LANDSLIDE HAZARD ASSESSMENT AND HISTORICAL LANDSLIDE DATA - AN INSEPARABLE COUPLE?

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Abstract

By definition, landslide hazard assessments must define the probability of landslide occurrence for a given region, area and/or time. If spatial information such as landslide distribution after a single landslide event is used for hazard analysis, the resulting hazard assessment is based purely on spatial components. Another approach for establishing the probability of occurrence involves time. As soon as temporal information is included, the need for historical data is obvious. Probabilities may then be calculated by using data on recent and past landslide failures, by means of recurrence intervals of the triggering agent or by a combination of both. These approaches lead, however, to temporal landslide hazard assessment. The ultimate step towards a comprehensive landslide hazard assessment is to combine both spatial and temporal probabilities. This increases the demand on reliable historical landslide data.

Different ways of approaching landslide hazard assessments are given using examples from Germany and New Zealand. It is shown with these examples that the different approaches vary in their input requirements, and also that, along with increasing complexity, different potential applications of the resulting landslide hazard assessments are possible.

1. Introduction

Landslide hazard assessments are a popular tool for evaluating the potential hazard represented by landslides. Various groups are concerned with this type of investigation, ranging from universities and governmental agencies to private consultants. Dependent on the party involved, demands on these assessments vary greatly. While some institutions have scientific interests such as increasing accuracy and validity of resulting spatial hazard maps, others might want an easy-to-use tool, applicable for regional planning purposes. Landslide hazard assessments can be used to design protection measures for the most endangered regions, or in a more advanced state as additional basis of early warning systems and emergency planning. Consequently, from an applied point of view, landslide hazard assessments are most important for decision makers. However, quite often natural hazard maps are not included in official planning procedures, unfortunately, this is particularly true for landslides.

To meet the previously addressed demands, the final product of a landslide hazard assessment has to provide answers to the following questions, adapted from Kienholz (1993) and extended further:

1. *What* could happen?
2. *What* could happen if something changes?
3. *What* could happen, and *where*?
4. *What* could happen, and *where*, if something changes?
5. *What* could happen, and *when*?
6. *What* could happen, and *when*, if something changes?
7. *What* could happen, *when* and *where*?
8. *What* could happen, *when* and *where*, if something changes?

It is evident that answers can be given in terms of probabilities only. The reply to the question *when* addresses the probability of occurrence in a given period, while *where* puts the focus on the probability of occurrence in a given area. Therefore landslide hazard expresses ultimately the spatial and temporal probability of landslide occurrence, i.e. within a given area for a specific period and the resulting hazard map must provide information on spatial and temporal probabilities of landslide occurrence (including information on types, magnitudes, velocities, etc.). If this definition is applied to many existing 'landslide hazard maps' it is apparent that numerous studies have not assessed the hazard in terms of temporal probability, rather, they give landslide susceptibility.

Following these general remarks, different approaches to landslide hazard assessment are introduced briefly (detailed discussion in Carrara and Guzzetti (1995), van Westen and Terlien (1996) and Wu *et al.* (1996)).

Aspects of hazard assessments that need to be given considerations include:

mapping, differentiated as direct field survey (heuristic approach) or indirect surveys using e.g. aerial photography;
relative techniques, such as likelihood of occurrence or absolute techniques such as determination of the Factor of Safety; and
scale of investigation in terms of region (national, regional, local) and of time (day, weeks, months, years, decades, centuries resolution).

The probability of landslide occurrence in space and in time can be established using two different concepts. A direct approach determines the probability of landslide occurrence using landslide records - the so-called 'precedent principle'. The indirect approach gives the probability of landslide-triggering conditions such as rainfall, or earthquake magnitude. Inherent in both concepts is, however, that basic information on landslide occurrences are required, derived either by actual measurements or by historical records. In this paper, both procedures are presented.

To undertake such hazard assessments, data sets require information on:

landslide occurrence;
associated triggering conditions including duration, intensity of impact, and antecedent conditions; and
movement controlling factors such as geology, soil, vegetation cover.

geomorphometric terrain characteristics and its derivates (slope angle, aspect, elevation, curvature, etc.).

It is evident that records need to be as comprehensive as possible. Indeed, date of occurrence and, within a spatial hazard assessment, location of failure are compulsory.

