Z. Geomorph. N.F.	Suppl.-Bd. 115	141–155	Berlin · Stuttgart	Juli 1999

Frequency and magnitude of landsliding: fundamental research issues

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with 5 figures and 1 table

Summary. Some fundamental research issues related to the application of frequency-magnitude analysis to landslides are discussed. It is shown that there are marked differences between the hillslope system and the fluvial system from which many of the original frequency-magnitude concepts were developed.

Parameters used to characterise the episodic behaviour of landsliding are presented and discussed with respect to their value in addressing specific research questions. Frequency-magnitude analysis should distinguish between first-time failures and reactivations of existing landslides and be applicable to both temporal and spatial distributions.

Methodological approaches to the establishment of temporal frequency and magnitude are presented and illustrated. Both empirical and deterministic methods are discussed. In particular, advances in empirical modelling are used to show the extent to which the probability of landslide occurrence can be determined within a regional context. This method requires recognition of a range of landslide-triggering rainfall thresholds and these in turn rely on the establishment of a comprehensive database on both climate and landslide history.

Frequency-magnitude analysis can also be applied to the spatial distribution of landslides. Whereas smaller landslides are more common than larger landslides, geomorphic work and land-forming dominance, in some areas, is achieved by the largest landslides on record.

Zusammenfassung. Einige grundlegende Überlegungen zur Frequenz-Magnituden Analyse von Hangrutschungen werden diskutiert. Es wird gezeigt, daß entscheidende Unterschiede zwischen dem Hangsystem und einem fluvialen System, von dem ursprünglich die Frequenz-Magnituden Analyse entwickelt wurde, bestehen.

Parameter, die das episodische Auftreten von Hangrutschungen charakterisieren, werden dargestellt und in Bezug auf ihre Aussagefähigkeit für bestimmte wissenschaftliche Fragestellungen diskutiert. Frequenz-Magnituden Analysen sollten zwischen Erstauslösung und Reaktivierung bereits existierender Hangrutschungen unterscheiden und sowohl für räumliche als auch zeitliche Fragestellungen anwendbar sein.

Methodologische Ansätze einer zeitlichen Frequenz-Magnituden Analyse werden aufgezeigt und illustriert. Empirische und deterministische Methoden werden diskutiert. Im Besonderen werden neue Erkenntnisse in der empirischen Modellierung benutzt, um die Wahrscheinlichkeit des Auftretens von Hangrutschungen im regionalen Maßstab aufzuzeigen. Diese Methode erfordert die Kenntnis einer Reihe von hangrutschungsauslösenden Niederschlagsschwellenwerten, welche wiederum nur durch die Erstellung einer umfassenden Datenbank, die sowohl klimatische Zeitreihen als auch historische Information über Hangrutschungen erhalten muß, erlangt werden kann.

Eine Frequenz-Magnituden Analyse kann auch auf die räumliche Verteilung von Hangrutschungen angewandt werden.

Obwohl kleinere Hangrutschungen häufiger Auftreten als große Hangrutschungen, wird in einigen Gebieten die geomorphologische Arbeit und die Landformung dominiert von den größten historischen Hangrutschungen.

0044-2798/99/0115-0141 $ 3.75

1 *Introduction*

Over the last few years, frequency-magnitude analysis, originally developed in the context of fluvial geomorphology, has been applied to a wide spectrum of geomorphic processes. The episodic behaviour of landsliding lends itself well to this approach. For example, knowledge of the frequency and magnitude behaviour of landsliding provides the basis for:

- Characterising landslide hazard (CROZIER 1996)
- Assessing rates of geomorphic work (TRUSTRUM et al., this volume)
- Identifying significant temporal change in the environmental factors which affect landsliding, such as, climate, seismic activity, vegetation, and land use. (CROZIER 1997)

To carry out these activities successfully a good quality database is required. In this respect, landslide studies are at a distinct disadvantage compared with more data-rich fields such as fluvial geomorphology. Most studies of landslide frequency and magnitude have had to develop their own primary data and, because of the effort required, are often limited in areal and temporal extent. There are few standardised systems in place for recording landslide activity and even fewer long-term records available. Current discussion on suitable recording protocols (GLADE & CROZIER 1996) has focussed attention on which landslide parameters are of value for specific management purposes and how databases should be structured and maintained.

