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## Interpretation of probability of landsliding triggered by rainfall

**Abstract** This paper is a contribution to an important aspect of the systematic and quantitative assessment of landslide hazard and risk. The focus is on site-specific and detailed assessment for rainfall-triggered landslides and, in particular, on the estimation and interpretation of the temporal probability of landsliding. Historical rainfall data over a 109-year period were analysed with particular reference to a site along the Unanderra and Moss Vale Railway Line in the State of New South Wales, Australia. It is shown that the recurrence interval of landsliding and hence annual probability of occurrence is subject to significant uncertainty and that it cannot be regarded as a constant. Accordingly landslide hazard varies spatially as well as being a function of time. For the example case study considered in this paper the annual probability of landslide occurrence was estimated to be in the range 0.026–0.172. However, the mean annual probability of landslide reactivation was estimated to be in the range 0.037–0.078. Utilisation of methods for probability assessment proposed in this paper will contribute to more realistic assessment of hazard and risk and, therefore, to more efficient risk management.

**Keywords** Landslide · Probability · Hazard · Quantitative risk assessment · Rainfall

### Introduction

Assessment and management of landslide hazard and risk requires consideration of geological, geotechnical and geomorphological factors. An understanding of the basic causative factors is essential along with the main triggering agents. Many landslides are triggered by rainstorms and therefore, it is valuable to carry out careful analysis of rainfall magnitudes over different durations. The impact of rainfall-induced landsliding can be severe to catastrophic and can include human casualty including loss of life. Consequently, researchers continue to devote a great deal of attention to hazard and risk assessment of rainfall-triggered landslides. Recent publications concerning hazard and risk of such landslides include Flentje (1998), Flentje and Chowdhury (2000), Fiorillo and Guadagno (2000), Glade (2000), Guadagno and Zampelli (2000), Hall and Corcoran (2000), Okada et al. (1999), Pang et al. (2000) and Yokota et al. (2000). The utilisation of probability values in the calculation of risk of human casualty is explained in recent papers (Flentje and Chowdhury 2002 and Ko Ko et al. 2003).

Landslide risk assessment may be carried out within a qualitative framework or a quantitative one. A qualitative assessment is often based primarily on an inspection of a site and its surroundings and is influenced significantly by subjective judgement. Lack of time and/or resources may not allow subsurface investigation and the analysis of available historical and observational data required for a quantitative approach. A qualitative

approach is useful for rapid assessment of sites and facilitates prioritisation for further detailed analysis. Likelihood or probability of occurrence is expressed by terms such as ‘rare’, ‘unlikely’, ‘moderate’, ‘likely’ and ‘almost certain’. The consequences of landsliding are expressed by terms such as ‘insignificant’, ‘minor’, ‘moderate’, ‘major’ and ‘catastrophic’. Risk is defined by a hazard-consequence matrix and expressed by terms such as ‘low’, ‘moderate’, ‘significant’ and ‘high’. A description of these terms is given, among others, by AGS (2000). A comprehensive qualitative approach using a hazard-consequence methodology is presented by Ko Ko et al. (2004).

A qualitative approach has a number of limitations and quantitative assessments based on analysis of detailed data are necessary in many situations and especially in urban areas and along transportation routes. Such an approach improves the accuracy of assessment by systematic analysis of available data. Moreover, errors associated with use of subjective judgement can be reduced significantly. Therefore, such an approach is a major advance over a qualitative approach. Even if available data are limited in extent, an order of magnitude of risk can be calculated reliably. This is much better than characterizing risk by just a descriptive term.

In a quantitative approach, the likelihood is assessed as a probability of occurrence of the landslide within a specific period. For example, one may calculate an annual probability of landslide occurrence. Based on that calculation and consideration of the consequences, one may calculate the risk to life as an annual probability of human casualty. Similarly property risk may be calculated as the expected annual loss of property from a landslide.

Quantitative likelihood or probability of the hazard (landslide occurrence) is clearly a very important component of both types of risk, the risk of human casualty and the risk to property. It is, therefore important to develop systematic approaches for the calculation of this probability. A valid approach must be consistent with the primary triggering factor and causative mechanism for landsliding in a particular region or area

The assessment should be based on available historical and observational data. Such data are often limited in extent and also imperfect or have variable quality. Thus the results of calculations based on such data may not always lead to very accurate results. However, even with limited data, a reliable estimate of the order of magnitude of the probability of occurrence can be expected by using a systematic, quantitative approach.

Moreover, it is also important to highlight the inherent variability of this probability in space and time reflecting the variability of geotechnical, geological and other factors.

With this background, the main aims of this paper are the following:

- To develop the basis of a valid approach for estimation of likelihood or probability of landslide occurrence that is triggered primarily by rainfall
- To explain the proposed methodology by applying it to a case study of a real site within a known landslide area
- To highlight the variability of estimated probability over time and in relation to the extent and nature of available data

Aspects of landslide risk assessment outside the scope of the present paper include geotechnical stability studies and calculation of failure probability. These have been presented in other publications such as Flentje and Chowdhury (2002), Ko Ko et al. (2003).

### Basic concepts

Risk assessment requires a consideration not only of spatial but temporal variability of hazard. Therefore, for rainfall-triggered landslides the estimation of recurrence intervals of rainstorm events and landslide events is essential. The annual probability  $P$  of landslide occurrence at a given site over an interval of time is simply the inverse of the recurrence interval in years. Thus denoting recurrence interval in years by  $T$ ,

$$P = (1/T) \quad (1)$$

It is important to recognize an important qualification concerning the concept of landslide recurrence triggered by 'threshold' or 'critical' rainfall. There may be many instances, in different geographical areas, of landslides not always reactivating when threshold rainfall has been exceeded. There can be two main reasons for this. Firstly, significant changes may have occurred to the geometry and hydrogeology of the landslide mass during previous movements. Secondly, the estimated rainfall thresholds may not be accurate because of the limited period for which historical and observational data were available for such estimation and because such data were of questionable or inconsistent quality. The assumption of reactivation associated with every exceedence of thresholds would, in general, provided a conservative estimate of the recurrence interval and hence that of the probability.

In the study area of this paper, many of the landslides do reactivate when the rainfall thresholds are exceeded except for a location where significant landslide remediation has been carried out since the previous reactivation. Moreover, rainfall thresholds have been estimated after detailed research over a number of years. Even so, it has been concluded that there are 'lower bound' and upper bound thresholds. Only 'upper bound' thresholds lead to disruptive movements that can be interpreted as landsliding. Subsurface movements associated with lower bound' thresholds are too small to be interpreted as landsliding (Flentje 1998). In this paper all further reference to thresholds, therefore, refers to the 'upper bounds'.

The recurrence interval  $T$  is variable in time and, in fact, one may consider  $T$  as the number of years separating two landslide events or between two consecutive landslide triggering rainfall events. Thus annual probability is also a variable. However average annual probability over an historical period may be computed as explained in subsequent sections of this paper.

Rainfall-triggered landsliding includes new sites where instability occurs for the first time as well as reactivation of instability at existing landslide sites. The probability of landsliding at new

sites is a product of  $P_{LR}$ , a conditional probability that instability will occur given the critical or threshold rainstorm event and the probability of occurrence,  $P_R$ , of that critical or threshold rainstorm event. This may be expressed by the following product

$$P = P_{LR} \times P_R \quad (2)$$

In general, both  $P_{LR}$  and  $P_R$  must be estimated for a given site. However, for those existing landslide sites that are expected to reactivate every time the critical or threshold rainfall is exceeded, the probability of landslide recurrence can be taken simply as the probability of occurrence of the critical or threshold rainstorm event. The study area of this paper will be described in the following sections. Historical evidence, observation and research in this area have revealed that many of the slow-moving landslides are reactivated when rainfall thresholds are exceeded (Flentje 1998). Consequently, for calculating the probability of recurrence of such rainfall-triggered landslides it is sufficient to carry out the following steps for hazard and risk assessment:

- Assess the critical landslide triggering rainfall (magnitude and duration).
- Assess the recurrence interval of the critical landslide triggering rainfall in years.
- Assess the annual probability of the hazard including its range and variability.

