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Regional Rainfall and Hydrologic Thresholds for Landslide Occurrence. Examples from New Zealand and Central Italy

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Abstract

Rainfall is a common trigger of landslides, and various attempts have been made to establish functional or statistical relationships between some measure of rainfall and the occurrence of landslides, i.e., to define rainfall thresholds. These thresholds have a variety of applications, and are particularly important for civil protection decision making, for issuing alarm messages to alert endangered population against diffused mass movements. The paper reviews the concepts and methods for the definition of climatic thresholds for the initiation of landslides on regional scales, and summarizes the results obtained by Glade (1997, 1998, 2000) and Glade *et al.* (2000) for the Wellington region, North Island, New Zealand, and by Reichenbach *et al.* (1998) for Central Italy. Glade defined three different types of regional rainfall thresholds based on the *daily rainfall*, the *antecedent daily rainfall*, and the *antecedent soil water status* models. Reichenbach *et al.* (1998a) defined hydrologic thresholds for the Tiber River Basin based on the analysis of daily discharge measurements and on an historical catalogue of landslides and floods. Both approaches have the potential to be included in regional landslide warning systems.

1. Introduction

Rainfall induced landslides occur worldwide in different geologic, climatologic and physiographic environments. In spite that the main causes of landsliding and their principal effects have long been known, the functional relationships between landslides and precipitation are still poorly understood. Investigations on rainfall-induced landslides have fostered our understanding of the triggering mechanisms, but remains largely site-specific and focused mostly on geotechnical analysis or, alternatively, they have been too generalized to be effectively included in land-use management or civil defence policy making. Most commonly, the rainfall triggering conditions are not known with sufficient detail, chiefly because of the lack of rainfall measurements or information on landslide occurrence. Where climatic data are available, they may not have been recorded with sufficient accuracy, they may exhibit large recording gaps, or may be available only for very short periods. For remote regions experiencing abundant landslides, climatic data are seldom available Additionally, the exact timing of occurrence of landslides is difficult to obtain.

In this paper we will review the concepts and methods for the definition of climatic thresholds for the initiation of landslides, and we will summarize the results obtained by Glade (1997, 1998, 2000) and Glade *et al.* (2000) for the Northern Island of New Zealand, and by Reichenbach *et al.* (1998a) for the Tiber River Basin in Central Italy.

2. Landslide Thresholds

A threshold is the minimum or maximum level of some quantity needed for a process to take place or a state to change (White *et al.*, 1996, p. 14). A minimum threshold is the lowest level below which a process does not occur. A maximum threshold represents the level above which a process always occurs (Crozier, 1996). For rainfall-induced landslides a threshold may represent the minimum intensity or duration of rain, the minimum level of pore water pressure, the slope angle, the reduction of shear strength or the displacement required for a landslide to take place. Thresholds can also be defined for the antecedent hydrogeologic conditions, or the soil depth required for a landslide to occur (Reichenbach *et al.*, 1998a).

The evaluation of rainfall thresholds for landslides consists in some sort of statistical analysis of the relationship between rainfall and the occurrence of mass-movements (see: Caine, 1980; Govi & Sorzana, 1980; Moser & Hohensim, 1983; Wieczorek & Sarmiento, 1983; Brand *et al.*, 1984; Govi *et al.*, 1985; Cancelli & Nova, 1985; Cannon & Ellen, 1985; Crozier, 1986; Wieczorek, 1987; Kim *et al.*, 1991; Ceriani *et al.*, 1992; Page *et al.*, 1993; Pollloni *et al.*, 1992; Premchitt *et al.*, 1994; Pollloni *et al.*, 1996; Crozier, 1997; Glade, 1997; Crosta, 1998; Glade, 1998, 2000; Glade *et al.*, 2000; Reichenbach *et al.*, 1998a).

The approach requires accurate rainfall data and detailed information on the occurrence of landslides. Landslide occurrence is ascertained by compiling an inventory showing the location and time of occurrence of failures. Rainfall data should be collected from a sufficiently dense network of recording rain gauges. Where temporal and spatial information on landslides and rainfall is available, plots can be prepared and threshold curves can be fitted as lower bounds for the occurrence of landslides. The most commonly investigated rainfall parameters are: total ("cumulative") rainfall; antecedent ("pre-event") rainfall; rainfall intensity and duration.

Various combinations of these parameters have been attempted. Landslide thresholds were defined for rainfall intensity (Brand *et al.*, 1984); the duration/intensity ratio (Caine, 1980; Cancelli & Nova, 1985); the duration above a pre-defined intensity level (Wieczorek & Sarmiento, 1983); the cumulative rainfall in a given time (Govi *et al.*, 1985; Page *et al.*, 1993); the antecedent rainfall/daily rainfall ratio (Kim *et al.*, 1991); the event rainfall/yearly average rainfall ratio (Govi & Sorzana, 1980); and the daily rainfall/antecedent excess rainfall ratio (Crozier, 1986). Most of the proposed thresholds perform well in the region where they were developed but can not be exported to neighbouring areas (Crozier, 1997; Crosta, 1998). In addition, the temporal accuracy of the proposed thresholds remains largely unverified (Crozier, 1996).