Within spatial analysis, GIS with its analytical, data storage and cartographic capacities allows a relatively quick and easy landslide hazard assessment for a given region. Therefore, it has been applied extensively to landslide hazard research, in particular within the last decade. The most often applied approaches using GIS techniques are based on multivariate statistics (Anbalagan and Singh 1996; Carrara 1983, 1989; Carrara *et al.* 1990; Carrara *et al.* 1991; Carrara *et al.* 1995; Carrara and Guzzetti 1995; Chung *et al.* 1996; Dikau and Jäger 1995; Guzzetti *et al.* 1999; Pike 1988) relating the distribution of landslides to various terrain characteristics. Other techniques use landscape models (Bonomi and Cavallin 1999; Miller 1995; Miller and Sias 1998; Montgomery and Dietrich 1994; Montgomery *et al.* 2000; Okimura and Kawatani 1986; Sakellariou and Ferentinou 2001; Terlien *et al.* 1996; van Asch *et al.* 1993; van Westen and Terlien 1996) coupled with physically based stability and/or hydrological models.

Although these approaches seem to work very well, there are some drawbacks to consider. Frequently, landslide hazard maps are not validated (Chung and Fabbri 1999; Chung *et al.* 1996; Jade and Sarkar 1993) and consequently are difficult to interpret. If direct mapping of landslide hazard is approached, results may vary with expert teams (van Westen *et al.* 1999). With respect to a comparison between models built on multivariate statistics and process-based landscape models, recent research by Gritzner *et al.* (2001) demonstrates no improvement of landslide prediction by including a process-based soil moisture index in contrast to 'traditional' multivariate statistical modelling. Consequently, further research has to prove the accuracy and reliability of such models and their additional value to a broader community in more detail.

Independent of the type of model, data bases of landslide information are necessary. The importance of including historical landslide data has been pointed out by Brunsden and Ibsen (1994), Glade and Crozier (1996; 1998; 1999), Guzzetti *et al.* (1994), Guzzetti *et al.* (1999) and Ibsen and Brunsden (1996). A review for European landslide data bases is given by Dikau *et al.* (1996). Based on two examples from New Zealand and Germany, this review draws attention to differences in interpreting hazard maps dependent on their data base, and to the use of historical data.

2. Methods

Information on historical landslides consist of spatiotemporal data. Spatial data have been obtained by aerial photograph interpretation, extensive ground surveys, and from historical information derived from archives (prints, chronicles, private), reports, scientific studies as well as from personal communications with affected home or property owners. Temporal data have been inferred from first appearance within sequential aerial photography and/or through correlation with known triggering events. The methodology is described in more detail for Rheinhessen, Germany by Jäger (1997) and for Hawke's Bay, New Zealand by Glade (1998). In each region, collection of

information lead to a spatiotemporal landslide inventory/data base used within this analysis.

Different techniques can be used to transfer these data into a GIS based zonation of landslide hazard. A landslide inventory, as the simplest product, shows locations of landslides, possibly in combination with other terrain characteristics. The heuristic analysis includes techniques such as photo interpretation and fieldwork, and in both approaches, experts can identify areas most prone to natural hazards. In contrast, statistical analysis using multivariate techniques can give indices for given landscape elements, e.g. failure rate. Deterministic analysis is mostly based on physically based models which are combined with spatial information. As a result of statistical and deterministic analysis, a susceptibility or hazard map can be derived.

Structure of data input, processing, and output are shown in Figure 1 for Rheinhessen and in Figure 2 for New Zealand. Inherent in both methods is a spatiotemporal database, from which data are used as input parameters for landslide hazard assessments.

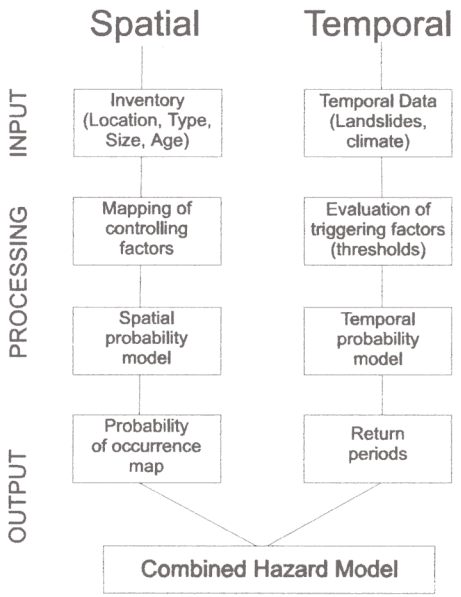

Figure 1. Spatial and temporal components of a landslide hazard model for Rheinhessen (based on Varnes (1984), adapted from Dikau and Jäger (1995) and Jäger (1997)).

2.1 RHEINHESSEN

Various combinations of input variables were analysed using multivariate statistics. Maximum likelihood-ratio tests and degrees of freedom were used as criteria to choose the most suitable factors for GIS analysis. Predicted probability of each factor combination was calculated for each cell and classified for cartographical display (refer to Jäger (1997) for more detailed descriptions of methodology).

