Uncertainties in rainfall-induced landslide hazard

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Abstract

The paper addresses the main uncertainties associated with the occurrence of rainfall induced landslides. Spatial variability of site conditions, local geology and rainfall contributes significantly to the uncertainty of landslide hazard. Urban landslide problems require the management of slopes of marginal stability. Assessment of hazard, vulnerability and risk require the use of observational approaches, the analysis of rainfall data and the relationship between rainfall magnitudes on the one hand and slope movement on the other. Details of research carried out in the Illawarra area of New South Wales, Australia are provided. Reference is made to the comprehensive database enabling the determination of landslide frequencies. The concept of antecedent rainfall percentage exceedence time (ARPET) is explained. The use of inferred threshold rainfall magnitudes for real-time prediction and warning is explained. Uncertainties concerned with this approach are explored with particular reference to rainfall distributions in the study area.

Keywords: geographic information systems, geomorphology, landslides, pore pressure, risk assessment, seepage, slope stability

Understanding of factors which influence slope stability should be firmly based on the principles of modern geomechanics such as the principle of effective stress and the influence of strains and deformations on shear strength. Moreover, the importance of geology, geological history and geological modelling can hardly be overstated (Fookes 1997; Fookes *et al.* 2000; Hutchinson 2001). The development of slope instability and the occurrence of landslides involves natural processes as well as changes due to human action such as deforestation and land development. It is not always easy to separate the effects of man-made changes from the consequences of natural processes and the relationships between these two types of changes may be quite complex. This is a major source of uncertainty in slope stability assessment of urban areas. Moreover, natural processes vary widely in the time rate of their impact. Events such as rainstorms and earthquakes often act as triggering agents for landsliding and their role is often self-evident. Significant landslide disasters triggered by rainfall are reported every year in different countries. For example, considering specifically the study area of interest in this paper, two people were killed as a result of a mudslide in Coledale within the Illawarra region of New South Wales, Australia in April 1988 and, a decade later, more than 150 landslides occurred in the same region following the rainstorm of August 18–21, 1998. As a relatively recent example from Europe of a major landslide disaster triggered by rainfall, one may refer to the mass movements in Sarno–Quindici area near Naples in Italy following the rainfall of 4/5 May, 1998. One hundred and sixty one people lost their lives. The possible causes and mechanisms of these failures have been discussed by Del Prete *et al.* (1998). In contrast to rainstorms and earthquakes, other natural processes act gradually over many years and even decades and are accompanied by progressive changes in stability.

This paper addresses the role of uncertainties in the assessment and management of landslide hazard with particular reference to rainfall as a triggering agent. The use of both qualitative and quantitative approaches is appropriate in assessing and solving geotechnical problems (Chowdhury & Flentje 1998; Flentje & Chowdhury 1999; Flentje *et al.* 2000).

In this paper reference is made to the need to relate the magnitude and frequency of rainfall to the potential for landsliding. Studies carried out in a coastal area of Australia, the Illawarra region of New South Wales, are described with particular reference to rainfall analysis, the concept of antecedent rainfall percentage exceedence time (ARPET) and the threshold rainfall magnitudes for the initiation of slope movement and disruptive failure.

Urban landsliding

Introduction

Management of landsliding in urban areas requires consideration of a wide range of instability problems, from very small landslide volumes to very large and from extremely slow movements to rapid slides, flows or falls. The most important aspect concerns the consequences of failure in terms of economic loss, human injury and loss of life. Low hazard-high consequence and high hazard-low consequence events are just two of the many combinations that have to be assessed as categories of risk and ranked in order of importance for landslide management.

Many natural slopes are only marginally stable at best even without a triggering agent such as a rainstorm. For example, in the study area referred above, some sites are subject to deep-seated but very slow sliding movements.

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Conventional stability analyses play a useful but limited role in assessing and managing such slopes. For a discussion of the merits and limitations of conventional deterministic and probabilistic analyses, the reader may refer to Chowdhury (2000), Duncan (2000) and Chowdhury & Flentje (1999). A detailed discussion of conventional analytical and numerical approaches is outside the scope of this paper.

Remedial measures to slopes in urban areas must involve minimum disturbance and may be thwarted by lack of public access to the respective sites. Trying to increase the factor of safety of such slopes requires significant expenditure of public funds. Even if such funds are available, legal liability issues may rule out or hinder the carrying out of some types of remediation. Therefore, it is desirable to assess hazard and risk using empirical and observational approaches before deciding how to manage such slopes. Improved capacity to make predictions about slope performance during rainstorms of different intensity and duration, and to provide timely warnings can be most valuable. In particular, real-time warnings can enhance safety and save lives.

Hazard, vulnerability and risk

The susceptibility of a slope to landsliding and the frequency of occurrence are components of 'hazard'. In urban areas and along transportation routes, it is important to identify also the 'elements' at risk from landsliding and the 'vulnerability' of those elements. The risk associated with landsliding includes both the hazard and the consequences. The risk may be defined with respect to economic loss (including damage and destruction to property) and, separately, also with respect to the loss of human life. For comprehensive reviews of the definitions, factors and approaches concerning hazard and risk assessment the reader may refer to Morgan *et al.* (1992), AGS (2000), Flentje *et al.* (2000) and Ho *et al.* (2000).

It is interesting to note that conventional geotechnical analysis approaches, deterministic or probabilistic, are insufficient to enable determination of the hazard and risk of landsliding. Most importantly, hazard must reflect the probability in both a spatial and a temporal sense. Its assessment must, therefore, involve historical data associated with field observation. Identification of elements at risk and assessment of their vulnerability also require observation, inference and subjective judgement.

