Climatic variations in rainfall thresholds for debris-flow activity

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ABSTRACT

Comparisons of the rainfall amounts required to initiate hazardous debris-flow activity in different parts of the world, suggest that the long-term precipitation climate has an important influence on these threshold levels. While it has been proposed that rainfall/debris-flow thresholds are proportional to mean annual precipitation (MAP), this relationship may not hold for widely separated points. The rainfall frequency, measured as the annual number of rain days (#RDs), is also an essential parameter. For normalization between climates where both MAP and #RDs vary significantly, thresholds may best be described in terms of the frequency of recurrence. Along the U. S. Pacific coast, recurrence may be described in terms of the rainy-day normal, RDN = MAP/#RDs, but a more general scheme may be needed for other regions of the world. A new normalization parameter is proposed, based on the estimated rainfall for a "reference storm" with a return period long enough to filter out the frequent, small rainfall events that dominate the MAP, yet short enough to estimate from a few decades of rainfall data. From an analysis of rainfall and debris-flow data from the U. S. Pacific coast, Hawaii and Puerto Rico, a return-period of 5 years appears optimal for the reference storm, with a lower-bound of approximately 4/3 of the reference rainfall as the threshold value.

1 INTRODUCTION

Real-time warning systems can play a significant role in debris-flow hazard mitigation by alerting the public when rainfall conditions reach critical levels for hazardous debris-flow activity. Such warning systems depend on comparing forecasts and real-time rainfall observations to threshold values required to initiate debris flows (Keefer and others, 1987). Empirically derived from historical data on rainfall and debris-flow occurrence, thresholds are combined values of rainfall intensity and duration that predict debris-flow initiation at susceptible sites within a specified area, generally a few tens of square kilometers. By normalizing for local orographic variations, rainfall/debris-flow thresholds have been extended to an area of as much as 20,000 sq. km in the San Francisco Bay region (Wilson and others, 1993).

In many parts of the world, however, the severe rainstorms that trigger debris flows are produced by vast continental and oceanic weather systems that may extend thousands of kilometers. These storms may trigger floods and debris flows in widely separated areas within a brief time period. If rainfall/debris-flow thresholds could be adjusted for regional variations in geologic, hydrologic, and climatic conditions, then debris-flow warning systems could operate on a much larger scale, similar to that of the storm systems (Wilson, 1997b).

2 THE CLIMATIC APPROACH TO RAINFALL/DEBRIS-FLOW THRESHOLDS

The development of rainfall threshold levels for debris-flow activity may be pursued in several ways, depending on the desired application and the technical background of the person making the attempt. The chart in figure 1 describes three of the many possible approaches in terms of the perspectives of three technical disciplines involved in debris-flow research. The geotechnical approach focuses on the material properties of the hillslope materials (friction, cohesion, density) and the geometry of the hillslope deposit (slope steepness, thickness). The result of the geotechnical analysis is usually expressed as the "factor of safety" which is the ratio of driving to resisting forces within the slope, particularly under conditions of full saturation. The hydrological approach, by contrast, focuses on the hydrological properties of the hillslope, principally the permeability of the slope materials, expressed either as hydraulic conductivity or, taking the thickness of surficial deposits into account, transmissivity. Finally, the climatological approach seeks to account for the interaction of the hillslope with the precipitation that triggers debris-flows, in the context of the long-term precipitation climate. The climatological approach is the focus of this paper.