The methodology for carrying out such an assessment is discussed in this paper with particular reference to a site along the Unanderra to Mossvale Railway line located close to the urban area of Wollongong and located within the Illawarra region of the state of New South Wales in Australia.

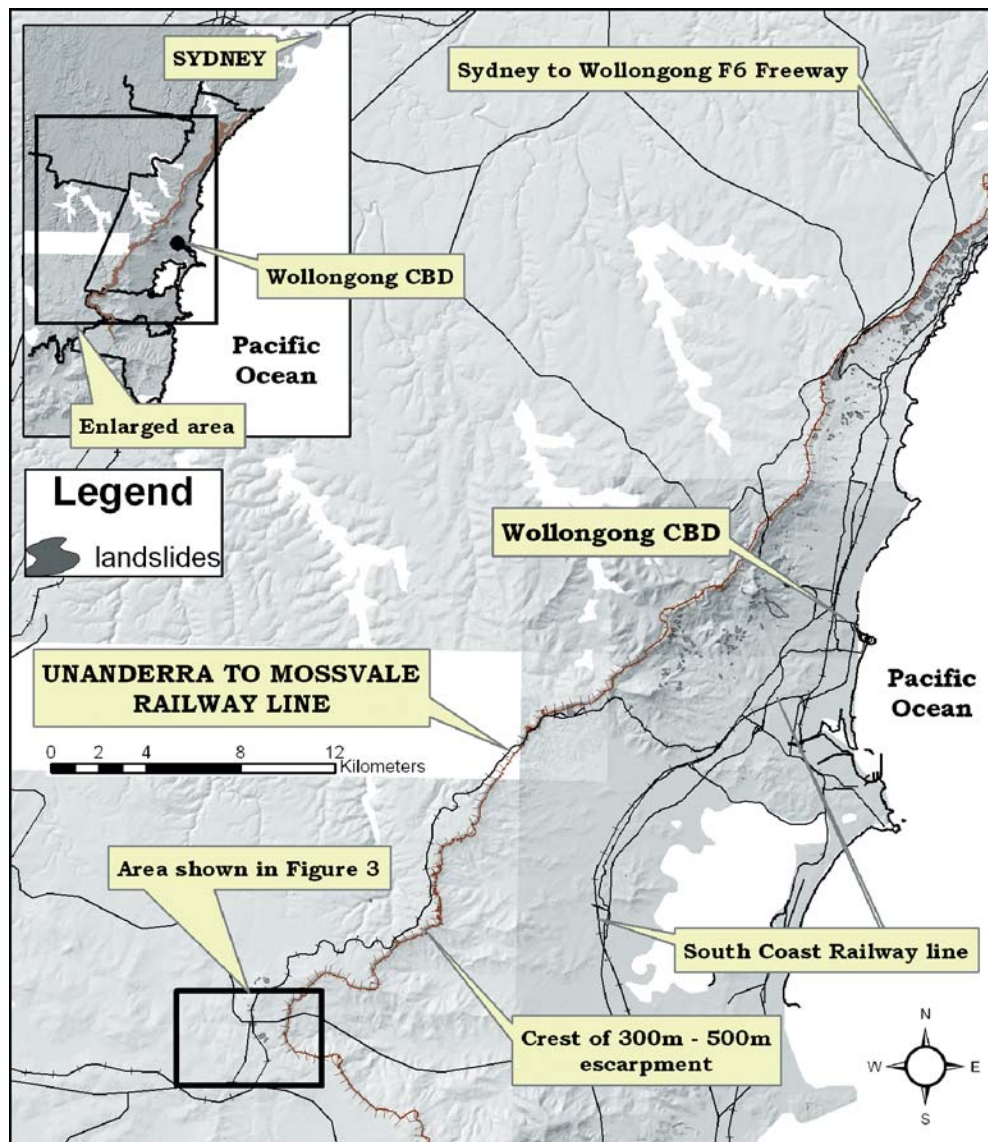
The following sections provide a brief description of the location, topography and geology and highlight the occurrence of slope instability and landsliding in the study area.

### The study area

The city of Greater Wollongong is the main urbanized part of the Illawarra region of the State of New South Wales, Australia (Fig. 1). From the early days of European settlement more than 150 years back, the occurrence of landsliding in this region has been observed and commented upon. As the population increased, there was steady increase in the economic and social impact of landsliding. This impact concerns primarily the major transportation routes (highways and railways) and the residential suburbs. The city of Wollongong is located along the east coast of Australia about 80 km south of Sydney

The Wollongong area consists of a narrow coastal plain of triangular shape, bounded on the west and south by the Illawarra erosional escarpment topped by spectacular vertical cliffs of Hawkesbury sandstone. The stratigraphic column showing the geological sequence of the region is included here as Fig. 2 and further reference to it will be made in the following paragraphs. The apex of the triangular coastal plain is 16 km north of the city centre at Coledale and the base, located 17 km south at Shellharbour, is 15 km wide. The middle and upper slopes of the escarpment range in inclination from moderate to steep. Differential erosion of alternate strong and weak rock units has led to the formation of near-horizontal benches at different elevations on the escarpment. Colluvium has been deposited over the slopes and benches to varying depths. Landsliding triggered by rainfall

**Fig. 1** Study area and landslide location plan



occurs frequently with slip surfaces located in the colluvium and, in many cases, partly along bedding planes or other discontinuities within weathered or sound bedrock

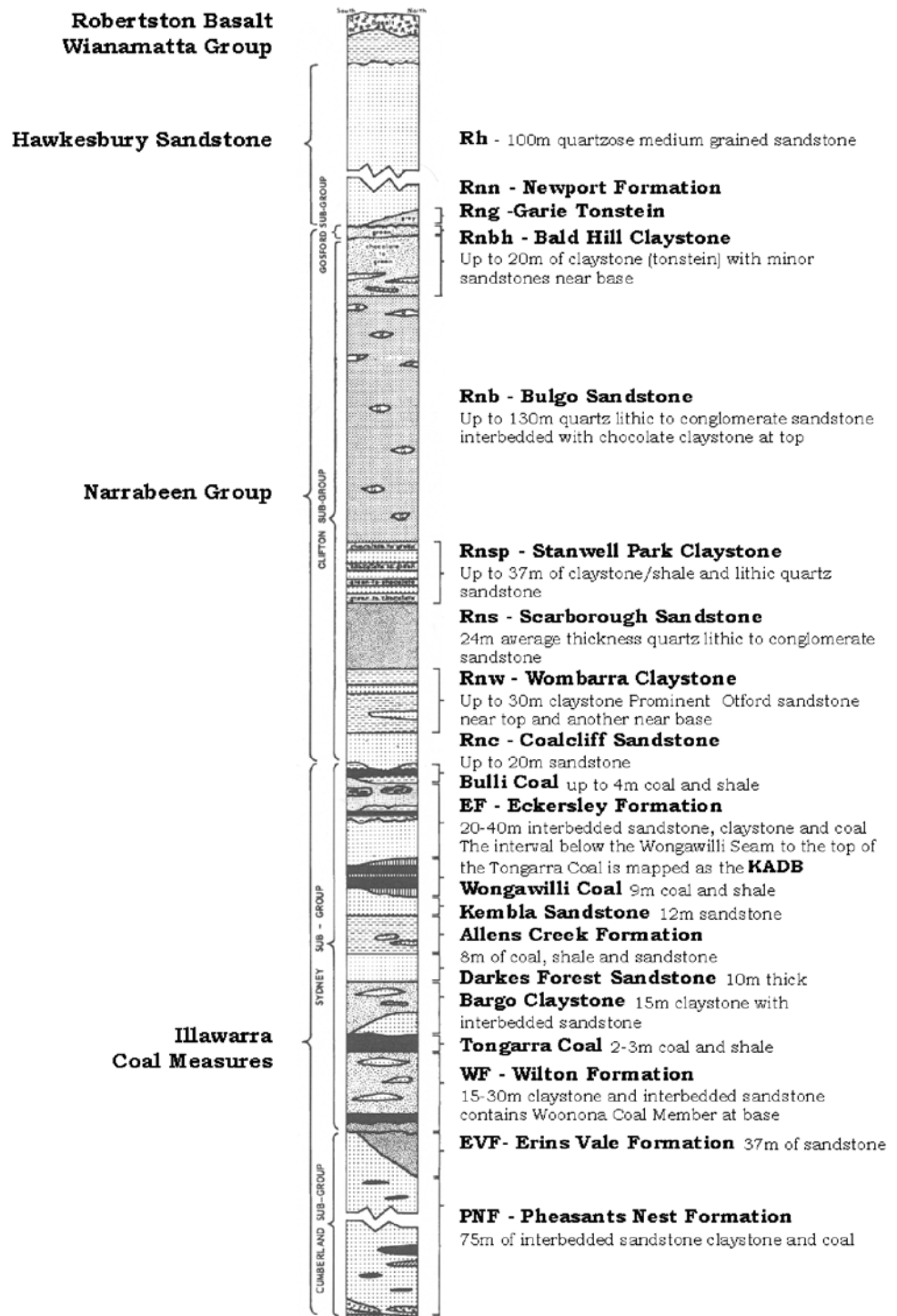
Geological and geotechnical studies concerning slope stability and landsliding have been carried out since 1970. Systematic and accurate mapping of geology and existing landslides within a GIS framework was started in 1993 after developing a borehole database and a comprehensive landslide inventory. Considerable progress has been made towards mapping of landslide hazard zones. Detailed rainfall studies based on data from a number of rainfall stations have been carried out. Access was obtained to a number of field stations that include installed piezometers and inclinometers. Data from these installations have been obtained several times a year for about 10 years. More recently, four field stations have been set up for continuous monitoring of subsurface movements, pore water pressures and rainfall. These new field stations are remotely accessed and several additional, automatically recording, remotely accessed stations are to be installed soon.