Traditional approaches to determining frequency and magnitude have centred on fluvial processes (WOLMAN & MILLER 1960) and have dealt with 'frequency' in terms of discrete hydrological events and 'magnitude' by measures of volume or mass of water and sediment associated with those events. They assume a direct relationship between the hydrological processes and the geomorphic response. In contrast, the relationship between a landslide and its initiating process (such as a rainstorm) is further complicated by the intervening behaviour and properties of the hillslope system.

The purpose of this paper is to raise some of the fundamental issues relating to the episodic behaviour of landsliding. Concepts and parameters are defined with respect to the anticipated end-use for the information. Different methodologies for obtaining and analysing information on landslide activity are reviewed. Finally, examples are presented which indicate the extent of our knowledge on the frequency-magnitude behaviour of landslides.

2 *Concepts and parameters*

As argued elsewhere (CROZIER, this volume), frequency and magnitude are just two of the many parameters which are required to characterise adequately the behaviour of an episodic geomorphic process. Bearing in mind the main purposes for studying episodic behaviour of landslides (assessment of hazard, geomorphic work, and environmental change), a comprehensive and purpose-oriented characterisation of episodic behaviour is required. Ideally, this should include information on starting and terminating thresholds, duration, and areal extent of occurrence as well as an appropriate characterisation of frequency and magnitude.

2.1 *Events, frequency, and duration*

'Frequency' of landsliding might initially appear to be a straightforward concept. However, landslides can occur either as 'first-time' failures or as subsequent reactivations. Whereas the effects of landslide events are important irrespective of their origin, the physical conditions and starting thresholds are quite different. First-time failures, in a given material, need to overcome higher material strength values than in the case of reactivations, as represented by differences between peak and residual strength respectively. Determining frequency from the behaviour of the triggering agent (a common approach) therefore needs to take these different strength-related thresholds into account. Reactivation of deep-seated landslides appears to be more frequent than the occurrence of first-time failures. REIMER (1995), for example, has noted that two-thirds of the landslides entering reservoirs are reactivations of existing slides. Because of this difference in the frequency of movement, it is common engineering practice to be much more concerned about the hazard presented by existing landslides than the probability of occurrence of first-time failures. By contrast, situations have been described involving shallow, regolith landslides where first-time failures are more common than reactivations. In these situations, special geomorphological conditions usually apply such as widespread destabilisation of the regolith by recent deforestation. The landslide deposits are either removed from the hillslope system or deposited at depths and angles which preclude further regolith failure (CROZIER & PRESTON 1998).

Thus there are two classes of landslide event to which frequency analysis can be applied; first-time failures and reactivations. Inventories of landslide activity should distinguish between these two types of movement, because of the fundamental geotechnical differences which apply.

Correspondingly, other parameters, such as duration, may refer to the first-time failure or to the reactivation. Differences in duration between the first-time failure and reactivations may be considerable. For example, MCSAVENEY et al. (1992) have shown that, in New Zealand schist terrain, certain existing deep-seated landslides which produce periodic seasonal reactivations may have initially failed around 250,000 years BP. No evidence was found for similar landslides occurring within the last 15,000 years. Thus, the frequency and duration of the initial first-time failure can be markedly different from that of the reactivations. Landslides clearly have distinctive lifetimes. Shallow regolith failures are often instantaneous, with a lifetime measured in seconds or minutes. Other landslides, after initial failure, may be subject to continual movement for hundreds of years before they cease movement altogether (Fig. 1).

Whereas the occurrence of a single landslide may be considered an event, the term 'landslide event' can have a broader connotation. For example, a single triggering event, such as an intense rainstorm, may produce up to hundreds or even thousands of individual landslides over a wide area (CROZIER et al. 1980, GLADE 1997) (Fig. 2). Consequently, frequency and magnitude analysis can also be applied to the spatial distribution of landslides occurring in a single triggering event as well as to temporal distributions. Frequency-magnitude relationships derived from spatial analysis may also be analysed in terms of the amount of geomorphic work achieved (INNES 1985).

Fig. 1. The deep-seated landslide (foreground) is subject to periodic reactivations, particularly during wet conditions of winter. (Photo: National Water and Soil Conservation Authority, New Zealand).