For regions in which rainfall is the main landslide triggering agent the major goals of urban landslide management can be summarized as follows:

- understanding the link between rainfall and landsliding
- estimating the frequency of landsliding in different areas
- prioritising slopes for preventive and remedial action.
- developing early warning systems and
- developing approaches for real-time assessment of hazard and risk during rainstorms

For the study area, located within the Illawarra Region of New South Wales (which includes the Wollongong City Local Government Area) the research reported below addressed some of the management objectives listed above. In particular, the following steps were carried out:

- determination of the frequency of landsliding in the urban area as a whole and also for its different parts over the historical period
- analysis of rainfall data from different rainfall stations within the area
- monitoring of subsurface shear movements at existing landslide sites
- monitoring of subsurface pore water pressures at different sites
- studying the relationships between rainfall magnitudes and slope instability

The study area

Introduction

The city of Greater Wollongong, also known as the northern Illawarra has a population of almost 200 000 people and consists of a narrow coastal plain bounded on the north, south and west by an escarpment ranging in height from 300–500 m (Fig. 1). The escarpment is capped by spectacular cliffs of Hawkesbury sandstone below which there are steep to moderate slopes with flat benches and intermediate cliff lines. Colluvium of variable thickness has been deposited over the bedrock and much of the escarpment is covered in thick vegetation. The average rainfall varies from 1200 mm on the coastal plain to 1600 mm along the top of the escarpment. Whilst higher monthly rainfall often occurs during the months of November to May, significant rainfall can occur in any month of the year.

The Illawarra coastal escarpment has long been recognized as an area of existing landslides and on-going landslide activity. During the 150 years of European settlement urbanization has spread from the coastal plain to the sloping areas, and, therefore, the impact of landsliding on residential properties as well as along transportation routes has become more pronounced. Millions of dollars have been spent in the last decade for upgrading and landslide remediation along road and railway lines which connect Wollongong to Sydney and other regions. The location and extent of the study area, of triangular shape, is shown in Figure 1 east of the bold line representing the top of the escarpment. The numbers indicate site reference codes of twelve landslide

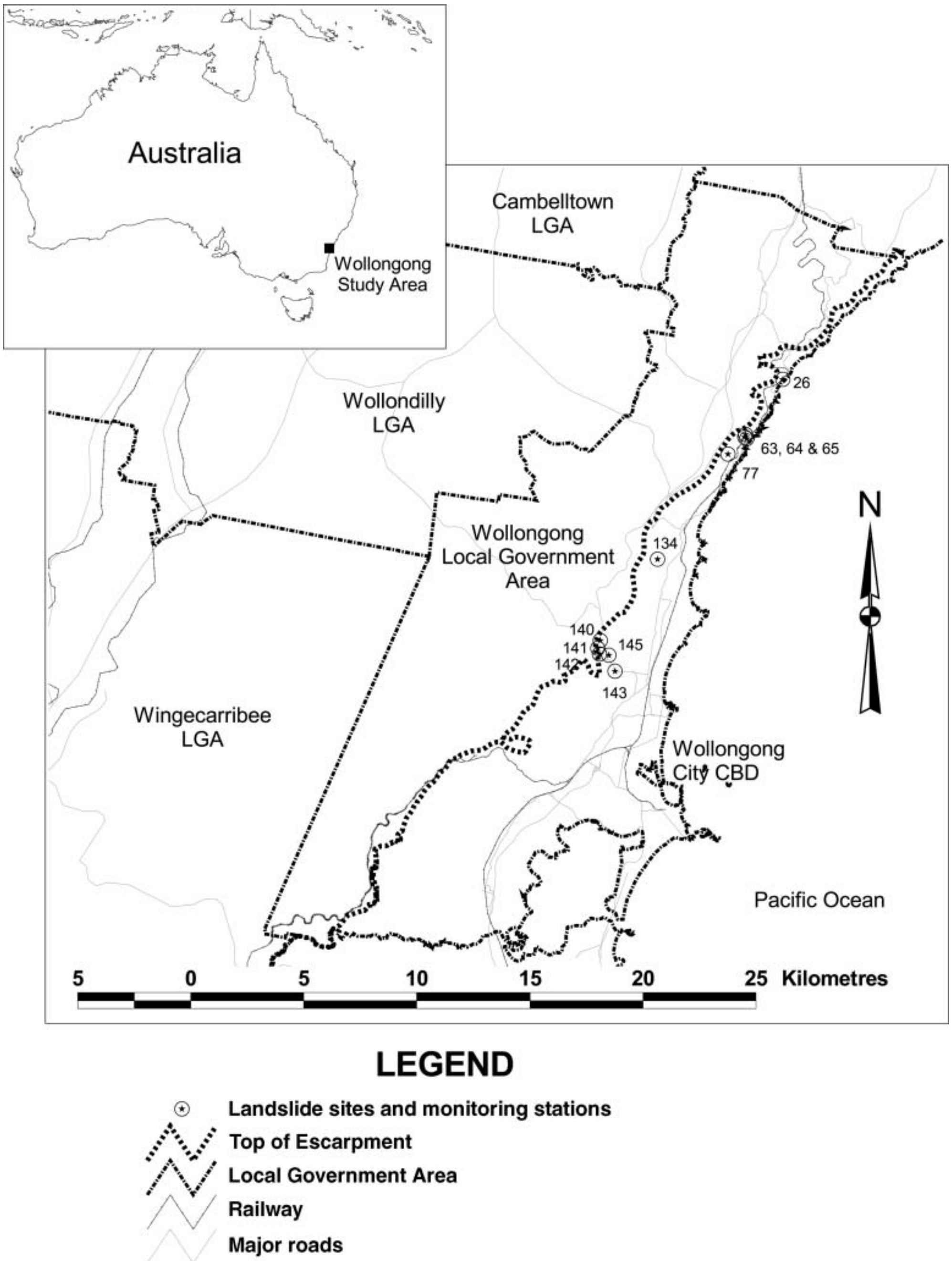

Fig. 1. Location plan and major transport routes of Wollongong. The escarpment is the western boundary of the study area (approx $100km^2$).

sites and associated subsurface monitoring stations to which reference is made in later sections of this paper.