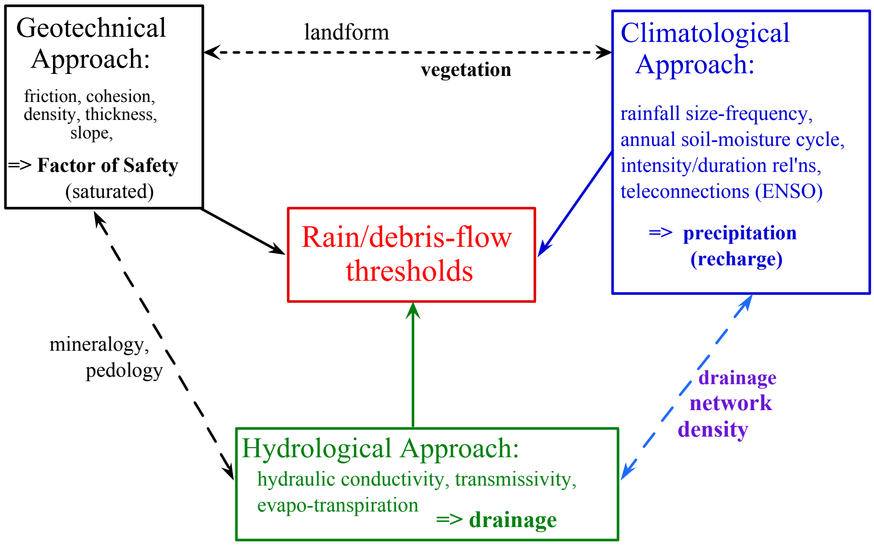

Figure 1: Diagram of three approaches to investigating the relation between rainfall and debris-flow occurrence.

Because it is not obvious that either the geotechnical or the hydrological properties of the slope materials are directly influenced by climate, neither the geotechnical nor the hydrological approaches devote much attention to climatic factors. The working assumption of the climatological approach, however, is that over a period of time (decades to centuries), the landscape equilibrates itself to the long-term precipitation climate, such that under "normal" conditions, the hillslope can balance infiltration with evapo-transpiration and surface runoff, while maintaining gravitational stability. Abnormally dry conditions for an extended period (drought) may result in zero runoff and soil moisture dropping below the "wilt limit". Abnormally wet conditions may result in over-saturation, leading ultimately to flash flooding and slope failure as debris flows and landslides.

The process of equilibration may encompass a number of mechanisms, known and unknown. Adjustments in the variety and abundance of hillslope vegetation may raise or lower the evapo-transpiration rates with consequent decrease or increase (respectively) in the soil moisture. Adjustments in vegetation might also increase or lower the strength and abundance of root fibers within the hillslope soils, with consequent changes in the (apparent) cohesion factor of the soil shear strength. Because hillslope soils are often thin (a few meters) and occupy slopes near the angle of friction, even a small change in cohesion can greatly affect the slope stability. The equilibration of the hillslope vegetation to the long-term precipitation climate could take place over a period of several decades to a few centuries.

The surface drainage network provides another possible equilibration mechanism. Under intense rainfall, the hillslope regolith begins to saturate and the drainage becomes dominated by shallow throughflow delivered to a network of ephemeral surface channels. Under these conditions, the drainage rate will be linked to the steepness of the hillslope, the thickness and permeability of the regolith, and the geometry of the channel network. Over time (centuries to millennia), the drainage density (total channel length divided by watershed area) equilibrates itself to the transmissivity of the regolith and the frequency of storms with sufficient rainfall to saturate the hillslope. In his empirical study of the relation between stream discharge and physiography, for example, Carlston (1963) found a strong correlation between the square of the drainage density and the mean annual flood runoff in 15 basins in the eastern United States.

2.1 Evidence for Climatic Variations in Rain/Debris-Flow Thresholds

That rainfall thresholds for debris-flow activity actually do vary widely between areas with different long-term precipitation climates may be demonstrated fairly easily. Figure 2 shows size-frequency plots of daily rainfall for two rain gauges on the Pacific Coast of the United States: (1) Bonneville Dam, on the Oregon shore of the Columbia River in the Pacific Northwest, and Big Tujunga, in the San Gabriel Mountains north of Los Angeles in southern California. Daily rainfall in millimeters (mm) is plotted against the expected frequency of occurrence (events/century), based on at least 30 years of record. (All rainfall data is from the National Climate Data Center, Ashville, North Carolina, USA.) The daily rainfall from two storms which triggered debris-flow activity that caused significant property damage and loss of life are also indicated on the plots--February 9, 1978 for Big Tujunga, and February 8, 1996 for Bonneville Dam.

