Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand

Thomas Glade

Abstract Landslide erosion has an established history in New Zealand. Some broad estimates of economic costs for short-term event damage, long-term landslide damage, and proactive measures are provided and compared on a national and international level. Frequency and magnitude analysis based on historical records of landslide-triggering rainstorms demonstrates that 1) landslides are a nationwide problem, 2) recognition and recording of these events is dependent on public awareness and therefore related to population distribution and extent of urbanized areas, and 3) deforestation increases the frequency of landslide events, but not necessarily the total magnitude of their impact. However, some regions such as Northland and Wellington in the North Island and Greymouth and North Otago in the South Island are more frequently and more strongly affected than others. Landslide occurrence in time and space, within representative study areas in Hawke's Bay, Wairarapa, and Wellington, is correlated with the climatic variable daily precipitation. Different regional hydrological thresholds for landslide triggering are established.

Key words Landslides recognition · Deforestation · Frequency · Magnitude · Rainfall thresholds

Introduction

This study aims to demonstrate the significant influence of the landsliding process on New Zealand hill country. Firstly, it assesses the cost of actual landslide damage for specific regions as well as for all of New Zealand, and compares this information with international figures. Secondly, a compiled national landslide database is analysed with respect to: 1) population size and distribution, 2) forest removal, and 3) vegetation cover in relation to various landslide parameters (such as landslide density and affected area). Thirdly, frequencies of landslide-triggering rainstorms are defined on a regional scale by analysing a landslide database compiled from available records. The recorded landslide-triggering rainstorm is defined in this study as precipitation which is mentioned in landslide reports as a trigger of at least one landslide in a given region. Fourthly, regional rainfall thresholds for landslide initiation are established on the basis of daily rainfall measurements in three study areas.

Landslides triggered by rainstorms are a nationwide problem in New Zealand (Eyles 1983; Harmsworth and Page 1991; Fig. 1). They cause different types of damage to affected people, organizations and institutions as well as to the environment. In the first instance, this damage can be represented by purely economic costs.

One focus of this project is to place New Zealand costs in a context of worldwide landslide damage. An international overview of landslide damage costs on event or yearly average basis is given in Table 1. For better comparison between countries, all total damage costs are expressed in US$ for the time at which they were originally determined and also are related to the population size at the

Fig. 1
Diffused landsliding in the Hawke's Bay hill country (Photograph: Hawke's Bay Catchment Board)

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Table 1
Examples of damage costs caused by landslides in different countries

Ref.	Region or Country	Event or period	Damage costs caused by landslides in million US$	Calc. aver. damage cost per capita in US$/capita/year
1	Rio de Janeiro, BRAZIL	1988–1991	300	0.65
1	CANADA	since 1991	5–10	0.04–0.09
2	–	annual average	50	0.40
3	CARIBBEAN	annual average	15	0.78
1, 3	CHINA	annual average	500	0.41
1	COLOMBIA	1974	1000	40.68
3	COSTA RICA	1987	12	4.54
3	DENMARK	annual average	1–3	0.19–0.59
1	ECUADOR	1987	1500	151.27
1	FRANCE	1983	1634	29.62
1	–	1984	640	11.60
1	–	1985	635	11.51
1	Rheinland-Pfalz, GERMANY	annual average	10	2.75
1	GERMANY	annual average	150	1.85
3	GHANA	annual average	0.5–1	0.04–0.08
1	Himalaya-Region	annual average	1000	23.89
4	INDIA	annual average	1000	0.00000150
3	ITALY	1982	600	10.62
1	–	annual average	1140	19.95
5	JAPAN	yearly costs 1973–1984	158–483	1.35–4.13
3	–	annual average	4000	33.13
6, 7	–	1992	4700	38.04
1	KOREA	1981–1988	475	1.39
8	–	annual average	11	0.25
1	NEW ZEALAND	1988	72	21.56
9	–	annual average	33	9.35
10	NORWAY	annual average	6	0.71
3	SOUTHERN AFRICA	1987	20	0.59
3	–	annual average	10	0.29
3	SPAIN	annual average	220	0.19
1	–	1986–2016 (estimation only)	6600	5.56
1	SWEDEN	1950	16	2.25
1	–	1957	11	1.48
1	–	1977	58	6.98
11	–	annual average	10–20	1.18–2.36
1	THAILAND	1988	250	29.21
1	TRINIDAD and TOBAGO	1979–1986	1.26	0.13
1	–	1985–1986	0.96	0.80
3	TURKEY	1969	1.5	0.04
12	San Francisco Bay Region, USA	1968–1969	53.5	13.38
1	–	3.–5. 1. 1982	66	11.00
1	–	14.–20. 2. 1986	10	2.22
13	USA	1970	1692	8.36
2	–	1971	400	20.00
2	–	1976	500	25.00
1	–	1987	3000	12.32
14, 2	–	annual average	1473	5.65
13	–	2000 (projected)	5869	22.52

References: *1* Keefer and others 1987; *2* Schuster 1996; *3* Brabb 1991; *4* Mathur 1982; *5* Oyagi 1989; *6* Moriyama and Horiuchi 1993; *7* Nishimoto 1993; *8* Yoon 1991; *9* Hawley 1984; *10* Gregersen and Sandersen 1989; *11* Cato 1982; *12* Sidle and others 1985; *13* Johnson 1995; *14* Schuster 1978

Notes: 1. Calculated average damage cost per capita is estimated on the basis of total population in the year when economic costs caused by landslides are reported. Dollar values are not adjusted and pertain to values at the time of the recording period or of the specific publication.
2. Economic costs are difficult to compare because of various recording criteria in the different countries. However, it allows a broad comparative view of the importance of landslide damage in different parts of the world.

time of damage. There is a wide variation in the costs of landslides among the countries listed suggesting that the impact of landslides as measured by their environmental, psychological and social effects, varies between countries as well as between regions and communities within each country.

In New Zealand, direct and indirect costs related to landslide damage can be viewed from different perspectives. Glade and Crozier (1996) summarized three different types of accessible expenditure related to landslide damage:

1. Costs of direct landslide event damage, such as building destruction, road blockage (Fig. 2) and deposition removal (Blong and Eyles 1989);
2. Long-term costs attributable to landslide damage, such as on-going reduction in pasture productivity (DeRose and others 1995; Douglas and others 1986; Trustrum and others 1990) and therefore reduction in livestock carrying capacity (Hicks and others, unpub. report 1993); and
3. Indirect costs of planning, preparedness, engineering design and maintenance of hazardous regions (East Cape Catchment Board, unpub. report 1988; Gillon and Hancox 1992; Riemer 1995).

