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Estimating temporal probability for landslide initiation along transportation routes based on rainfall thresholds

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ABSTRACT

The estimation of the temporal probability of landslide initiation is an essential component in landslide hazard assessment. In this paper a temporal probability model is presented for the initiation of shallow translational debris slides and debris flows along cut slopes of a railroad sector in southern India, for which an extensive landslide database was available, covering a time span of 15 years. The model is based on rainfall thresholds and gives the likelihood of occurrence of rainfall that can trigger landslides with a certain density. The temporal probability was calculated as the joint probability of annual exceedance probability of the rainfall threshold, determined using a Poisson probability model and the probability of landslide occurrence once the threshold had been exceeded. The model was tested for a 19-km long railroad alignment in the Nilgiri hills, which was divided into a number of sections on the basis of terrain characteristics. A landslide inventory, containing dates of occurrence, was prepared from historical records for the period 1987 to 2007. Daily rainfall for the same period was collected from 15 rain gauges. Rainfall thresholds were established for the sections based on the relationship between daily and antecedent rainfalls. Four thresholds were defined for rainfall events that can trigger one or more landslides within each section and one threshold that can trigger 15 or more landslides along the entire route. The annual temporal probability varies from 0.27 to 0.49. The model was also found useful in predicting landslides in a nearby road with similar characteristics. The result indicates that more than 60% of the recorded landslides along the road occurred within the sections with high temporal probability values (>0.40). The temporal probability derived from the model forms the basis for future landslide risk analysis along the transportation routes.

1. Introduction

Varnes (1984) defined landslide hazard as “the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon”. Thus, landslide hazard has two independent components: spatial and temporal. Some workers have also included landslide magnitude or intensity as a component to evaluate damages related to a landslide (Guzzetti et al., 1999, 2005). Numerous publications on spatial assessments of landslide susceptibility are available (e.g. van Westen, 1994; Soeters and van Westen, 1996; Chung and Frabbri, 1999; Guzzetti et al., 1999). However, much less work is done on the establishment of the temporal probability of landslides (Lips and Wieczorek, 1990; Coe et al., 2000; Guzzetti et al., 2002, 2005).

Some models have been used to calculate the temporal probability of landslide occurrence for an area by assuming that the rate of landslide occurrence will remain the same in future under the given geo-environmental conditions (Coe et al., 2000, 2004; Guzzetti et al., 2005). Such studies require a complete landslide inventory and the results obtained are generally only applicable to the modeled area. The temporal probability of rainfall-induced landslides can be analyzed by evaluating the temporal probability of the rainfall events themselves combined with an analysis of the rainfall threshold, which is the minimum intensity or duration of rainfall required to trigger a landslide (White et al., 1996; Crozier, 1997; Reichenbach et al., 1998).

Temporal probability of landslide initiation can be estimated either using physically-based or empirical rainfall threshold methods. The physically-based threshold models use local terrain characteristics (e.g. slope gradient, soil depth, and lithology) in a dynamic hydrological model in which rainfall is the most important variable (Wilson and Wieczorek, 1995; Crosta, 1998; Terlien, 1998; Montgomery et al., 1998). These models are less suitable for larger areas as they require detailed knowledge of the boundary conditions (e.g. soil properties, changes in groundwater level, discharge conditions, and shear

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parameters), which are difficult to extrapolate outside the test sites instrumented with piezometers, tensiometers, etc.

Empirical methods for temporal probability assessment are based on the estimation of rainfall thresholds obtained by studying rainfall conditions that have resulted in landslides. They are usually contained in envelope curves based on variables such as cumulative rainfall, antecedent rainfall, rainfall intensity, and rainfall duration (Caine, 1980; Wieczorek, 1987; Glade, 1998; Crozier, 1999; Chleborad, 2000; Crosta and Frattini, 2003; Aleotti, 2004; Giannecchini, 2005; Chen et al., 2006; Jakob et al., 2006). The most commonly used empirical model is based on the rainfall intensity and duration. This threshold model requires data with high quality and temporal resolution (at least hourly rainfall data), which are not frequently available. Other models based on antecedent rainfall work with daily rainfall data, which are relatively simple and inexpensive to measure over large areas.

In this paper, we propose a method to determine the temporal probability for landslide initiation using the probability of exceedance of a rainfall threshold and the probability of occurrence of landslides related to the rainfall threshold. The method helps in understanding the relationship between rainfall and landslide occurrence and any variation in the threshold due to the change in local topography. The method requires complete information on landslides including the dates of occurrence in order to correlate them with rainfall.

The method is applied to a rail route in southern India. This study area was selected because of the availability of complete historical landslide records including the dates of occurrence of the landslides, and daily rainfall records from a well-distributed network of 15 rain gauge stations.

2. Site characteristics

The study area includes a 19-km long section of a small-track historic railway alignment, which is declared as a world heritage site by UNESCO, and a 26-km long section of the national highway connecting Mettupalayam and Coonoor in the state of Tamilnadu in southern India (Fig. 1). The road and railway almost run parallel on the southern slopes of the Nilgiri plateau.

These transportation routes are cut through soil and laterite, underlain by charnockite and garnetiferrous quartzo-felspathic gneisses belonging to the Charnockite Group of the Archaean age (Seshagiri and Badrinarayanan, 1982). The regional strike of the foliation ranges from ENE–WSW to E–W direction with moderate to steep dips. The subtropical climate and intense physical and chemical weathering have resulted in a thick yellowish to reddish brown soil (Seshagiri and Badrinarayanan, 1982). The regolith thickness varies from <1 to 20 m, as observed in the cut slopes along the road and the railway. The contact between bedrock and weathering soils is often exposed in the