These two debris-flow-producing storms have roughly the same frequency of occurrence, approximately 2 events/century, but the daily rainfall for Big Tujunga, 274 mm greatly exceeds that for Bonneville Dam, 139 mm. A climate-independent threshold that fit Bonneville Dam, therefore, would predict a frequency of significant debris-flow activity at Big Tujunga of at least 30 events/century, much higher than that observed in historic times (roughly 3-6 events/century). Conversely, a threshold fitting Big Tujunga, would be virtually impossible at Bonneville Dam (< 1 event/10,000 years), and would certainly far exceed the rainfall that produced significant debris-flow activity during the February, 1996 storm.

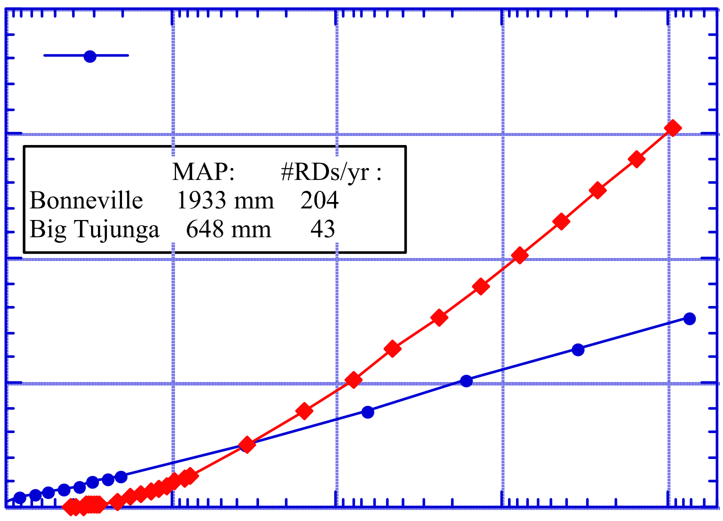

Figure 2: Plot of daily rainfall amount versus frequency of occurrence for two stations with different climatic conditions.

Another noteworthy aspect of this comparison is that the rain gauge with the higher daily rainfall amount for triggering debris flows, Big Tujunga, has a much lower MAP, 648 mm, than the gauge with the smaller threshold amount, Bonneville Dam, where MAP = 1933 mm. In light of the number of papers in which rainfall/debris-flow thresholds are normalized to MAP, this is rather surprising. A possible explanation is that the MAP reflects the total sum of rainfall, divided by the years of record, and is therefore influenced by the number as well as the size of the rain storms. The rainfall frequency at Bonneville Dam, 204 days/year, is much greater than that at Big Tujunga, 43 days/year. The greater frequency at Bonneville Dam more than makes up for the smaller size of the largest storms in the distribution. Rainfall days are much less frequent at Big Tujunga, but the individual rainstorms that do occur can be quite intense, so that large storms (> 50 mm) are more frequent than at

Bonneville Dam. The rainfall/debris-flow thresholds appear to be more strongly influenced by the size of the exceptional rain storms (several events/century) than by the aggregate sum represented by the MAP.

2.2 Climatic Effects on Local and Regional Scales

Precipitation climate variations may occur on both local (< 100 km) and regional (> 500 km) scales, although the mechanisms of variation may differ. Orographic effects, caused by the interaction of weather systems with mountain ranges, are among the most important source of local variations in the long-term precipitation climate. As a weather system encounters higher elevations, moist air is forced to rise along with the local ground surface, perhaps hundreds or thousands of meters vertically, within a few tens of kilometers of lateral movement. This abrupt rise in elevation subjects the air mass to adiabatic cooling, causing increased precipitation, so that on a long-term average, higher precipitation occurs at higher elevation on the windward sides of topographic highs. On the leeward side of the mountain range, however, storm rainfall is quickly depleted by the rain shadow effect. As storm systems pass over the crest and descend the leeward flank of the range, they begin to lose elevation and undergo adiabatic warming; thus markedly decreasing condensation and precipitation. The long-term result is a significantly lower MAP on the leeward flank of the range.