Non-accessible expenditure includes personal and group responses to landslide occurrences. As previously mentioned there are costs associated with the psychological and sociological aspects of landslide damage. These may range from therapy (for example after loss of friends and/or relatives) and/or related medical treatment (The Dominion 1996) to dealing with a sense of helplessness in having to cope with the effects of landslide occurrence (farm loss). These clearly need further investigations and should not be underestimated (Berezovsky 1994; Takahashi 1981).

Examples of direct landslide event damage in terms of economic loss in New Zealand are given in Table 2. Direct comparison of individual figures is difficult because of different methods in assessing landslide damage costs. However, Table 2 gives a first broad overview of regional landslide damage costs. These costs range between US$ 0.02–9.19 M (million) per region and event. This is between US$ 2.04 and 345.00 per person per event in the affected region, which does not reflect the region's capability to cope with this problem. The average personal income of a given region is introduced because income can be seen as a strong variable which reflects a region's health and also its capability of handling landslide damages and related costs. Table 2 demonstrates clearly that even if the total damage is not significant in absolute damage costs, as for example in Reporoa and Kaikoura, the effect on the people, represented by the percentage of damage costs to income per head, is actually very high because of both low population size and low incomes.

Fig. 2
Clearance of a road-blocking landslide in Wellington (Photograph: M.J. Crozier)

Table 2
Examples of damage costs caused by landslides related to per capita income of the appropriate region in New Zealand expressed in US$ (In some cases with comparison to the overall damage costs of an inducing event)

Region	Event or period	Damage costs in M US$		Landslide damage costs	
		of landslides	in total	per head in US$	as percentage of aver. income
Torepatutahi (Reporoa) Region[a]	1967	0.14	n. av.	22.10	3.47
Eastern Whangarei County[a]	1975	0.07	n. av.	2.05	0.09
Kaikoura Region[a,b]	12. 3. 1975	0.14	1.41	55.63	2.27
Wairarapa Region[c]	July 1977	0.42	n. av.	16.41	1.04
Tauranga/Te Puke Region[a]	1979	0.13	n. av.	9.45	0.13
Clarence (Kaikoura) Region[a]	1979	0.02	n. av.	16.86	0.22
Abbotsford, Otago[d]	1979	6.4–9.19	n. av.	238–345	3.39–4.90
Hawke's Bay and East Coast[e]	6.–9. 3. 1988	1.78	70.65	15.66	0.14
Manawatu-Wanganui Region[f]	22.–24. 7. 1992	0.55	4.50	10.92	0.09

[a] Stephens and others 1983
[b] Bell 1976
[c] Hawley 1980; Lambert and others 1984
[d] Blong and Eyles 1989
[e] East Cape Catchment Board 1988; Eyles and Newsome 1991; Trotter 1988
[f] Hicks and others 1993

However, if landslide-triggering rainstorms are large enough, such as Cyclone Bola in 1988 which damaged wide areas in Hawke's Bay and East Cape, the impact on the affected population is very high, as reflected again in high percentage values (Table 2).
Another example of direct costs is the number of claims made to the New Zealand Earthquake Commission as the compulsory insurer of landslip damage. This organization has paid US$ 14.8 M for landslip claims within the last 22 years, on average US$ 0.67 M per year (Glade and Crozier 1996). In addition to direct short-term costs, long-term costs for the whole of New Zealand were calculated by Hawley (1984) as a yearly average expenditure of US$ 2.12 M for urban landslides and US$ 21.20 M for rural landslides. Indirect costs for preventative and remedial actions are indicated by the yearly expenditure of Regional Councils throughout New Zealand. These measures cover expenses on soil conservation, erosion control, as well as sustainable land management programmes and education and amount to US$ 38.15 M for the 5-year period 1990–1995 (Glade and Crozier 1996).
Other countries have programmes to reduce landslide hazard. In the United States, US$ 5 M was spent for landslide research (U.S. Committee on Ground Failure Hazards 1985). Geotechnical studies and landslide-preventative works with an annual expenditure of US$ 25 M were funded by the Hong Kong government (Brand 1989), and Japan spends approximately US$ 4 billion per year on landslide control works (Oyagi 1989). Figures for other countries were not available for this study, although it is obvious from Table 2 and from Brabb and Harrod (1989) that they do have significant slope stability problems.
Both Tables 1 and 2 show from an international and national perspective the influences of landslide occurrence on countries and societies in terms of direct damage costs. Over time, such measures of damage may be treated as indicators of change in various conditions, including the level of reporting, the number of assets at risk and their vulnerability, as well as the physical conditions affecting slope stability. Conditions for landslide recognition and recording are influenced by population size, spatial population distribution, temporal population growth as well as public and official (e.g. regional councils) awareness of the landslide problem. Crozier (1989) indicated important environmental conditions for slope failure as follows: 1) preparatory factors which dispose the slope to movement (such as forest removal); 2) controlling factors which dictate the condition of the actual movement (such as vegetation cover or soil depth); and 3) triggering factors which initiate movement (such as precipitation).
In this study all previously mentioned conditions and factors which influence the landslide problem as a whole are examined at different scales throughout New Zealand. Main attention is given to landslides in relation to temporal and spatial change of population conditions, to temporal change of forest cover as a preparatory factor, and to spatial differences in daily precipitation as a triggering agent.

Clearly, personal costs such as psychological effects and sociological influences (Berezovsky 1994) should also be considered in a full assessment of costs. However, isolation of personal or economic costs resulting from landsliding is difficult, and their evaluation even more so, because landslide damage is often related to other simultaneously occurring natural hazards such as floods. Although psychological and sociological aspects are very important in a comprehensive landslide hazard study, these factors do not come within the scope of the current study.

Methods

For the development of a national landslide database, all available and accessible landslide records were compiled. The availability, accessibility, format and compilation of landslide records, including all associated problems, are discussed by Glade and Crozier (1996).
The landslide database developed for this study is analysed at a national scale with respect to different parameters, such as date and place of occurrence, recorded daily rainfall, vegetation cover, landslide area, landslide density and landslide volume per hectare. Analysis of date and place of landslide occurrence provides a picture of the spatial distribution and a regional frequency of recorded landslide-triggering rainstorms. The problem of landslide recording is highlighted in relation to both population growth and to changes in forest cover. Both variables are compiled from the Official New Zealand Yearbook, first published in 1893. The landslide database allows an assessment of the influence of different types of vegetation cover on landslide parameters, such as affected area, volume per hectare, and landslide density. A purely statistical description of this empirical relationship is carried out in this study.
The daily rainfall associated with each landslide event is compared with the long-term daily rainfall record on a regional basis. The climatic data were provided by NIWA (National Institute of Water and Atmospheric Research Ltd.). This regional analysis is carried out for three typical landslide-prone areas of the North Island of New Zealand: Hawke's Bay, Wairarapa, and Wellington. The resulting relationship between daily measured rainfall and recorded landslide-triggering rainfall leads to regional probability thresholds of landslide-triggering rainfall, including probability of landslide occurrence associated with a given 24-h peroid rainfall magnitude.