Possibly, the best known rainfall threshold is that proposed by Caine (1980), who summarized the information available at the time and proposed a worldwide relationship between rainfall intensity and duration of landslide-triggering rainstorms. Although Caine's threshold is not valid for all regions in the world (Crozier, 1997), and it is not suited for deep-seated landslides or for landslides triggered by low-intensity rainfall events, it remains a milestone in the definition of rainfall thresholds for landslide initiation. Other rainfall intensity/duration thresholds have been proposed for the San Francisco Bay region (Cannon & Ellen, 1985; Wieczorek, 1987), for Carinthia (Moser & Hohensim, 1983), for the Southern Alps (Cancelli & Nova, 1985; Ceriani *et al.*, 1992; Polloni *et al.*, 1992; Crosta, 1994; 1998), for the Pre-Alpine regions of Northern Italy (Crosta 1994; 1998), and for the Piedmont region (Polloni *et al.*, 1996). Attempts were made to include probability measures into rainfall analysis. The approach, first proposed by Crozier & Eyles (1980) and by Crozier (1981), was recently enhanced by Glade (1997) who developed for the Wellington region of New Zealand rainfall thresholds based upon three distinct models.

A different approach to the definition of thresholds for the (temporal) occurrence of landslides is based on the analysis of runoff measurements and was proposed by Reichenbach *et al.* (1998a) for the Tiber River Basin in Central Italy. Runoff is the result of a complex interaction between rainfall, infiltration, percolation to the groundwater table, overland flow, interflow and channel flow occurring along the drainage network and on the slopes. Runoff measures the temporal and spatial response of a basin to a meteorological event (a "rainstorm") as well as the basin hydrological antecedent conditions.

Hence, it is possible to relate the variation in water level at a gauging station (discharge measurements) in a river basin to the occurrence of landslides and floods in the basin. Requirements for such analysis are: an inventory of landslides and floods (date and time of occurrence), and a record of runoff measurements.

3. Landslide-Triggering Rainfall Thresholds in New Zealand

In New Zealand extensive records of landslides and climatic conditions (i.e., rainfall and temperature) are available. These data were used to estimate different rainfall thresholds for landslide initiation, based on three different models of various complexities. Probabilities of landslide occurrence within a specific region and period of time can be associated with exceedence of given thresholds. A prerequisite in designing these models is that they were defined so that they can be transferred to other parts of the world, if the appropriate input data are available. Application in three different regions in New Zealand proved their potential for application in various regions (Glade, 1997). In this paper we review three different approaches and provide rainfall thresholds for the Wellington region, in the southern part of the North Island in New Zealand.

The study area is characterised by an average yearly rainfall of 1241 mm, occurring on an average of 196 rainy days. Maritime location and windiness ensures a relatively even distribution of temperature during the year, with mean daily temperatures of 16-18^{0}C in the Summer and of 7-9^{0}C in the Winter. Bedrock consists of alternating argillite and greywacke sandstone, Mesozoic in age. Soils are yellow-brown earths and related steep land soils; depressions are filled with colluvium. The area was deforested on European arrival in the mid 19th century and converted into pasture. Large farmland has been abandoned and is now covered with pioneer and regenerating vegetation. Topography is characterised by moderately steep to steep slopes, strongly dissected by fluvial cutting, mostly along fault lines. Since European arrival, landslides have been reported throughout the region.

3.1 Methods

Basic data required by each model is *daily* rainfall, temperature and date of landslide occurrence. Daily precipitation and temperature provided by the National Institute of Water and Atmosphere for 21 gauging stations were used within the Wellington region. Daily potential evapotranspiration was calculated using the Thornthwaite method (Thornthwaite, 1948; Thornthwaite & Mather 1955), which was originally developed for monthly values, but has been successfully applied in New Zealand for calculation of daily measures by Coulter (1973) and Toebes (1968).

As with any model, a few assumptions were made, namely:
- Maximum daily rainfall measured somewhere in the region was associated with the lowest evapotranspiration; and
- Landslides occurred in the region were triggered by the maximum (recorded) precipitation.

Type of landslides, magnitude and new vs. reactivated failures was not considered, due to the limited quality and quantity of information. Indeed, any historical landslide information is incomplete, however, no alternatives are available (Glade *et al.,* 1998).