The Wollongong Landslide Inventory (Flentje 1998) currently includes 552 landslides of which over 450 are slide type landslides. Many of the slide category landslides are deep-seated and sub-surface movements have been monitored with inclinometers. Such landslides are episodically active in response to higher levels of rainfall and display characteristic slip-stick behaviour. The velocities of such slip-stick landslides are in the range extremely slow to slow using the terminology proposed by Cruden and Varnes 1996.

Study of monitored sites within the region together with analysis of rainfall has enabled the estimation of rainfall thresholds for landsliding in the region. Each estimated threshold is expressed as a rainfall magnitude associated with an appropriate antecedent period of rainfall.

For these slip-stick landslides with very low velocities, two rainfall thresholds have been identified during research over several years (Flentje 1998). At the 'lower bound' threshold, the magnitude of subsurface movements can often be imperceptible and only identifiable with the aid of instrumentation. However, at

**Fig. 2** Stratigraphic column of the Permian—Triassic sequence of the northern Illawarra (after Bowman 1972)



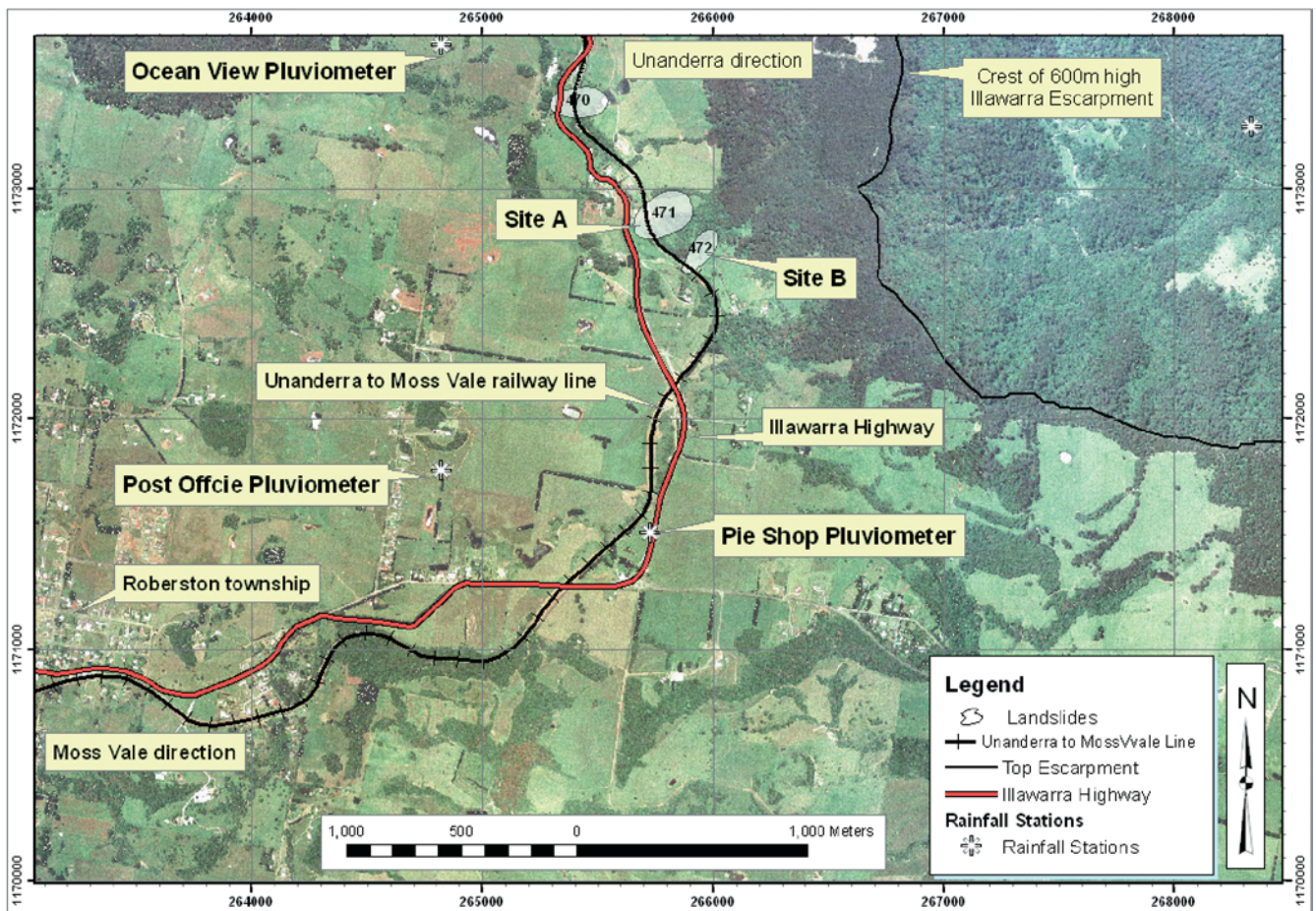
the upper bound threshold, the subsurface movements are sufficient to cause disruptive behaviour of the ground surface, which can readily be interpreted as landsliding. Thus the real 'critical' or 'threshold' rainfall is the 'upper bound'.

Debris flows associated with shallow sliding occur due to high magnitude rainfall over relatively shorter periods (6 hours up to several days). However, more deep-seated movements occur in response to longer periods of rainfall (one week to three months) as discussed in Flentje (1998) and Flentje and Chowdhury (2001).

#### Unanderra to Moss Vale Railway line

The Unanderra to Moss Vale Railway Line, is located south of the City of Wollongong as shown in Figs. 1 and 3. This railway line encounters various geological formations and units belonging to the Sydney Basin rock formations. Measuring from Sydney Central Railway Station, the study track length commences from kilometerage 91.00 km near Unanderra railway station and terminates at kilometerage 123.50 km, approximately 4.8 km short of Robertson Station, a total of 32.5 km in length. This railway line





**Fig. 3** Location of case study site comprising two adjacent sites Site A (471, RSA Project 2758) and Site B (472, RSA Project 2759), Unanderra to Moss Vale Railway Line

interconnects the eastern low-lying Illawarra coastal plain to the Southern Highland plateau located south west of Wollongong City. The escarpment gradually rises from the flat coastal area at Unanderra passing through different topographical features and crossing multiple gullies and steep slopes as it ascends towards Moss Vale.