2.2 *Magnitude*

The term 'magnitude' is a measure of scale which, in the strict sense, refers to the mass or volume of material moved in an event. However, the scale of an event may be more appropriately represented by some other measure of magnitude, depending on the overall purpose of the study. For example, in conventional hazard and risk analysis, hazard is defined as 'the probability of occurrence of a given magnitude of event' (VARNES 1984). In this instance, where the intention is to measure danger or threat, it may be better to represent magnitude by some parameter that conveys the scale of danger more accurately than volume. Landslides with similar volumes may be quite different in terms of their hazard potential. For example, two landslides might both have a volume of 5,000 m^3 but one is 10,000 m^2 in area and only 50 cm in depth and the other 1000 m^2 in area and 5 m in depth. Clearly the deeper one is a much more serious threat to buildings and infrastructure than the shallow one, which may, on the other hand, be a greater problem in terms of soil degradation. The parameter used to represent 'magnitude' in the 'frequency-magnitude' calculation of hazard should therefore be one matched with the overall objective of the analysis. Parameters representing hazard potential ('impact

Fig. 2. Shallow first-time landslides triggered during the one rainfall event, North Island, New Zealand. (Photo: Garth Eyles).

characteristics' (CROZIER 1996), besides depth and volume, include areal extent of scar, distance of runout, velocity, duration, and degree of disruption. The frequency distribution in time of any of these parameters is largely unknown and constitutes an important area of future landslide hazard research. The lack of knowledge of frequency-magnitude behaviour of landslides has meant that, to date, most so-called landslide hazard maps simply rank terrain in terms of its susceptibility (CROZIER 1995).

Landslide events producing multiple landslide occurrences (clusters or swarms) are an important phenomenon in many parts of the world. In a given region, multiple occurrence events appear to be much less frequent than single events. In the mountains around the Japanese city of Kobe, for example, individual shallow landslides are estimated to have a return period of about 10 years whereas swarms occur with a return period of 30 years (OKUNISHI et al., in press).

To assess the frequency and magnitude with which multiple occurrence landslide events occur, requires a different set of parameters in addition to those used for individual landslides. The 'magnitude' of this type of event can be represented by measures of severity of landsliding within the affected the area. This first requires definition of 'affected area'. Theoretically, this measure is defined as the landsurface area within an envelope enclosing the cluster of landslides that occurred during the event. In practice, this is difficult to define because of the presence of landslides lying outside the main cluster of occurrences. Nevertheless, the parameter, 'affected area' is seen as a useful measure of event magnitude. In the case of earthquake-triggered landslides, KEEFER (1984) has demonstrated that there is a close relationship between the magnitude of the forcing process (earthquake magnitude) and the magnitude of the affected area.

Initial definition of the 'affected area' then allows other associated measures of magnitude to be employed. These include: the percentages of the affected area subject to erosion, transport and deposition (respectively or collectively), density of landslides (number per unit area), and material displaced per unit area (sometimes inaccurately expressed as a lowering or denudation rate of the 'affected area'). Alternatively, area and volume measurements may be expressed in absolute terms. The use of some of these measures is illustrated in Table 1.

Table 1. Magnitude parameters for multiple occurrence landslide episodes derived for three regions, North Island, New Zealand (GLADE 1997).

Magnitude parameter	Hawke's Bay	Wairarapa	Wellington
Study area (km^2)	49.04	122.72	25.16
Total landslide scar area (km^2)	0.16	0.81	0.10
Scar area (%)	0.32	0.66	0.40
Number of landslides	19,189	6,080	1,027
Landslide density (no/ha)	3.90	0.50	0.40
Mean scar area (m^2)	8.30	132.70	97.90
Mean volume (m^3/m^2)	2.20	0.73	0.78
Total volume displaced (m^3)	337,726	588,981	78,430
Mean scar volume (m^3)	4.08	96.90	76.4
Study area denudation (mm)[1]	6.80	4.8	3.1

[1] Denudation refers to specific landslide episodes.

2.3 *Frequency-magnitude relationships: rivers versus hillslopes*

Early frequency-magnitude research was driven by the debate over *uniformitarianism* versus *catastrophism* with respect to the geomorphic work done in the landscape. WOLMAN & MILLER (1960) thus designed their work to isolate the 'dominant discharge' which, measured by the product of its frequency and magnitude, was the class of event that achieved the largest amount of work in the period of record. Theoretically, the dominant landslide magnitude is also obtainable for landsliding by obtaining the product of frequency and magnitude of landslides in the record on either a spatial or temporal basis.