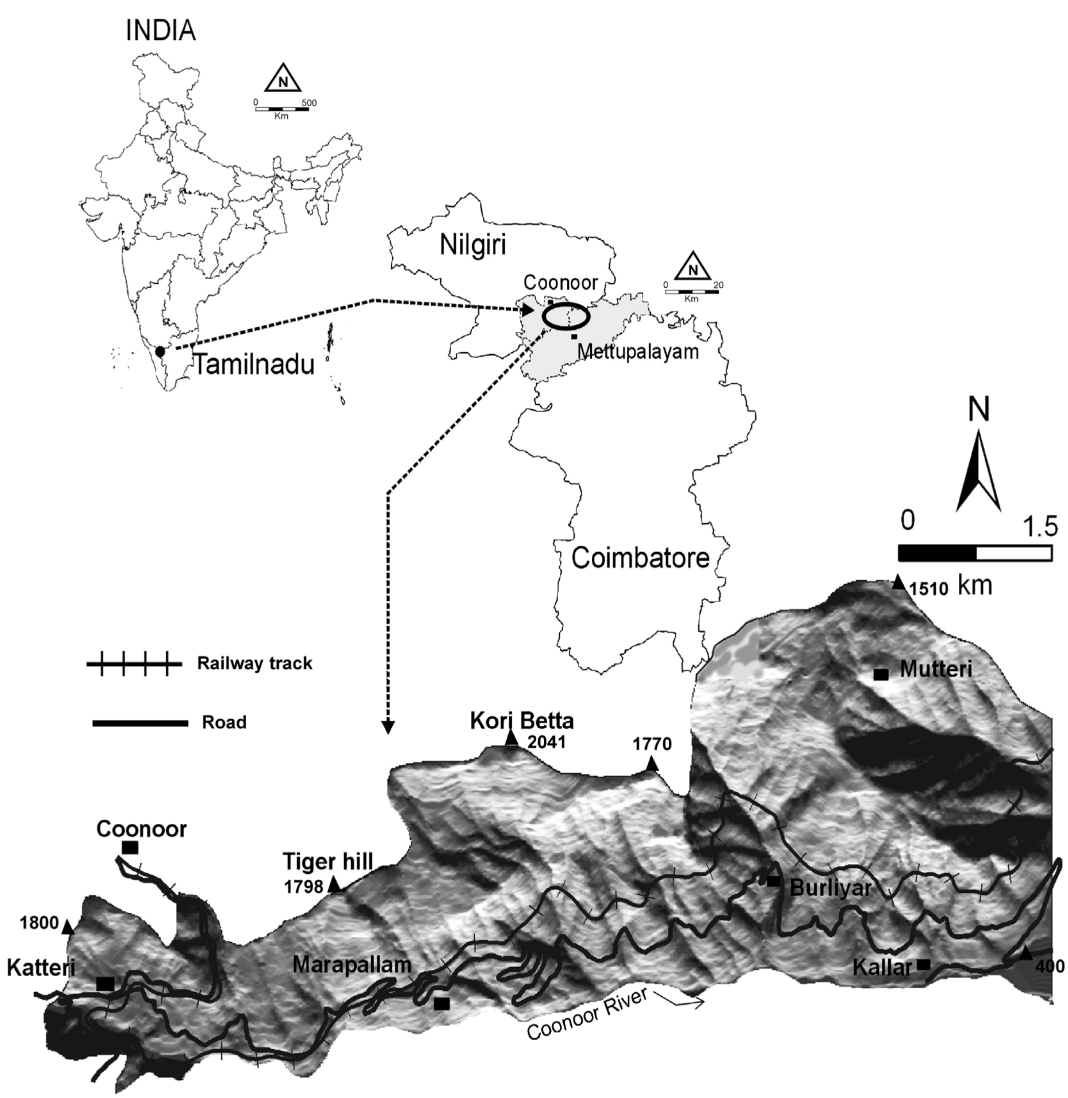

Fig. 1. Location map of the study area. Black triangles are the spot height measured in meters above the mean sea level.

cut slopes, which make them more susceptible to landslides due to the build-up of pore pressure on the contact (Campbell, 1975; Iverson, 2000; Zezere et al., 2005).

2.1. Landslide distribution

In the study area numerous landslides normally occur in the period from October to December due to the retreating monsoonal rainfall. For instance on 4 October 1905, a rainfall of 170 mm was recorded in 3 h; on 12 November 1979, 150 mm in one day recorded at the Coonoor rain gauge; and on 11 November 1993, 177 mm in one night around Marapallam, resulting in numerous landslides. The rainfall event of 1979 has alone resulted in 200 landslides within the Nilgiri district (Seshagiri and Badrinarayanan, 1982). In the study area, landslides are mostly shallow translational debris slides and debris flows triggered by rainfall. Their spatial distribution is shown in Fig. 2. These landslides are individually small in size ($1.5–2.0 \times 10^5$ m^3; average = 404 m^3, and median = 50 m^3) but occur in a large number and cause substantial damage to the railway and the road. The railway company alone has to spend about 0.25 million US dollars each year for restoring the track due to landslide damage. Based on the historical records such as the railway landslide maintenance registers (from 1992 to 2006) and technical reports (from 1987 to 2007), a total of 790 landslides were identified within the 25 km^2 study area in the 21-year period 1987 to 2007. About 94% of these landslides occur along cut slopes and 6% in natural slopes. The majority of failures (97.2%) are classified as shallow translational debris slides, and only 2.4% as debris flows. The historical records provide information on the date of occurrence of the landslide. In this paper, we use the term ‘landslide-triggering event’ for those days for which one or more landslides were triggered. During the investigated period, from 1 January 1987 to 31 October 2007, 94 individual landslide-triggering events were differentiated, of which 71 occurred in the months from October to December. There was at least one landslide event per year, except in 1995. The average rate of occurrence was 20 landslides per year. Major activities were observed during 1992, 2001 and 2006.

2.2. Rainfall distribution

For the study area, daily rainfall data were collected from 15 rain gauges belonging to the tea estates (nine stations), the horticulture department (three stations) and the railway office (three stations). These organizations have the tasks to maintain daily rainfall records and they have installed their own rain gauges. The distribution of the rain gauges is shown in Fig. 2. All gauges are non-automated tipping bucket type. Everyday readings are taken in the morning hours (0830 h).

Daily rainfall data from the three rain gauges of the railway office were analyzed to know the variation in the rainfall pattern from west to east in the study area. These gauges are located in Coonoor (west of the area), Hillgrove (center) and Kallar (east). The analysis of the daily rainfall data from 2002 to 2006 indicates that the average cumulative rainfall between April and August appears to be uniform throughout the area, but that between October and December shows a slight decrease in the central part. The average annual rainfall recorded at Coonoor and Kallar is 1939.4 and 1853.2 mm, respectively and the difference from west to east is 86.2 mm, which is very small. The study of daily rainfall records reveals that the area experiences rainfall in two periods: from April to August (normal monsoon), and from October to December (retreating monsoon), of which November is the wettest month. The lowest recorded annual rainfall is 750 mm and the highest is 3165 mm. The number of days with recorded rainfall also varies, depending on the season and the area. The total number of days with recorded rainfall in October to December is less than that in April to August, particularly in the Coonoor and Hillgrove areas but even there winter rainfall contributes approximately 50% to the total annual rainfall. The maximum rainfall recorded in a single day between October and December is twice as much as that between April and August. The maximum daily rainfall varies from 49 to 245 mm.

Although there is not much variation in total annual rainfall from west to east, there is a large variation in the rainfall during the landslide-triggering events. Fig. 3 shows the variation in the rainfall on the representative landslide-triggering events measured at six rain gauges. The events considered for this analysis had resulted in more than 20 landslides in different parts of the study area depending on the amount of rainfall. The amount of daily rainfall on the landslide-triggering events varies considerably and Fig. 3 shows no clear trend from west to east. Most of the landslides have occurred in areas where the rainfall was relatively high. For instance on 14 November 2006, more than 150 mm rainfall around Hillgrove and Burliar resulted in numerous landslides in these areas, but not in the western part of the study area.