On the central California coast, for example, the Santa Cruz Mountains, up to 1200 m high, form the backbone of the San Francisco Peninsula. Along the coastline, the MAP is approximately 500 mm, but rises to over 1000 mm along the highest ridges, then falls to as little as 350 mm along the shore of San Francisco Bay, in the lee of the range. The rainfall frequency along the coastline averages 86 days/year, stays nearly constant up to the ridgecrest, but is then reduced to as few as 65 days/year along the leeward lowlands. These changes in elevation, MAP, and #RDs take place within a lateral distance of only 25-30 km.

On a larger, regional scale, interactions with very large (>1 million sq. km.), perennial features of the atmospheric circulation may also produce important climatic variations. The coastal areas along the Pacific coast of the North America, for example, receive virtually all of their precipitation from Pacific frontal systems during the winter months. These frontal systems are related to a constellation of perennial features of the atmospheric circulation over the North Pacific Ocean. An area of low pressure (the Aleutian Low) is generally centered southwestward of Alaska. An area of high pressure (the East Pacific High) is usually located off the Pacific coasts of Mexico and Central America. These long-term barometric features are superimposed on the global zonal atmospheric circulation, which produces a zone of eastward flowing air (westerlies) in the mid-latitudes.

This circulation system generates and channels marine cyclonic systems along a broad, but well-defined storm track, which stretches from south of Japan across the North Pacific toward British Columbia. This storm track, which may be seen clearly on charts of oceanic precipitation measured by microwave scattering from polar-orbiting satellites (Spencer, 1993), produces a general decrease in the amount of precipitation southward along the US Pacific coast from Canada to Mexico. This decrease takes the form of a marked decrease in the storm frequency southward from ~225 days/year in the Pacific Northwest to ~50 days/year in southern California (fig. 3). In fact, much of the discrepancy in rainfall/debris-flow thresholds versus MAP shown in fig. 2 can be explained by this decrease in storm frequency.

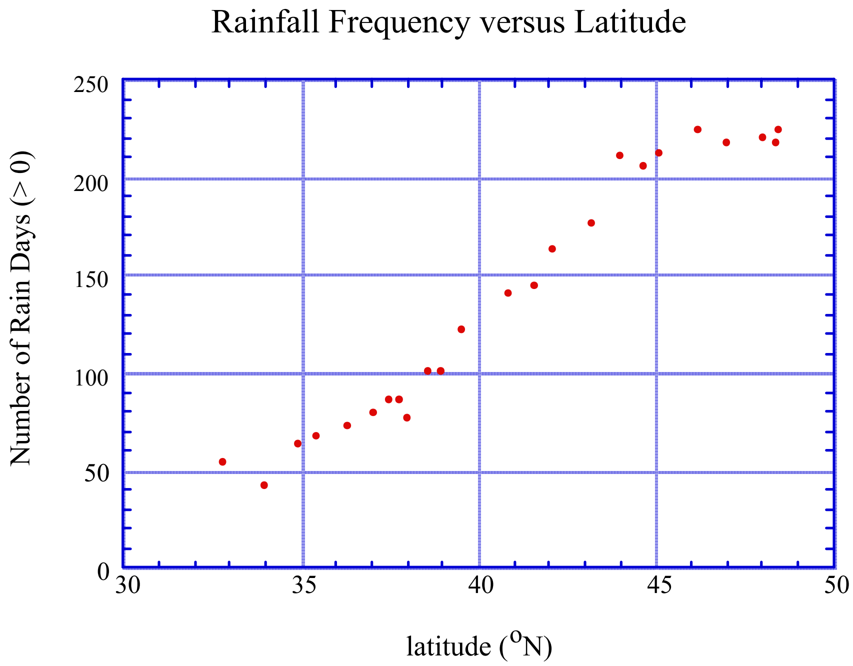

Figure 3. Plot of rainfall frequency versus latitude along the U. S. Pacific coast.