In practice, however, there are number of differences between the event data that is obtained from a given channel reach in a fluvial system and the event record of landslides. First, landslide events are much less frequent than streamflow events and, in order to obtain a comparable database, the landslide observational period must be longer. Consequently, as the required observational period increases, there is a greater chance that the evidence of smaller events will be obliterated or overlooked thus affecting the overall frequency distribution. Second, unlike river gauging stations, the location of landslide sites generally varies with each event thus introducing variation in the suite of controlling factors, including those which influence landslide magnitude. Finally, the concept of geomorphic work, which in the discharge event is a function of magnitude and frequency, may not be adequately represented by these factors in the case of landsliding. The reason for this is that the magnitude of a landslide actually represents the mass of material 'displaced' and not true work in terms of mass multiplied by distance moved. Some landslides, although large in volume, may be displaced only a few centimetres and remain in that position for hundreds of years thus playing only a small role in landform evolution.

A stable relationship between frequency and magnitude and the reliable designation of 'dominant' or 'effective' events can only be achieved if the system is in a state of equilibrium. While this may prevail for certain types of channel system over short periods, it is rarely the case in a landscape affected by landsliding. Landsliding is a self-annihilating process. Its very action tends to destroy the conditions which favour its initiation. Deep-seated landslides reduce the critical height or slope as a consequence of their action. In addition there is evidence (PRESTON, this volume) that regolith landslides events successfully exhaust the available material and alter terrain conditions with each event, changing the triggering-thresholds with time. Thus the scale of mass movement initiated by a given magnitude of triggering rainstorm or seismic shock may change with time. The rate at which thresholds vary with time is not well understood.

A study of south Taranaki, North Island, New Zealand provides an indication of how the 'effective' landslide event may change in the course of landform evolution (CROZIER & PILLANS 1991). In this area, continual uplift and exposure of marine sediments, at a rate of up to 1 mm per year for over two million years, has produced a landscape of young marine terraces at the coast and deeply dissected, older terraces and hill country inland. By comparing terraces of different ages it is possible to substitute space for time. This shows that, in the first half million years of slope development, modal valley side slope angles (approximately 30 degrees) are produced by shallow rainstorm-triggered landslides continually removing the regolith as it forms. Landslide activity of this type occurs somewhere in the region about every five or six years. However, for terrain that has experienced longer periods of uplift and fluvial dissection, sufficient relief is formed to produce stress within the bedrock itself. This allows seismic activity to trigger deep-seated landslides. These landslides occur at a frequency of hundreds to thousands of years; they are high magnitude-low frequency events compared with the effective events operative in the earlier stages of landform evolution. The deep-seated landslides destroy the shallow landslide equilibrium slopes and produce an entirely different topography. As the 'residence time' of landslide topography produced in this way (relaxation time) is greater than the return period for deep-seated landslide events (transient form ratio – BRUNSDEN & THORNES 1979), the topography is evidently undergoing irreversible change.

3 *Methods of investigation*

There are two fundamental approaches to determining the temporal frequency-magnitude behaviour of landslide activity, empirical and deterministic. The deterministic approach is still in its infancy and relies on predetermined relationships between the external triggering mechanism and the balance of stresses within the slope. The empirical approach, on the other hand, has been developed over a longer period and relies on the establishment of a record of landslide occurrence.

Methods for establishing the required record of landslide activity can be classed into two main groups, 'on-site' and 'off-site'. The on-site group includes:

- direct monitoring of hillslopes and existing landslides. This method is generally used to record reactivations rather than first-time failures and involves the use of sophisticated sensors such as strain gauges, inclinometers, and precise survey of surface and subsurface positional indicators (GILLON & HANCOX 1991).
- survey and direct field dating of actual landslide remnants. Many standard relative and absolute dating techniques have been successfully applied to landslides (LANG et al., in press, MCSAVENEY et al. 1991, BULL 1996, CROZIER et al. 1995, WEISS 1988).
- the use of documentary sources, including sequential air and ground photo coverage (BRUNSDEN & IBSEN 1994, GLADE 1996, GUZZETTI et al. 1994, THOMAS & TRUSTRUM 1984).
- Surrogate histories of landslide activity built up indirectly from records of associated infrastructural damage (SORRISO-VALVO 1997).
- Techniques which provide indirect physical evidence of movement, eg. Dendrogeomorphological studies of debris impact on trees (VAN STEIJN 1996, FANTUCCI & MCCORD 1995).