3. Probability model

As discussed in Section 2.2, landslides are found to be associated with certain intensity of rainfall. Thus, for our analysis, we assume that the probability of occurrence of a landslide is related to the probability

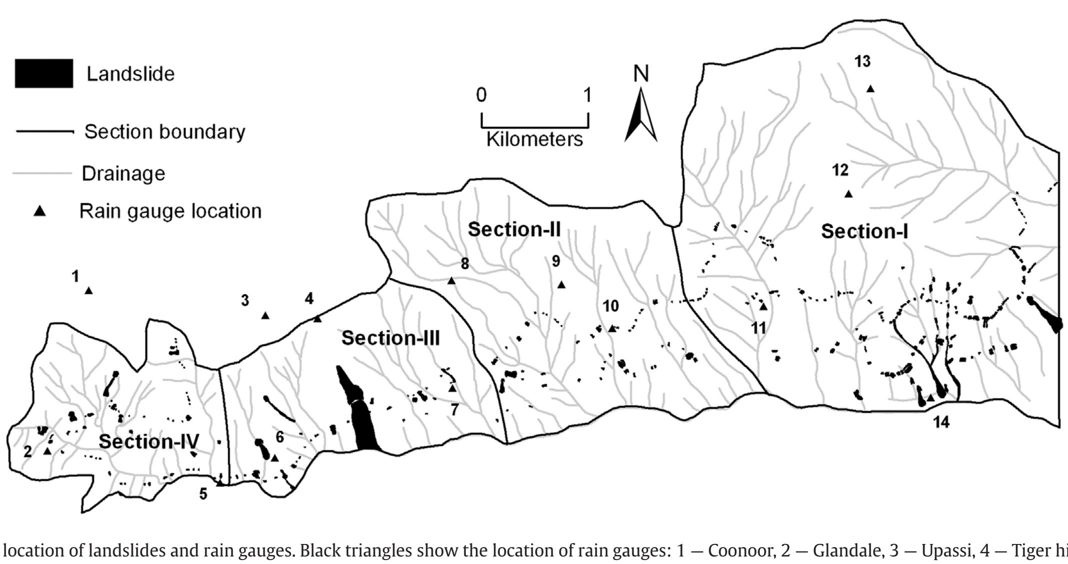

Fig. 2. Map showing location of landslides and rain gauges. Black triangles show the location of rain gauges: 1 — Coonoor, 2 — Glandale, 3 — Upassi, 4 — Tiger hill, 5 — Runneymede, 6 — Katteri farm, 7 — Marapallam, 8 — Singara_UD, 9 — Singara_LD, 10 — Hillgrove, 11 — Burliyar, 12 — Adderley, 13 — Mutteri, 14 — Kallar. Sections I, II, III and IV are the areas used for determining rainfall thresholds.

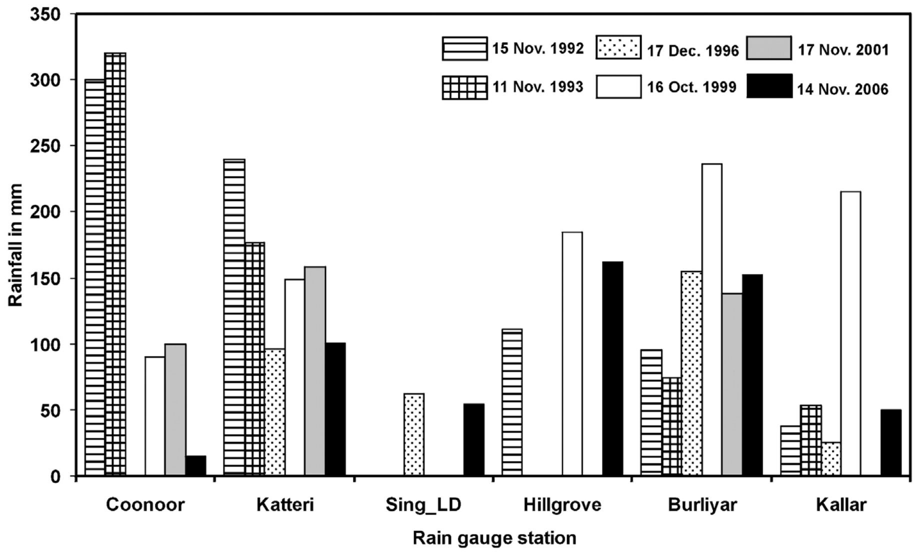

Fig. 3. Rainfall recorded during landslide-triggering events at six rain gauge stations. Each event has triggered more than 20 landslides.

of occurrence of the triggering rainfall threshold. The threshold is the minimum amount of rainfall needed to trigger landslides.

The input of the threshold rainfall is the time series of daily rainfall $R_d(t)$ in mm day^{-1}, where t is time. For a landslide $\{L\}$ to occur, the daily rainfall must exceed a threshold, which is a function $R(t)$ of the total rainfall in a period, and of the amount of the antecedent rainfall $R_{ad}(t)$, i.e. rainfall that have occurred prior to the day of landslide,

$$R(t) = f[R_d(t), \quad R_{ad}(t)] \tag{1}$$

where $R(t)$ is the amount of rainfall in a given period (e.g. daily), in mm, and $R_{ad}(t)$ is the antecedent rainfall also in mm. This function of R defines the probability of occurrence of the landslide L: $P\{L\}$. If R_T is the threshold value of R then,

$$P[L|R > R_T] = 1 \quad \text{and} \quad P[L|R \geq R_T] = 0. \tag{2}$$

Thus, in this simplified model, landslides always occur when R exceeds R_T and never occur when the value of R is lower than or equal to R_T. In the former case, the probability of occurrences of landslide $P\{L\}$ depends on the exceedance probability of $P[R > R_T]$, i.e., $P[L] = P[R > R_T]$.

In reality, however, the threshold may be exceeded without resulting in any landslide. This may be attributed to some other factors which locally influence the initiation of a landslide and are not fully understood (Aleotti and Chowdhury, 1999). This difference can be reduced when the final probability is viewed as the conditional probability of a given threshold exceedance $[P\{R > R_T\}]$ and the probability of occurrence of a landslide $[P\{L\}]$, given the exceedance (Floris and Bozzano, 2008). Thus, the probability of landslide occurrences can be given by the intersection of two probabilities

$$P\{(R > R_T)L\} = P\{R > R_T\}P\{L|R > R_T\}. \tag{3}$$

This means that the probability of occurrence of both $\{R > R_T\}$ and $\{L\}$ is equal to the probability of $\{R > R_T\}$ multiplied by the probability of occurrence of $\{L\}$, assuming that $\{R > R_T\}$ has already occurred. The probability of $\{R > R_T\}$ can be obtained by determining the exceedance probability of the rainfall threshold and the probability of $\{L\, R > R_T\}$ relies on the frequency of occurrence of landslides after the threshold has been exceeded.