The main coastal plain has been formed in geological time by westward erosion and recession of the plateau resulting in the formation of a steep escarpment up to 500m high. A talus or colluvium covered slope has developed below the upper cliffline covering the topographic benches resulting from the interbedding of sandstones and mudrocks of the Narrabeen Group. The debris mantle or talus covering the upper slopes and benches of the Illawarra Escarpment has steep to very steep slopes with gradient range of 20–50%. Local relief is 50–500 m. This slope debris has a variable depth and could reach up to 20 m in thickness in the Wollongong area. The downslope movement of slope debris is part of the natural processes associated with complex geological and geomorphological development of the escarpment. Thus large landslips are common features of the landform (Hazelton and Tille 1990).

The top of the escarpment usually comprises a near vertical cliffline of Hawkesbury Sandstone (Fig. 2). The erosion and weathering of the Newport Formation and Baldhill Claystone at

the base of the Hawkesbury Sandstone result in overhangs that fail along vertical joints. A similar process has resulted in the structural benches of the Narrabeen Group.

Once above the escarpment the railway line heads towards the elevated Southern Highland plateau. Hawkesbury Sandstone outcrops over much of the deeply dissected undulating plateau with residual outcrops of Wianamatta Group shales and Robertson Basalt occurring as rolling hills towards Moss Vale (Hazelton 1992). It is in this latter setting in which the two case study landslides are situated.

#### The case study site

Occurrences of rainfall-triggered landslides and rockfalls are common along this railway track. The case study which is the subject of this paper consists of two adjacent but related landslide sites (Site A and Site B, Figs. 1 and 3) which are located between kilometerage 123.1 km - 123.55 km along the Unanderra to Moss Vale Railway Line.

The site is situated close to the lateral extent of the extrusive Robertson Basalt, which is of Tertiary age. This basalt is underlain by the Late Triassic age Wianamatta Group typically comprising of claystone and siltstone with interbedded lithic sandstones. The track in this particular area is founded on the red-brown residual basaltic clayey soil. This soil is known to be highly susceptible to

