Mediterranean Storms
(Proceedings of the EGS Plinius Conference held at Maratea, Italy, October 1999)

A review of rainfall thresholds for triggering landslides

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ABSTRACT

The identification of regional rainfall thresholds for triggering shallow landslides represents in the broadest sense a statistical approximation of minimum rainfall conditions for triggering landslides for a particular mix of regional geologic, hydrologic, and topographic variables. With recent improvements of remote real-time rainfall measurement and digital techniques for accurately depicting the topography and modeling the hydrologic response, rainfall thresholds could become more useful for identifying not only the time, but the specific locations of potentially damaging shallow landslides during intense rainfall.

1 INTRODUCTION

The concept of rainfall thresholds as presented by Caine (1980) built upon earlier recognition by Campbell (1975) of the relationship of high intensity rainfall in the triggering of shallow landslides and by Starkel (1979) who theorized a critical rainfall which was a combination of rainfall intensity and duration. Campbell postulated that infiltration of intense rainfall created temporarily perched aquifers with positive pore water pressures that reduced the effective strength of surface soils and initiated the landsliding. Caine (1980) utilized published data from 73 worldwide examples where rainfall intensity and duration had been measured in association with the triggering of shallow landslides to develop a minimum rainfall intensity-duration threshold for debris flows.

2 IDENTIFICATION AND APPLICATION OF THRESHOLDS

Rainfall thresholds for triggering shallow landslides have been identified in many specific regions and in a few cases thresholds have become the basis for landslide warning systems. Near La Honda, in a part of the San Francisco Bay region, California,, Wieczorek (1987) identified a threshold for the triggering of a single shallow landslide within a relatively small (10 km^2) area very prone to landsliding. The storm of January 3-5, 1982, triggered abundant landslides in many areas throughout the San Francisco Bay region, with more than 30 debris flows per square kilometer (Wieczorek et al., 1988). Cannon and Ellen (1985) used hourly records from recording gages and known times of nearby debris flows from this storm to derive rainfall intensity-duration thresholds for the abundant triggering of landslides. Not surprisingly, the thresholds of Caine (1980), Cannon and Ellen (1985) and Wieczorek (1987) are distinctly different due to the data sources and varying geologic settings. Within the San Francisco Bay region, Cannon and Ellen (1985) found that areas with high mean average precipitation (MAP) and low mean average precipitation had different thresholds for triggering landslides. Within the United States, rainfall thresholds have also been identified in Puerto Rico (Jibson, 1989) and Hawaii (Wilson et.al., 1992) (fig. 1).

Rainfall intensity-duration thresholds for triggering of landslides have been widely identified in many different climates and geologic settings. For example, De Vita and Reichenbach et. al (1998) compiled a recent summary of the literature on the subject of rainfall triggered landslides. In Italy, Govi and Sorzana, (1980), Cancelli and Nova (1985), and Crosta (1998) identified a series of thresholds for regions. The regional variation in these thresholds suggests that many factors may be responsible for the differences, particularly soil permeability and thickness.

A similar threshold has been found for an area that is subject to exceptionally intense storms, including hurricanes, in the Blue Ridge of central Virginia. A preliminary rainfall intensity-duration threshold was identified for storms capable of triggering debris flows. This threshold (curve BR in fig. 1) indicates that sustained intensities of 70 mm/hr for 2 hours, 50 mm/hr for 4 hours, 40 mm/hr for 6 hours, and 25 mm/hr for 12 hours, are sufficient to trigger debris flows in the colluvial soils developed from granitic rocks of the Blue Ridge of central Virginia. This exceptionally high range of intensities and durations of rainfall may be met by a variety of storms, including short, but intense convective storms and hurricanes. The threshold in this temperate forest of mixed hardwoods of the Blue Ridge of central Virginia is the highest recognized (fig. 1), exceeding those of tropical, humid environments of Puerto Rico and Hawaii. The threshold for the Blue Ridge greatly exceeds that of the high MAP parts of the San Francisco Bay region (Cannon and Ellen, 1985), an area with a strongly seasonal Mediterranean climate. All of these regions have steep slopes with soils susceptible to debris flows during intense rainfall.