The above assumption that landslide has to occur whenever a given rainfall threshold is exceeded may not hold always and everywhere. However, it is also expected that landslides will not occur below the rainfall threshold. Hence, for rainfall-triggered landslides, this assumption can be an acceptable first-approximation to work with and to estimate the frequency of landslides by establishing relations between the landslide trigger, its magnitude and the occurrence of the landslides.

4. Determination of the rainfall threshold

4.1. Methodology

Different types of landslides respond differently to rainfall e.g. shallow debris slides along cut slopes will require different conditions to initiate than those on natural slopes. It is therefore necessary to determine separate thresholds for each type of landslide. To determine the rainfall threshold we selected only the shallow translational debris slides and debris flows associated with the cut slopes along the railway in the months from October to December. This subset represents 82% (648) of the total number of the recorded landslides. Out of this subset, we further separated three events of 2006 and one event of 2007 for the validation of the threshold model.

For this study, we have selected a threshold model based on antecedent rainfall, because only daily rainfall data are available and easy to implement. Data required for the model are derived from the historical records of landslides and daily rainfall records.

Because of the variation in the daily rainfall totals associated with landslide occurrences (Fig. 3) and the presence of 15 rain gauges within the study area (Fig. 2) it was important to select representative rain gauges for establishing the landslide–rainfall relationship along the different sections of the rail route. The selection was made based on the horizontal distance and elevation difference with respect to the rail route, and also on the landslide distribution and topographical location of the rain gauges. The Burliyar rain gauge was taken as representative of the area east of Burliyar since it is located on the same elevation and topographic situation of that of the railway. The rain gauges located at Hillgrove, Katteri and Runneymede were taken as representatives of the other sections of the area.

Depending on the type of landslides and their geo-environmental setting, the number of antecedent days can vary from 3 days for shallow landslides to 30 days for deep landslides (Kim et al., 1992; Aleotti, 2004; Zezere et al., 2005; Chleborad et al., 2006). To determine the suitable number of antecedent days required for shallow debris slides and debris flows to occur along the cut slopes, we selected 54 landslide-triggering events that have occurred between 1992 and

2006 around Burliyar. These triggering events have resulted in 270 shallow landslides around this area. After analyzing the 3, 5, 15 and 30-day antecedent rainfall, according to the method suggested by Zezere et al. (2005), the 5-day antecedent rainfall was considered suitable for the analysis.

To determine R_T, a scatter plot was prepared showing daily rainfall against the corresponding 5-day antecedent rainfall, for each day with one or more triggered shallow landslides. The envelope curve is manually drawn such that it demarcates the lower end of the plotted points. The line can be represented by a linear mathematical equation (Crozier, 1999; Chleborad, 2000).

For the calculation of the thresholds, the 19-km long transportation corridor was divided into four sections (Fig. 2), based on topography, land use types, and terrain gradient. Rainfall conditions at each section were determined from the nearest rain gauge. Besides the rainfall threshold for the four individual sections, a general threshold was established for major landslide events that have resulted in 15 or more landslides. During the period 1992 to 2006, the railway route has experienced 14 landslide-triggering rainfall events that have resulted in several landslides per day (from 15 to 118 failures). Such events have occurred on average once a year except in 1994, 1995, 2003 and 2005. From the 14 events only one has triggered more than 100 landslides in a day, two in 30 to 40 landslides and 11 resulted in 15 to 25 landslides. In the study area about 50% of such events have occurred when the daily rainfall was more than 100 mm and 29% when it was more than 230 mm. Such events have affected different parts of the route in different years. The determination of a threshold for the individual sections was not possible, due to the paucity of data. A threshold for the entire railway route was determined for the events that have individually resulted in 15 or more landslides.

4.2. Results

The first section east of Burliyar transects through steep forested slopes. It contains 270 landslides resulting from 54 landslide-triggering events. Here R_T above which a landslide can occur for the given 5-day antecedent rainfall (R_{5ad}) is represented by the equation $R_T = 66 - 0.93\ R_{5ad}$ (Fig. 4). The figure indicates that initially at least 50 mm of antecedent rainfall is required for a daily rainfall of 19.5 mm to initiate a landslide. When R_{5ad} is more than 75 mm, even a continuous normal monsoon is capable of triggering a landslide. The small limit of R_{5ad} makes the section more susceptible to landslides.

The section west of Burilyar, around the Hillgrove rain gauge, passes through steep forested slopes and moderate slopes covered by tea plantation. It contains 64 landslides resulting from 18 landslide-triggering events during the period 1992 to 2006. The threshold is represented by the equation $R_T = 165 - 1.32\ R_{5ad}$ (Fig. 4). This section requires very high magnitude of daily rainfall ($R > 100$ mm) at the beginning of October to trigger a landslide. When R_{5ad} exceeds 125 mm there is a possibility of getting landslides even when there is no rain.

The section of the rail route around Marapallam passes through rocky terrain, with tea plantations and forests. It is relatively less prone to landslides. During the period from 1992 to 2006, only 15 landslide-triggering rainfall events have taken place resulting in 19 landslides. The threshold is given by the equation $R_T = 230 - 1.32\ R_{5ad}$ (Fig. 4).

The route east of Runneymede up to Coonoor passes through gentler terrain with tea plantations and residential areas. Only at some places the cut slopes are steep and prone to landslides. This section has witnessed 22 landslide-triggering events which have resulted in 72 landslides. The threshold is represented by the equation $R_T = 250 - 1.5\ R_{5ad}$ (Fig. 4).

The general threshold for the major landslide events is given by the equation $R_T = 220 - 0.61\ R_{5ad}$ (Fig. 4). The small slope (0.61) and high intercept (220) of the envelope curve indicates that such events either require very high magnitude daily rainfall or a very high amount of 5-day antecedent rainfall during the monsoon to trigger landslides.

In a few cases, landslides were also reported when no rainfall was measured on any specific day. These were the cases when high antecedent rainfall alone has resulted in landslides. We attribute the failures to pore pressure rising due to water percolating from upslope areas. This holds for landslides associated with cut slopes because during excavation toe of such slopes are removed and the unsupported overburden mass becomes more prone to failure under the given condition. Thus, for all the listed thresholds, the lower boundary of the envelope curve was set to zero daily rainfall. In our model, some of the daily rainfall related to no-landslide events has occurred above the envelope curve. These are events which rainfall was relatively high, but did not result in landslides.