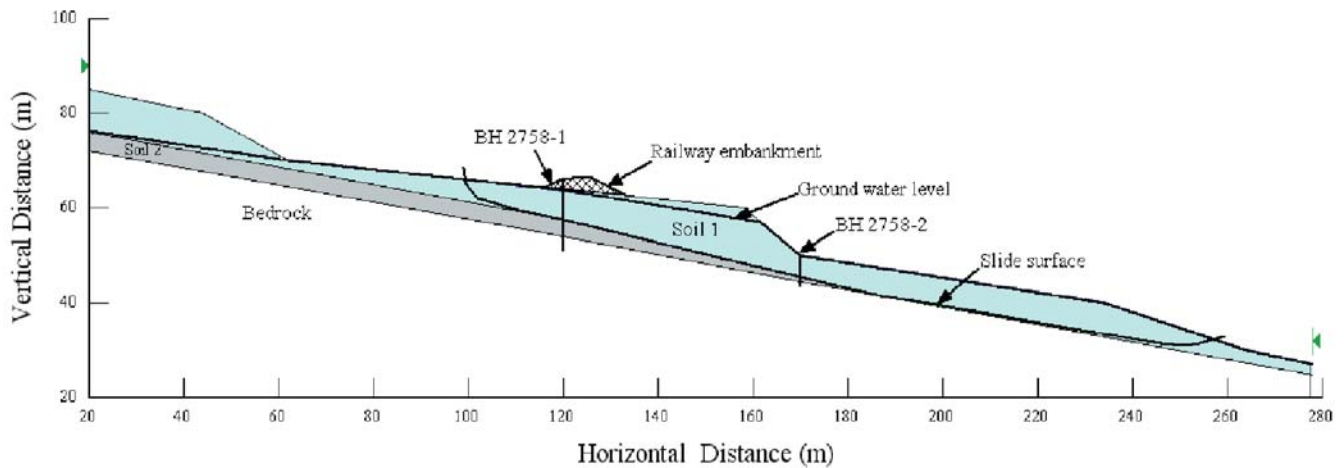


Fig. 4 Longitudinal cross section of Site A, Unanderra to Moss Vale Line

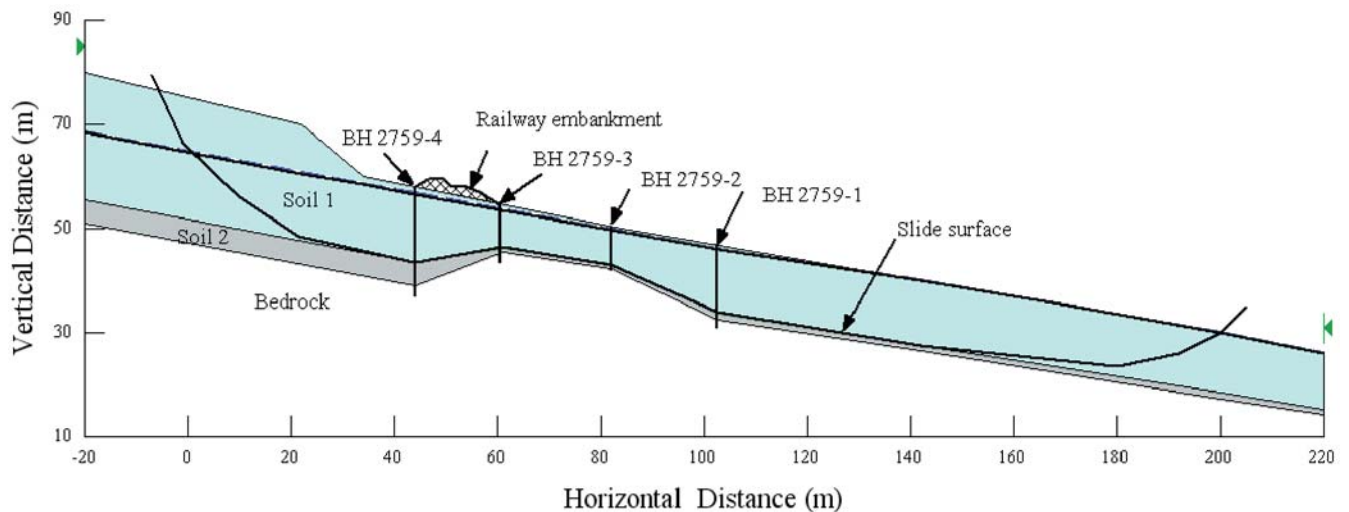


Fig. 5 Longitudinal cross section of Site B, Unanderra to Moss Vale Line

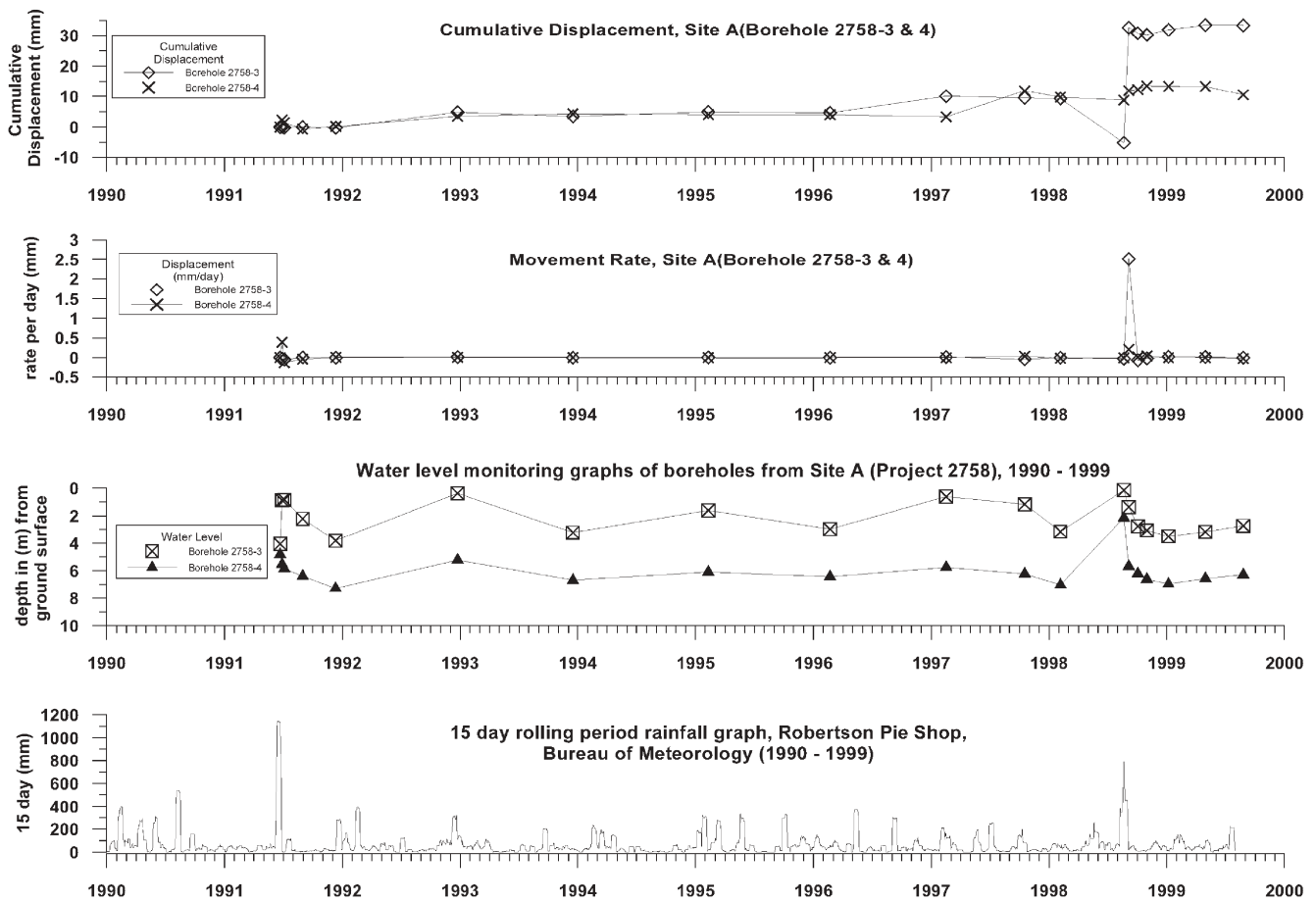
landsliding. Localised scarps, hummocky ground and leaning trees, which are common indicators of slope instability can be observed in this area. Site A and Site B are located on adjacent sides of a gully sloping down to the northeast. The general ground slope inclination varies between  $16^{\circ}$  -  $20^{\circ}$  and tends to be gentler at the base of the slopes to the east. The area is sparsely vegetated with few trees and shrubs and is used for stock grazing.

Field observations and investigation borehole logs are consistent with the regional geological context mentioned above. Data from investigation boreholes also confirm that the site is overlain by red brown silty clay with basalt core stones. This red brown silty clay horizon is derived from basalt and the thickness of this zone ranges between 5.5m to 14.5 m according to the borehole data. Immediately underneath this layer is a clay layer (yellow/orange, Site B) and a silty clay layer (light orange brown and, grey and black, Site A), which has been identified as a residual soil. This layer grades into weathered pale grey to grey shale and medium grey siltstone. The thickness of this layer is approximately 3 to 5 m. The immediate bedrock consists of shale, siltstone with thin sandstone interbeds and sandstone belonging

to the Wianamatta Group. Longitudinal cross sections of both sites are shown in Figs. 4 and 5. In these two figures, the sub-surface profile has been idealized for the purpose of geotechnical modelling and analysis as two soil layers over bedrock. Details of this idealization and its justification have been explained by Ko Ko (2001).

A total of 8 geotechnical investigation boreholes were drilled by Rail Services Australia (RSA) during June 13–21, 1991 (4 holes at each site) and inclinometers and piezometers or standpipes were installed. Early warning systems (EWS) were also installed at the study site (two near Site A and one near Site B) and the data from these are available from 22nd April, 1994 to the present day. Most of the subsurface data for this site were provided by the Railway Services Authority (RSA) of New South Wales (now known as Rail Corp) who carried out the geotechnical investigations and monitoring.

Available rainfall data from five rainfall stations covering a period of 109 years has been utilised for this research. Only two of the five rainfall stations were considered to be directly of value for the case study described in this paper. Moreover, subsurface



**Fig. 6** Site A, (Case Study I, RSA Project 2758), kilometrage 123.25 km, inclinometer monitoring (borehole 2758–3 and 2758–4) cumulative shear displacement, rate of shear, ground water level and 15 day rolling period rainfall curve from 1991 to 1999

movement data from inclinometers and pore water pressure data from piezometers available over 9 years has been scrutinised carefully in relation to the rainfall data. The complete information may be found in Ko Ko (2001). It includes information on the topography and geology of the whole study area as well as the cross-sections of specific sites for which detailed analyses were carried out including the location of critical slip surfaces. Limit equilibrium slope stability analyses (back analyses) were carried out to validate the geotechnical models of the case study sites. Full results are presented in Ko Ko (2001) and selected results are also published in Ko Ko et al. (2003). The landslide susceptibility of different geological units was also studied. Maps of landslide and rockfall susceptibility were prepared. All these aspects of the complete study are outside the scope of this particular paper due to space limitations.

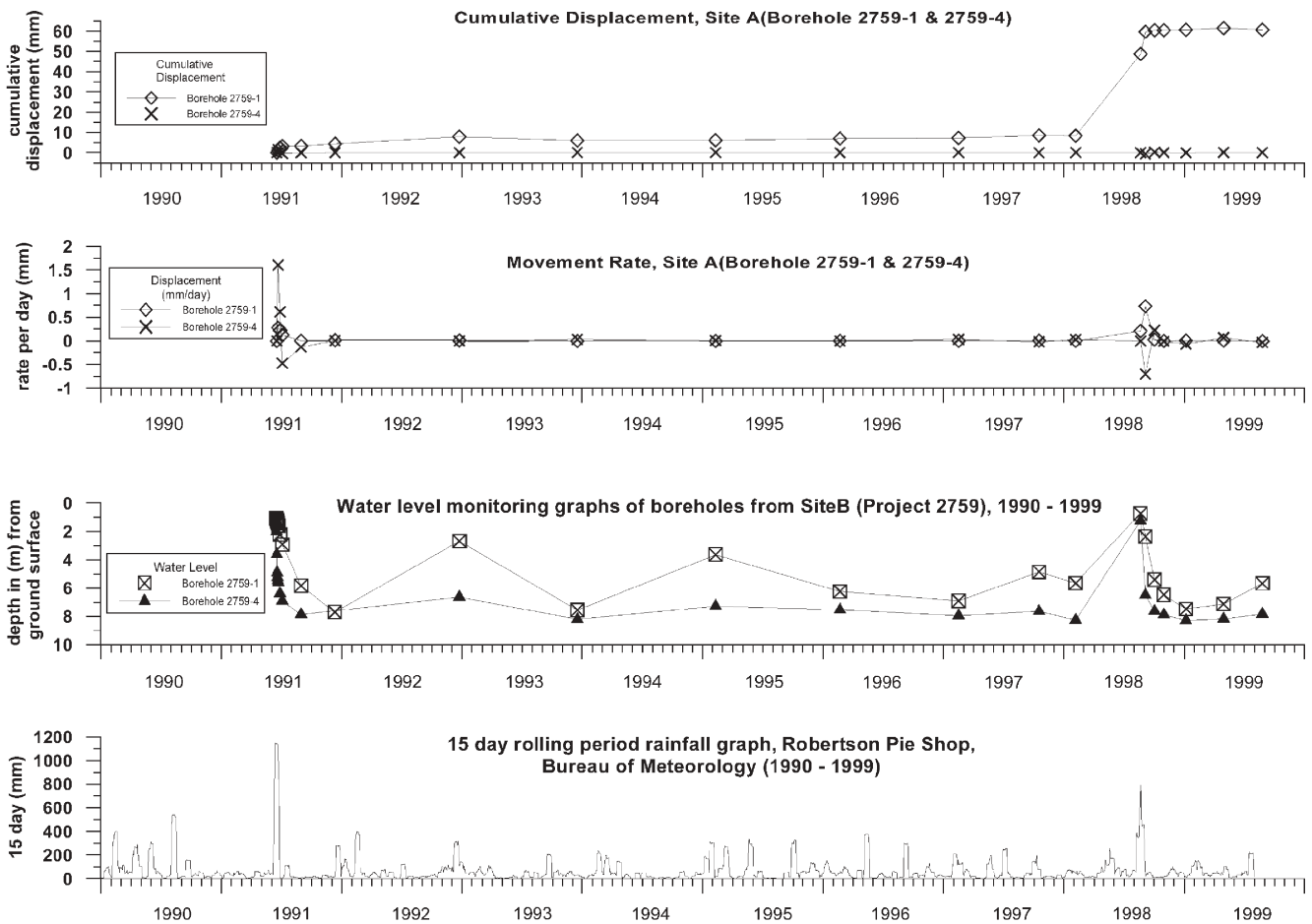
**Subsurface movements resulting from two rainfall events (June 1991 and August 1998)**