Results

Information sources

For compiling all available landslide information, the existing institutional database was evaluated. Different types of information sources were accessed and compiled to get the most comprehensive landslide record possible. Types of information currently available on landslide problems include: 1) articles in newspapers and scientific journals; 2) official and/or internal reports from governmental agencies (such as Department of Scientific and Industrial Research's Soil Bureau, Ministry of Works and Development's Water and Soil Division), departments, ministries or institutes; 3) reports and theses from universities; and 4) landslide information held by the national transport authorities (Transit New Zealand and New Zealand Rail Ltd.). All sources have information recorded on national, regional, and site scales, except the transport authorities, which have no information at the national scale (see Glade and Crozier 1996 for details).

Before analysing the compiled information, different factors influencing the record and consequently the completeness and comprehensiveness of the landslide database need to be discussed. Problems arising from the recording process influence the landslide database in different ways. Landslide records are stored in various places, in dissimilar formats and scales. Different affected authorities have different perceptions of the importance of slope failure. Whether action is taken in the form of remedial work, or even simply the reporting of landslide occurrence, may be influenced by public awareness, and population density, as well as the type and importance of infrastructure damaged such as railway, highways, powerlines, water supply, communication lines, etc. Also the experience of the investigator can affect the actual results of the report, and consequently the comprehensiveness of the database. All these constraints have to be considered while working with this database and therefore results can only be seen as a partial preliminary step towards a robust landslide frequency analysis on a national scale. The problem of different recording procedures, perceptions of affected organizations and non-standardized reporting schemes and protocols is reviewed for the Isle of Wight area in Great Britain by Ibsen and Brunsden (1996) and for New Zealand in general by Glade and Crozier (1998). However, there are no alternatives available to solve this problem.

Analysis on a national scale

Interpretation of the years and places with a low occurrence of landslide-inducing rainstorms is problematic. An explanation may be found in the history of population development in New Zealand. Such a working hypothesis implies that gaps in the landslide database were caused by a lower level of recognition of landslides resulting from lower population numbers.

Within New Zealand, the rate of population growth in different provincial regions varies strongly (Papps 1985). The provincial regions have generally been the basis for recording population data through the census established in the 1850s. As a result of renaming and reorganization of provincial districts in the early 1860s and from 1981 onwards, the development of the relation between recorded landslide occurrence and population is based only on the period 1861–1981.

In this study, the total population of a given region was divided by geographical area and is expressed as population density for that region. Population density has reached its highest level in the North Island, mainly in the Auckland and Wellington provinces (Fig. 3). One

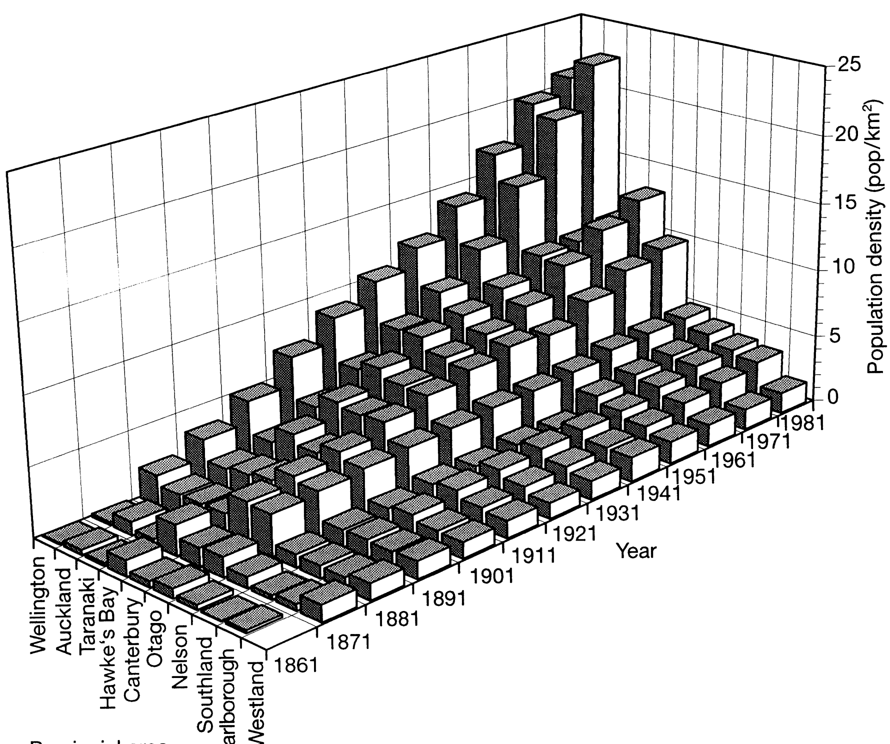

Fig. 3
Change of population density in time and space in New Zealand (Data source: New Zealand Official Yearbooks)

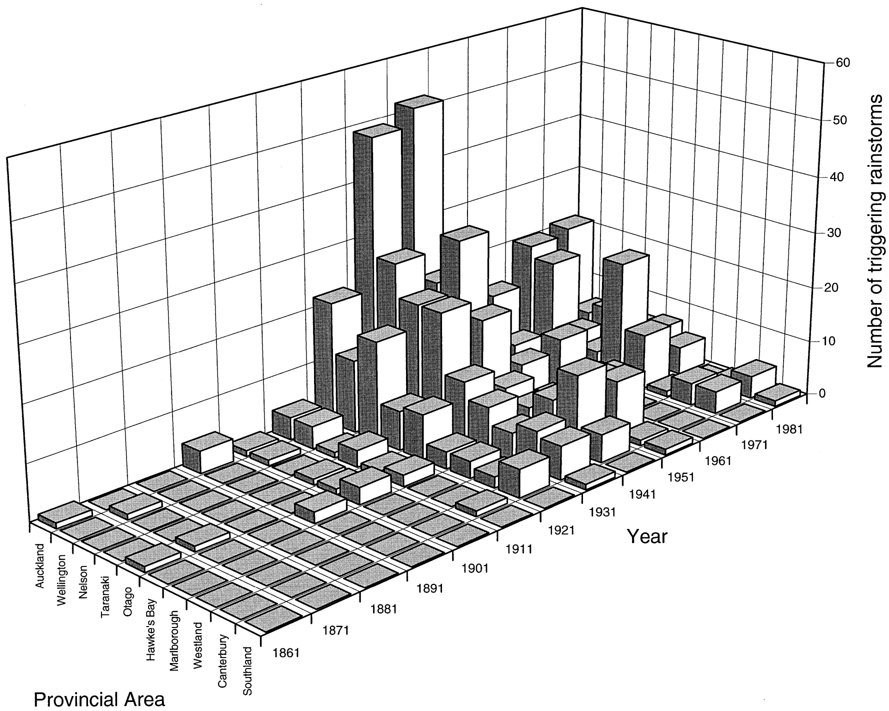

Fig. 4
Spatial and temporal distribution of recorded landslide-triggering rainstorm events in New Zealand

might expect that with increasing population density, there would be an increase in recorded landslide occurrence too. However, if population density is compared with the temporal distribution of the recorded number of landslide-triggering rainstorm events for the same provinces and periods (Fig. 4), there does not seem to be a strong relationship between these two parameters. In spite of the lack of a positive correlation between these two parameters, it should be pointed out that a record is also dependent on the magnitude of a rainfall event. A high rainfall event covering a large area will be noted, regardless of population density.