In order to facilitate various demands by practitioners and data availability, three different landslides triggering rainfall threshold models were developed. The simple *Daily Rainfall* model is based on daily rainfall only, and relates landslide triggering rain days with none triggering rainy events (Glade, 1998). The strength of the model lays in its simplicity; the model can be easily applied in other regions. As a drawback, both antecedent conditions and soil moisture conditions are not considered.

To attempt to overcome this limitation, a more complex *Antecedent Daily Rainfall* model was developed, that considers the antecedent rainfall conditions. These are influenced by the length of the antecedent rainfall period, and a decay factor representing the rate of soil moisture decrease in a specific period of time. Calculation of antecedent conditions takes the form:

$$Pa_0 = P_1 + 2^{k_d} P_2 + 3^{k_d} P_3 + \ldots\ldots\ldots + n^{k_d} P_n$$

where, Pa_0 is antecedent daily precipitation for day 0 (mm), k_d is a constant representing the outflow of the regolith, and P_n is precipitation on the n^{th} day before day 0 (mm). For the Wellington region, 10 days were chosen as the length of antecedent rainfall period and the decay factor k_d was calculated as -1.57 (Glade *et al.*, 2000).

In the graphs showing distribution of landslide triggering and none-triggering rainfall events, two distinct boundaries can be identified. These are: the minimum probability threshold, below which landslides have never occurred; and the maximum probability thresholds, above which landslides have always occurred. These thresholds include the landslide probability range which is characterised by increasing probability associated with increasing rainfall "magnitude". Both thresholds rely heavily on the available data on past landslide occurrence. Statistical analysis was used to calculate probability thresholds for the *Antecedent Daily Rainfall* model, testing different (physically meaningful) combinations of daily rainfall magnitude and antecedent rainfall conditions that resulted in landslide occurrence. The residual deviance was determined for each combination. The most important criteria for deciding which statistical model best describes the relation between climatic conditions and landslide occurrence is the improvement of residual deviance in models of increasing complexity (see Glade *et al.,* 2000).

In addition to antecedent rainfall, potential evapotranspiration and soil moisture is particularly important in determining antecedent moisture at a given location. To account for evapotranspiration and soil moisture conditions, the *Antecedent Soil Water Status* model was developed by Crozier & Eyles (1980), and refined by Glade (2001). The model requires information on potential evapotranspiration and soil moisture parameters, on soil properties (texture, porosity, depth), and on precipitation and temperature. The daily interaction between these parameters is calculated using this model. The result is the probability of landslide occurrence for a given combination of daily rainfall magnitude and soil moisture, expressed as the soil water status index (Glade, 2000). This index includes both the Deficit Soil Moisture Storage (*DS*, in mm) below 0, and the Daily Excess Rainfall (*EP*, in mm), equal or greater than 0. The equation for *DS* is:

$$DS_0 = DS_1 - (P_0 - PE_0)$$

where, DS_0 is the deficit storage on day 0 (mm), DS_1 is the deficit storage for day one day before 0 (mm), P_0 is the rainfall on day 0 (mm), and PE_0 is the potential evapotranspiration for day 0 (mm).

Where DS_0 is 0 or greater, field capacity and the potential capillary storage of soil water are reached. Any additional water will be held in the soil as gravitational water. Consequently, negative values indicate available capillary soil storage. In the case that the deficit is equal to soil moisture capacity, the soil has dried out to wilting point. If soil capillary storage is recharged by a rainstorm water, any additional water is considered to be excess rainfall within this model. As a consequence, with any available excess rainfall, positive pore water pressure characterises the soil conditions and functions as a preparatory factor for landslide occurrence. The daily excess rainfall (*EP*) is expressed as:

$$EP_0 = (P_0 - PE_0) - DS_1$$

where, EP_0 is the excess rainfall on day 0 (mm).

The assumption of this equation is that excess rainfall drains rapidly through the soil, with no remaining water above field capacity from previous days. Although this assumption may be accepted for coarse textured soils on steep slopes, it does not represent realistically most soils consisting of finer grained particle sizes. Consequently it can be assumed that some of the excess rainfall remains within the soil as gravitational water. This might be stored at collection sites, such as convex terrain or bedrock hollows. Slope resistance is likely to be reduced by this available water through diminishing soil cohesion and developing positive pore water pressures. In addition, slope stability will be influenced by drainage of gravitational water through the soil continuing over a number of days. In recognition of these factors and to define preparatory conditions of probable landslide failure more accurately, Crozier & Eyles (1980) developed an antecedent excess rainfall index (*EPa*). This index has been further refined by Glade (1997) in the following form:

$$EPa_0 = EP_1 + 2^{k_d} EP_2 + ... + n^{k_d} EP_n$$

where: EPa_0 is the antecedent excess rainfall index on day 0 (mm), and EP_n is excess rainfall on the n[th] day before day 0 (mm).

