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Objective definition of rainfall intensity–duration thresholds for the initiation of post-fire debris flows in southern California

Abstract Rainfall intensity–duration (ID) thresholds are commonly used to predict the temporal occurrence of debris flows and shallow landslides. Typically, thresholds are subjectively defined as the upper limit of peak rainstorm intensities that do not produce debris flows and landslides, or as the lower limit of peak rainstorm intensities that initiate debris flows and landslides. In addition, peak rainstorm intensities are often used to define thresholds, as data regarding the precise timing of debris flows and associated rainfall intensities are usually not available, and rainfall characteristics are often estimated from distant gauging locations. Here, we attempt to improve the performance of existing threshold-based predictions of post-fire debris-flow occurrence by utilizing data on the precise timing of debris flows relative to rainfall intensity, and develop an objective method to define the threshold intensities. We objectively defined the thresholds by maximizing the number of correct predictions of debris flow occurrence while minimizing the rate of both Type I (false positive) and Type II (false negative) errors. We identified that (1) there were statistically significant differences between peak storm and triggering intensities, (2) the objectively defined threshold model presents a better balance between predictive success, false alarms and failed alarms than previous subjectively defined thresholds, (3) thresholds based on measurements of rainfall intensity over shorter duration (≤60min) are better predictors of post-fire debris-flow initiation than longer duration thresholds, and (4) the objectively defined thresholds were exceeded prior to the recorded time of debris flow at frequencies similar to or better than subjective thresholds. Our findings highlight the need to better constrain the timing and processes of initiation of landslides and debris flows for future threshold studies. In addition, the methods used to define rainfall thresholds in this study represent a computationally simple means of deriving critical values for other studies of nonlinear phenomena characterized by thresholds.

Keywords Debris flow · Wildfire · Rainfall · Thresholds · Warning system

Introduction

Rainfall-initiated landslides and debris flows are a common hazard in mountainous terrain throughout the world. As human population grows and landslide-susceptible areas are further developed, the frequency and severity of landslide and debris-flow impacts to populations and infrastructure are likely to increase. A common goal of landslide and debris-flow research is to improve predictions of the occurrence of these events in both space and time. Susceptibility maps and models are typically used to estimate where these events are likely to occur (Carrara et al. 2008; Godt et al. 2008; Cannon et al. 2009; Baum et al. 2010), while critical thresholds are used to define the meteorological, geotechnical or hydrological conditions that, when exceeded, are likely to produce landslides or debris flows (Caine 1980; Wieczorek and Guzzetti 2000; Bracchini and Zannoni 2003; Godt et al. 2006; Guzzetti et al. 2007; Cannon et al. 2008; Guzzetti et al. 2008; Baum and Godt 2010; Cannon et al. 2011).

In general, critical thresholds represent the point at which slight changes in an internal or external variable produces abrupt changes or failures within the affected system (Schumm 1973). For shallow landslides and debris flows, a measurement of rainfall is typically used as the external variable, such as average intensity (Caine 1980; Guzzetti et al. 2008), antecedent rainfall (Martelloni et al. 2012), rainfall intensity as measured over a given duration (Cannon et al. 2008, 2011), or some combination of measures (Aleotti 2004; Godt et al. 2006; Ponziani et al., 2012). The critical value of the threshold is governed at the site- or region-specific scale by physiographic properties such as antecedent conditions, topography, lithology, soil properties and land cover.

Studies aimed at defining the rainfall intensity–duration (ID) thresholds are the most common type of threshold used in landslide and debris-flow studies. They may be defined empirically using historical data (Caine 1980; Aleotti 2004; Godt et al. 2006; Guzzetti et al. 2007; Cannon et al. 2008; Coe et al. 2008; Guzzetti et al. 2008; Cannon et al. 2011), theoretically using physically based models (Montgomery and Dietrich 1994; Iiritano et al. 1998; Godt and McKenna 2008; Baum et al. 2010; Salciarini et al. 2011), or through some combination of empirical and theoretical methods (Crozier 1999). A challenge for applying physically based models is that they require detailed meteorological, hydrological and geotechnical data for accurate model calibration and prediction. These data can be difficult to collect over large geographic areas. Consequently, regional and global predictions of the temporal occurrence of landslides and debris flows are usually made using empirical thresholds derived from more easily obtained data on rainfall and the presence/absence of landslides or debris flows during a given storm (Caine 1980; Larsen and Simon 1993; Godt et al. 2006; Hong et al. 2006; Guzzetti et al. 2007; Cannon et al. 2008; Coe et al. 2008; Guzzetti et al. 2008; Cannon et al. 2011).

Empirical ID thresholds are typically represented by a power law equation in the form of $I = \alpha D^{\beta}$, where I is the rainfall intensity (in mm/h), D is the duration (in hours), and α and β are empirically derived parameters (Caine 1980). The threshold approach to predicting landslide and debris-flow occurrence using a power law equation is based upon two assumptions. First, there is a nonlinear increase in the probability of landslide or debris flow initiation with increasing rainfall intensities. This is represented by the actual threshold value for slide or flow initiation. Below the threshold value, there is a lower probability of debris flow or landslide initiation. At and above the threshold, there is a rapid, nonlinear increase in the likelihood of initiation. In the power law equation, the coefficient α and the exponent β define the location of the critical intensity value. Second, as the duration of rainfall increases, there is a decrease in the intensity of rainfall needed to trigger landslide or debris flow