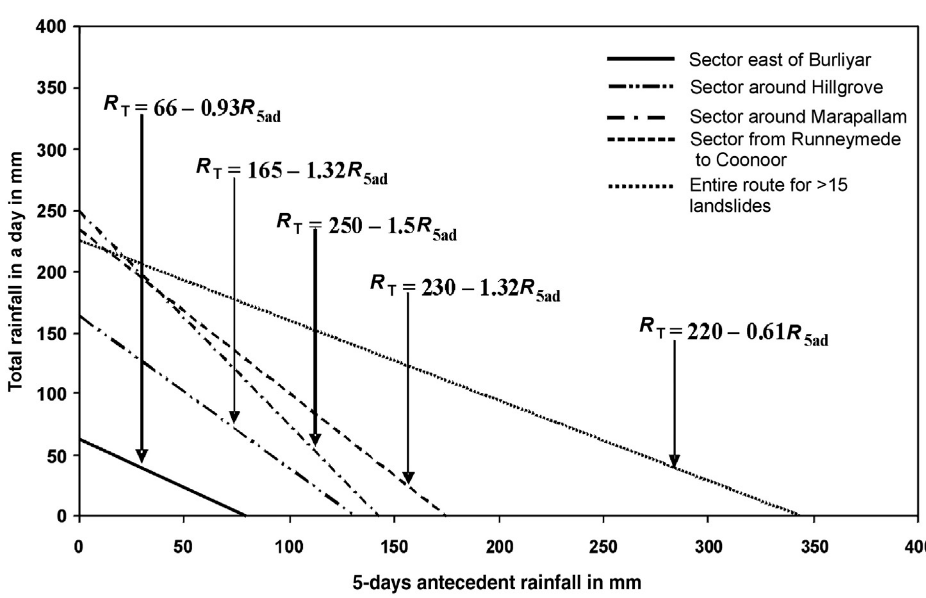

Fig. 4. Envelope curves for shallow translational debris slides and debris flows at different sections of the railway route. R_T is the threshold rainfall and R_{5ad} is the 5-day antecedent rainfall.

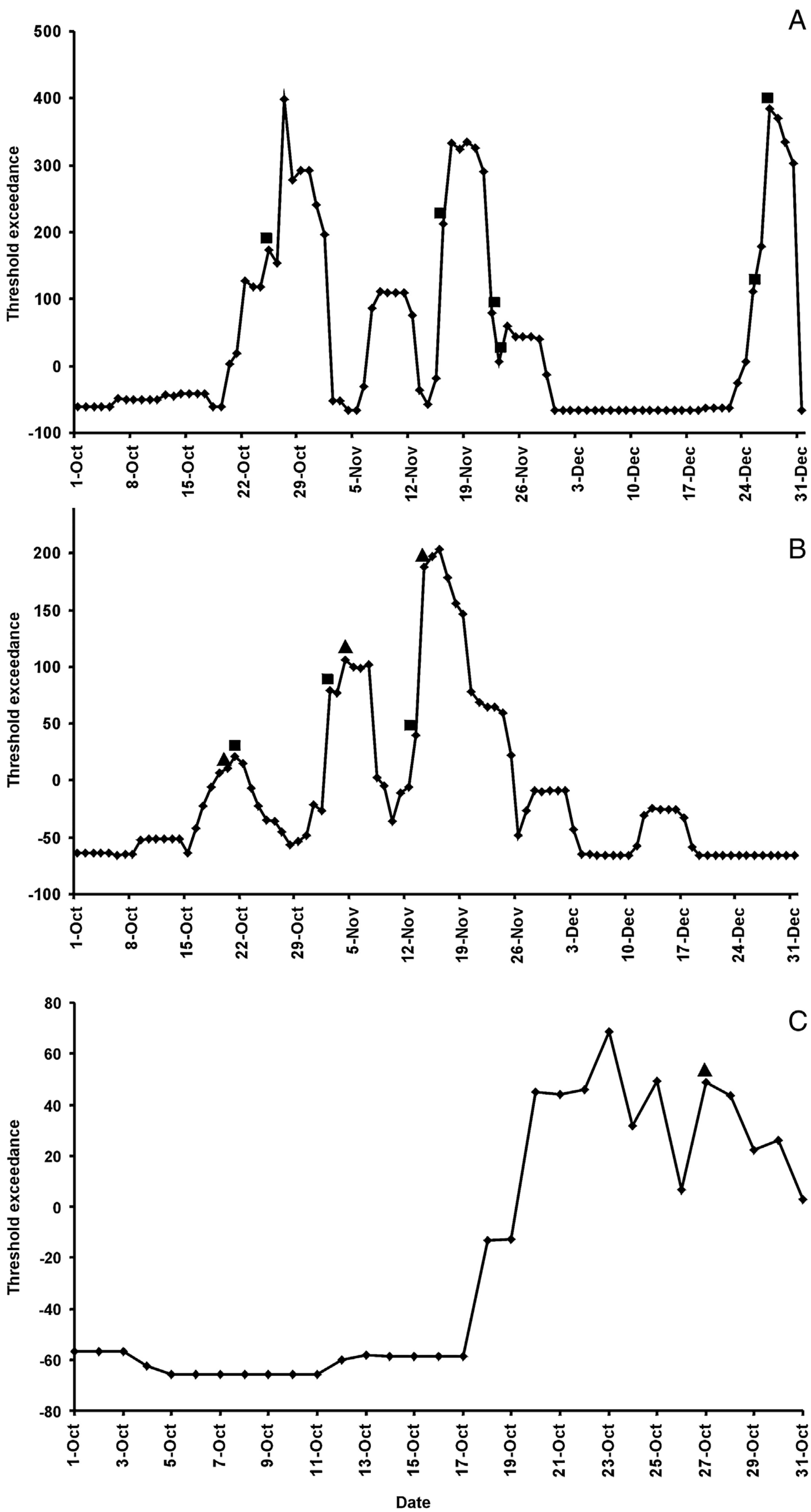

Fig. 5. Validation of the threshold equation $R_T = 66 - 0.93\ R_{5ad}$ for the railway section east of Burliyar. Validation was done for the year 2001 (A), 2006 (B) and 2007 (C). Positive values on the *y*-axis indicate threshold exceedance ($R > R_T$). Black squares indicate the dates of landslide-triggering rainfall events considered in the model. Black triangles are the event dates that were not considered in building the threshold model.

4.3. Validation of the threshold model

The rainfall thresholds can be used to predict landslides both spatially and temporally. The temporal aspect is related to the daily variations in rainfall and the spatial aspect can be related to the use of different thresholds for different areas. An indirect way to test the predicting capability of the thresholds is to validate them with the control data sets, which were not used in the model.