Geology

The geological bedrock sequence of the Wollongong area is essentially flat-lying with a low angle dip, generally less than five degrees, towards the NW. This gentle dip to the NW is a result of the location of the district on the southeastern margin of an extensive mid-Permian to mid-Triassic sedimentary basin which is known as the Sydney Basin. The geological units encountered include the Shoalhaven Group, the Illawarra Coal Measures (including intrusives known as the Gerringong Volcanic facies), the Narrabeen Group and the Hawkesbury Sandstone.

The Narrabeen Group contains several claystone formations such as the Bald Hill, Stanwell Park and Wombarra Claystones. These claystone formations have been shown to have high correlations with the spatial distribution of landsliding (Flentje 1998). The Illawarra Coal Measures contain numerous economically significant coal seams. These coal seams include thin, very weak tuffaceous claystones and have an important

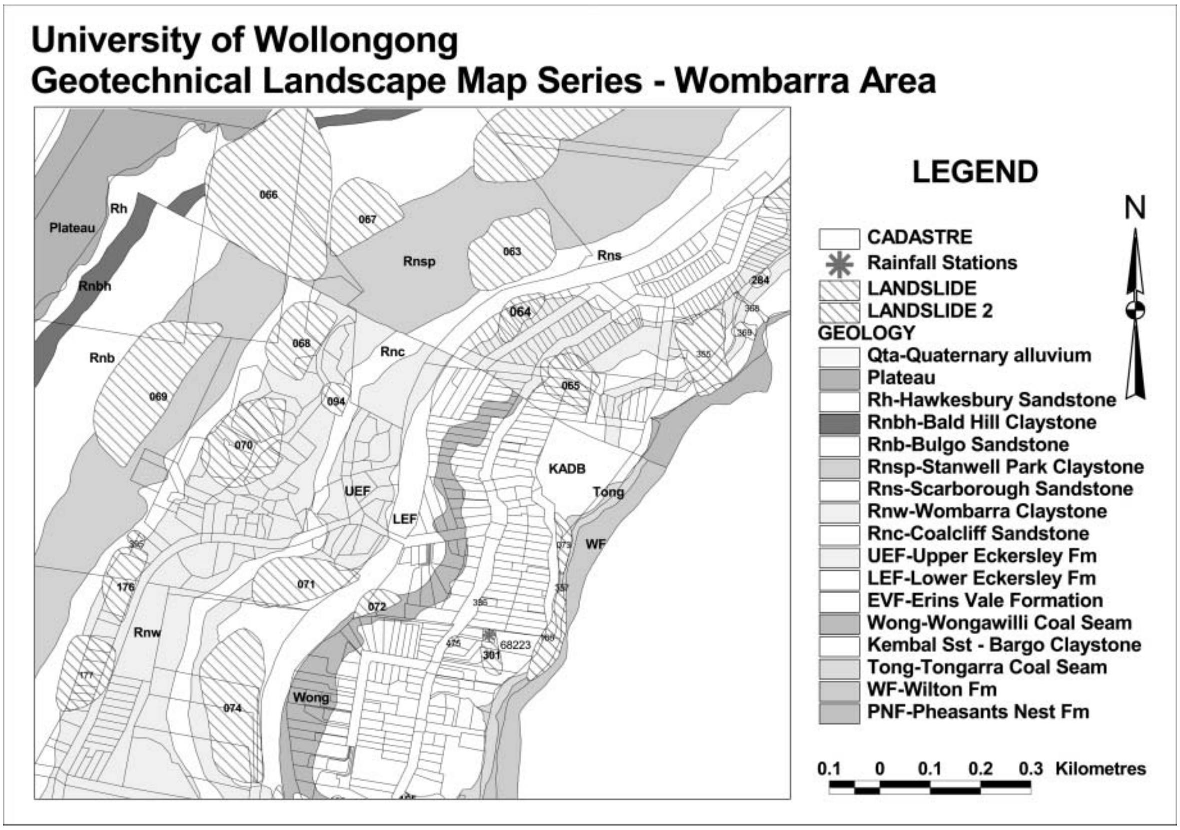

Fig. 2. A segment of the Geotechnical Landscape Map Series. Geology, Landslides and Cadastre Themes are shown. Each known landslide is labelled with its unique three digit Site Reference Code. Site 064 is discussed in the text.

influence on the local groundwater pressures and subsurface flow. The presence and location of these coal seams has been considered significant in several cases of land instability.

Accurate GIS-based maps of geology and existing landslides have been developed and updated regularly since 1996 and printed at a large scale of 1:4000 (Flentje 1998) to match commercially available orthophoto maps. These geology maps have been based on extensive field mapping, analysis of a comprehensive borehole database and available geological maps which have a smaller scale. Figure 2 shows a segment of one such map.