2.2 HAWKE'S BAY

Relevant data were digitized either from analog maps or from aerial photography, extracted from the NZLRI (New Zealand Land Resource Inventory (Crippen and Eyles 1985)), and calculated from a digital elevation model using Arc/Info routines. The Inverse Distance Weighted Interpolation method provided by Arc/Info was chosen to calculate spatial rainfall probability maps. This method is frequently used with sparse data sets, thus it seemed applicable to rainfall values for single climatic stations which are distributed throughout the whole region. These input data were combined within the GIS software Arc/Info. Histograms of each layer in combination with multivariate regression analysis were used to identify the factors most important for explaining landslide occurrence. Analogous to the Rheinhessen methodology, the probability of each factor combination was predicted. Resulting probability surfaces were classified into areas of low, medium and high hazard for the final hazard map (refer to Glade (1997) for more detail).

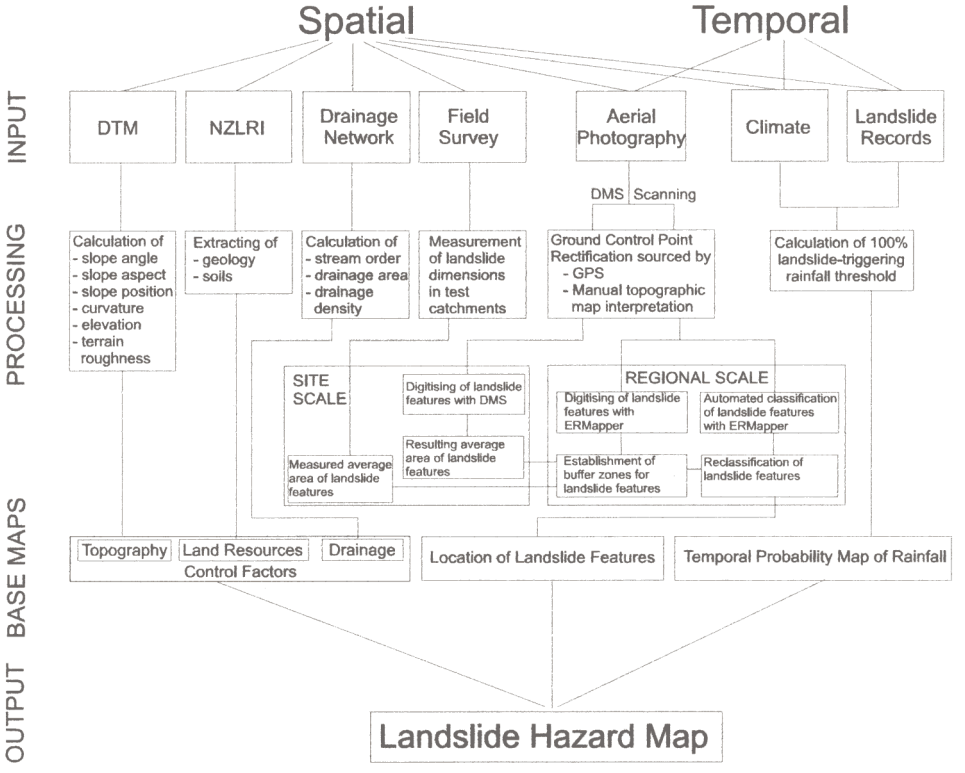

Figure 2. Structure of data input, processing, analysis and output within the GIS (Note: Digital stereo digitizing was performed with StereoDigitizer supplied by DMS (Digital Mapping System)).

3. Study areas

3.1. ENVIRONMENTAL SETTING OF RHEINHESSEN

The German study area is located in Rheinhessen, southwest Germany (Figure 3) and covers an area of approx. 500 km^2. Underlying geology consist of horizontal layers of Oligocene clay and marls, topped with resistant Miocene limestone. Some tectonic faults with minor movements are supposed (Rothausen and Sonne 1984). An escarpment has developed and the plateau area is covered by loess over Pliocene Rhine gravels. Longitudinal slope profiles are concave, characterised by generally steep upper parts, lower slope angles in the mid slopes and low angles in lower slope positions. The region is in high agricultural use, dominated by vineyards on the slopes. Climate is moderate with an annual average temperature of 9.6^0 C and 550 mm average yearly rainfall. However, more than half of the rainfall total occurs in singular rainstorm events during summer. A more detailed description of this area is given by Jäger (1997) and Glade *et al.* (2001).