The temporal validation of the threshold equation $R_T = 66 - 0.93\ R_{5ad}$ for the section east of Burliyar is shown in Fig. 5. The validation was carried out using 2001, 2006 and 2007 rainfall and landslide data. The 2001 and part of 2006 event data were also used in building the model. These are included here to visualise the performance or success of the model. Fig. 5 indicates that in the period from October to December the rainfall has exceeded the threshold curve several times. Between two successive positive periods (i.e., the period for which the threshold was exceeded) there may be a period with no rainfall or very low rainfall. Each rise in the threshold curve indicates that either there is a sudden increase in the magnitude of daily rainfall or there is a constant rise in the 5-day antecedent rainfall. The width of each positive curve (or positive amplitude) denotes the period of consecutive rainy days in a given month. The crossover of the curve from negative to positive values indicates the time when the threshold is crossed and the conditions favourable for landsliding begins. One or more landslide events are expected before the positive curve decays to the zero threshold value.

In 2001, the threshold was exceeded on four occasions and landslides were found associated with the rise in the threshold curve except for the period from 7 to 13 November (Fig. 5A). Similarly, in 2006 the threshold was exceeded on three occasions and landslides were associated with each rise. In this year the threshold was successfully validated by three landslide events that were not included in the model. In contrast to 2001, peaks of 2006 are associated with medium and low magnitude daily rainfall. For 2007 the validation is done in October. In this month, the threshold was exceeded once and it was associated with landslides (Fig. 5C). The daily rainfall in this period remained below 50 mm. The figures also indicate that landslides are not always associated with the rise in the threshold curve and at times they occur a few days after the exceedance. This could be due to the variation in the pore pressure resulting from changes in the amount of antecedent rainfall. Similar validations were carried out for the other threshold equations: $R_T = 165 - 1.32\ R_{5ad}$, $R_T = 250 - 1.5\ R_{5ad}$ and $R_T = 230 - 1.32\ R_{5ad}$ using the 2001, 2006 and 2007 rainfall and landslide data. The analysis reveals that during October to December all the threshold curves show consistent rise and fall in the trend except for October 2007. In this year the curves did not exceed the threshold value and hence no landslides have occurred. In 2006, there was no threshold exceedance during 1 to 16 October and from 25 November to 31 December, and no landslide had occurred in these periods. Similarly, in 1995, thresholds were not exceeded in any of the rain gauges and there were no reports of landslides.

The spatial validation of the model was carried out along the 14-km railway line west of Coonoor, directly adjacent to the area where the thresholds were derived. The geo-environmental setting there is similar to that of the sector from Runneymede to Coonoor, and therefore the threshold equation $R_T = 250 - 1.5\ R_{5ad}$ was used for the validation. The daily rainfall data were taken from the rain gauge located at Ketty. A multi-temporal landslide inventory map was prepared from the railway maintenance register for this area as well. From the period 1992 to 2007 during October to December, 19 rainfall-triggered landslide events were recognised that have individually resulted in one or more landslides. The result of the validation is shown in Fig. 6. The figure indicates that in the years 2000, 2003, 2004, 2006 and 2007 the threshold was exceeded on a maximum of two occasions each year and occurrences of landslides are associated with each exceedance except for 2003 and 2006. In 1992, 1997, 2004 and 2006 one landslide-triggering event occurred when the threshold was not exceeded, normally just 1 day before the threshold was reached. Because of their close proximity to the envelope curve these events are considered as the exceedance event. During the period from 1992 to 2007, the threshold was exceeded on 17 occasions and for 12 times it had led to one or more landslides. Thus, the prediction rate is 12/17 or 70%.

5. Determining temporal probability of landslide initiation

5.1. Methodology

The annual exceedance probability (*AEP*) is the estimated probability that an event of specific magnitude will be exceeded in any given year (Fell et al., 2005). For a given rain gauge *AEP* of the threshold $[P\{R > R_T\}]$ was determined using a Poisson probability model. This model has been used to determine the exceedance probability of landslides in time by, e.g., Coe et al. (2000, 2004) and Guzzetti et al. (2005). According to the Poisson model, the exceedance probability or the probability of experiencing one or more landslides during time t is given by

$$P[N(t) \geq 1] = 1 - exp(-t/\mu) \quad (4)$$

where μ is the mean recurrence interval between successive landslides, which can be obtained from the multi-temporal landslide inventory data.

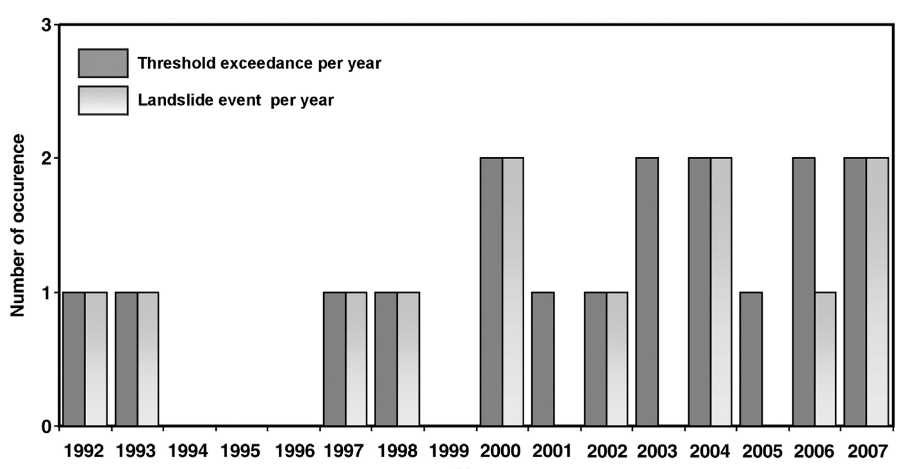

Fig. 6. Spatial validation of the threshold equation $R_T = 250 - 1.5\ R_{5ad}$ along the railway route, east of Coonoor. Bars with dark grey indicate the number of times the threshold was exceeded in a year and bars with light grey indicate the number of times that a landslide-triggering event was associated with the threshold exceedance.