Occurrence and causes of landslides

The types of landslides identified in the area include complex and composite slide flows, debris-slides, debris-flows and rock falls. A landslide database developed since 1995 now includes details of 478 landslides (Chowdhury & Flentje 1998). Many of these are pre-existing landslides that may be reactivated after periods of intense and prolonged rainfall. From time to time, new landslides, occurring for the first time, are observed. Accordingly, the GIS-based maps of landslides, first developed in 1996, are updated from time to time. The number of recurrences and hence the frequency of different landslides in the historical period can be estimated from this database. This has proved useful in ranking the existing landslides according to the severity of the hazard.

High pore water pressures, that are generated after prolonged and intense rainfall, trigger most cases of significant landsliding in the Wollongong area. Relatively shallow landslides have the main slip surface within the mantle of colluvium. Often failure occurs progressively over time and the mobilized shear strength is close to the residual strength of the colluvium which may be as low as $c'_r = 0$ and $\varphi'_r = 15°$. For deep-seated landslides mobilized shear strength parameters as low as $c' = 0$ and $\varphi' = 9°$ have been determined from back analyses. These values are close to residual shear strengths measured in the laboratory.

Many of the relatively large landslides have their main or lowest slip surface located at or near the interface between colluvium and bedrock. This is particularly the case for relatively deep-seated landslides that move very slowly and intermittently and require subsurface monitoring with inclinometers (Chowdhury & Flentje 1998). Typical average rates of movement range from 0.1 mm per day up to 15.6 mm per day. According to the WP/WLI (Working Party on World Landslide Inventory), 1995, these correspond to velocity ranges from extremely slow to slow. However, many of these landslides have progressively caused significant damage or destruction to residential properties.

Table 1. *Example of Inclinometer summary data, for Site 064 as discussed below.*

Borehole Name	SRC	Suburb	Drilled	Number readings	depth to shear (m)	peak rate mm/day	average rate mm/day
3	064	Scarborough	3 March 1989	53	7.0–8.0	1.93	0.07
7			5 October 1989	35	1.5–2.5	2.09	0.06
10			20 July 1999	4	1.5–2.5	0.0500	0.0020
11			20 July 1999	4	7.0–8.0	0.0036	0.0002

Rainfall analyses

Introduction

Experience in the study area has shown that significant or widespread landsliding is rarely caused by intense rainstorms of short duration unless there has also been significant rainfall prior to such a rainstorm. Periods of rainfall with some associated threshold magnitudes that may induce landsliding vary from less than 24 hours for shallow debris flows (Wilson & Wieczorek 1995; Larsen & Simon 1993; Caine 1980) to a few months for deep seated slow moving landslides (Flentje 1998).

For example, 250 mm of rainfall over an antecedent period of one month was proposed as a threshold for landsliding in Wollongong by Young (1976). On the other hand Bowman (1972) suggested that 350 mm of rainfall over an antecedent period of one month was required to initiate landsliding in Wollongong. Furthermore, in several unpublished reports by local geotechnical engineers, antecedent periods ranging from one month to three months and the corresponding threshold magnitudes of 350–650 mm have been proposed for individual sites. However, there had been no systematic study of the relationship between rainfall and the initiation of slope instability. It was, therefore, decided to carry out such a study and a number of antecedent rainfall periods were selected in order to analyse the data, most of which was available only as daily rainfall magnitudes at different rainfall stations.

Antecedent rainfall periods considered for rainfall analysis

In order to study the frequency of rainfall magnitudes of different duration and to determine rainfall thresholds required to initiate slope instability, a comprehensive analysis of data from numerous rainfall stations has been carried out. Initially a 20 year record of daily rainfall from one rainfall station was analysed and subsequently this was extended to cover a 110 year period from January 1, 1888 to December 31, 1997. More recently, analyses have been carried out for a number of different rainfall stations within the study area. The analyses are currently being updated to include rainfall during the period 1997–2001 which includes an extreme 5 day storm event in August 1998.

In addition to one day (24 hour) rainfall, magnitudes of cumulative rainfall were calculated for the following daily rolling periods: 7, 30, 60, 90 and 120 days. Although references in the literature referred to periods up to only 90 days, a period of 120 days was included to be on the conservative side. Durations shorter than 24 hours have also been considered in some recent research work that is mentioned only briefly in this paper while discussing spatial variability. More details are given in Flentje & Chowdhury (2001).

For each of these five rolling periods, cumulative rainfall totals may be plotted against time in days. These plots have been combined with plots based on subsurface inclinometer monitoring data which show magnitudes and rates of displacement with time. Such information has been used to determine threshold rainfalls which can trigger landsliding, as discussed below.

Observational approach

Subsurface monitoring & threshold rainfalls

As stated earlier, many important landslides in the study area move very slowly and, even after rainstorms, landslide movements may not be detected by visual observations. Therefore, 57 inclinometers and/or piezometers (stand pipes, pneumatic or vibrating wire) have been installed at 23 sites and have been monitored over many years. For example, information gained from inclinometers installed at Site 064 is summarized in Table 1.

As stated in the previous section, time records of subsurface shear movement are superimposed on cumulative rainfall curves for the same time periods. Considering all the information and plots together, it is then possible to identify the peaks in the shear movement curves and identify the antecedent rainfall period to which they correspond the best.

For example, a landslide may have occurred at some Site S on a certain date, say January 25, 1978. The rainfall plots may show that 30 day cumulative rainfall was increasing or peaked on that date at 380 mm while the 1 day, 7 day, 60 day, 90 day and 120 day cumulative rainfalls were not increasing or did not peak on that day. Consequently the relevant threshold rainfall would be taken as the cumulative 30 day rainfall of 380 mm.