Combinations of excess precipitation and daily rainfall calculated using the *Antecedent Soil Water Status* model give rectilinear probability thresholds. Model determination and establishment of thresholds are discussed by Glade (2000).

3.2 Results

In the analysis, daily rainfall and historical landslide data for the period 1862 to 1995 from the Wellington region were used. Results of all three models indicate that increasing total daily precipitation is associated with increasing probability of landslide occurrence. Consequently, the probability of landslide occurrence associated with a given rainfall magnitude increases to a maximum threshold, above which any rainfall magnitude has triggered landslides in the past.

For the *Daily Rainfall* model, precipitation values were grouped into 20 mm classes. An upper probability threshold of 140 mm and a lower threshold of 20 mm can be established (Figure 1). All past rainfall events above 140 mm have triggered landslides, while no single historical occurrence of landslides was recorded for precipitation below 20 mm.

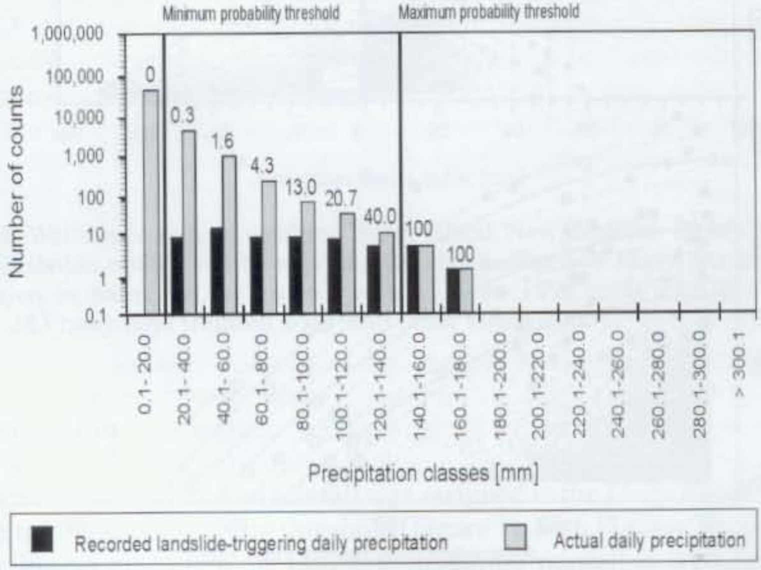

Figure 1. Wellington region, southern North Island, New Zealand. Rainfall probability thresholds established by applying the *Daily Rainfall* model. Calculation is based on the period from 1862 to 1995 with 48,514 observations/26,109 rainy days (rainfall ≥ 0.1mm) (after Glade, 1998).

Including antecedent rainfall conditions in the *Antecedent Daily Rainfall* model leads to Figure 2. Rainy days without landslides are marked as small dots, landslide-triggering rainfall as large dots, and probable landslide occurrence as open circles (see Glade *et al.,* 2000 for details). The exponential soil drainage decay factor k_d was calculated as -1.57. In Figure 2, 95% confidence intervals are shown for each probability threshold curve as dashed lines. The shape of the threshold line was calculated by fitting logistic regression models to the data using the method described above. The probability of occurrence for the Wellington region is given by:

$$\log\left(\frac{P_L}{1 - P_L}\right) = -8.07745 + 0.07215 * r + 0.00036 * r_a^2$$

where, P_L is probability of landslide occurrence at a given value of r and r_a, r is daily rainfall, and r_a is antecedent daily rainfall.

The probability thresholds based on a quadratic model show that the magnitude of daily precipitation is most important for days with little antecedent rainfall (i.e., antecedent dry period) (Figure 2). With increasing antecedent rainfall amount, the importance of triggering rainfall magnitude decreases and leads to conditions where only very low rainfall inputs are sufficient to trigger landslides. This suggests that soil moisture conditions should also be considered when looking at antecedent climatic conditions.