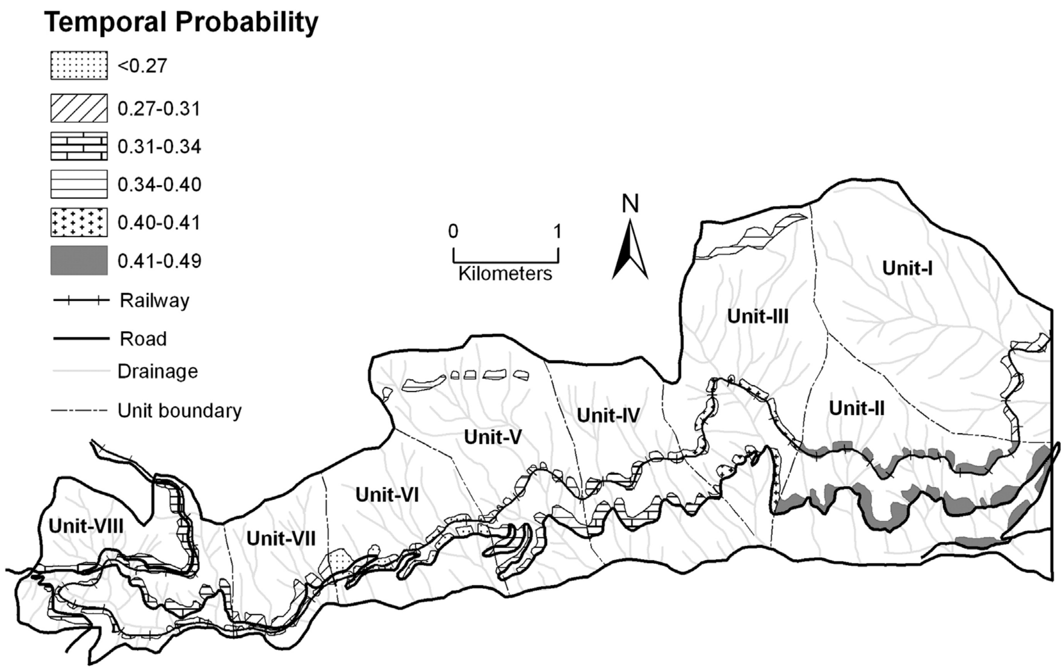

Fig. 7. Annual temporal probability of landslide initiation along the cut slopes of the railway and the road route. Temporal probability is based on the exceedance probability and frequency estimates of threshold rainfall in the different units along the routes. The areas shown on the upslope of units III and V are along the local road.

To determine *AEP* of the rainfall threshold for a particular area, R_T is calculated from the threshold equation, and the result is subtracted from *R*. Each phase of continuous positive values ($R > R_T$) is considered as the period of maximum likelihood for landslide initiation. In this study, *AEP* calculation was based on the 15-year daily rainfall data from 1992 to 2006 in the months from October to December for landslide initiation along the railway route.

The next step after calculating *AEP* of the rainfall threshold is the assessment of the probability of landslide occurrence after the threshold has been exceeded. The frequency can be established from the rainfall and landslide records, for different sections of the railway line (Fig. 2). From this frequency, the probability of $\{L\}$ conditioned on $\{R > R_T\}$, i.e. $P\{L|\ R > R_T\}$, can be estimated. To achieve this, the transportation routes were further subdivided into eight smaller topographic units based on the variation in the land use type and the height of the cut slope (Fig. 7). This was done to take account of variation in the landslide distribution in different units resulting from the unequal response of the terrain towards the threshold due to changes in local relief and land use. In the field we observed, particularly in the east of Burliyar, that the same rainfall intensity over the section had resulted in different number of landslides because of differences in the height of the cut slope and availability of larger upslope area for a landslide to retrograde. For a given amount of rainfall the chances that a slope will fail depend on the morphology of the slope and the land use. Steep slopes have higher cut slope height than gentle slopes and thus provide more surface area for landslides to occur. Similarly land use such as tea plants provides more strength to soils as they are closely planted and have strong roots, which increase shear strength of the soils.

As indicated earlier, the temporal probability of landslide initiation was calculated by multiplying:

(i) *AEP* of the rainfall threshold, i.e. a probability of the threshold being exceeded in a year, by
(ii) the probability of landslide initiation given that the threshold is exceeded $P\{L|\ R > R_T\}$.

5.2. Results

In the section east of Burliyar, the threshold was exceeded 53 times in 15 years, in the considered months. The mean recurrence interval (μ) between successive threshold exceedances was 15/53 or 0.28. According to Eq. (4), *AEP* of the rainfall threshold during these months is 0.97. For the other sections, according to the threshold equations given in Fig. 4, the rainfall threshold was exceeded 29, 27, 30, and 15 times, for a section around Hillgrove, around Marapallam, east of Runneymede up to Coonoor, and for entire route, respectively. The corresponding *AEP* values based on Eq. (4) were determined as 0.85, 0.83 0.86, and 0.63, respectively (Table 1).

Table 1
Temporal probability of landslide initiation along different units of the railway route.

Area	Units	Threshold equation	Number of expected landslides	Number of times the threshold exceeded	$P[R > R_T]$	Frequency of landslide in units	$P[L\ R > R_T]$	Temporal probability ($P[R > R_T] \times P[L\|R > R_T]$)
East of Burliyar	I	$R_d = 66 - 0.93R_{5ad}$	> 1	53	0.97	17	0.32	0.31
	II			53	0.97	27	0.51	0.49
	III			53	0.97	23	0.43	0.41
Around Hillgrove	IV	$R_d = 165 - 1.32R_{5ad}$	> 1	29	0.85	12	0.41	0.34
	V			29	0.85	14	0.48	0.40
Around Marapallam	VI	$R_d = 230 - 1.32R_{5ad}$	> 1	27	0.83	9	0.33	0.27
West of Runneymede	VII	$R_d = 250 - 1.5R_{5ad}$	> 1	30	0.86	11	0.36	0.31
	VIII			30	0.86	12	0.40	0.34
For entire route	–	$R_d = 220 - 0.61R_{5ad}$	> 15	15	0.63	11	0.73	0.46

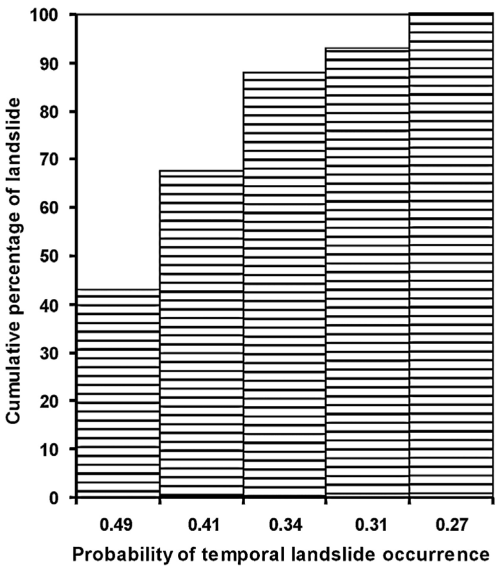

Fig. 8. Frequency distribution of landslides in different temporal probability classes along the road.