3 CLIMATIC NORMALIZATION OF THRESHOLDS

In order to mitigate the problems caused by significant variations in rainfall frequency, I have suggested (Wilson, 1997b) that the rainy-day normal (RDN), defined as MAP/#RDs, be used as the basis for normalization. Using a small data-set of daily rainfall from storms that each triggered substantial debris-flow activity along the U. S. Pacific coast, a high degree of correlation was found between the storm rainfall (maximum daily) and the RDN. Daily rainfall amounts for debris-flow triggering storms generally range from 14 to 20 times the corresponding RDN value (figure 4).

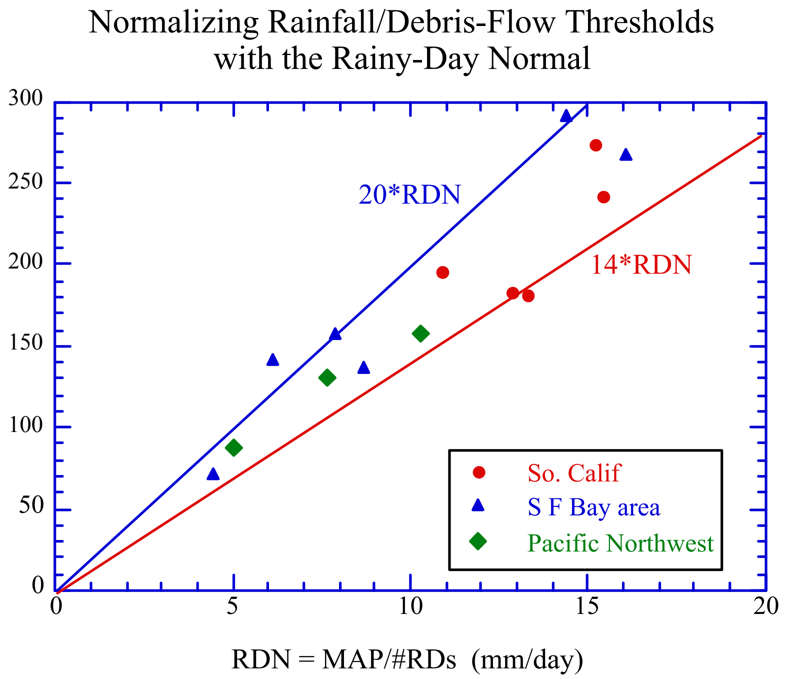

Figure 4. Plot of peak 24-hour rainfall from storms triggering debris flow versus rainy-day normal values for the corresponding gauges.

While RDN-normalization appears promising, it depends on the fact that rainstorms along the U. S. Pacific coast follow a highly precise size-frequency distribution wherein the square root of daily rainfall is normally distributed (Wilson, 1997a). This square-root normal distribution (SQRND) is thought to reflect the production of precipitation by a single, uniform meteorological process, consistent with the broad, well-defined North Pacific storm track noted above. Significant departures from the SQRND have been found, however, in other parts of the world (e.g. the Hawaiian Islands) where precipitation appears to be produced by two or more separate meteorological processes. In such areas, the RDN-normalization method may not work as well.

It would be desirable, therefore, to devise a more general method for normalizing rain/debris-flow thresholds for climatic variations without a requirement that the rainfall size-distribution take a particular form. In fact, what is really needed is a means to identify those storms that are "exceptional events," as opposed to the more frequent, but much smaller, storms that dominate the MAP value for most stations. The RDN ratio is but one measure of "exceptionality".

Inspection of fig. 2 suggests that significant debris-flow activity may be triggered by storms that occur with approximately the same frequency, approximately twice a century. At most rain gauges, unfortunately, daily rainfall data has been collected for only a few decades, too brief a period to record an adequate sample of these events. This makes it difficult to estimate frequency reliably without a limiting assumption about the form of the rainfall size-frequency distribution.