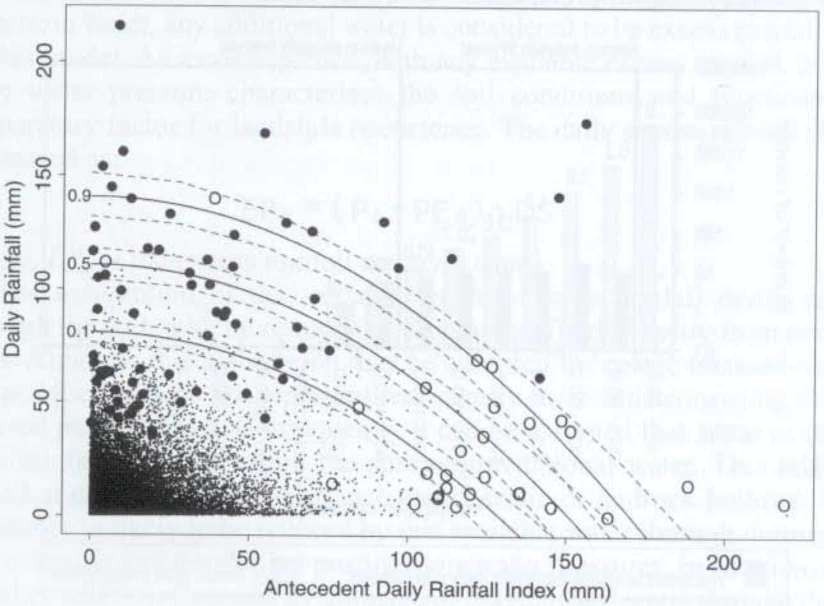

Figure 2. Wellington region, southern North Island, New Zealand. Rainfall probability thresholds established by applying the *Antecedent Daily Rainfall* model. Calculation is based on the period from 1862 to 1995 with 48,514 observations/26,109 rainy days (rainfall ≥ 0.1mm) (after Glade *et al.,* 2000).

Determination of the soil water content critical for slope failure was approached by Crozier & Eyles (1980) through the development of the *Antecedent Soil Water Status* model. Figure 3 indicates that landslides occurred only when field capacity was exceeded, i.e. when positive pore water pressures were reached. The rainfall magnitude of 140 mm and an excess rainfall of 55 mm define the upper probability threshold. Whenever this condition was met in the past, landslides have always occurred. The lower probability threshold is given by a rainfall magnitude of 9 mm and an antecedent excess rainfall of 10 mm (Figure 3). It is worth noticing that the value of each probability line refers to all data points above the respective threshold.

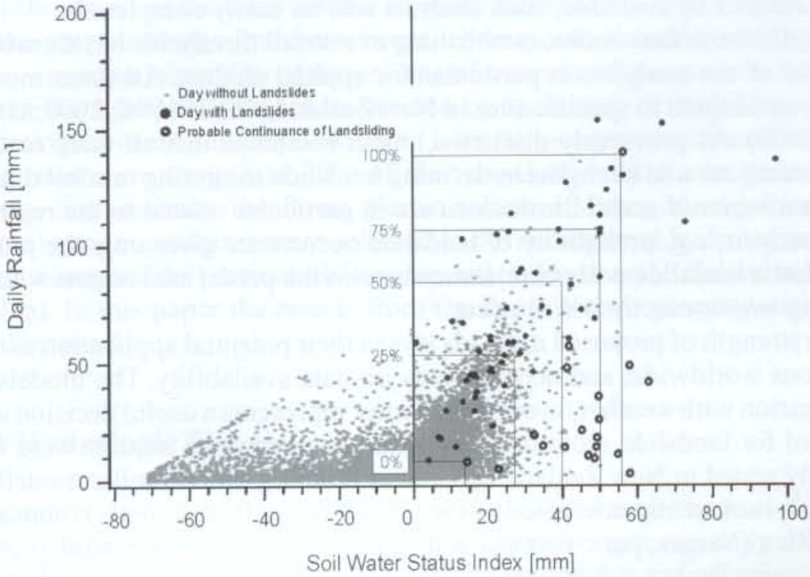

Figure 3. Wellington region, southern North Island, New Zealand. Rainfall probability thresholds established by applying the *Antecedent Soil Water Status* model. Calculation is based on the period from 1931 to 1995 with 23,376 observations/11,383 rainy days (rainfall ≥ 0.1mm) (after Glade 2000).

3.3 Discussion

Although the value of 20 mm rainfall was assigned in the *Daily Rainfall* model as the minimum probability threshold (Figure 1), both Figures 2 and 3 show that the lowest magnitude of landslide-triggering rainfall is well below 20 mm. The difference is due to recording problem of rainfall and in landslide occurrence (Glade, 1998). However, largest rainfall magnitudes associate correctly with recorded landslide occurrence and are of great interest to practitioners. Hence, general trends can be determined.

The established rainfall thresholds should be used with care, irrespective of which model is used. The basic assumption in the analysis is that triggering conditions are not influenced by natural changes or by landslide occurrence. Despite this assumption, research by Crozier (1999a) and Preston (1999) has demonstrated that a change of terrain characteristics over time influences the magnitude needed to initiate landslides on local scales. This change cannot yet be integrated into the model assumptions, representing a problem for any frequency/magnitude relationship (Crozier & Glade, 1999). Due to the lack of more detailed historical data, it is not yet possible to differentiate "landslide occurrence" by landslide type, landslide activity (new vs. reactivated failures), and landslide magnitude. When more detailed landslide data will be available, such analysis will be easily completed.