However, it can be seen from both Figs. 3 and 4 that in regions with low population density such as Southland and Westland, there are fewer landslide reports. This does not reflect reality at all, because there is physical evidence of extensive landsliding in these areas (D. L. Hicks, pers. comm.). But the result of fewer landslide reports in regions with low population density confirms the hypothesis, that change in population size and its distribution in time and space has a strong effect on landslide records and available information. However, this result contradicts the previous conclusion showing a lack of statistical associations. Clearly, factors other than just population must influence the records.

As seen above, landslide information and records are not only dependent on population. Early studies demonstrate the effect of urbanization on slope instability (Cant and Johnston 1973) and of the creation of road sections on steep country (Eyles and others 1974). Human activity in terms of agricultural and farming practices, and land use in general, increases landslide occurrence too (Alexander 1993; Derbyshire and Meng 1995). These effects of human activities leads consequently to the hypothesis, that some human activities result in slope instability and lead to landslide occurrence. This hypothesis will be tested with one objective parameter: change of forest cover over time. Information on forest cover reflects human activity on land very well in terms of deforestation for various purposes such as urbanization, increase of farm land as well as in terms of afforestation for conservation or plantation purposes.

With the arrival of the first European settlers, the practice of extensive indigenous forest and scrub clearance was introduced in New Zealand (Fig. 5). The European settlers used some of the felled forests to export timber, mainly to England. They also burnt down the forests to gain cleared land for pastoralism (Guthrie-Smith 1969). Especially on steeper slopes, the conversion of forest to pasture changed the natural equilibrium of conditions which existed between slope angle, soil depth and strength, and soil moisture and watertable levels, which had been established over thousands of years (O'Loughlin 1974). This removal of vegetation destabilized the slopes and made slope segments susceptible to failure from the next rainstorm that was large enough to trigger landslides. Various studies have shown the strong relationship between forest removal and increased landsliding on a regional scale in New Zealand (Clough and Hicks 1993) and overseas (King 1989). The effect of forest removal on slope instability on a national scale has not yet been considered in previous studies.

The effect of the change in New Zealand's forest cover on the number of storms able to trigger landslides is shown in Fig. 6. The term "forest cover" stands here for only indigenous and exotic forests. Removal of forest cover as a

Fig. 5
Removal of indigenous forest by early settlers between Wanganui and New Plymouth, Taranaki, New Zealand (Photograph: Turnbull Library, Wellington, New Zealand; Note the beer bottle on the stump in the foreground!)

preparatory factor (Crozier 1989) appears to have had its maximum influence by the early 1930s. This is shown by a maximum of reported landslide-inducing storms occurring in the decades 1930–1940 and 1940–1950. Also the second period of forest removal in the 1960s was followed, after a lagtime of a few years, by an increase of rainfall-triggered landslide reports. These historical data demonstrate a strong relationship between forest cover and landslide occurrence. This result is also supported by many local councils who responded to the high economic, ecological and social impact of forest clearance by running reforestation programmes to reduce the effects of resultant landslide erosion (Hicks 1992; Phillips and others 1990). However, another explanation of this trend

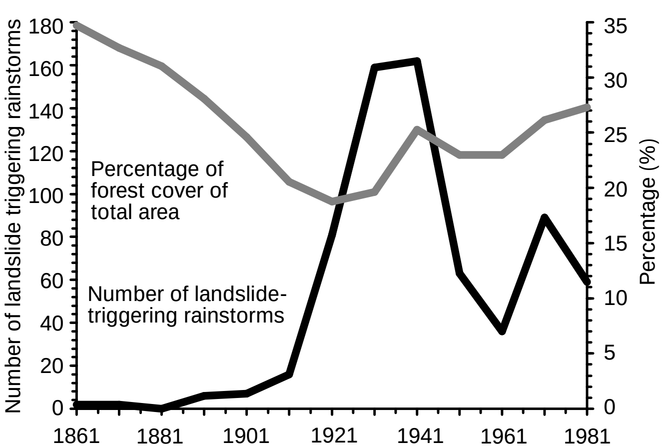

Fig. 6
Relationship of forest cover to recorded number of landslide-triggering rainstorm events between 1861 and 1991 in New Zealand

could be variations of the climatic regime over time such as an increase of heavy rainfalls (Fowler and Hennessy 1995). This question will be followed up in future detailed research.

Further analysis of the landslide database has been performed to relate the vegetation cover to the landslide parameters affected area of landslide [surface over which rupture has occurred in (ha)], landslide density [number of landslides per hectare in (no/ha)], and volume of landslides per hectare [in (m^3/ha)]. The vegetation types mentioned in the literature as dominant vegetation cover were classified into three categories: forest, scrub and pasture. Figure 7a shows that landslide events in forested land affect smaller areas than those occurring in pastureland. The affected area is given for scrubland in only two references and therefore, the vegetation-type scrub is excluded from Fig. 7a. The volume of landslide material displaced per hectare, however, is more variable with the largest events occurring in forested land, although on average events in pastures are marginally larger (Fig. 7b). Landslides occurring in scrubland have significantly lower volumes. Combining the results from Fig. 7a and b, even a smaller affected area in forested land could in some instances have a similar or greater volume than landslides in pasture land. A remarkable difference in landslide density in scrubland compared to pasture and forest can be seen in Fig. 7c. The number of landslides per area is highest in pastureland while forest cover tends to stabilize a slope in terms of failure number, expressed by the lowest landslide densities. If volume per hectare are similar, this result suggests pasture slips are smaller than forest ones. Despite the low observation numbers in some vegetation categories, Fig. 7 demonstrates a tendency that landslide parameters appear to be influenced by vegetation type and the role of vegetation has to be con-