As an approximation, however, we could estimate the rainfall from a smaller "reference storm" that would have a shorter, fixed, return-period (reciprocal of event frequency). This return period would be long enough to filter out the small, frequent rainfall events that dominate the MAP values, yet short enough that an empirical estimate of the reference rainfall can be made from daily records of a few decades duration, using plots similar to those in fig. 2. These reference storm values may then be plotted against the (higher) levels of peak daily rainfall for the storms that produced debris flows, in search of a consistent pattern and a lower-bound threshold. After some experimentation, I found that a return period of about five years appears to be optimal for the reference storm, yielding a fairly well-constrained distribution of data points and a distinct lower-bound threshold of approximately 4/3 of the reference rainfall value (figure 5).

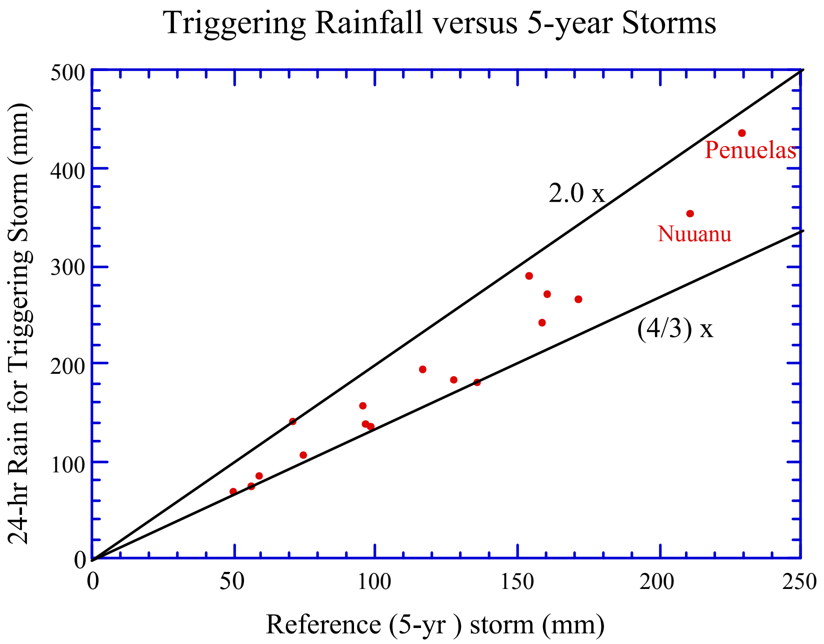

Figure 5. Plot of peak 24-hour rainfall from storms triggering debris flow versus 5-year "reference storm" values for the corresponding gauges.

The data plotted in fig. 5 include the U. S. Pacific coast data from Wilson (1997), along with two new points from tropical climates with frequent heavy rainfalls (>200 mm/day) and rainfall distributions that deviate from square-root normal. The point labeled "Nuuanu" refers to the Nuuanu Reservoir #4 rain gauge near Honolulu, Hawaii. A storm produced 356 mm (14 inches) of rainfall at this location on March 5, 1958, and triggered many debris flows in the upper part of the Nuuanu Valley (Torikai and Wilson, 1992). The point labeled "Penuelas" refers to a rain gauge near Ponce, Puerto Rico, where 437 mm (17.2 inches) of rain poured down from a tropical depression on October 7, 1985, triggering a dense concentration of debris flows near Penuelas (Jibson, 1989). The two tropical points appear to plot along the same trend as the points from the U. S. Pacific coast.

In areas which lack a detailed history of debris-flow activity, but have a reliable record of daily rainfall for at least 30 years, the lower-bound threshold in fig. 5 might serve as a useful approximation for the (daily) rainfall required for a level of debris-flow activity likely to pose a significant threat to the property and personal safety of the populace.

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