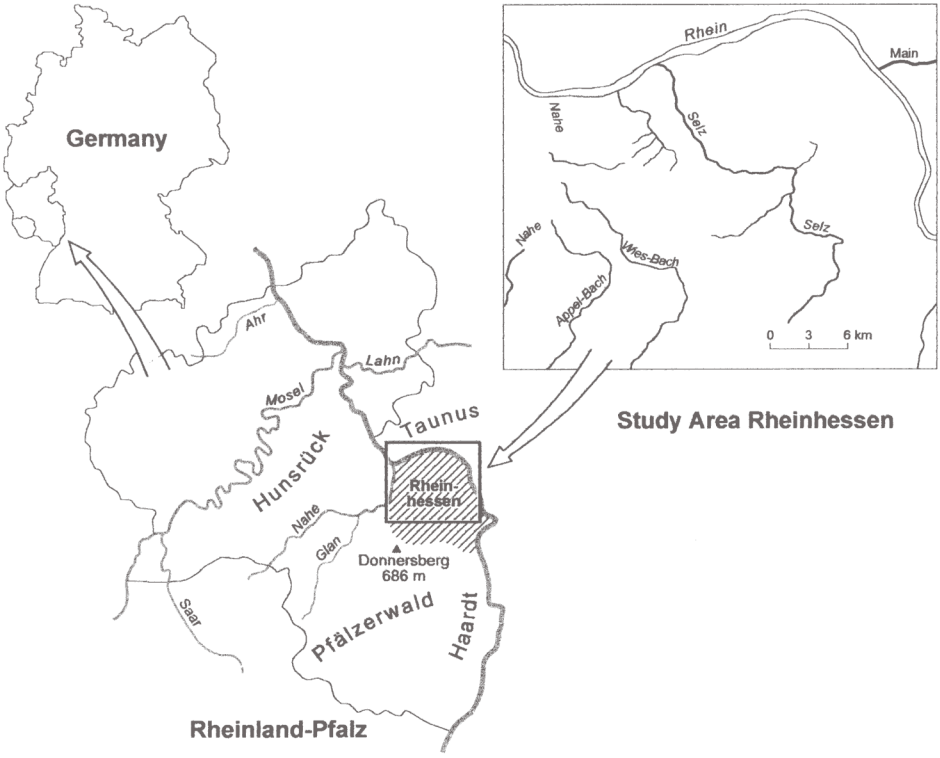

Figure 3. Location of the Rheinhessen study area in southwest Germany.

Landslides are well known in this area. Unfavourable climate conditions such as long prolonged wet periods and intense short term rainstorm events have triggered

landslides. Jäger (1997) concluded that critical climatic landslide-triggering conditions occur on average every 5 years. It is supposed that first failures occurred in the Pliocene (Beck 1994). Historical reports on landslide events throughout the region are available for the last two centuries (Glade *et al.* 2001). The last landslide event affecting a large region occurred in winter 1981/82 and triggered more than 240 landslides. This event was used in the presented study for further analysis.

3.2. ENVIRONMENTAL CONDITIONS OF HAWKE'S BAY

The New Zealand study area (Hawke's Bay) is located in the northeast of the North Island (Figure 4) and covers an area of approx. 49 km^2. This area is part of the forearc basin of the convergence zone between the Pacific Plate and the Australian Plate. Consequently, it is tectonically very active with uplift rates of 0-2 mm/yr for the last 10,000 years. The underlying bedrock is mainly sedimentary rock of Pliocene and early Pleistocene age. The dark blue-grey silty mudstones are interbedded with conglomerates and very fossiliferous limestone bands. The overall uniform dip of 2^0 to 10^0 is south-east towards the Hawke's Bay coast.