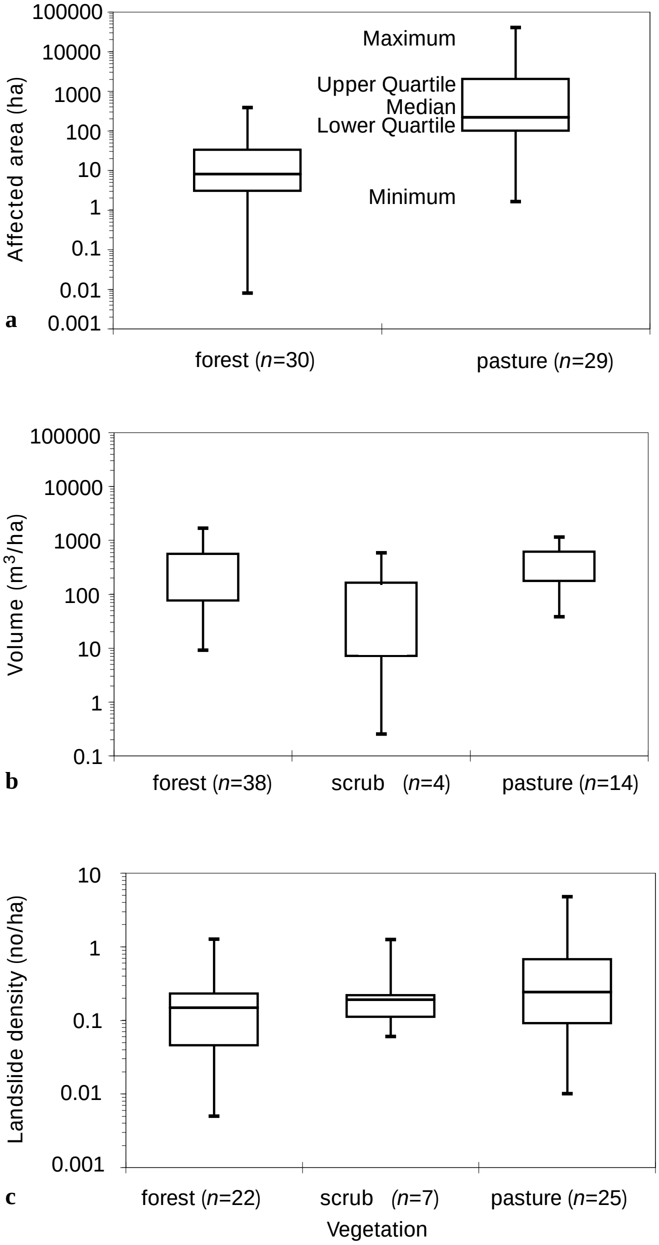

Fig. 7a–c
Effect of vegetation on **a** affected area, **b** volume of landslides per hectare, and **c** landslide density

sidered further. This has already been done on a regional scale by various authors (Blaschke 1988; Hicks 1991; Tsukamoto 1990), but needs to be followed up in a comprehensive analysis on the national scale.

The affected area of landslides and landslide density is higher for pasture than forest, which is also found by other authors (Blaschke and others 1992; Clough and Hicks 1993). Certainly, the landslide volume per ha may be similar, especially in long-term perspectives, but it is the landslide area that is important to people over shorter time scales, because these are the periods for which high damage costs must be borne, especially in terms of pasture productivity (Blaschke and others 1992). Therefore, extensive landsliding is defined as a function of low magnitude/high spatial frequency represented by shallow, mostly translational landslides rather than of high magnitude/low spatial frequency events of deep-seated, mainly rotational landslides. Both landslide types can be inferred from values of the landslide parameters affected area, landslide density and landslide volume per ha, e.g. we can interpret a large affected area, with a high landslide density, but a low landslide volume as an example of the shallow landslide type, which are characterized by mainly translational shear planes. Analysis of the existing landslide database suggests that these low magnitude/high frequency events are the ones that are of interest even though there are some indications that over long periods they produce the same amount of denudation and geomorphic work in a given landscape. This supposition has to be proven in more detail by further research, however.

Although the landslide database used in this study has the problems discussed in the section on information sources, it is the only source available from which to make a first attempt at describing regional frequencies of landslide-triggering rainstorms in New Zealand. All the compiled data on landslide-triggering rainstorms are summarized in Fig. 8. Occurrence of landslide-triggering rainstorms is indicated in Fig. 8 as a point. Each point reflects one or more landslide-triggering rainstorm events at a given place, and the point marker symbolizes only the location of the event, not the event magnitude or the extent of damage. As shown in Fig. 8, landslide and slope stability problems occur throughout the country. However, records indicate that some regions are more affected than others. Northland and Wellington on the North Island and Greymouth and North Otago on the South Island (all four regions are indicated on Fig. 8) are the regions with the highest probability of receiving more than one landslide-triggering rainstorm within a 2-year period. Certainly, this is dependent on landslide recognition but despite all the potential errors, it also reflects generally understood trends that some regions are more susceptible to landslides than others. This is particularly evident for large rainstorms with a great extent because they are noticed and recorded irrespective of the factors that would otherwise influence recording procedures. More detailed analysis could be done by improving the landslide database, as already suggested by Glade and Crozier (1996).

The preceding analysis of population size and distribution, temporal change in forest cover, influences of vegetation types on landslide parameters, and frequency of landslide-triggering rainfall events was carried out at the national scale and demonstrated the need to undertake detailed studies on a regional scale.

Detailed studies on a regional scale

Climatic parameters and their spatial and temporal behaviour at a regional scale, were examined for Hawke's Bay, Wairarapa, and Wellington on the North Island of New Zealand (Fig. 9). These areas have excellent aerial

