteorological Service model and is printed out by the standard programme for each month. Daily 'excess' rainfall (EP) can be easily derived from the programme by the following equation:

$$EP_0 = (P_0 - PE_0) - DS_1 \quad (3)$$

where EP_0 is excess rainfall on day 0,

P_0 is rainfall on day 0,

PE_0 is potential evapotranspiration on day 0,

DS_1 is deficit storage on the day before day 0

The graph for Kelburn, 1974 (Figure 2), shows that the summer and autumn months of that year were dry with soil moisture deficit reaching 120 mm for a brief period in January and February. From mid-April to the end of October soil moisture storage was almost at, or above, field capacity. The year 1974 is the worst on record in terms of number of landslides experienced in Wellington City, with most of the estimated 2000 occurring on 29 May, 2 July and 8 October; the three days in which rainfall 'excess' reached 60 mm.

The model was applied to historic landsliding in Wellington City (Eyles, 1979) using newspaper reports to identify events. A reasonably consistent relationship was discovered, with daily rainfalls 50-55 mm or more in excess of soil field capacity triggering landsliding sufficiently serious to be reported by the news media. However, during 1974 several hundred mass movements in Wellington City occurred on days other than the three with high excess rainfalls. The model clearly, therefore, allows recognition of only the most serious events.

4 ANTECEDENT EXCESS RAINFALL

An assumption in the soil moisture balance model as

5 DAY WATER BALANCE

Kelburn 1974

Rainfall 1706 mm

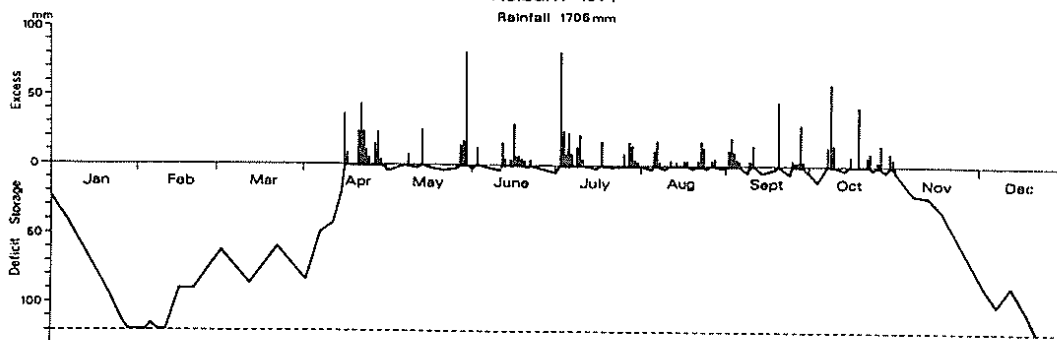


Figure 2 Soil moisture balance graph representing Wellington City, 1974

used above is that 'excess' rainfall drains through the top 76 cm of the regolith very rapidly, with no carry over of water above field capacity into the next day. While this may be valid for the steepest slopes and coarsest-textured greywacke regolith, it is not a realistic representation of the typical Wellington soil, much less of soils derived from finer-grained sedimentary rocks, typical of much of New Zealand's hill country.

Excess rainfall remaining in the soil in the form of gravitational water is likely to reduce slope resistance by diminishing soil cohesion or by developing positive porewater pressures. In many situations drainage will be sufficiently slow for gravitational water to exert an influence lasting over a number of days. In recognition of this factor, an antecedent excess rainfall index has been used in Figures 3 and 4 in an attempt to define more accurately landslide triggering conditions.

The antecedent excess rainfall index (EP_a) is calculated by the equation:

$$EP_a = KEP_1 + K^2 EP_2 \dots + K^n EP_n \dots \quad (4)$$

where EP_a is the index for day 0,

EP_n is excess rainfall on the n'th day before day 0

For the same reasons used to establish the antecedent daily rainfall index, an exponential decay function employing a K factor of 0.84 over a 10 day period has been chosen for this index.

The antecedent excess daily rainfall index thus provides some measure of the overall soil water status when soil moisture is in excess of field capacity. At other times, the most appropriate measure of the soil water status is soil moisture storage, defined as deficit storage by the water balance model. Deficit storage and antecedent excess rainfall form a continuum representing the status of soil water existing immediately prior to any rainfall event. The soil water status defined in this way has been plotted on the abscissa in Figures 3 and 4 for the Otago Peninsula and Wellington City study areas.

In both localities, this approach has permitted the delineation of a single envelope which represents a distinct threshold separating landsliding conditions from non-landsliding conditions. The threshold lines for the two localities are nearly parallel and indicate a clear regional difference

in susceptibility to landslide triggering conditions. For example, if both regions had reached a soil water status of 'antecedent excess rainfall' equalling 20 mm, the daily rainfall required to produce landslides in Wellington City would be 23 mm greater than the triggering rainfall on the Otago Peninsula.