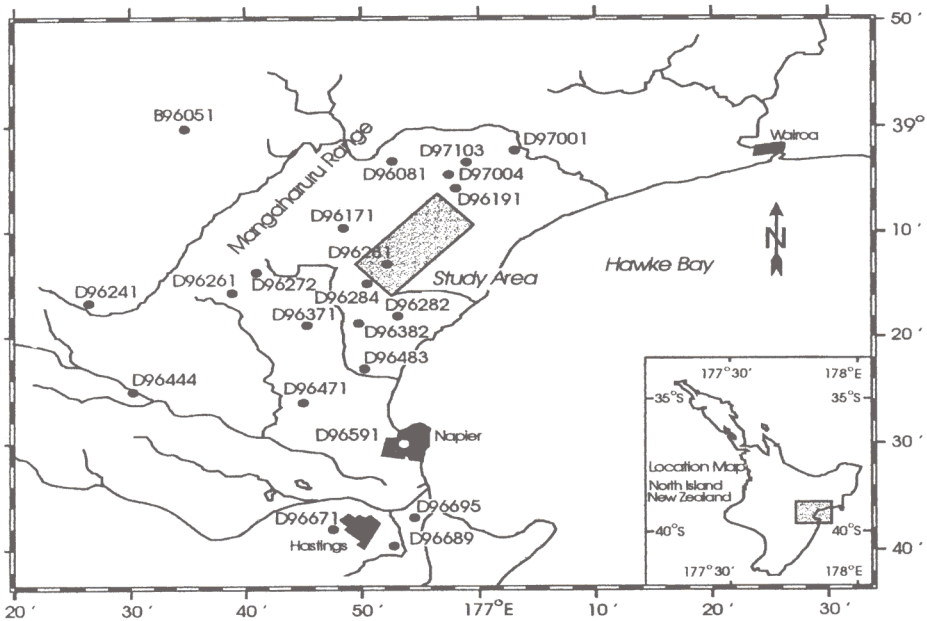

Figure 4. Location of the Hawke's Bay study area on the North Island of New Zealand. Points indicate locations of climatic stations used in the analysis. Numbers refer to the official station identification assigned by the New Zealand Meteorological Service. The study area is shaded grey.

The area is steeply dissected by rivers. Slope profiles are characterised by steep upper parts, moderate to steep mid parts and low slope angles in lower parts. Soils are based in particular on volcanic ash fall deposits, which are moderately weathered with silt loam or sandy loam textures. The study region was until recently covered in lowland conifer-

broadleaved forest, with patches of beech-conifer-broadleaved forests. Between 1870 and 1900 clearing, burning and overgrazing depleted native vegetation cover in most areas, and it was replaced with pasture. Recently, however, forestry companies have begun to buy or lease farmland and grow pine trees in plantation. Climate is moderate with a mean annual temperature of approx. 12^0 C. Annual average rainfall is 1390 mm. Due to extra-tropical cyclonic depressions passing over the region, extreme and intense rainstorm events with low return periods and lasting in general for 3-4 days occur commonly in autumn from March to May (more details in Glade (1997)).

The combination of steep relief with long slopes, minimal vegetation cover, shallow highly permeable soils underlayed by nearly impermeable mudstones, and extreme rainstorm events make the region most susceptible to landsliding. Detailed records of landslides are available for historic time (since 1873) and for pre-historic times through the use of dating techniques such as pollen analysis, tephra, ^{14}C, OSL and TL (e.g. McGlone (1978), Page and Trustrum (1997), Wilmshurst *et al.* (1997), Wilmshurst (1997)). One of the largest landslide events hit the region between the 8th and 11th of March 1988 and caused thousands of landslides. This event was used within this study.

4. Data

Within this study both deterministic data and probabilistic data have been used. The first group involves information on geomorphology, topography and related derivates, soil, geology, land use and consequently vegetation, hydrology, and climatic conditions. Probabilistic data include information on the spatial and temporal probability of controlling and/or triggering factors.

For Rheinhessen, the following data were available in digital format and used within the analysis:

- landslide locations of the 1981/82 event (digitised from a landslide inventory compiled by the Geological Survey Rheinland-Pfalz, and extended by the MABIS-project Dikau and Schmidt (2001); refer to Jäger (1997) and Glade *et al.* (2001) for details);
- geology, digitised from analog maps at a scale of 1:25,000; and
- digital elevation model in a 40 m resolution (including derived parameters such as slope angle, vertical and horizontal curvature, slope height, slope position).

For Hawke's Bay, data obtained from various sources include:

- landslide locations of the 1988 event (Cyclone Bola);
- information derived from the New Zealand Land Resource Inventory (geology, vegetation, soils);
- digital elevation model in a 10 m resolution (including terrain characteristics such as slope angle, position on slope, elevation, curvature, etc. and hydrological parameters such as drainage basin, stream order, drainage density); and
- a spatial rainfall map showing the probability of occurrence of a landslide-triggering daily rainstorm with a magnitude larger than 120 mm and a return period of ten years.

5. Results

5.1. RHEINHESSEN

Approximately 240 landslide were triggered by a low magnitude rainfall in winter 1981/82. This rainfall event was coupled with a large temperature increase within a few days, which led to a quick snow melt and thus saturation of the soil. More than 90 % of all landslides are classified as shallow earth and debris slides with an estimated shear plane depth ranging between 2 to 6 m. Temporal analysis of climatic conditions and landslide activity lead to the conclusion, that the triggering event of 1981/82 has a recurrence interval of approx. 50 years (Jäger 1997).

Multivariate statistical analysis of all input parameters demonstrated that the most important parameters determining the probability of landslide location were slope angle, slope position and geology (Jäger 1997). The landslide susceptibility map shows, that upper slopes with slope angles larger 15^0 and Oligocene clays and marls of the Tertiary escarpment are especially prone to landslides (Figure 5).

Historical data were not used to assess the landslide hazard for Rheinhessen. However, Jäger (1997) incorporated the temporal probability by using the historical landslide data base and comparing it with climatic records. Thus, Jäger (1997) indicated the temporal validity of the resulting susceptibility map by calculating the return period of the triggering event, which in the case of Rheinhessen is 50 years. Therefore, the landslide susceptibility map of Figure 5 shows the distribution of probabilities of landslide occurrence on a given slope segment for a triggering event with a return period of 50 years.