Geotechnical investigation, including the installation and monitoring of subsurface instrumentation (inclinometers, maximum water level indicators and early warning systems using horizontal extensometers) were carried out by the Rail Services Australia soon after an occurrence of a slip during June 1991 at both sites. A displacement of 400 mm was observed at Site A during this June 1991 event and this was significant enough to cause a train de-

railment had it been left undetected. However, early detection of track displacement during routine maintenance led to cancellation of railway operations and thus prevented such a catastrophic event. Rainfall data from Robertson Pie Shop station reveal that daily rainfall ranging from 105 mm to 380 mm had occurred during a five-day rainstorm event (7–11th June 1991) prior to landslide movement. A daily total rainfall of 160 mm was recorded on the 12 June 1991, the day during which the landslide occurred. Total rainfall for the six-day period between 7 – 12th June 1991 was 1,115 mm. After 1991, the next significant displacements were recorded by the inclinometers at both sites in August 1998, triggered by a regional rainstorm event during that month. Total displacements of 37 mm for Site A and 40 mm for Site B were observed between the 20th August and the 4th September 1998.

The authors have classified both the landslides (according to Cruden and Varnes 1996) as ‘episodically active, slow to extremely slow moving, moist to wet earth slides’. For such ‘stick – slip’ slides initial movements during wet periods may momentarily reach velocities of between 4 and 400 mm per day reducing by orders of magnitude during drier periods to very slow or even extremely slow velocities. In many cases movement ceases altogether during extended dry periods (such as drought conditions along the East Coast of Australia caused by the El Nino events). As stated earlier landslides of this type are typical in the Wollongong area.





**Fig. 7** Site B (Case Study I, RSA Project 2759), kilometerage 123.5 km, inclinometer monitoring (borehole 2759-1 and 2759-4) cumulative shear displacement, rate of shear, ground water level and 15 day rolling period rainfall curve from 1991 to 1999

Slope stability analysis and modelling of the case study discussed in this paper also indicates that both sites are marginally stable once rainfall-induced seepage occurs throughout the slope depth. Detailed results of geotechnical modelling and slope stability analyses have been presented in Ko Ko et al. (2003). Water level monitoring indicated that the borehole water levels were in the proximity of ground surface during the two major rainstorm events of June 1991 and August 1998. The relationship between rainfall, water levels and landslide movement are illustrated in Figs. 5 and 6. Analysis of relevant data reveals that the critical rainfall value causing the landslide movement is approximately the same for the two sites (15 day cumulative rainfall of 788 mm as discussed in the next Section).

There was no subsurface monitoring or other record of slope instability at the case study site before 1991. Therefore, assessment of the probability of instability before 1991 must be based on indirect evidence. First one must establish the critical triggering rainfall from events for which both rainfall and subsurface movement data are available. Then we can examine the whole historical period of 109 years for which only rainfall data are available. As explained in the following sections, this examination shows that there were other times when the landslide triggering rainfall thresholds were exceeded. Therefore, for the purposes of the assessment of likelihood of probability of occurrence, one

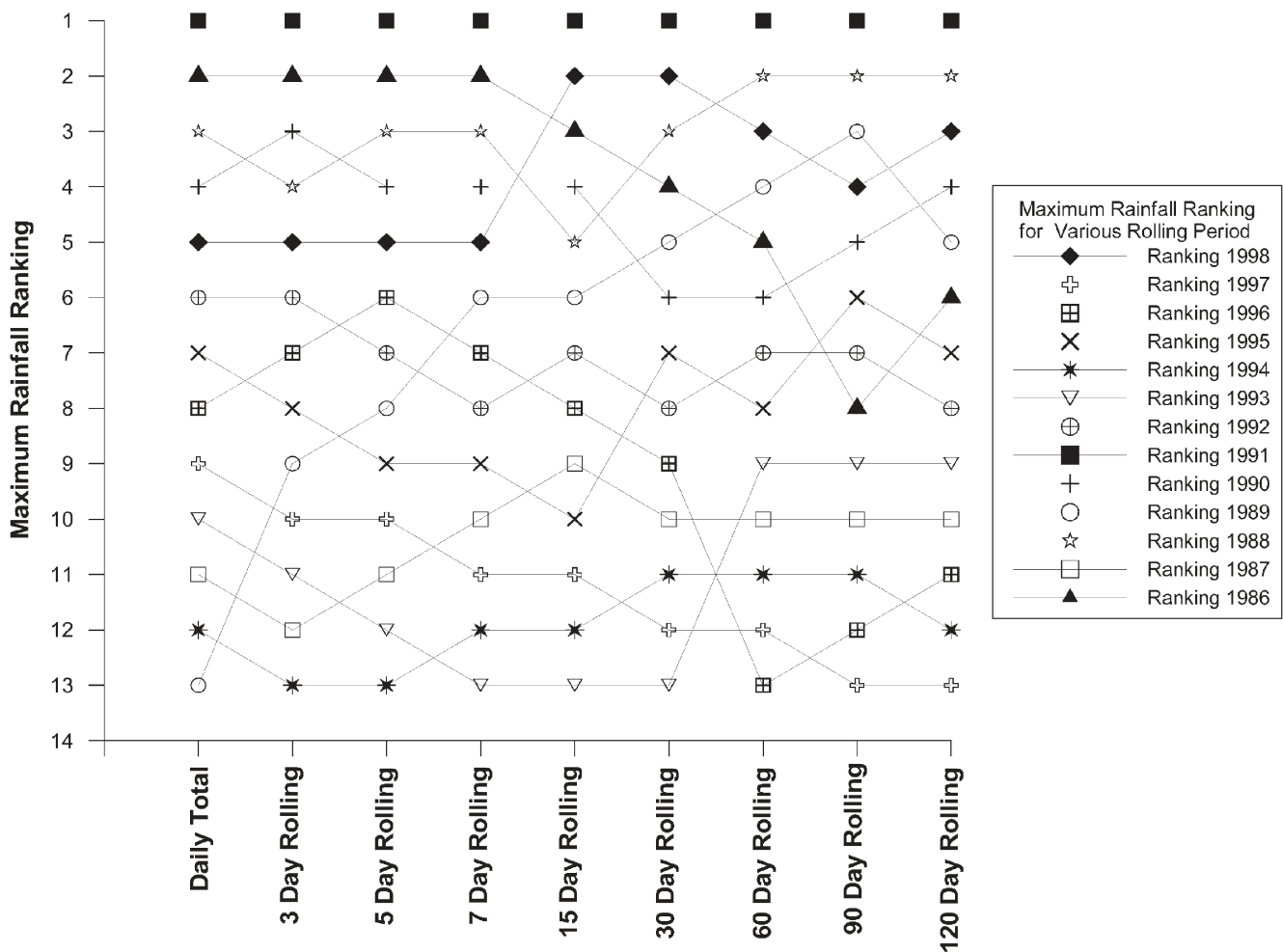
may assume that slope instability would have occurred at those times when the threshold was exceeded.