The measures used in Figures 3 and 4 to define the water status of the soil have successfully explained landslide producing conditions for all but one event. This occurred in Wellington City in response to a 10 mm rainfall when antecedent excess rainfall had amounted to only 27 mm. Apart from local site factors, a possible explanation for this event might lie in the occurrence of an unusually high short-term rainfall intensity during the day concerned. This would facilitate a rapid build up of gravitational water which although only momentarily stored may be sufficient to induce instability. The development of temporary stores of gravitational water (perched water tables) can be enhanced not only by high rainfall intensities but also by the presence of relatively low permeability strata located within the regolith. The landslide event which occurred in response to a 91 mm daily rainfall (Figure 3) possibly reflects the presence of a low permeability stratum being located close to the soil surface and the consequent development of a perched water table during the rainstorm. This would account for the triggering of movement even though the daily rainfall appeared to be insufficient to bring soil moisture storage to full capacity. This illustrates that a soil moisture capacity of 120 mm is only an average figure based on assumed soil depth, and cannot be expected to adequately represent the variety of local conditions which exist throughout any region.

5 APPLICATIONS

The definition of threshold conditions for landsliding in different regions (Figure 5) can be used to rank the sensitivity of various terrain types to climatically induced slope instability. The 100% probability lines in Figure 5 indicate that the sensitivity of region B is greater than A which in turn is greater than C.

Sensitivity ranking alone, however, will only be a measure of relative susceptibility to landsliding under homogeneous climatic conditions. The ranking of regions on the basis of landslide susceptibility for land use planning purposes, therefore, generally requires an analysis of the regional climatic conditions. If the slip-triggering conditions represented by the threshold line can be

LANDSLIPPING ON OTAGO PENINSULA

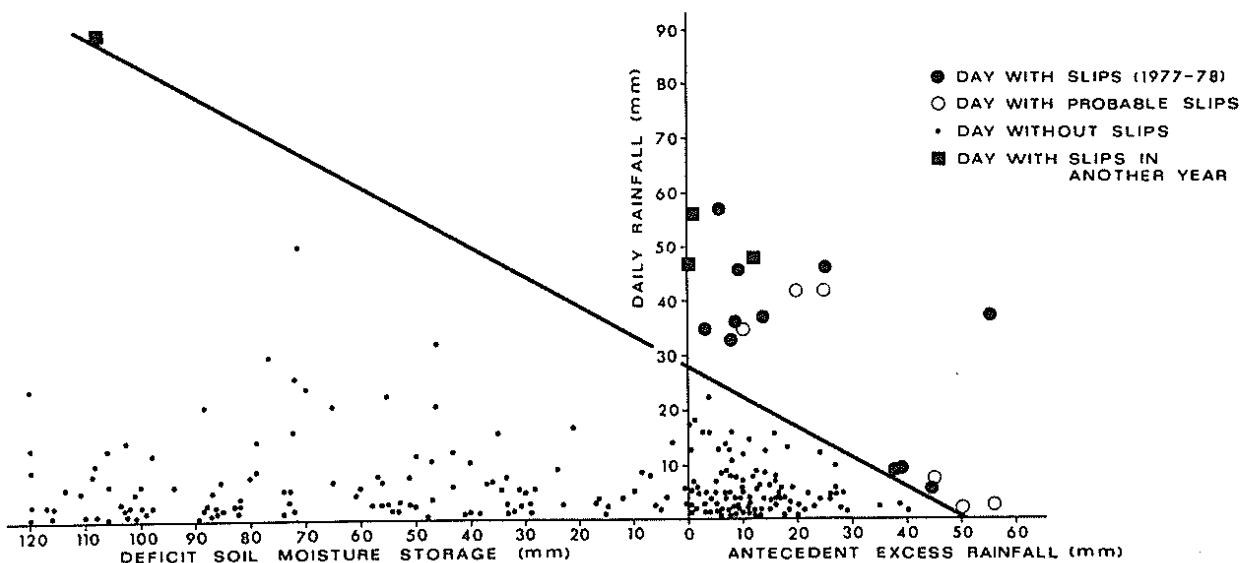


Figure 3 Days of landsliding in relation to daily rainfall and antecedent soil moisture status, Otago Peninsula