'Off-site' records rely mainly on stratigraphic analysis of sediment in depositional sites (PAGE et al. 1994, PAGE & TRUSTRUM 1997). Because of the obliteration of evidence in the active geomorphic environment of hillslopes, off-site records have the potential to extend over longer periods than on-site records. On the other hand, the signature of landslide activity recorded off-site may be obscured by complex transportational behaviour within the source catchment.

Whether established by on-site or off-site methods, a record of landslide activity can be used either directly or indirectly to obtain a measure of frequency. The direct approach is simpler and is achieved by dividing the number of landslide events or classes of landslide event by the length of the observational record. This provides the 'historical frequency' of events.

The indirect approach, in contrast, is more complex but has greater potential for forecasting landslide activity and determining the mass movement response to climatic change and other triggering factors. The indirect approach couples the forcing-process with a process-response. For rainfall-triggered landslides this involves establishing an initiating threshold between rainfall parameters and landslide occurrence (CROZIER 1989, JULIAN & ANTHONY 1994, GLADE et al., in press). For earthquake-triggered landslides, the threshold between non-occurrence and occurrence is usually either a value of shaking intensity or earthquake magnitude (KEEFER 1984).

Thresholds established in this way simply measure the susceptibility of the terrain under study to the landslide-triggering process. Clearly, inherent stability conditions and consequently thresholds will vary from place to place. A reliable regional threshold, however, may be used to determine the probability of occurrence (statistical frequency) of landslide activity by reference to the frequency-magnitude distribution of events for the triggering agent.

In situations where there is only a limited record of previous landslide activity, the empirical method is of little value. However, with the development of combined hydrology, slope stability, computer simulation models (ANDERSON 1996), a deterministic approach offers a promising alternative. This can be used to establish initiating thresholds for landslides in terms of rainfall input, and porewater pressures (either positive or negative). Essentially, in a validated model with the appropriate parameters for slope hydrology and strength, rainfall can be 'applied' incrementally, until on-going iterative stability analysis indicates failure. The rainfall total at failure thus represents a landslide-triggering rainfall threshold and this can be applied to frequency-magnitude distribution of the climate record to obtain probability of landslide occurrence. As with all modelling of this type, the set of parameters employed represent only a sample of what exists in the field. The representativeness of this approach is limited and it is likely to produce its most reliable results for individual slopes rather than large areas of terrain.

4 *Frequency and magnitude findings*

A few examples are given here to indicate the type of frequency and magnitude information that has been obtained by using the research methods discussed above. In general, the most detailed information relates to small areas and short periods of time.

4.1 *Regional frequency*

GLADE (1997) has employed a range of methods to obtain regional frequency data for New Zealand. Much of the work involved the initial establishment of a comprehensive database (GLADE 1996) which, although extensive, was unable to yield sufficient information for magnitude analysis. Using this database, it was possible, however, to produce historical frequencies for all New Zealand regions. In addition, by using the indirect threshold approach, probabilities of occurrence were calculated for three regions studied in detail.

Three different threshold models were applied to all three regions: the daily rainfall model, which simply compares rainfall magnitude and landslide occurrence, the antecedent daily rainfall model, which includes also information on antecedent rainfall over a defined period, and the antecedent soil water status model, additionally reflecting the soil moisture condition.

In the following case study, results obtained by applying the simple daily rainfall model to the Wellington region, North Island, New Zealand, are used to demonstrate the establishment of broad landslide-triggering rainfall thresholds. Subsequently, the probability of daily rainfall exceeding these thresholds is calculated. The results are intended to represent region-wide conditions only and do not represent landslide frequencies for individual sites.

The daily rainfall model expresses the relationship between landslide occurrence and actual daily rainfall. Intervals of 20 mm have been used to classify the daily precipitation values. These values were derived from climatic stations within each region. Each value has been stored within the respective class as one count. The 24h rainfall values associated with landslide occurrence were classed in the same 20 mm intervals. Fig. 3 shows the resulting frequency distribution of both variables for the Wellington region.

As Fig. 3 indicates, there is no record of landsliding associated with rainfalls in the precipitation class 0 to 20 mm. In contrast, rainfall values greater than 140 mm have always been associated with landslide occurrence. Thus it is possible to establish two empirically based rainfall thresholds, the 'minimum' and 'maximum' threshold respectively. These thresholds enclose a probability range, in which landslide probability values are assigned to the rainfall classes. This probability value reflects the likelihood of landslide occurrence with a given rainfall and is calculated simply as the ratio of the number of recorded landslide triggering daily precipitation counts to the actual measured total counts of daily precipitation within each class.