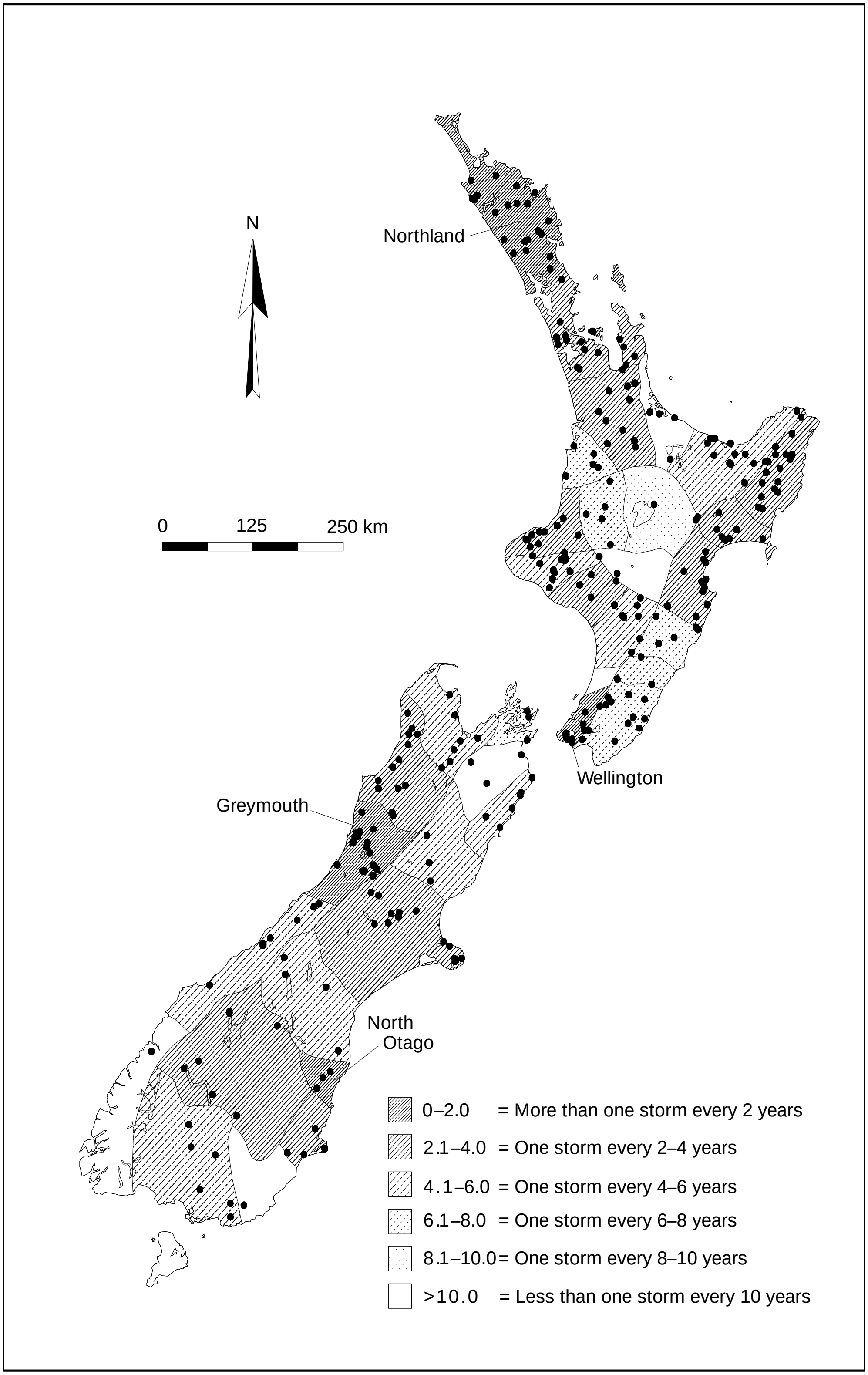

Fig. 8
Frequency of recorded landslide-triggering rainstorms in different regions between 1870 and 1995 in New Zealand (Note*:* Point may reflect more than one landslide-triggering rainstorm event. The point marker symbolizes only the location of the event, not the event magnitude or the extent of damage)

photo coverages made after highly damaging landslide-triggering rainstorms, comprehensive historical records on landslide-triggering events, complete climatic records in terms of a high density of climatic stations and long recording periods, and distinctive differences in the physical environment.

Regional analysis is focused on daily precipitation and its relation to historical records of landslide occurrence (Omura and Hicks 1991). Years when 24-h-rainfall records are available for the three study areas are shown in Fig. 10. Daily precipitation data of the climatic time series have been categorized in 20 mm intervals and values are

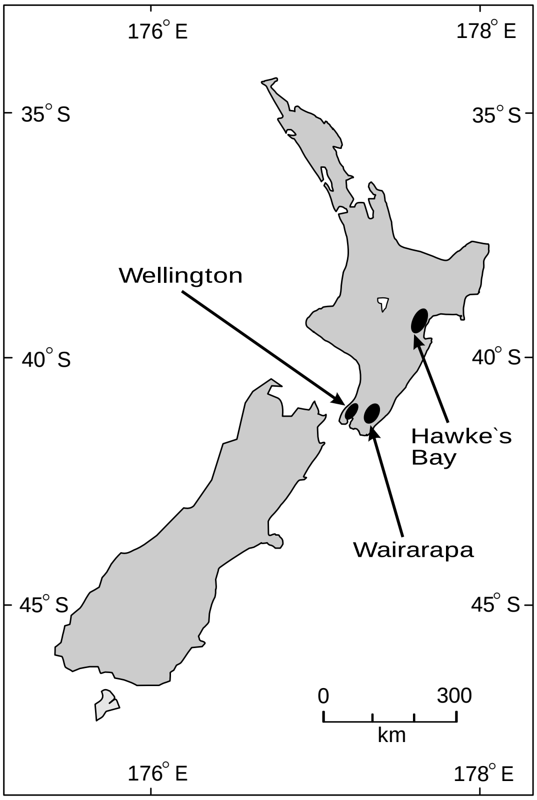

Fig. 9
Locations of the study areas Hawke's Bay, Wairarapa and Wellington in New Zealand (Note: Ellipse size is not related to actual study area size. It gives broad location only)

stored within appropriate classes as one count. The 24-h-rainfall variable of landslide-triggering rainstorms, derived from the compiled landslide database, was classed into the same 20 mm intervals. Figure 11 provides the resulting frequency distributions of both variables. Daily precipitation measured by climatic stations is recorded over decades, thus allowing for natural seasonal and annual variability. Consequently, the different length of climatic records may influence the absolute number of counts within each magnitude class, but because of the length of the records it probably does not change the overall frequency distribution.

Probabilities of landslide occurrence including minimum and maximum thresholds were established empirically for given event magnitudes (Fig. 11). In this study, the minimum threshold of a given region refers to the margin below which mass movement does not occur (landslide probability equals 0%) and above which it may occur under certain conditions (Crozier 1989). The maximum probability threshold is defined as the margin above which the defined level of mass movement always occurs. Above this threshold there is a 100% probability of occurrence. The probability of landslide occurrence is calculated as the ratio of the number of recorded landslide-triggering daily precipitation counts divided by the actual measured total daily precipitation counts.

Figure 11 indicates that the different regions do have a varying susceptibility to landslides. The minimum daily rainfall required to trigger landslides in all three regions is 20 mm. The maximum threshold is much more variable between the regions, naturally dependent on precipitation supply. In Hawke's Bay, one could expect landslides to occur following any rainstorm exceeding 300 mm daily rainfall (Fig. 11a). In the Wairarapa (Fig. 11b), every storm over 120 mm has triggered landslides, while the maximum probability threshold for Wellington is 140 mm (Fig. 11c). One factor which proved to be problematic for the analysis was the use of different recording procedures. Daily precipitation values provided by NIWA are read at the respective climate station at 9 a.m. every day. The resulting values relate to the preceding 24-hour period. The compiled landslide-triggering values refer only to the mentioned values in the literature source. It was not possible either to identify the original source of cited values or to distinguish the period of measurement, e.g. from 9 a.m. to 9 a.m., or from noon to noon, or midnight to midnight, etc. This recording difference could explain why there are some classes with only landslide-triggering rainfall recorded and some with only actual measured precipitation recorded (Fig. 11b). However, it can be assumed that rainfall events greater than the maximum threshold of 120 mm were very likely to have triggered landslides. Perhaps the single values compiled from the literature were too low and refer to the higher actual measured values. For example, if a rainstorm starts at 1 p.m. and lasts until 6 a.m. the next day, it will be fully represented in one actual measured value, but it may have been recorded in the literature as two different, smaller values because it occurred over two calendar days.