LANDSLIPPING IN WELLINGTON CITY 1974

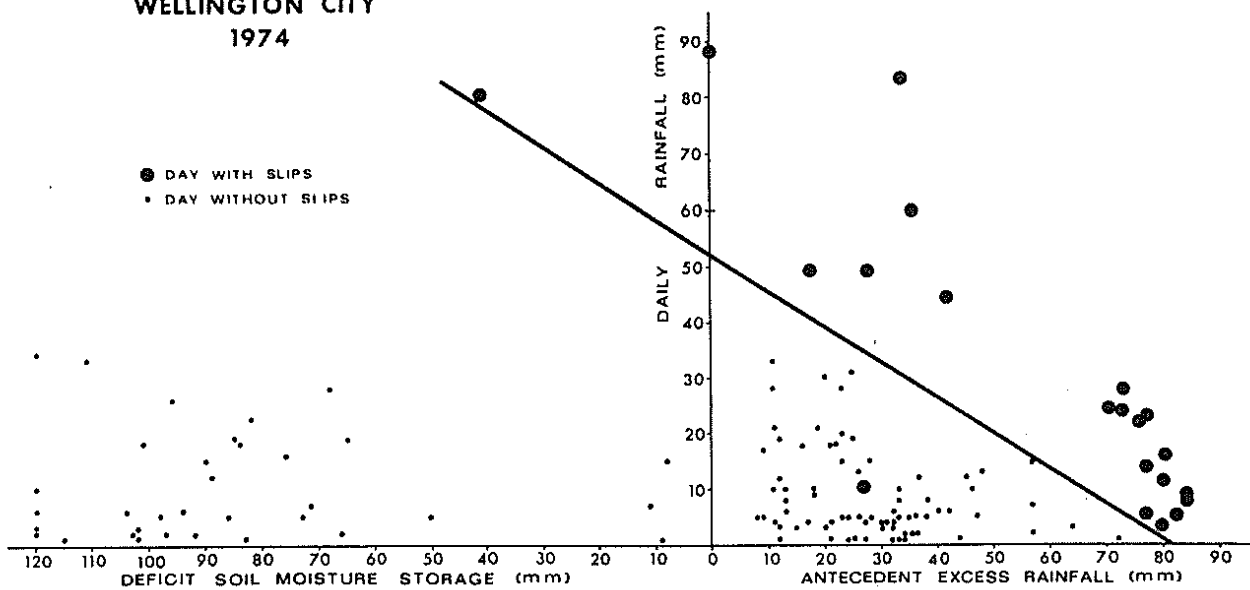


Figure 4 Days of landsliding in relation to daily rainfall and antecedent soil moisture status, Wellington City, 1974

LANDSLIP PROBABILITY

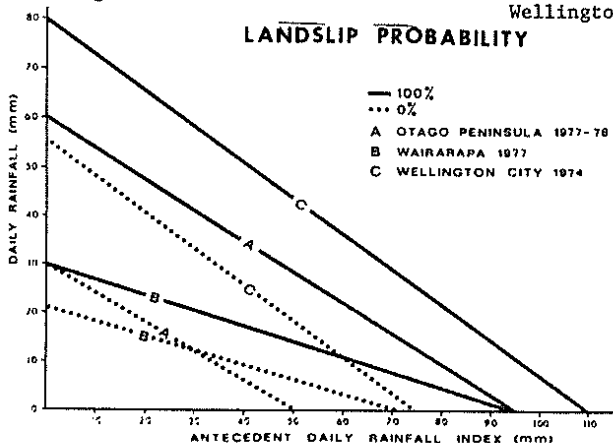


Figure 5 Probability of landsliding in three regions

assigned return periods on the basis of magnitude/frequency analysis, then the susceptibility of each region can be ranked in terms of the probability of landslide triggering conditions being achieved within a finite time period. This represents an empirical approach to slope stability assessment which is not only less expensive than many other methods but most importantly recognizes the range of climatic induced stresses experienced in the field.

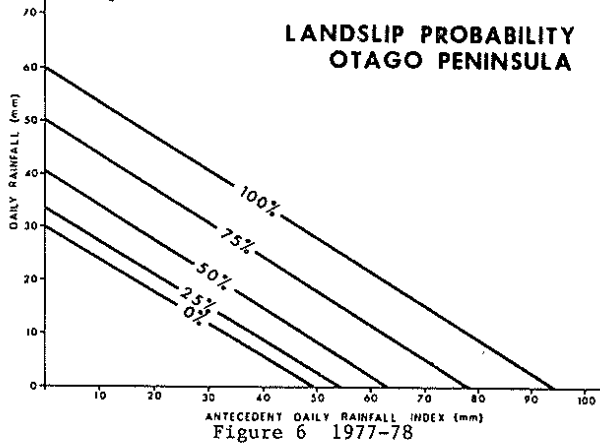
The other major application of this work is the provision of a procedure to quantitatively assess the likelihood of landsliding at any point in time. Assuming that regional landslide triggering thresholds have been established, the only calculation required is the updating of the antecedent daily rainfall index or the antecedent excess rainfall on a daily basis. From (1), for example, it is evident that:

$$Pa_0 = K(Pa_1 + P_1) \quad (5)$$

Where Pa_0 is the antecedent daily rainfall index for day 0,

Pa_1 is the antecedent precipitation for the day before,

and P_1 is precipitation for the day before



Using the more readily calculated antecedent daily rainfall index as an example, the historical data can be presented in the form of a probability threshold diagram (Figure 6). Referring the updated index to the diagram, it can be seen that when a value of 54 mm is reached there is a 25% chance that the next rainfall will produce landsliding, at 64 mm a 50% chance, at 79 mm a 75% chance and at 95 mm a 100% chance. Although the index can be monitored in this way to reveal the onset of a critical soil water status, it is obvious that there is always a chance that a rainfall event of sufficient magnitude could trigger landsliding even when the index is less than 50 mm.

Information on current synoptic weather situation may complement the forewarning procedures outlined, as frontal and orographic induced rainfall is generally unable to produce landsliding on Otago

Peninsula when the index is less than 20 mm. However, depressions, particularly tropical cyclones, may provide sufficient rainfall to cause slipping even when the soil moisture storage is in deficit.

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