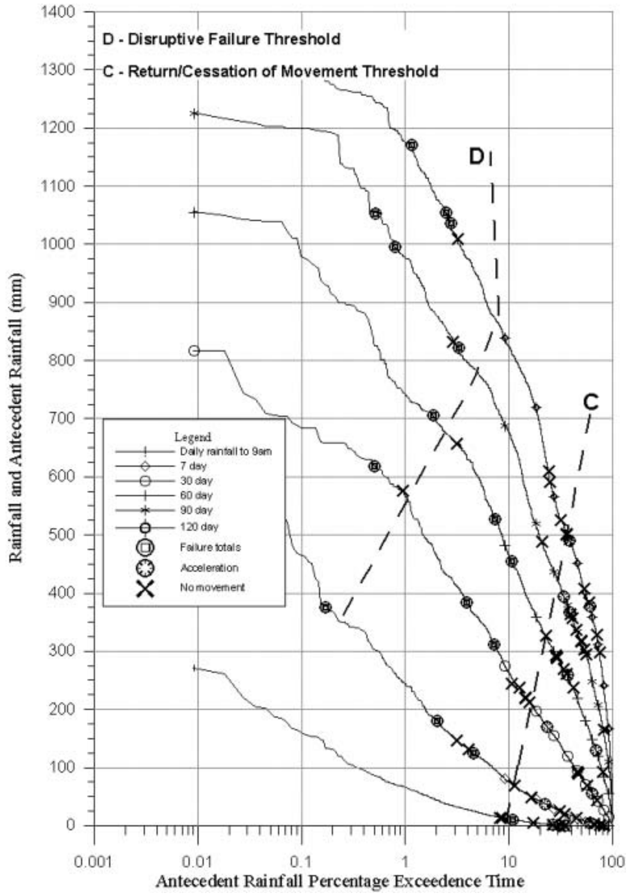

Fig. 3. ARPET graph for Site 064 in Wombarra.

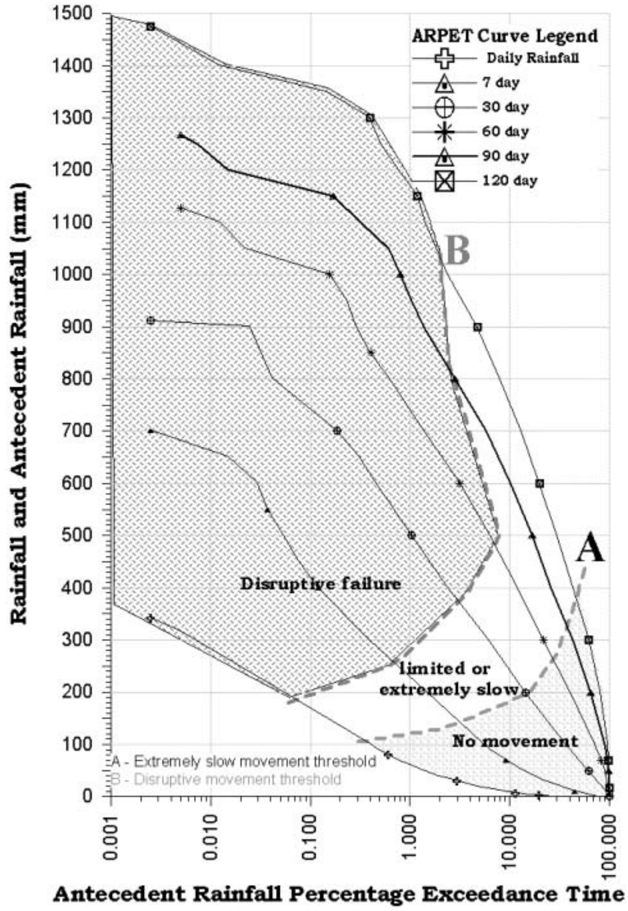

Fig. 4. ARPET graph for 12 sites in the northern suburbs.

In addition to subsurface movement data from inclinometer monitoring, data concerning surface movements and visual observations of failure may also be used for interpretation of threshold rainfall magnitudes for initiating landslide movement at a given site.

Frequency and ARPET concept

Considering the same example, it is of further interest to know the frequency of that 30 day rainfall. Therefore, rainfall data is further analysed to determine the relative frequency of the rainfall magnitudes calculated before. This is done in terms of antecedent rainfall percentage exceedance time (ARPET). The plots of antecedent rainfall in mm against ARPET values (plotted on a log scale) are shown in Figures 3 and 4 respectively for one site only and for 12 sites considered together. Thus, there is an ARPET value corresponding to each magnitude of cumulative rainfall for any selected antecedent period. In the hypothetical example considered above, the ARPET value for a 30 day total of 380 mm may be (3×10^{-2}) or 3%. This is a quantitative measure of the percentage of separate days during the historical period associated with 30 day antecedent cumulative rainfall equal to or exceeding 380 mm. Such frequency magnitudes are useful for quantitative assessment of hazard and risk. These values provide a historical measure of probability of occurrence.

The ARPET diagram shown in Figure 3 has been generated from the closest (1 km distant) rainfall station to Site 064 (shown NE of centre in Fig. 2) and is based on a 30-year recorded rainfall history. With the aid of the inclinometer monitoring record, it is possible to distinguish between periods of stability on the one hand and episodes of landslide movement on the other. Rainfalls which triggered failure at Site 064 plot between the boundaries shown as C (lower bound) and D (upper bound) in Figure 3.