Despite these drawbacks, establishing of rainfall thresholds has shown the potential of the analysis, in particular for applied studies. All three models have been adopted to specific sites in New Zealand (Glade 1998, 2000; Glade *et al.* 2000). As previously discussed, it can be shown that all three models have limitations and strengths in defining landslide triggering rainfall thresholds on a *regional* scale. Limitations are in particular related to the regional scale analysis, e.g. probability of landslide occurrence gives only the probability that a landslide will occur somewhere in the predefined region without knowing *where* exactly it will occur.

The strength of proposed methods lays in their potential application to other regions worldwide, and depends only on data availability. The models, in combination with weather forecast scenarios, represents a useful decision support tool for landslide monitoring systems. The proposed models were successfully tested in New Zealand by Crozier (1999b), and a similar modelling approach is currently attempted in the United States (Godt , pers. comm.), in Costa Rica (Vargas, pers. comm.) and in Italy (Aleotti , pers. comm.).

4. Hydrologic Thresholds for Landslides and Floods in Central Italy

In the Tiber River Basin of Central Italy an attempt was made to use historical information on landslides and floods, coupled with daily discharge measurement at several gauging stations, to define regional hydrologic thresholds for the occurrence of landslides and floods (Reichenbach *et al.*, 1998a).

4.1 Input Data

The Tiber River basin has a history of landslides and floods going back to Etruscan and Roman ages. Historical investigations have shown that in the 20^{th} century at least 1495 landslide events occurred at 936 sites, and 1051 flooding events occurred at 388 different localities (Reichenbach *et al.*, 1998b). This historical catalogue of landslides and floods is quite certainly affected by recording problems, related to the human perception of hydrologic catastrophes, and the historical record reflects only the minimum number of events that actually occurred. For about 1/3 of all reported landslides (560) and 95% of all reported floods (1005) the date of the event is known.

Mean daily discharge measurements for 27 gauging stations in the Tiber River were available from the Servizio Idrografico Nazionale. Seven gauging stations were preliminary selected for the analysis. For each of these 7 stations the frequency distributions of mean daily discharge and daily discharge volume were computed. Inspection of the cumulative curves revealed that about half of the total volume of water has flown in approximately 80% of the entire record of measurements, corresponding to days of low water flow. The remaining 50% of the volume of water has flown in a limited number of days (about 20%), characterized by sustained, or high flow. Hence, hydrologic events possibly associated with the occurrence of landslides and inundations are limited to 20% of the record of daily discharge measurements. Successively, the Ponte Nuovo (south of Perugia) and Ripetta (in Rome) gauging stations were selected to define regional hydrologic thresholds because of the particularly long record ($\geq$ 55 years) (Reichenbach *et al.*, 1998a). In this paper the results from the Ponte Nuovo gauging station will be discussed.

4.2 Hydrologic Events

To establish hydrologic thresholds based on historical data, "hydrologic events " were defined as a series of consecutive days having mean daily discharge exceeding a defined value. At each gauging station this cut off value was selected equal to 80% of the cumulative frequency distribution of mean daily discharge, corresponding to about half of the total volume of water discharged by the Tiber River. For the Ponte Nuovo gauging station the selected cut off value was 100 $m^3 sec^{-1}$. For each hydrologic event, identified by systematically searching the record of daily runoff, a set of hydrologic parameters were measured, namely:

- the maximum value of mean daily discharge ($m^3 sec^{-1}$);
- the estimated total flood volume (10^6 m^3);
- the event duration (in days); and
- the event intensity (in $m^3 sec^{-1} km^{-2}$), computed dividing the average value of the event daily discharge by the basin area (4147 km^2).

These parameters reveal different aspects of each hydrologic event. The maximum mean daily discharge (a measure of peak water flow) and the estimated flood volume (a measure of the total amount of water) allow for ranking the events according to their "magnitude". The duration and intensity provide information on the geographical extent of the event. In general, severe events lasted for several days, extended over the entire basin and were characterized by large flood volumes and moderate to high daily runoff.

For each hydrologic event, the number and location of all landslides and inundations known to have occurred were counted. Catastrophic events (for which both landslides and inundations are reported) exhibit larger values of maximum mean daily discharge, flood volume, event duration and event intensity than the events for which no information is available in the historical catalogue. In general, long-lasting and severe hydrologic events were associated to a greater occurrence of landslides and inundations.