Considering all associated problems, these figures give a first broad introduction into regional maximum and minimum probability thresholds for precipitation triggering of landslides. One possible application of these empirically determined thresholds is real-time landslide-warning systems as has been done in the United States by Keefer and others (1987), in Hong Kong by the Geotechnical Control Office (GCO) within the Engineering Department of the Hong Kong Government (Geotechnical Control Office 1985), in Italy by Panizza and others (1996), and in South Africa by Garland and Olivier (1993). Recent application of this methodology in New Zealand has been undertaken by Crozier (1996a) to evaluate landslide hazard and risk for a given region.

However, a number of points, arising out of the establishment of these thresholds, need to be made:

1. Both frequency distributions reflect recording periods of up to 125 years. It is possible that the rainfall threshold for landslide triggering may change over time (Crozier 1996b) as well as in space within a region. These changing thresholds could be induced by, for example, forest removal, slope cuttings for urbanization or infrastructure lines, or by slope failure itself (Preston 1996).

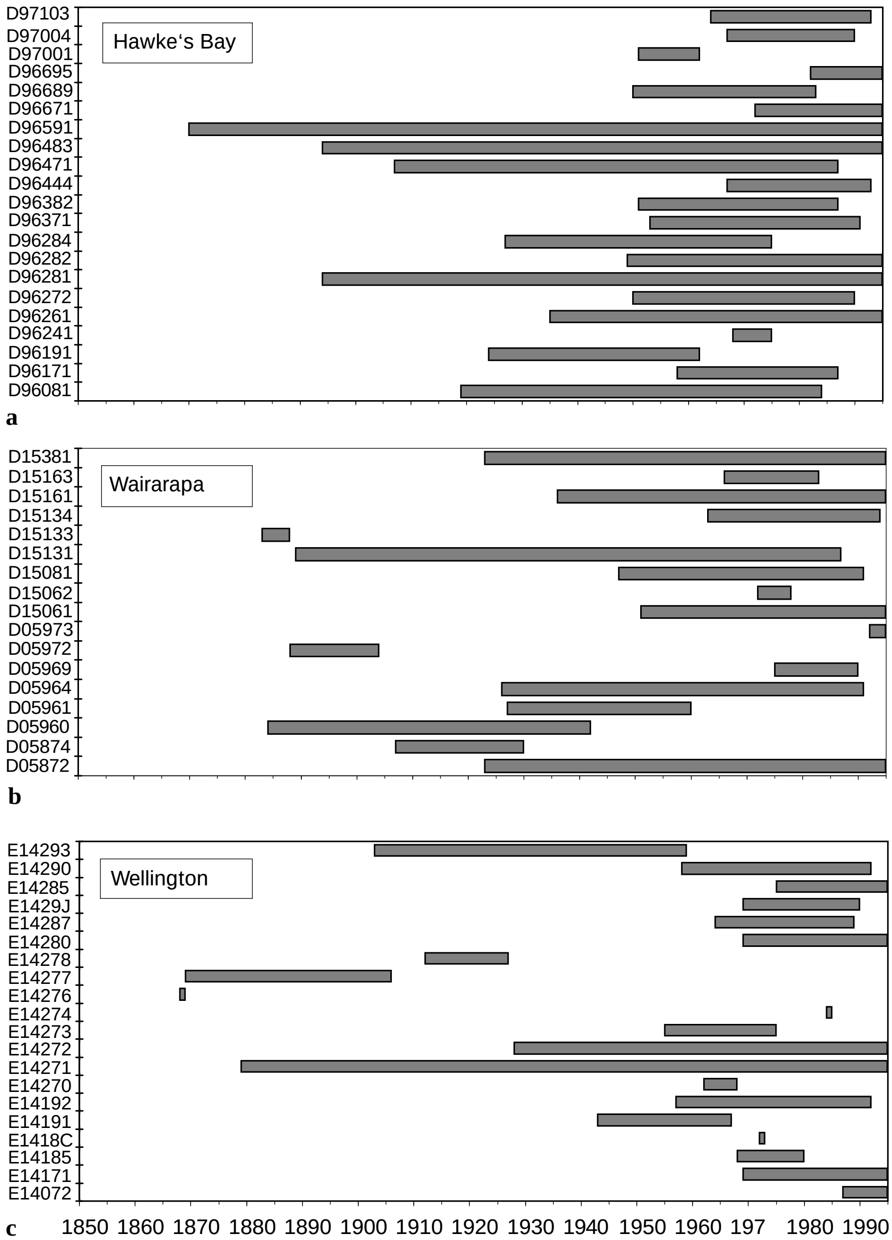

Fig. 10a–c
Length of daily precipitation records in the study areas **a** Hawke's Bay, **b** Wairarapa, and **c** Wellington. Index number on y-axis refers to a climate station of the New Zealand Meteorological Service

2. Shifting thresholds of controlling factors are still under debate. Does slope failure lead to an increase or decrease in slope stability? This question has to be addressed at an individual case-study level and will give case-dependent different answers. This specific issue has to be acknowledged in a regional study, but cannot be applied to a region because of the scale problem.
3. Antecedent climatic conditions were not considered, as would be necessary in a comprehensive study, especially for establishment of warning models. Ongoing study involves the application of antecedent conditions to slope failure.

Conclusions

The study shows, on both a national and regional scale, the influence of landslide occurrence on New Zealand's resources and livelihood. Different landslide-related costs such as personal costs, economic loss, and environmental costs can be identified. Tables 1 and 2 highlight these economic costs. These figures alone demonstrate the need for this study and subsequent studies in the future to provide our society with important information on highly influential slope failures.
An analysis of the existing landslide database gives information on a national scale. Analysis of the landslide record demonstrates some methodological problems, such as a discrepancy between actual and recorded landslide