#### Interpretation of rainfall data in relation to slope instability

Experience over several decades has shown that the occurrence of slope instability at new sites and its recurrence at existing sites in the Illawarra region requires consideration of cumulative rainfall over periods ranging from several days to several months. Therefore, it was decided to select several antecedent periods for which cumulative rainfall would be quantified on a daily rolling basis over the whole historical period.

Initially rainfall graphs for (a) daily total and (b) cumulative 3 day, 5 day, 7 day, 15 day, 30 day, 60 day, 90 day and 120 day rolling periods were produced from 15 years of rainfall records. In combination with the sub-surface monitoring data it was possible to determine the likely landslide triggering rainfall. Since the study sites have experienced two significant movements in June 1991 and August 1998 respectively, the rainfall analysis was focused initially on the period 1990 – 1998. In the next stage of analysis, however, rainfall analysis was carried out for the complete 109-year historical period. Most of the rainfall graphs are not included here due to space limitations. However, the most relevant information is included in Figs. 6, 7 and 8. The last of these (Fig. 8) represents a rainfall-ranking graph for the years 1986 – 1998 (11 years).





**Fig. 8** Rainfall ranking graph for daily total, 3 day, 5 day, 7 day, 15 day, 30 day, 60 day and 120 day rolling periods considering the years 1986–1998, the Pie Shop Station (Robertson), Bureau of Meteorology

Considering various cumulative rainfall rolling periods, Fig. 8 reveals that the June 1991 rainfall event has the highest ranking in terms of daily rainfall and all the other cumulative rainfall periods, that is 3 day, 5 day, 7 day, 15 day, 30 day, 60 day, 90 day and 120 day cumulative rainfall. As for August 1998 the ranking varies from 2 to 5, rank 5 for daily total, 3 day 5 day and 7 day rolling period, and rank 2 for 15 day and 30 day rolling period etc).

For the June 1991 rainstorm event any cumulative rolling rainfall period could be chosen as the critical landslide triggering rainfall. However, the selected rolling period should be consistent with the August 1998 rainstorm event, (a) movements monitored by inclinometers and (b) groundwater level monitoring. It is obvious that not all the rainfall graphs would satisfy the movement records. For example, although it is a fact that movement occurred in 1998, selecting the daily total or any of 3, 5 and 7 day rolling periods would not reflect the required triggering value because, as explained earlier, the 1998 event ranks only 5 for all those periods. The same applies if the maximum rainfall for 60, 90 or 120 day rolling period for year 1998 is selected. However, 15 day and 30 day rolling periods in August 1998 rank 2 (Fig. 8). Thus if one of these values is selected as a minimum rainfall landslide triggering value it would be consistent with the incli-

nometer movement records (considering both the 1991 event and the 1998 events).

After careful consideration, the 1998 cumulative rainfall value for the 15 day rolling period has been selected as the minimum rainfall value required to initiate slope instability or landsliding. It is obvious from Fig. 8 that the 15 day cumulative rainfall period for the June 1991 rainstorm event is higher than the 15 day cumulative rainfall for the August 1998 event. Note that the 15 day rolling period rainfall graph has a very good correlation with the water level graphs, especially with borehole 2758–4 (Site A) and 2759–4 (Site B), see Figs. 6 and 7. The actual magnitude of the 30-day rainfall was only slightly higher than the 15-day rainfall associated with the landslide movement. Thus slope instability could be expected to occur after the shorter cumulative period of 15 days provided the triggering magnitude has been reached. Selecting the 15-day cumulative period in preference to the 30-day period is, in any case, a conservative judgement. The detailed reasoning for choosing 15-day antecedent rainfall period in preference to the 30-day antecedent rainfall period has been provided by Ko Ko (2001).

**Table 1** Variability in recurrence interval and annual probability of 15 day rolling rainfall exceeding the threshold value of 788 mm triggering landslide (unadjusted data)

Number	Station	Date	Peak 15 day rainfall (mm)	Years since last occurrence T	Variable annual probability P
1	Robertson Post Office	29-05-43	1073	>53.4?	0.0187?
2	Robertson Post Office	03-04-78	1009	34.9	0.0287
3	The Pie Shop (Robertson)	12-06-91	1147	13.2	0.0758
4	The Pie Shop (Robertson)	21-08-98	788	7.2	0.1389

#### Estimation of variable return period and variable probability

From the known movement records, the relevant triggering rainfall magnitude was chosen after plotting the relevant graphs of both rainfall and subsurface movement with time. The maximum 15-day rolling period rainfall for the two known landslide events are 1,147 mm (June 1991) and 788 mm (August 1998). To determine the return period for the past 109 years, the daily rainfall data of the Robertson Post Office Station (1890 to 1989) was used to generate the 15-day rolling period rainfall graph.

From the graphical analysis it was clear that 4 events of rainfall above or equal to the threshold value of 788 mm 15 day rolling rainfall have taken place in this period and these are listed in Table 1 below. The return period of critical rainfall events and the probability of occurrence are shown in the last columns of Table 1. It is clear that the probability of occurrence varies by an order of magnitude. The interval between each event appears to have become shorter in recent years from the 35 years to 7 years recurrence interval. Due to a number of unrecorded months during the period 1891 to 1921, the interval of more than 53 years (Table 1) before 1943 rainfall event may not be accurate. Moreover, there are spatial rainfall variations between the two rainfall stations and the interval between successive events would change once adjustment is carried out for the spatial variability of rainfall.

The overlapping of the rainfall-recording period for about 5 years allows us to determine the rainfall variation within the two rainfall stations. These two stations are approximately 0.90 km apart. The Robertson Post Office pluviometer is 1.35 km to the south east of the Case Study location while the Pie Shop pluviometer is 1.1 km south of the Case Study location. The average variation in rainfall is 9.5% between the two stations where the 'The Pie Shop' station has the higher rainfall in general as shown in Table 2.

A more detailed analysis of rainfall spatial variability, using all of the data for 109 years was considered unnecessary. This is because the data for this long historical period was of inconsistent reliability. Consequently a highly accurate analysis was unjustified. The simpler approach was found to provide better estimates of the of the fluctuation in the return period after corrections were applied

An adjustment was carried out by adding the 9.5% to the Robertson Post Office station values in order to obtain the corrected rainfall values. The adjusted data reveals that the frequency of 15 day rolling period above the triggering minimum threshold value increases from 2 events to 5 events for the Robertson Post Office rainfall station, and reduces the recurrence interval of the threshold rainfall and hence of landsliding (Table 3). The adjusted data indicates that the recurrence interval between 1956 and 1998 ranges between 5.8 to 16.3 years. The range of probability values also narrows relative to that before the adjustment for spatial

**Table 2** Annual maximum 15 day rolling antecedent rainfall variation for the two rainfall stations for the overlapping years

Year	Peak 15 day rainfall at two sites		Variation
	Robertson P.O.	The Pie Shop	
1985	350.2mm	386.0mm	+10.22%
1986	455.2mm	611.0mm	+34.23%
1987	408.8mm	345.2mm	-15.56%
1988	492.8mm	538.0mm	+9.17%
1989	369.4mm	404.4mm	+9.47%

variability of rainfall. As noted above, both rainfall stations are located more than 1 km from the landslide sites, and hence the actual rainfall at the landslides may be different to that recorded by the rainfall stations. The corrected rainfall magnitudes can, at best, approach the true magnitudes of rainfall relevant to the site but the true values cannot be determined accurately.