At the Ponte Nuovo gauging station, for the 65 years between 1925 and 1990, 642 hydrologic events were identified. This is an average of 11.7 events per year. For 84 events the historical catalogue reports information on landslides and/or floods. This is an average of 1.5 catastrophic events per year. For the majority of these events (52%) only floods are reported. For the remaining events, 27% have historical information on landslides, and 21% on both landslides and floods. About half (45%) of the events that lasted for 10 days or more caused landslides or floods in the basin. The frequency of catastrophic events decreases for shorter events. About 90% of the events for which nothing is reported exhibits a maximum mean daily discharge of less than about 450 m^3sec^{-1}, an estimated flood volume of less than 125 millions cubic meters, and an event intensity of less than 0.06 $m^3sec^{-1}km^{-2}$. For the same runoff 25% of inundations and 40% of landslides are reported. For a similar flood volume 40% of landslides and 40% of inundations, and for the same intensity 50% of landslides and 30% of inundations are reported in the historical catalogue.

4.3 Regional Hydrologic Thresholds

The analysis of the frequency distributions of the maximum mean daily discharge, the total flood volume, and the event intensity were used to define regional hydrologic thresholds for the occurrence of landslides or floods upstream of the Ponte Nuovo gauging station. The relationship between the event estimated flood volume and the corresponding maximum mean daily discharge (Figure 4) reveals that the most damaging events, i.e., those for which both landslides and inundations were reported, are located in the upper right section of the diagram, where hydrologic conditions (water level and flood volume) are more severe. Horizontal dashed line, at about 450 m^3sec^{-1}, represent the 90% threshold for the events for which no information is reported in the historical catalogue. In other words, only 10% of the events for which no information is available exceeds this threshold. The vertical dashed line represent the 90% threshold for the event estimated flood volume. In this case, only 10% of the events that exceeded the given threshold did not generate landslides or floods. Similar considerations can be made for the relationship between the event maximum mean daily discharge and the corresponding intensity (Figure 5).

Thick lines in Figures 4 and 5 are empirical (heuristic) regional hydrologic thresholds, separating hydrologic conditions that, based on the available historical information, are more (or less) prone to the occurrence of landslides or floods. The "upper" thresholds (thick lines) correspond to regional "maximum" thresholds, whereas the "lower" thresholds (thin lines) are higher than the "minimum" regional thresholds. At Ponte Nuovo the most damaging events (black squares) are all located in the higher probability zone (above the "upper" threshold), where water level is higher and flood volume is larger. In the same area few open dots are also present. They represent events for which no information on landslides or inundations is reported. These events occurred in the decade 1940-1950 when the quality of the historical catalogue is poor.

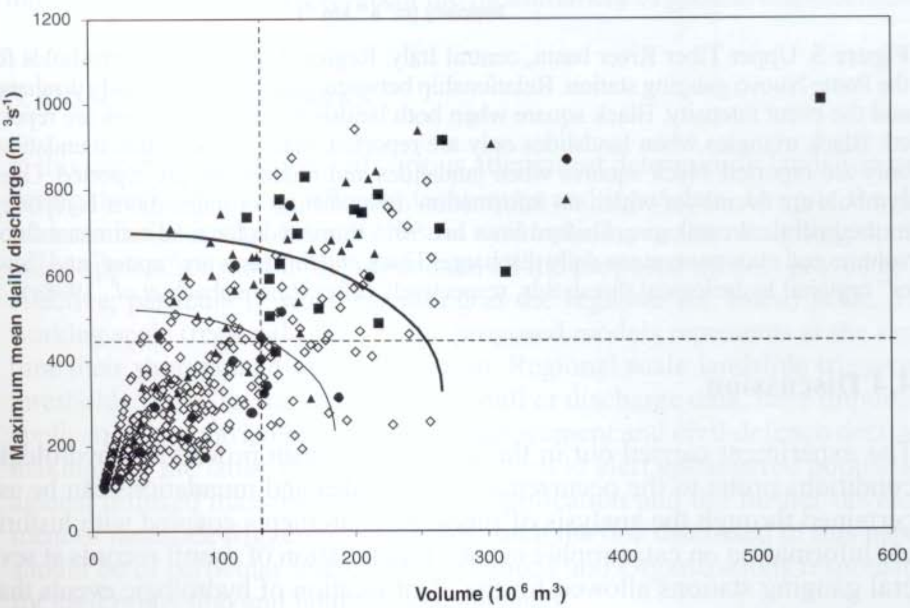

Figure 4. Upper Tiber River basin, central Italy. Regional hydrological thresholds for the Ponte Nuovo gauging station. Relationship between maximum mean daily discharge and total estimated flood volume. Black triangles when landslides only are reported, black circles when inundations only are reported, black squares when landslides and inundations are reported. Open symbols are events for which no information on landslides or inundations is reported in the historical catalogue. Dashed lines are 90% thresholds for total estimated flood volume and maximum mean daily discharge. Thick and thin lines are "upper" and "lower" regional hydrological thresholds, respectively (after Reichenbach *et al.*, 1998a).