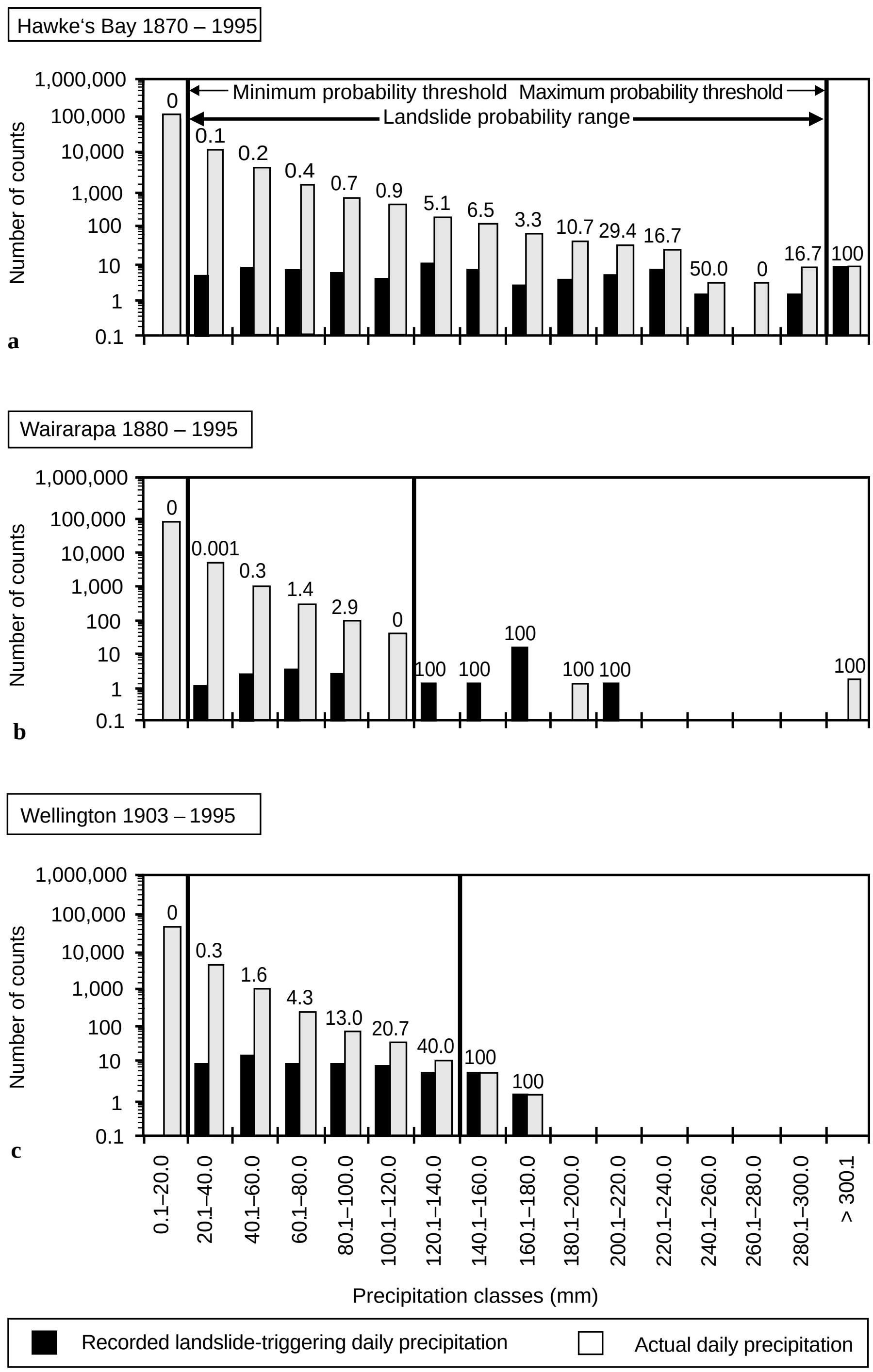

Fig. 11a–c
Probabilities (%) of landslide occurrence associated with rainfall of a given magnitude in the study areas **a** Hawke's Bay, **b** Wairarapa, and **c** Wellington. For example, a value of 50 means 50% of all measured daily rainfalls in a given category produced landslides in the past

occurrence, various recording procedures, different perceptions of importance from individual investigators and/ or organizations, and storage at various places, in different formats and scales. Despite these limitations of the database, it is the most comprehensive source available for a national analysis of rainfall-triggered landslides in New Zealand. Therefore it is used in further analysis.
The problem of landslide recognition is highlighted with respect to changes in population size and distribution in time and space in New Zealand (Figs. 3 and 4). Higher population influences the database by enabling more precise landslide recognition while less-populated regions have fewer landslide reports, which does not reflect reality at all. Also natural environmental factors are considered with the example of temporal change of forest cover. Strong correlations between degree of forest cover and counts of landslide-triggering rainstorms are recognized (Fig. 6). This relates mainly to an increase in rainfall-triggered landslides after deforestation with a lagtime of one or two decades and a decrease in landslide occurrence after afforestation. Despite the good correlation between changes in forest cover and the incidence of landslides

there remains a possibility that variation in the climatic regime through time may be another factor explaining this trend. The different vegetation types, forest, scrub, and pasture, are compared by landslide parameters (Fig. 7). Lowest values of affected area (0.008 ha) and landslide density (0.001 landslides/ha) are found in forested land. Numerous shallow landslides mainly occur in pastureland, while deep-seated landslides with high volumes occur, less frequently, in forested land. This is consistent with the commonly held view that geomorphic work and denudation by landslides is for the long-term timescale the same under both forest and pasture cover. However, this magnitude/frequency issue has to be addressed in more detail in further studies. Regional frequencies of landslide-triggering rainstorms on the basis of reported information are calculated (Fig. 8). Although landslide recognition problems as discussed earlier have to be considered, it appears that the regions Northland and Wellington on the North Island and Greymouth and North Otago on the South Island of New Zealand are more affected by landslide-triggering rainstorms than others.

Regional scale analyses were carried out in the three study areas Hawke's Bay, Wairarapa and Wellington (Fig. 9). Correlation of daily precipitation with landslide-triggering 24-h-rainfall values cited from the literature gives probability margins for the landslide-triggering precipitation. Regional thresholds are established and compared (Fig. 11). The minimum probability threshold of a landslide-triggering rainstorm is 20 mm daily precipitation in all three study areas. The maximum probability threshold is much more variable between the regions and is in Hawke's Bay 300 mm/24 h, Wairarapa 120 mm/24 h, and in Wellington 140 mm/24 h. These conditions are likely to be influenced by shifting thresholds over time and area. However, the establishment of regional rainfall thresholds is useful and provides important information for any landslide warning system. A test study has even demonstrated the possibility of using these defined rainfall thresholds to predict landslide hazard in a given region in the near future.

The questions raised in this study will be followed up in ongoing research. These forthcoming studies will be focused on:

1. The development of a standardized reporting scheme to provide a similar recording basis;
2. The consideration of antecedent soil moisture conditions of landslide-triggering rainfalls;
3. Shifting thresholds in time and space in respect to both human activity and physical environment, influenced by the erosion process itself;
4. The role of controlling factors such as geology, regolith type and depth, vegetation, geometric slope parameters;
5. The landslide hazard assessment for given regions; and
6. The downscaling of landslide warning information from the regional scale to the site level by coupling hydrological and mass movement models.

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