5.2 HAWKE'S BAY

Within the study area of approx. 49 km^2, 10,893 landslides, in particular debris flows and slides, were triggered during Cyclone Bola in March 1988. Landslide density is 2.2 per ha. In total, 2.56 km^2 or 5.2 % of the region failed, which gives an average failure size of 235 m^2. The storm lasted for three days over the region with a total of 670 mm rainfall.

Landslide locations were digitized and combined in a GIS with maps of the distributions of factors described above. Multivariate statistics showed that the variables slope angle, soil type and the rainfall probability best explain landslide occurrence (refer to Glade (1997) for more details). Consequently, these three variables were used to calculate the probability of landslide occurrence. The calculated rainfall value refers here to the probability that the maximum landslide-triggering rainfall threshold of 300 mm will occur in this area within 10 years. This value was derived using the Daily Rainfall model as described by Glade (1998) and applied to the landslide hazard assessment, because it corresponds well to the maximum daily rainfall magnitude of Cyclone Bola, which triggered the digitized landslides. The resulting landslide hazard map shows the distribution of the landslide classes, which is mainly dependent on slope angle (Figure 6).

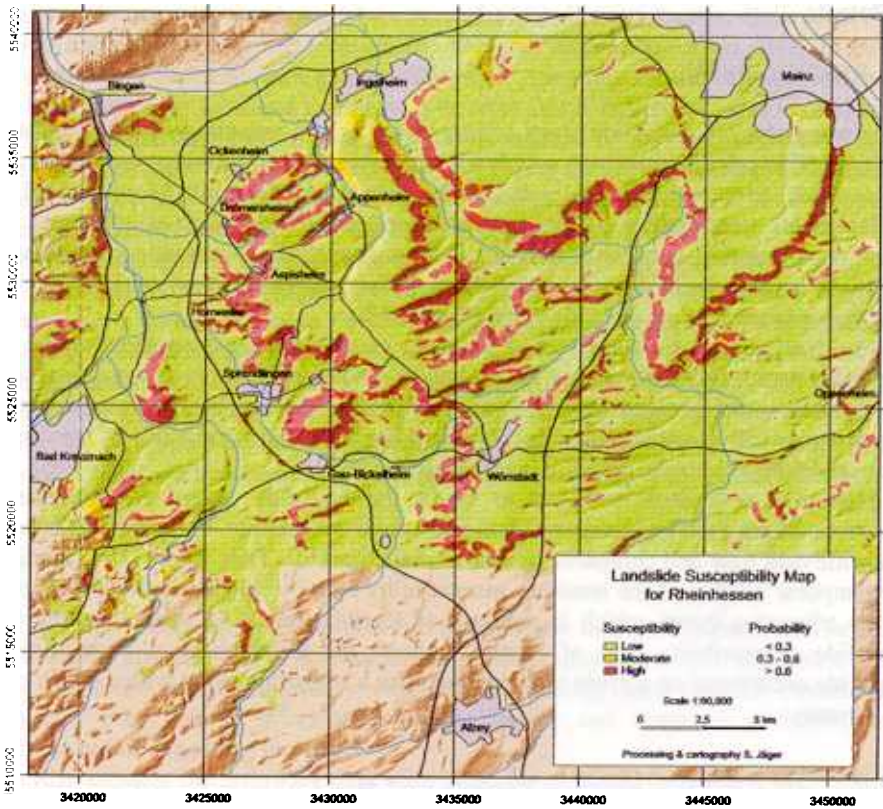

Figure 5. Landslide susceptibility map for Rheinhessen, Germany (Jäger 1997). Similarly coloured areas refer to regions with similar predicted probability values within the climatic class range. Thus, red areas indicate regions which are most likely to fail during similar climatic conditions as in winter 1981/82. Raster size is 40 m (*Note*: more details in Jäger (1997)).

Within this landslide hazard assessment, historical data - and therefore temporal probability - is incorporated. The data layer 'spatial rainfall' is based on the calculation of a return period for a given rainfall event (in this case: 300 mm/d within 10 years). Consequently, this data layer could be exchanged with another probability function such as 300 mm/d within 1 day, 1 month, 1 year, 50 years, or any other time period.

6. Conclusion and Discussion

Both landslide maps are based on statistical techniques to derive the probability of failure. The main difference is, however, that the Rheinhessen susceptibility map shows the spatial probability of failure for specific landscape segments during a similar landslide-triggering event as to 1981/82. It is not possible to change probability of occurrence for different periods. Following the internationally accepted terminology of natural hazard given by Varnes (1984), the Rheinhessen landslide map is not a hazard assessment per definition, it is rather a susceptibility assessment for a given storm event.