Using such data for a number of sites and using surface and subsurface observational data on shear movements and disruptive failures, a predictive diagram for the study area can be developed. Thus Figure 4 represents a summary for the 12 deep seated, slow moving landslide sites (including Site 064). It shows three zones:

(i) Zone for which slope instability is not expected; cumulative rainfall totals plot below curve A,
(ii) Zone for which limited or extremely slow shear movement is expected but disruptive failure is not expected; cumulative rainfalls plot between curves A and B, and

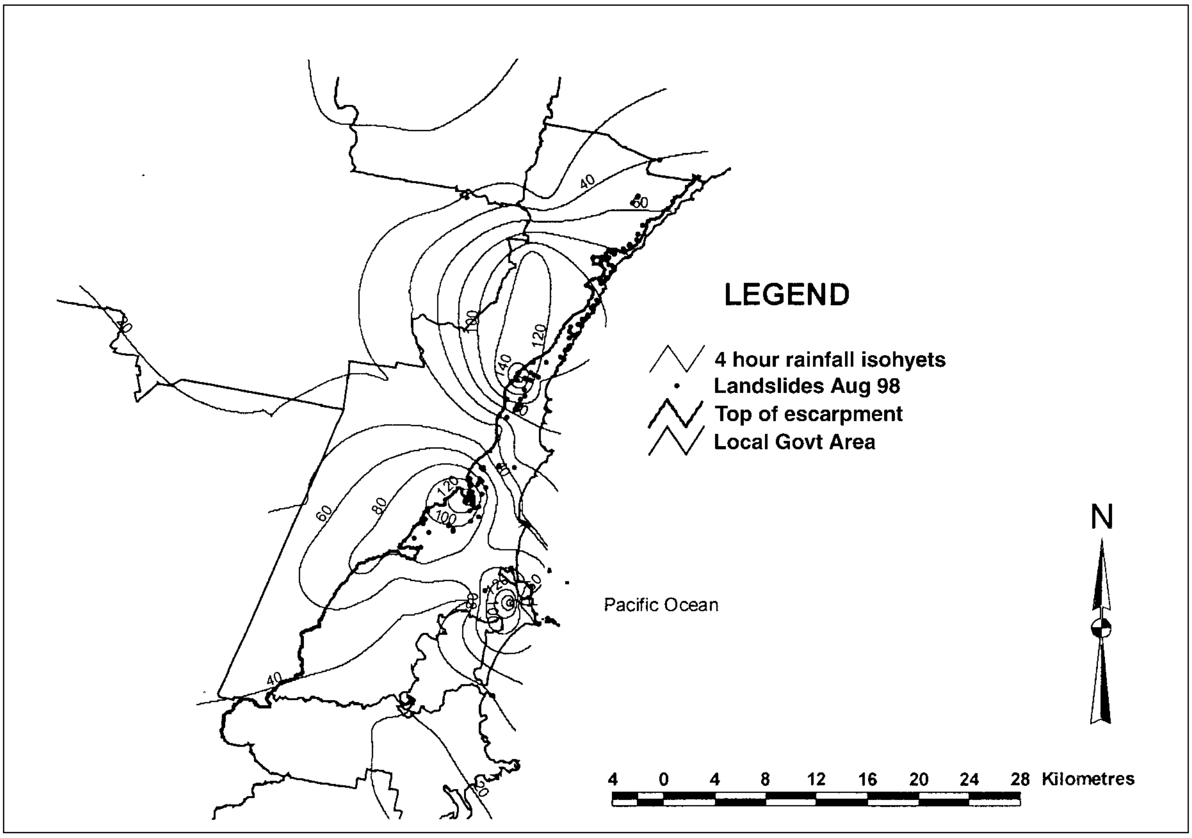

Fig. 5. 4 hour rainfall (mm) isohyets for the period 3pm–7pm, 17 August 1998 (after Murray 2001); landslides locations are also shown.

(iii) Zone for which disruptive failure or landsliding is expected; cumulative rainfalls plot above the curve B.

Spatial rainfall distribution

Research concerning rainfall magnitudes has revealed that there is considerable spatial variability of rainfall over the study area. It has been widely recognized that annual rainfall is significantly higher on the escarpment relative to the coastal plain. However, based on records of many rainfall stations, analysis has shown that variability is not due to elevation alone and that characteristics of each individual rainstorm can be quite complex. Moreover different types of variation may be evident for different time periods of a rainfall event. Based on data from a number of rainfall stations, rainfall distributions are shown in Figures 5 and 6 (Murray 2001) for the August 1998 rainstorm, which triggered 72 new landslides and reactivated 76 existing landslide sites. Figure 5 represents the distribution of 4 hour rainfall preceding 7pm on 17 August and Figure 6 represents the distribution of the 48 hour rainfall on 17 and 18 August 1998. In both cases the spatial variation along the escarpment is significant even for different locations along the escarpment that have the same elevation.

Uncertainties in the empirical/observational approach

The procedure outlined in the previous sections combines rainfall analyses with an observational approach with respect to slope movements and landsliding.

This procedure has proved useful for assessment and monitoring of hazard and for issuing real time warnings. During the August 1998 storm, the University of Wollongong landslide research team issued a media release warning of imminent landsliding within the study area about 12 hours before many significant deep seated landslides occurred and caused significant damage to properties. In one instance, the self-evacuation of approximately 130 residents from several streets in the village of Mount Kembla occurred in response to loud noises from the escarpment slopes during the night following the warning. Daylight revealed the development of a series of debris flows along a small cliff line on the mid slopes of the escarpment. The debris flows also represented the toe of a large deep seated, slow moving landslide which was triggered by the rain-storm event. This landslide had not been recognized prior to August 1998. It is not certain if the landslide was a reactivation of an existing landslide or a first-time event.