As one might expect, the probability of landslide occurrence increases with increasing rainfall magnitude. The minimum daily rainfall required to trigger landslides appears to be 20 mm, irrespective of antecedent conditions. This implies that combinations of antecedent soil moisture and rainfalls below 20 mm have never been sufficient for the slope to attain 'critical water content' (CROZIER 1997). In contrast, every rainstorm event greater than 140 mm has triggered landslides in the past. This boundary represents the maximum probability threshold for the Wellington region. As shown in other analyses, maximum thresholds vary from region to region, reflecting different terrain susceptibility to landsliding (GLADE 1996).

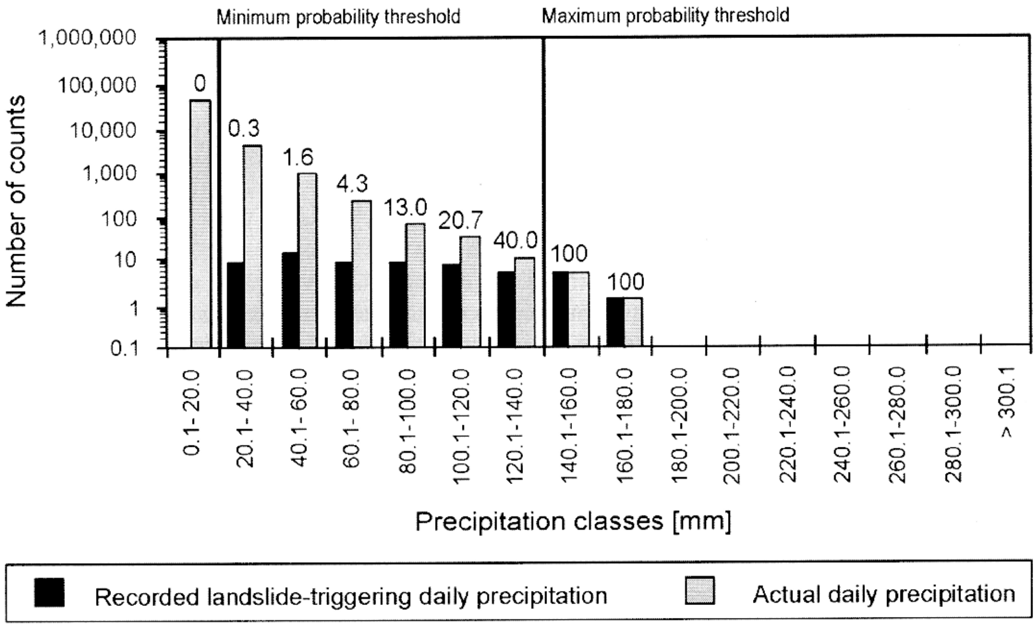

Fig. 3. Probabilities (%) of landslide occurrence associated with rainfall of a given magnitude in Wellington, New Zealand (note: a value of 50 means 50% of all measured daily rainfalls in a given category produced landslides in the past. The recording period is from 1862 to 1995).

The establishment of a maximum landslide-triggering rainfall threshold, in combination with the return period and the probability of occurrence of the respective rainfall magnitude, is a fundamental step in the evaluation of landslide hazard and risk analysis. Consequently, a frequency-magnitude analysis of daily rainfall has been carried out. Fig. 4 gives the return periods for the Wellington region for different rainfall magnitudes and shows the distinct relationship between the precipitation magnitude and return period.

To minimise the error of the trend line, the data set was separated into two parts. The first logarithmic function with an r^2 of 0.972 describes the relationship between these two variables for the rainfall magnitude of 0.1 to 100 mm with respective return periods of 0.004 to 2.5 years. Any rainfall magnitude above 100 mm and with a return period greater than 2.5 years is defined by the second logarithmic trend line with an r^2 of 0.983. The return period of the maximum probability threshold of 140 mm as taken from Fig. 3 is 20.1 years. Therefore, the Wellington region can expect at least every 20.1 years, a rainstorm which has a 100 % probability of triggering landslides. However, as indicated by the range between the maximum and minimum thresholds, there is also a chance (although of lower probability) that rainfalls with return periods less than 20.1 years will trigger landslides.

Another prognostic parameter, directly related to the return period, is the probability of occurrence within different periods. The maximum threshold of landslide-triggering rainfall, identified in Fig. 4 with a value of 140 mm, has a probability of occurrence on any day of 0.02%, within 30 days of 0.2% and within a year of 5% (Fig. 5).