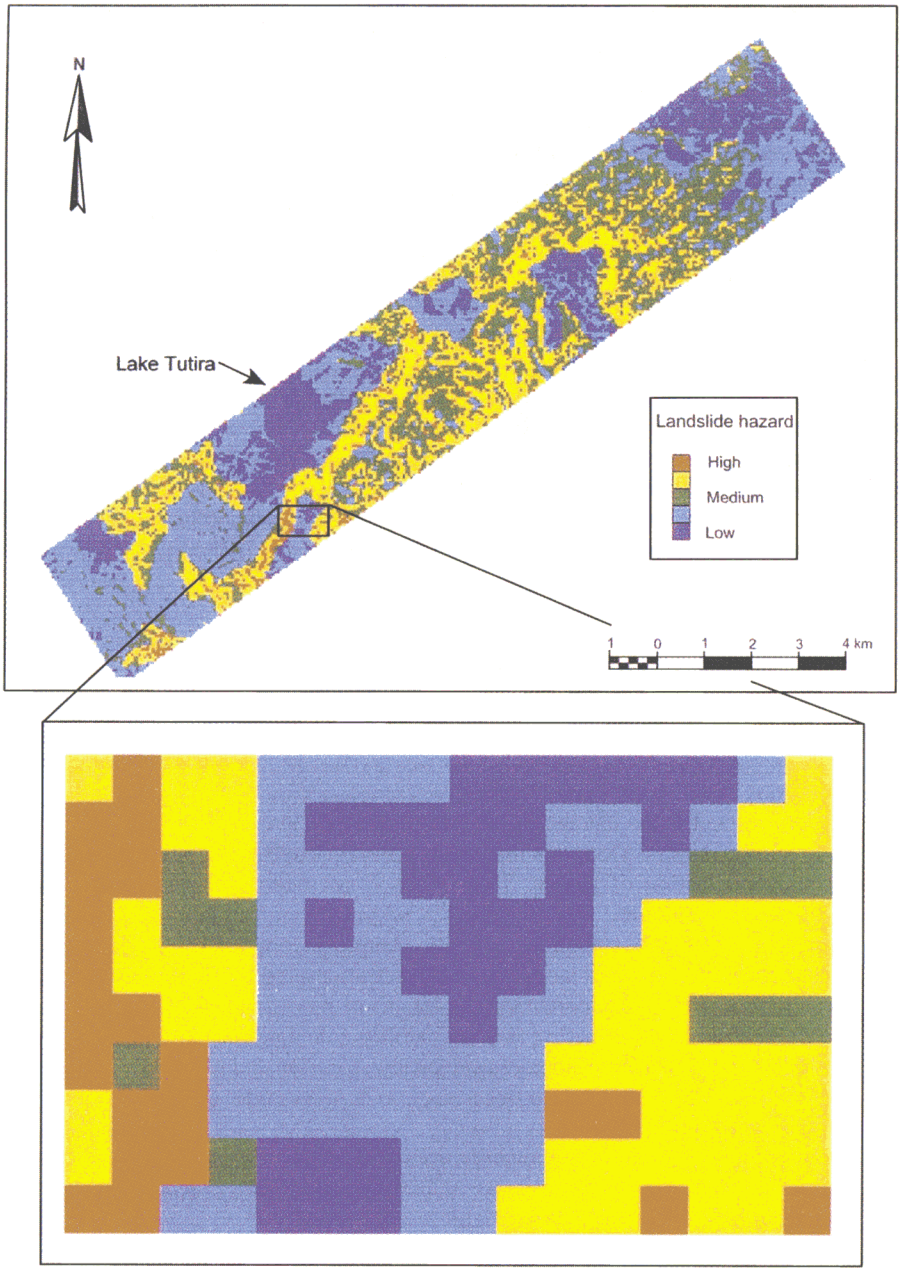

Figure 6. Landslide hazard map for Hawke's Bay, New Zealand. The red areas indicate regions which are most likely to fail with the next rainstorm which exceeds the landslide-triggering rainfall threshold of 300 mm (Note: Threshold is determined through the Daily Rainfall Model, described in detail by Glade (1998). Raster size is 50 m. Enlargement shows flat plateaus in blue colours and adjacent steep slopes in green, yellow, red).

Consequently, this susceptibility map is static.

In contrast, the New Zealand case study demonstrates that by adding information on spatial rainfall probability for a given event magnitude within a predefined period, the susceptibility map can be changed to a hazard map according to the input of the rainfall probability surface. There is a dynamic element inherent, because this temporal rainfall probability can be calculated for any requested time period.