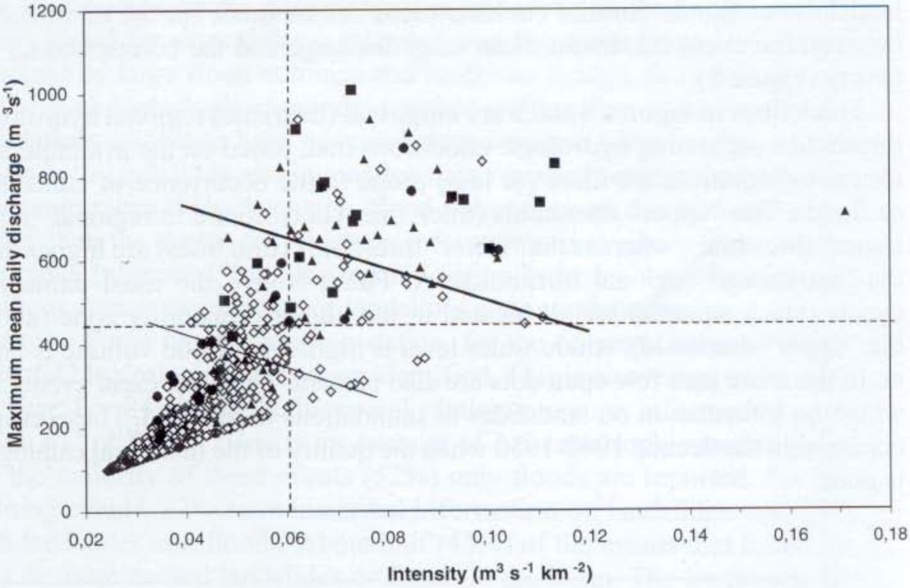

Figure 5. Upper Tiber River basin, central Italy. Regional hydrological thresholds for the Ponte Nuovo gauging station. Relationship between maximum mean daily discharge and the event intensity. Black square when both landslides and inundations are reported. Black triangles when landslides only are reported, black circles when inundations only are reported, black squares when landslides and inundations are reported. Open symbols are events for which no information on landslides or inundations is reported in the historical catalogue. Dashed lines are 90% thresholds for total estimated flood volume and maximum mean daily discharge. Thick and thin lines are "upper" and "lower" regional hydrological thresholds, respectively (after Reichenbach *et al.*, 1998a).

4.4 Discussion

The experiment carried out in the Tiber River basin proved that hydrologic conditions prone to the occurrence of landslides and inundations can be ascertained through the analysis of runoff measurements coupled with historical information on catastrophic events. Examination of runoff records at several gauging stations allowed for the identification of hydrologic events that were ranked according to maximum mean daily discharge, estimated flood volume and event intensity. These parameters, expressing different hydrologic characteristics, allowed for the statistical definition of regional, heuristic thresholds for the occurrence of landslides and floods. Such thresholds can be used to issue regional warnings and may be helpful in planning civil protection policies. A detailed analysis of the benefits and drawbacks of these thresholds is given by Reichebach *et al.* (1998a).

The definition of hydrologic thresholds has conceptual and operational advantages over rainfall thresholds. Ideally, they better conform to the rather complex physical processes involved in the occurrence of inundations and landslides. Operationally, they maximize the information content of historical data on natural catastrophes, and they prove effective where rainfall and geotechnical data are not available with the adequate resolution. Limitations are due to the availability, quality and accuracy of the historical records, as well as to geomorphological and physiographical constraints. The approach works only for catchments where the drainage network reflects the hydrologic behaviour of the territory. It cannot be applied where runoff is episodic and peak water levels are difficult to measure, where catchment are underlain by highly permeable rocks, or where the natural water flow is artificially controlled.

Further limitations refer to the assumption that all environmental variables controlling runoff remain constant. Significant changes in runoff due to the build up of reservoirs, the change in land-use practice (clear-cutting, reforestation, etc.), or an intense urbanisation may limit the definition and reliability of hydrologic thresholds. Lastly, the spatial resolution of hydrologic thresholds is lower than that of warning thresholds based on the analysis of rainfall data, the monitoring of piezometric levels or the measurement of ground displacements.

5. Concluding Remarks

In this paper have summarised various attempts at determining landslide triggering thresholds using different techniques and input data. Despite the differences in the model framework and assumptions, in the modelling operational application, and in the input data, all the proposed models proved to be effective, particularly when operating at the regional (or basin) scale. The working scale (regional scale) of the proposed models represents at the same time their strength and major limitation. Regional scale landslide triggering thresholds, based on the analysis of rainfall or discharge data, have important applications for agriculture, land-use management and civil defence decision making. For the latter, thresholds can be used to alert endangered population against diffused mass movements. The application and the further development of landslide triggering thresholds, such the one discussed in this paper, should be of particular interest to Institutions and Organizations responsible for civil protection and land-use management.

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