Information on both return period and probability of occurrence are of particular interest for management and planning purposes. Established rainfall probabilities in combination with

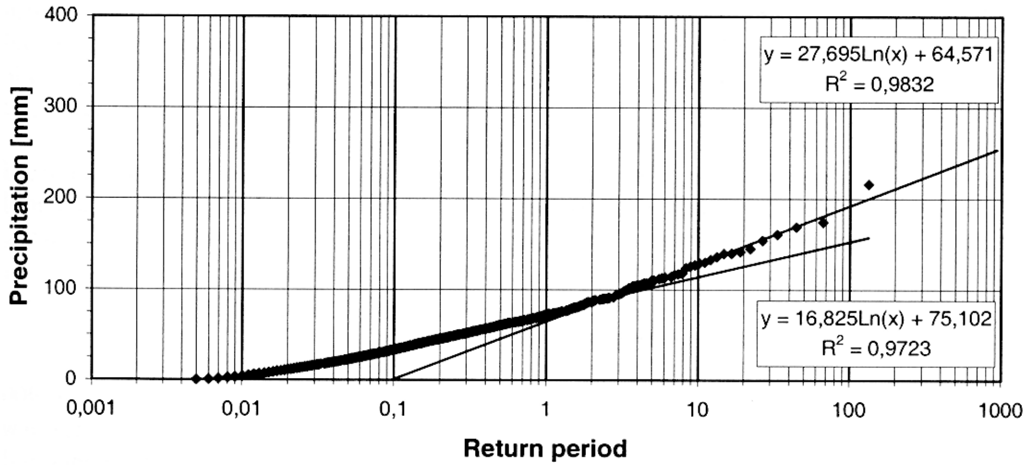

Fig. 4. Return periods of daily precipitation and fitted logarithmic trend lines in the Wellington region, New Zealand.

weather forecast can be used to indicate the likelihood of landslides triggered on the following day. Depending on the vulnerability of the region, the intensity of the following rainstorm event and past experience of landslide occurrence, suitable warning and mitigation measures can be taken by the appropriate organisations.

The major drawback of this analysis is, however, that neither landslide magnitude nor type of movement has been taken into account. This example shows frequency of landsliding only.

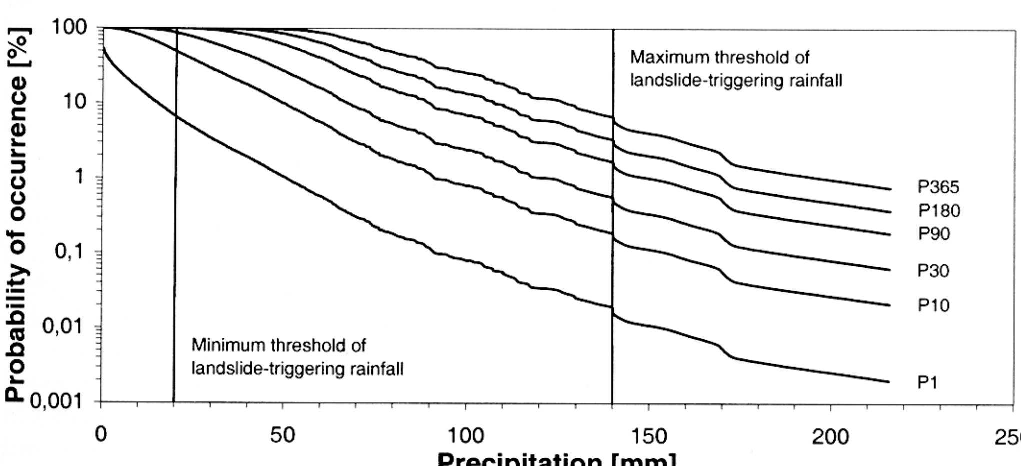

Fig. 5. Probability of occurrence of daily precipitation equalling or exceeding given values in Wellington, New Zealand. (Note: different lines refer to a probability of occurrence of a specific rainfall magnitude at each single day (p1), within a period of 10 days (p10), within a month (p30), etc. The empirically established minimum and maximum thresholds of landslide-triggering rainfall (140 mm) are shown by the thin vertical lines.).

Nevertheless, some qualitative consideration of the expected magnitude may be derived from the existing landslide data base. This database shows that each time the maximum threshold was passed, considerable damage occurred in the region. Correlation of landslide magnitude with triggering rainfalls below the maximum threshold, however, is not possible because of lack of standardisation in event records.