#### Estimation of average annual probability

Let N be the number of critical rainfall triggering events over the historical recorded time period  $T_H$ . Then the average recurrence interval  $T_{AV}$  is given by:

$$T_{AV} = T_H/N \quad (3)$$

The average annual probability of the recurrence of landsliding is given by:

$$P_{AV} = N/T_H \quad (4)$$

One may also express it as the inverse of the average recurrence interval:

$$P_{AV} = 1/T_{AV} \quad (4a)$$

It is important to note that the estimated magnitude of average recurrence interval will depend on:

- the particular rainfall station selected for the data to be used for analysis, and
- whether data for the whole of the recorded period are used or only for that portion of it which is considered to be the most reliable, and
- whether data are corrected and adjusted for spatial variability.

The average annual probabilities vary from 0.037 to 0.078 depending on (a) whether the whole of the rainfall record is considered (109 years) or only part of it (77 years) and (b) whether rainfall data are adjusted for spatial variability or not. These results are presented in Table 4. All these results are based on the critical landslide triggering rainfall for 15-day rolling period, which has a distinct correlation with landslide movement. However, as explained in the previous section the annual probability

**Table 3** Variability of recurrence interval and annual probability based on occurrence of 15 day rolling rainfall with magnitude above the threshold triggering value for the Robertson Post Office Data (after adjustment for spatial variability)

Number	Station	Date of critical	Peak 15 day rainfall	Adjusted 15 day rainfall	Years Since Last occurrence T	Annual probability
1	Robertson Post Office	23-07-04	758	830	>14.6?	<0.0685?
2	Robertson Post Office	29-05-43	1073	1175	38.8*	0.0258*
3	Robertson Post Office	23-02-56	743	814	12.7	0.0787
4	Robertson Post Office	02-12-61	731	801	5.8	0.1724
5	Robertson Post Office	03-04-78	1009	1105	16.3	0.0613
6	The Pie Shop (Robertson)	12-06-91	1147	1147	13.2	0.0758
7	The Pie Shop (Robertson)	21-08-98	789	789	7.2	0.1389

\*denoted some unrecorded periods

**Table 4** Average Annual Probability values of landslide triggering rainfall event based on records of different rainfall stations with or without adjustment for spatial variability

Number	Rainfall station data	Record	Critical rainfalls N	Total number of years $t_h$	Average probability $p_{AV}$
1	Robertson Post Office unadjusted and The Pie Shop combined	1890-1998	4	109	0.037
2	Robertson Post Office adjusted and The Pie Shop combined	1890-1998	7	109	0.064
3	Robertson Post Office unadjusted and The Pie Shop combined	1922-1998	4	77	0.052
4	Robertson Post Office adjusted and The Pie Shop combined	1922-1998	6	77	0.078

varies significantly over the historical period of 109 years and this variation is shown in the last column of Table 1 and again in the last column of Table 3 for adjusted data which takes into account the spatial variation of rainfall.

### Discussion

In order to estimate the risks associated with landslides triggered by rainfall, it is first necessary to estimate the likelihood or probability of occurrence. Qualitative estimates are often based primarily on visual site inspection and are, therefore, influenced significantly by subjective judgement. Quantitative estimation of probability of occurrence is highly desirable and is facilitated by the availability of historical and observational data concerning the particular site and also the surrounding area or region of study. Data concerning landslide activations and reactivations may not be available over a sufficiently long historical period in order to enable the direct estimation of return periods. Therefore, it is very useful to make use of historical data concerning the main triggering agent such as rainfall. Usually data concerning rainfall are available over much longer periods than the data concerning landslide occurrence or monitored subsurface movements. For some part of the historical period data will be available regarding both the movements and the rainfall thus facilitating the estimation of 'critical' or 'threshold' rainfall. The next step is to analyse rainfall over the entire historical period for which such data are available. Thus all the likely reactivations can be estimated by making use of the estimated rainfall thresholds

However, it is important to recognize the assumptions implicit in this approach and an effort must be made to check if those assumptions are valid for a particular study area.

The main assumption is that reactivation of a landslide will occur each time the rainfall threshold is exceeded. This assumption

is considered valid for the stick-slip, very slow-moving landslides in the study area of this paper provided that the estimate of rainfall threshold is reliable. Detailed research has been carried out over a number of years and two bounds to the threshold have been identified. Only the upper bound can be regarded as the real threshold for landsliding. Once that fact is recognized, the assumption stated above can be regarded as justified

However, one must acknowledge that, some types of landslides in a different study area may not always reactivate when thresholds estimated for those sites or those areas are exceeded. This may be due to changes in the geometry and hydrogeology of the landslide mass or because of inaccurate thresholds. In order to investigate such issues fully, detailed research over a number of years must be carried out in those particular areas and regions.

The variation of rainfall relating to geographical location and time should be carefully scrutinised during the analysis of rainfall data over a historical period. Data concerning the monitored movements should also be analysed although such data is available for much shorter periods.

Individual landslide sites may respond differently to different patterns and durations of rainfall depending on the nature of subsoil conditions and the groundwater regime. Hydrogeology, geomorphology and changes in original ground condition due to construction and development would influence the infiltration and seepage of rainfall and hence the pore water pressures along the slip surface associated with a particular landslide site. Accordingly the magnitude of critical rainfall threshold for triggering landsliding will be different for each site. For the case study site considered in this paper, the data concerning subsurface movements in 1991 and 1998 together with a detailed and careful analysis of rainfall led to the conclusion that 15-day cu-



mulative or antecedent rainfall of 788 mm may be regarded as the threshold for landsliding.

The 15 day cumulative rainfall was then considered for the whole of the historical period in order to determine the number of times that the threshold had been exceeded. In this way the recurrence intervals were determined. The assessed trend of its variation depends on the rainfall data recorded at the stations selected for use. A critical rainfall value derived from data using say Station A could be greater than that based on data from another Station B data if Station A has a localised higher rainfall than Station B. Thus a predicted landslide triggering rainfall value should be considered as a variable.

Two nearby rainfall stations were selected for the case study presented in this paper. The combined rainfall data extends over 109 years. Depending on (a) length of records and (b) adjustment of data the variable annual probability ranges from 0.026 to 0.172 and the mean value varies from 0.037 to 0.078. Recurrence interval decreases and probability increases once the rainfall data of Robertson Post Office Station is adjusted for spatial variability. Average annual probability for a given historical period also increases once the rainfall data from Robertson Station is adjusted for spatial variability. This implies reduced average recurrence interval. The use of data over a shorter historical period (77 years rather than the 109 years) leads to an increase in the annual probability based on unadjusted rainfall data as well as that based on data adjusted for spatial variability.

### Conclusions

Rainfall-triggered landslides occur frequently in many parts of the world and their impact can vary from moderate property damage and traffic disruption along roads and within urban areas to severe and catastrophic losses including human casualty. Therefore systematic and rational methods of hazard assessment must be developed in order to improve risk management. In particular, reliable hazard and risk assessment can facilitate better design of early warning systems and improved methods for loss prevention. For example, the suspension of traffic along roads and railway lines during severe rainstorms can prevent accidents and save lives.

For rainfall-triggered landslides the method proposed in this paper can be applied anywhere in the world provided data are available concerning historical rainfall over a significant historical record period and data on associated subsurface landslide movements are available over at least part of that historical period. This method is a significant improvement on qualitative methods of hazard and risk assessment such as the hazard-consequence matrix approach mentioned in the introduction section of this paper. Although qualitative assessments are useful in many situations, they need to be validated and calibrated by the use of detailed method such as the one presented here. It is true that some assumptions are necessary to carry a quantitative assessment. Yet, the degree of subjective judgment required is much less than that for a qualitative assessment. The order of magnitude of the probability of occurrence can be estimated reliably even when data are limited.

An important lesson from the case study presented here is that the spatial and temporal variations of annual probability of occurrence and hence of landslide hazard can be significant. To improve the quality of rainfall data for the research carried out at the University of Wollongong, rainfall pluviometers have now

been installed at selected landslide sites. The rainfall data from these installations is continuously recorded and accessed remotely. Continuously recorded inclinometers and vibrating wire piezometers have also been installed at these sites. Highly accurate data is being obtained from these installations. Therefore, better estimates of the probability of landslide occurrence can be made in the future than those based on historical data alone.

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