Despite this early success with real-time prediction, it is important to refer to several significant uncertainties

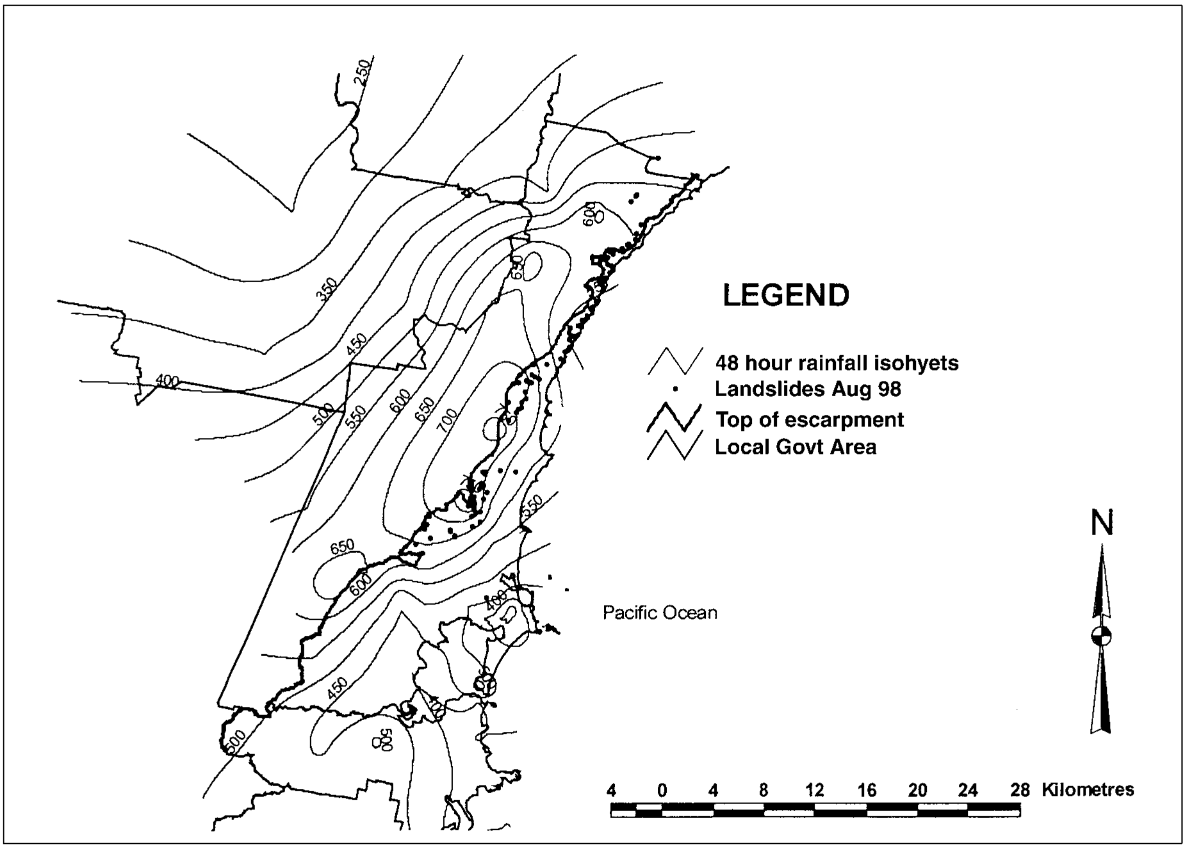

Fig. 6. 48 hour rainfall (mm) isohyets for the period 9am 17 – 9am 19 August 1998 (after Murray 2001); landslides locations are also shown.

which can be identified with regard to this empirical/observational approach.

Firstly, the diagram showing threshold curves is a composite based on twelve sites within the study area. The magnitude of rainfall at these locations can vary significantly during any particular rainstorm. This variability introduces uncertainty regarding the exact location of curves such as A and B in Figure 4. Secondly, the distinction between initiation of landslide movement and disruptive failure, although based on visual observation and/or subsurface monitoring, requires some degree of subjective judgement. This is also an important source of uncertainty. Thirdly, analyses leading to the construction of ARPET curves are based on data from a selected rainfall station. The plots in Figure 4 are based on data from one station in Woonona and, where some data are missing, data from another station in Wollongong City have been used. The combined record from these two stations spans an unbroken 110 year period from 1888 to 1997. The selection of rainfall stations was dictated by the continuity and reliability of the record. However, given the significant rainfall variability within the study area, it can be argued that significant differences in rainfall magnitudes would be apparent if a different rainfall station had a continuous record and had, therefore, been selected.

Studies concerned with local geological and geotechnical conditions and their variability must supplement the empirical/observational approach relating rainfall to landslide occurrence. In particular, attention must be given to the variability in the depth and type of colluvium and in the hydro-geological conditions. Without such supplementary studies, the location of potential landslides can not be determined with confidence. Given a rainstorm scenario, the feasibility of 'predicting' the occurrence of landslides within the region has been established. However, during the August 1998 storm, when a warning was successfully issued, specific locations of potential landsliding were not predicted. Although it was known that existing landslides would be reactivated, not all such reactivations took place. Moreover, suburbs that are known for the greater spatial intensity of past landsliding might have been expected to have greater frequency of new landslides than other suburbs. But this was not the case. Significant new landslides took place elsewhere reflecting the importance of a combination of geotechnical and geological factors as well as that of rainfall magnitude and its variability, spatial and temporal.

Conclusions

In this paper, important aspects of research concerning rainfall triggered landslides have been described.

Reference has been made to concepts of hazard, vulnerability and risk. The importance of rainfall magnitudes for different antecedent daily rolling periods has been highlighted. Reference is made, in particular, to intermittent, slow-moving landslides in the study area, the Illawarra region of New South Wales, Australia.