This case study provides an empirical method for assessing the frequency and magnitude of landsliding. Its further development as a means for answering geomorphic questions or as a tool for management depends on the establishment of comprehensive post-event recording systems.

4.2 *Frequency-magnitude and geomorphic work*

Innes (1985) carried out a spatial analysis of the frequency-magnitude relationships of 900 debris flows in a number of different sites in Scotland and Norway. His is one of the few empirical studies to examine geomorphic work accomplished in relationship to frequency and magnitude of landslides. Although this is essentially a spatial analysis, the debris flows studied had occurred as the result of a number of events taking place over a period of 500 years.

For the whole population as well as for individual multiple landslide events, the frequency of debris flows was found to decline with magnitude, in an apparently exponential fashion.

Work achieved by a given magnitude of landslide was measured as the percentage of the total amount of work done collectively by all landslides present. In this way Innes was able to test some of the conclusions put forward by Wolman & Miller (1960). However, he discovered that the regular relationship between frequency and magnitude was not reflected in the work done by debris flows of a given magnitude. Work done by small and large debris flows was fairly similar in most sites although there was considerable variability. At one site all the work was done by debris flows of less than 20 m^3 in volume while at another, 30% of the work was completed by two flows of approximately 130 m^3. At yet another site, the work done by large flows was similar to that of small flows, indicating that despite the decreased frequency of larger flows, they were geomorphically significant owing to their magnitude.

Other studies have shown that when a forcing-process exceeds the threshold of initiation there is usually some form of positive relationship between the magnitude of the forcing agent and the magnitude of landslide response. As forcing processes such as rainfall, seismic shaking, and earthquake magnitude all exhibit clear negative relationships between event frequency and magnitude, it implies that, as indicated by Innes (1985), there will also be some form of negative relationship between the frequency and magnitude of landsliding. Indeed in spatial analysis of 8,000 landslide scars from the western Southern Alps of New Zealand, Hovius et al. (1997) demonstrate this negative relationship with a robust power-law magnitude frequency distribution. In this study, magnitude was represented by landslide surface area rather than volume.

Similar relationships between frequency and magnitude of landsliding have been found by temporal analysis of deposits in Lake Tutira, New Zealand (Trustrum et al., this volume). In this study landslide magnitude is measured off-site by the thickness of sediment deposited during an event. As was the case in certain sites studied by Innes (1985), a disproportionate amount of lake sediment can be attributed to the low-frequency high-magnitude events.

From spatial analyses of separate multiple landslide events, close relationships have been found between the amount of rain falling on a slope and the percentage of the area eroded (Eyles & Eyles 1982, Omura & Hicks 1991, Gallart 1995). Gallart presents a probabilistic model which describes the increase of landsliding as a function of event rainfall depth. He then calculates the product between a log-normal probability density function for rainstorm depth and a log-normal cumulative frequency distribution representing recurrence intervals. From the resultant peak value (maximum work event) in the distribution of products, the recurrence interval of the event carrying out the most work can be determined, in much the same way as was done by WOLMAN & MILLER (1960). Not surprisingly, regional results differ widely, with the Wairoa region of New Zealand yielding a recurrence interval for the maximum work event of 20 years compared to 1,000 years for the Llobregat valley in Spain. KEEFER (1984) has also found positive relationships between the Richter magnitude of measured earthquakes and the size of the area affected by landslides.

5 *Conclusion*

The frequency and magnitude of landslide activity varies both in time and space according to the susceptibility of the terrain and the potency of the triggering regime. Identifying the relationship between magnitude of the triggering agent and its response, by threshold analysis, provides a useful tool in identifying rates of geomorphic work, susceptibility of the terrain, and hazard. Considerable progress has been demonstrated in determining the probability of occurrence of landsliding on a regional basis. However, the success of this approach, whether achieved by deterministic or empirical modelling, depends on the quality of the data base. At present, it appears that the development of methodology has outpaced the development of suitable databases. Significant effort is still required to standardise parameters used and to establish consistent procedures for measurement and recording.

There is still insufficient data to test whether 'work' and 'effective event' theories derived from early fluvial studies have relevance for landslides. While smaller events are clearly more frequent, it appears that, in some areas, the biggest events on record do as much work with more geomorphic effect as the smaller events, despite their frequency.

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