The probability of occurrence of a landslide after the threshold has been exceeded was estimated for each of the eight topographic units. To the East of Burliyar, R_T was exceeded 53 times in the 15-year period 1992–2006 (Table 1). In 17 cases, it triggered landslides in unit I, corresponding to an estimated probability $P\{L|\ R>R_T\}$ of 17/53 or 0.32. Similarly, in units II and III, during the same period, landslides were triggered on 27 and 23 times giving $P\{L|\ R>R_T\}$ of 0.51 and 0.43 respectively. Results for the other topographic units are listed in Table 1.

The annual temporal probabilities for different topographic units of the transportation routes for the months from October to December are given in Table 1 and their distribution is shown in Fig. 7. The probability of having one or more rainfall events that can trigger landslides in any given year varies from 0.27 to 0.49. The highest probability values are assigned to the units II, II and V. These areas also have the higher incidences of reported landslides. All these events are capable of triggering one or more landslides, in the months from October to December.

5.3. Validation of temporal probability outside the model area

The rainfall-based temporal probability values that have been obtained for the railway line were used to test their applicability in a nearby road corridor having similar terrain characteristics. The results of the prediction are shown in Fig. 8. The frequency distribution of the recorded landslides during the period 1987 to 2007 indicates that more than 60% of the landslides have occurred within the road sectors with high temporal probability of occurrence (>0.40) and 7% in the zones with the lowest probability value (0.27). This validates the predicting performance of the model for shallow translational debris slides associated with cut slopes outside the modeled area.

6. Discussion

The proposed method allows us to determine the temporal probability of landslide initiation along transportation routes of a hilly area. The model is applicable to shallow debris slides and debris flows associated with cut slopes and triggered by rainfall. Though there is a possibility that landslides initiating on natural slopes may affect the railway route, no such incidences have been reported in the area. At some places, debris flows have followed the stream courses and reached up to the road level. Only the Marapallam and Kallar debris flows have directly affected the road. About 82% of the recorded landslides in the inventory are associated with the railway cut slopes. The relative lack of data along the road might be due to the fact that smaller landslides are not reported as they do not cause damage to the road itself. Due to the possible incompleteness of the inventory along the road it was difficult to determine the temporal probability based on the frequency of landslide occurrence. The proposed model based on the rainfall thresholds allows us to extend the result to other areas of similar geo-environment and rainfall conditions.

The 19-km railway line is represented by four thresholds which on exceedance can result in one or more landslides. The thresholds are found to be dynamic and vary with changes in the local terrain conditions and thus a threshold can be considered as a proxy of terrain susceptibility. For the same landslide-triggering event, different areas are represented by different envelope curves. Areas west of Hillgrove are represented by an envelope curve with high slope and intercept values. These areas have gentle slopes and thus require relatively more rain to fail than the area east of Burliyar where the terrain is steep.

Numerous publications on the regionally-derived thresholds of rainfall intensity and duration for landslides are available (e.g., Dahal and Hasegawa, 2008; Guzzetti et al., 2008; IRPI, 2009). Different climatic regions have shown different threshold values for rainfall intensities. Guzzetti et al. (2008) have attributed this to the change in morphology, soil types, and vegetation cover. Due to the lack of similar works in the neighbouring areas it was difficult to compare our results with any established threshold of the similar geo-environment. The threshold of the Himalayan region is to some extent comparable with our thresholds. The Himalaya initially needs high intensity of rainfall for landsliding (Dahal and Hasegawa, 2008) but lesser intensity than the global threshold when the rainfall duration exceeds 4 days even due to continuous monsoonal rainfall (Guzzetti et al., 2007). A similar work in Hong Kong (Lumb, 1975) for minor landslide events indicates that >50 mm of daily rainfall is required for landsliding if 15-day antecedent rainfall is >50 mm. This value is only comparable with our threshold for Section 1 with steep forested slopes. Due to the large variation in the thresholds, a proper examination of the terrain is needed before selecting an appropriate threshold for hazard specific work. Any attempt to use regionally-derived thresholds could lead to incorrect predictions.

In principle, each time the rainfall exceeds the threshold, it should trigger one or more landslides, but in reality this only happens with a probability ranging from 0.32 to 0.73 (Table 1). This means that other factors such as shear strength of the soil, topography, the saturation condition of the ground prior to the rise in the threshold curve, and successive periods of wet and dry days also influence and control the occurrence of landslides. The Poisson model is used to estimate the probability that one or more threshold will exceed in any year in a given rain gauge area. The exceeded threshold is expected to trigger shallow translational debris slides or flows on the cut slopes anywhere within the section around the rain gauge area. Thus, the specific location and also the size of landslides are not predicted by this model and this should be considered when interpreting the results for hazard or risk analysis. The Poisson model has been successfully tested for determining exceedance probability in spite of certain limitations and assumptions as discussed by Guzzetti et al. (2005). The assumptions such as that the mean recurrence of events will remain the same in the future as it was observed; the number of events that occur in disjoint time intervals are independent; and the probability of more than one event in a short time interval is negligible, should be considered when interpreting and using the results of the probability model.

The thresholds show high exceedance probability varying from 0.63 for the events that can cause more than 15 landslides to 0.97 for events resulting in one or more landslides. In spite of this high annual exceedance, landslides are only triggered in 32% to 73% of the cases when the threshold is exceeded. Thus, the temporal probability of occurrence of a rainfall that can trigger landslides in any given year from October to December varies from 0.27 to 0.49. The high annual exceedance of the thresholds agrees well with the incidences of landslides in the area. From the historical records it is evident that at lest one landslide occurs every year, but the relative temporal probability of experiencing one or more landslide events depends on the local terrain and its maximum is estimated as 0.49. In this study it is assumed that within a geographic unit the rainfall may not vary significantly and thus, the temporal probability is expected to be the same in a given unit.

7. Conclusions

We have proposed an approach to incorporate a threshold model for determining quantitative temporal probability of landslide initiation over an area. Our results form the basis for an improved assessment of landslide hazard. The model requires data on daily rainfall from a well-distributed network of rain gauges combined with the actual dates of landslide occurrences. This model may not be applicable if the exact dates of landslide incidences are not known or if the multi-temporal landslide inventory is prepared from remote sensing data where the age of landslides is relative to the date of acquisition of the data. For this study we prepared the multi-temporal landslide inventory from the railroad maintenance records (locally called railway slip register) and other technical reports which provided information on the absolute temporal and spatial distribution of the landslides. The model was also found applicable in other nearby areas with similar geo-environment conditions. The study illustrates the importance of the use of empirical minimum rainfall threshold models for the determination of temporal probability of landslide initiation over an area and the possibility of extending the results in the areas where data are incomplete such as road data in our case. It may be noted that this model is only applicable to shallow translational debris slides and flows associated with cut slopes and may not hold true for other landslides such as those on natural slopes and rock slides.

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