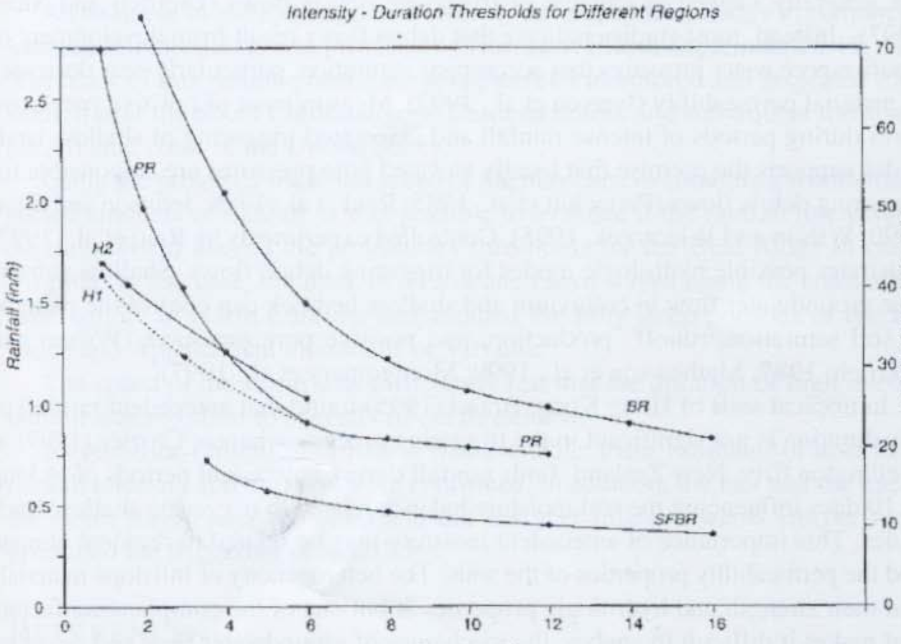

Figure 1 - Comparison of debris-flow thresholds within the United States. A) Debris-flow thresholds for Blue-Ridge (BR), Hawaii (H1, H2) (Wilson et al., 1992), in areas of high mean annual precipitation (high MAP) with the San Francisco Bay region (SFBR) (Cannon and Ellen, 1985); and Puerto Rico (PR) (Jibson, 1989)

Real-time rainfall data compared with rainfall thresholds can be incorporated into a landslide warning system, such as operates in Hong Kong (Brand, 1995; Hansen, 1995). In Hong Kong a system of about 50 automatic raingages monitors rainfall during real time and provides information on critical rainfall to civil defense authorities. A real-time landslide warning system which operated in the San Francisco Bay region, California used a real-time rainfall monitoring system and National Weather Service satellite based quantitative rainfall forecasts in comparison with rainfall thresholds for issuing landslide warnings (Wilson et al., 1993). As a verification of the thresholds of Cannon and Ellen (1985), the times of landslide warnings in the storms of February 1986 were found to correspond well with documented times of failures (Keefer et al., 1987).

3 PHYSICAL SIGNIFICANCE OF RAINFALL THRESHOLDS

Although triggering of shallow landslides by intense rainfall has been widely observed, the processes by which this occurs can be complex and have been widely discussed (Johnson and Sitar, 1990; Iverson et al., 1997). Rainfall infiltration under unsaturated conditions may reduce soil moisture suction, however, this process is not generally viewed as capable of triggering debris flows (Dietrich and Sitar, 1997). Instead, most studies indicate that debris flows result from development of positive pore water pressures that accompany saturation, particularly near decreases in material permeability (Iverson et al., 1997). Measurement of positive pore pressures during periods of intense rainfall and associated triggering of shallow landslides supports the premise that locally elevated pore pressures are responsible for triggering debris flows (Premchitt et al., 1985; Reid et al., 1988; Johnson and Sitar, 1990; Wilson and Wieczorek, 1995). Controlled experiments by Reid et al. (1997) illustrates possible hydrologic modes for triggering debris flows. Shallow subsurface groundwater flow in colluvium and shallow bedrock can control the patterns of soil saturation, runoff production, and positive pore pressures (Wilson and Dietrich, 1987; Mathewson et al., 1990; Montgomery et al., 1997).

In tropical soils of Hong Kong, Brand (1995) found that antecedent rainfall of any duration is not significant in the triggering process, whereas Crozier (1999) in Wellington City, New Zealand, finds rainfall during antecedent periods of as long as 10 days influencing the soil moisture balance related to triggering shallow landslides. This importance of antecedent moisture may be related to regional climate and the permeability properties of the soils. The heterogeneity of hillslope materials and their strength and hydrologic properties is but one of the complicating factors that makes it difficult to analyze the mechanics of groundwater flow and development of instability with simple stability models. Macropores created by borrowing animals for example, can introduce abundant water into the subsurface and dramatically increase pore water pressures (Pierson, 1983). Surface topography and geologic heterogeneity can generate areas of increased pore pressure (Pierson, 1980; Montgomery et al., 1997) .

4 UTILIZATION OF RAINFALL THRESHOLDS USING REMOTE SENSING

The development of recent remote sensing techniques make rainfall thresholds more useful for landslide hazard warning. The quantification of rainfall estimates using Doppler Radar can provide a continuous near-real-time comparison with rainfall thresholds to form the basis of landslide warnings. A compilation of rainfall estimates at 6-minute intervals based on cloud reflectivity from Doppler radar was utilized for analyzing the rainfall intensity-duration characteristics for debris flows in Madison County, Virginia (Smith et al., 1996). The fact that the radar-based rainfall data can be spatially refined to a 1-km pixel spacing suggests the possibility of landslide warnings that utilize near-real-time rainfall estimates in combination with topographic and other spatial data.

Montgomery and Dietrich (1994) and Borga et al. (1998) using digital elevation developed models for evaluating stability for shallow landsliding in terms of expected daily rainfall, which provide a spatial refinement to the application of rainfall thresholds.

An example of the application of recently developed technology in conjunction with rainfall thresholds was provided by Hurricane Floyd, September 15-19, 1999. The track of this Atlantic hurricane was carefully monitored and projected for its landfall near the South Carolina/North Carolina border and subsequent traverse up the Atlantic coast of the United States.

Using the projected track and speed of the hurricane in combination with the expected amounts of rainfall, it was possible to evaluate if the rainfall intensity and duration would exceed the preliminary thresholds for the Blue Ridge of central Virginia. In this case, the track of Hurricane Floyd stayed along the coast after it came ashore in North Carolina and avoided the hilly steep portions of the Blue Ridge and Appalachian mountains of Virginia.

The speed of the storm was sufficiently fast that the duration of high intensity rainfall was too short to exceed critical thresholds.

As real-time rainfall information was available, these estimates of insufficient rainfall intensity and duration were confirmed; in addition, the fact that the track of the storm stayed near the coast and did not veer inland towards steeper terrain precluded the triggering of landslides.

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