The concept of Antecedent Rainfall Percentage Exceedance Time (ARPET) is presented and an approach for determining threshold rainfall magnitudes for initiation of slope movement or instability is discussed briefly. This approach can be applied to a single site or to a group of sites within a region, provided there are sufficient reliable data from monitoring of landslide movement and also a good historical record of daily rainfall. This approach has proved successful in providing real-time warnings in the study area in August 1998. This success has led to confidence in the developed concepts and methodology.

Uncertainties concerning this observational approach, in its present state of development, must be understood. More precise predictions require a fuller understanding of spatial variability of geological and geotechnical conditions as well as the spatial variability of rainfall. More research is currently being undertaken in these directions. Finally, in urban areas it is also necessary to give due consideration to (a) the long-term or delayed effects of previous deforestation and urbanization, (b) continuing and new urbanization/ deforestation processes and, (c) external disturbances such as individual excavations, significant fills and changes in surface and subsurface drainage conditions.

References

AGS 2000. Lanslide risk management concepts and guidelines. *Australian Geomechanics Society*, **49**, 49–92.

Bowman, H.N. 1972. *Natural Slope Stability in the City of Greater Wollongong* **2**, in the Records of the Geological Survey of New South Wales.

Caine, N. 1980. The Rainfall Intensity—Duration Control of Shallow Landslides and Debris Flows. *Goegrafiska Annaler*, **62A**, 23–27.

Chowdhury, R.N. 2000. Developments in Geotechnical Engineering, Invited Paper. *Evolving Geotechnical Reliability Assessment Strategies, Proceeding of the Conference 'Geotech—Year 2000'* 87–93 AIT, Bangkok, Thailand.

Chowdhury, R.N. & Flentje, P. 1998. Effective Urban Landslide Hazard Assessment. *Proceedings 8th IAEG Congress* **2**, 871–877.

Chowdhury, R.N. & Flentje, P. 1999. Consideration of probability assessment relevant to hazard and risk for landslides. *Proceedings ICASP8 Conference* 247–253.

Del Prete, M., Guadagno, F.M. & Hawkins, A.B. 1998. Preliminary Report on the Landslide of 5 May 1998, Campania, Southern Italy. *Bulletin of Engineering Geology and the Environment*, **57**, 113–129.

Duncan, J.M. 2000. Factors of Safety and Reliability in Geotechnical Engineering. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 4, **126**, 307–316.

Flentje, P.N. 1998. *Computer Based Landslides Hazard and Risk Assessment (Northern Illawarra Region of New South Wales, Australia)*. PhD Thesis, University of Wollongong, New South Wales, Australia.

Flentje, P. & Chowdhury, R. 2001. Aspects of Risk Management for Rainfall–Triggered Landsliding. *Proceedings of the Symposium on Engineering and Development in Hazardous Terrains, August 2001 at Christchurch, New Zealand*. Geotechnical Society 2001 143–150.

Flentje, P. & Chowdhury, R. 1999. Quantitative landslide hazard assessment in an urban area. *Proceeding 8th Australia-New Zealand Conference on Geomechanics* **1**, 115–120.

Flentje, P., Chowdhury, R. & Ko Ko, C. CD Rom, (also Abstracts Volume Page 52) 2000. *A Matrix Approach for Assessing Landslide Risk in the Context of a Comprehensive Strategy*. Proceedings, Geo Eng 2000 Conferences, **52**, Technomic Publishing Co. Inc., Melbourne, Australia.

Fookes, P.G. 1997. Geology for Engineers: the Geological Model, Prediction and Performance, The First Glossop Lecture. *Quarterly Journal of Engineering Geology*, **30**, 293–424.

Fookes, P.G., Baynes, F.J. & Hutchinson, J.N. 2000. Total geological history: a model approach to the anticipation, observation and understanding of site conditions. *Geo-eng 2000, an International Conference on Geotechical & Geological Engineering, Melbourne* **1**, 370–460.

Ho, K., Leroi, E. & Roberds, B. 2000. Quantitative risk assessment—application, myths and future directions. Keynote Paper. *Geo-Eng Conference* **1**, 269–312.

Hutchinson, J.N. 2001. Reading the Ground: Morphology and Geology in Site Appraisal, The Fourth Glossop Lecture. *Quarterly Journal of Engineering Geology and Hydrogeology*, **34**, 6–50.

Larsen, M.C. & Simon, A.A. 1993. Rainfall Intensity-Duration Threshold for Landslides in a Humid-Tropical Environment, Puerto Rico. *Goegrafiska Annaler*, **75A**, 13–23.

Morgan, G.C., Rawling, G.F. & Sobkowicz, J.C. 1992. Evaluating total risk to communities from large debris flows. *Proceedings of the 1st Canadian Symposium on Geotechnique and Natural Hazards* 225–236.

Murray, E. 2001. *Rainfall Thresholds for Landslide Initiation in the Wollongong Region* Internal report to Australian Geological Survey Organisation and SPIRT Project Team at the University of Wollongong, unpublished.

Wilson, A. & Wieczorek, G. 1995. Rainfall Thresholds for the Initiation of Debris Flows at La Honda, California. *Environmental & Engineering Geoscience*, **1**, 11–27.

WP/WLI (Working Party on World Landslide Inventory) 1995. A suggested method for describing the rate of movement of a landslide. *Bulletin of the International Association of Engineering Geology*, **52**, 75–78

Young, A.R.M. 1976. *The distribution, characteristics and stability of debris mantled slopes in northern Wollongong*. MSc Thesis, University of Wollongong.

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