The New Zealand hazard assessment relies heavily on historical data. Indeed, a spatial landslide susceptibility map could be calculated using the terrain conditions and landslide locations only. However, this susceptibility map would be of minor use to the public and planners, because both want not only information on the most likely place of occurrence of the next landslide for a predefined event magnitude, of particular interest is the probability in time of landslide occurrence associated with a given triggering magnitude. And this information can only be supplied by including temporal probabilistic data obtained from a long and comprehensive historical record, thus extending the instrument record further back into the past. In contrast to fluvial archives, where long records of instrumental measurements are available, landslides have not been equipped and monitored for such long periods, if at all. Therefore, it is even more difficult to calculate a spatiotemporal probability of occurrence without historical data.

Although the advances of the use of historical landslide is obvious, some limitations have to be addressed.

- Firstly, it is nearly impossible to compile landslide records including all events. This is particularly true for records of high frequency/low magnitude events. In addition, the chances of obtaining historical records decreases with age of landslide event. As a consequence, any probability calculation using historical records gives a best case only. However, it can be assumed that the most disastrous events have been recorded.
- Another aspect is the change of land surface conditions in time. As Preston (1999) have shown, spatial slope stability changes with each subsequent landslide event through exhaustion of slopes. This effect is not been included in any landslide hazard assessment yet.
- Based on the same principle, climate change is not reflected as well. In any compilation of historical landslide data, it is attempted to include as many records as available. However, increasing the length of records leads to the destruction of the overall assumption within any probability calculation: no change of boundary conditions for the time under consideration. Crozier and Glade (1999) discussed this problem with respect to frequency and magnitude of landsliding in more detail.
- As already mentioned in the introduction, validation of analysed susceptibility and hazard maps is frequently missing (Chung *et al.* 1996; Jade and Sarkar 1993). Consequently, these maps are difficult to interpret.

Although these limitations seem crucial, <u>all</u> data sets including historical data are confronted with these problems (e.g. Trimble 1998). Nevertheless, this paper demonstrates that historical data is one data type which improves hazard assessments. This is in particular important with respect to potential applications. Such applications range from better information for emergency operations ('Where to look first in case of

an event?') to additional data for planning guidance (e.g. Shrestha *et al.* 1999).

This is in particular evident by revisiting the eight questions important for landslide hazard assessments, which have been addressed in the introduction. The Rheinhessen landslide susceptibility assessment could answer questions 3 and 4, asking for *What* could happen, and *where* (question 3) if something changes (question 4 respectively). In contrast, the Hawke's Bay hazard assessment could answer all questions due to the changeable temporal element inherent in the assessment. Therefore, the advantages of the hazard approach over the susceptibility method using historical data are evident.

6. Perspectives

With respect to the previously raised issues, spatiotemporal landslide research is on-going in both regions. Work in the Rheinhessen study area includes:

- comparison of an already developed physically-based slope stability model using soil mechanical response units within a GIS Möller *et al.* 2001 with the multivariate landslide model as described in this paper;
- calculation of improvements of a physically-based GIS model to a multivariate susceptibility model;
- determination of the errors associated with probability surfaces and consequently validation of the susceptibility map;
- comparison of results based on DEM's at 20 m resolution with 40 m raster size as used in this paper; and
- extending the susceptibility map to a hazard map and including elements at risk, their potential damage potential and their vulnerability towards landslides, thus calculating spatiotemporal landslide risk.

Future work in Hawke's Bay is focussing on:

- variation of spatial rainfall probability surfaces;
- validation of landslide hazard maps using methods suggested by Chung *et al.* (1996) and Chung and Fabbri (1999);
- coupling spatial slope stability calculation (Preston and Crozier 1999) with hydrological modelling;
- comparing spatial distributions of different events (e.g. 1938, 1964, 1988) with respect to their controlling factors such as geology, vegetation, terrain characteristics (e.g. slope angle, slope aspect, slope position, vertical and horizontal curvature, distance to divide, etc.); and
- calculation of landslide risk maps based on similar methodology as described in the Rheinhessen study area.

In the title of this paper, the question was posed: *Landslide hazard assessment and historical data - an inseparable couple?* The answer is: NO, they are not an inseparable couple. It might be possible through long-term measurements of parameters such as displacement rate to establish a temporal probability of occurrence. Unfortunately, such long-term measurements of landslide behaviour are rarely available. Therefore,

alternatives such as historical data have to be applied to establish temporal probabilities.

It has been shown on the examples provided, that by including historical data into landslide assessments, a susceptibility map might be extend to a hazard map. These hazard assessments can be used to display scenarios for different time periods. Therefore the answer to the posed question should ultimately be: YES - historical data improve hazard assessments!

8. Acknowledgements

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