Geomorphology 273 (2016) 396–411

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Forecasting inundation from debris flows that grow volumetrically during travel, with application to the Oregon Coast Range, USA

Mark E. Reid [a,*], Jeffrey A. Coe [b], Dianne L. Brien [a]

[a] U.S. Geological Survey, 345 Middlefield Road, MS 910, Menlo Park, California, USA
[b] U.S. Geological Survey, Box 25046, MS 966, Denver Federal Center, Denver, Colorado, USA

ARTICLE INFO

Article history:
Received 13 February 2016
Received in revised form 28 July 2016
Accepted 28 July 2016
Available online 30 July 2016

Keywords:
Debris flow
Growth
Entrainment
Oregon

ABSTRACT

Many debris flows increase in volume as they travel downstream, enhancing their mobility and hazard. Volumetric growth can result from diverse physical processes, such as channel sediment entrainment, stream bank collapse, adjacent landsliding, hillslope erosion and rilling, and coalescence of multiple debris flows; incorporating these varied phenomena into physics-based debris-flow models is challenging. As an alternative, we embedded effects of debris-flow growth into an empirical/statistical approach to forecast potential inundation areas within digital landscapes in a GIS framework. Our approach used an empirical debris-growth function to account for the effects of growth phenomena. We applied this methodology to a debris-flow-prone area in the Oregon Coast Range, USA, where detailed mapping revealed areas of erosion and deposition along paths of debris flows that occurred during a large storm in 1996. Erosion was predominant in stream channels with slopes > 5°. Using pre- and post-event aerial photography, we derived upslope contributing area and channel-length growth factors. Our method reproduced the observed inundation patterns produced by individual debris flows; it also generated reproducible, objective potential inundation maps for entire drainage networks. These maps better matched observations than those using previous methods that focus on proximal or distal regions of a drainage network.

1. Introduction

Fast-moving debris flows that grow during travel downstream present a great hazard, as increased flow volumes can lead to larger inundation areas, higher travel speeds, and enhanced momentum (Iverson et al., 2011). Debris flows that grow occur in a variety of mountainous settings worldwide (cf. Hungr et al., 2005), including steep forested slopes (e.g., Fannin and Rollerson, 1993; Guthrie et al., 2010), alpine terrain (e.g., Berti et al., 1999; Marchi and D'Agostino, 2004), post-wildfire burned landscapes (e.g., Cannon and Gartner, 2005; Santi et al., 2008), breached glacial lakes (e.g., Breien et al., 2008), and volcanoes (e.g., Pierson et al., 1990; Scott et al., 2005). They can initiate from discrete landslides (e.g., Iverson et al., 1997) or from rainfall or snowmelt runoff (e.g., Kean et al., 2013).

Debris-flow growth can result from various physical processes, including erosion and entrainment of channel bed sediment (Hungr et al., 1984; Takahashi, 1991; Iverson et al., 2011), collapse of stream banks (Johnson, 1970), sediment contributions from nearby landslides (Hungr et al., 2005), rilling and surface erosion of slopes adjacent to a flow channel (Santi et al., 2008), and coalescence of multiple debris flows downslope or downstream (Coe et al., 2011a, 2011b). A number of studies have focused on the entrainment of channel bed sediment by overriding debris flows, including field investigations (Berger et al., 2010; McCoy et al., 2012) and field-scale experiments (Iverson et al., 2011; Reid et al., 2011) that document entrainment rates. Yet, in some cases, growth phenomena other than bed entrainment can dominate.

Explicitly incorporating these diverse processes into physics-based models suitable for debris-flow hazard forecasting is difficult. Some previous investigations have focused on modeling specific aspects of growth. Researchers have proposed flow dynamics models that include bed sediment entrainment (cf. Iverson and Ouyang, 2015), including some models that have erosion rate formulas for debris flows (Takahashi, 1991; Egashira et al., 2001; Cao et al., 2004; McDougall and Hungr, 2005; Chen et al., 2006; Medina et al., 2008; Quan Luna et al., 2012). Others have proposed methods for modeling bed entrainment from dry granular material or rock avalanches (e.g., Crosta et al., 2009; Mangeney et al., 2010). Several physics-based models used for debris-flow hazard assessment, such as DAN (McDougall and Hungr, 2005; Hungr and McDougall, 2009) and RAMMS 2-D (Christen et al., 2010; Hussin et al., 2012), aim to account for the effects of sediment entrainment from the channel. Nevertheless, modeling the physics

* Corresponding author.
E-mail addresses: mreid@usgs.gov (M.E. Reid), jcoe@usgs.gov (J.A. Coe), dbrien@usgs.gov (D.L. Brien).

http://dx.doi.org/10.1016/j.geomorph.2016.07.039

of debris-flow growth remains challenging, as diverse growth phenomena, controlled by different processes, are difficult to represent in models.

As an alternative, we propose an easy-to-use empirical/statistical approach to forecast inundation from debris flows that increase volumetrically as they travel down slopes and channels. This approach employs flow volume/area relations used in the Laharz model (Griswold and Iverson, 2008) and uses a GIS framework to create inundation maps for regional hazard assessments. By using an empirical growth function, our method uses one term to account for varied growth processes. We apply this new approach to an area in the Oregon Coast Range, USA, where a large storm in 1996 triggered many debris flows that grew as they traveled downstream. We analyze individual debris-flow tracks where mapped erosion and deposition occurred, as well as entire drainage networks, and compare our results with other previously used volume/area inundation approaches.

2. Methods

We focus on developing an easy-to-implement method to delimit areas inundated by debris flows that grow as they travel downstream. The goal is to aid hazard assessments. Our approach begins with the empirical morphometric observations that debris-flow inundation areas (planimetric and cross-sectional) scale with flow volume, as related through statistically calibrated power-law equations (e.g., Iverson et al., 1998; Griswold and Iverson, 2008). Well-established methodologies apply these relations to provide automated, GIS-based processes for mapping potential debris-flow inundation in a digital elevation model (DEM) through computer codes such as LAHARZ (Schilling, 1998), now called Laharz_py (Schilling, 2014), and DFLOWZ (Berti and Simoni, 2014).

These methods, however, do not explicitly account for the growth of debris flows as they travel, and thus they can over- or underpredict inundation areas potentially affected by enlarging debris flows (see Section 3.6). Our method builds on the Laharz approach and adds the capability to forecast areas that could be inundated by debris flows that grow in volume. As with Laharz, our tools delineate potential inundation areas without resorting to more elaborate dynamic or flow routing models.

2.1. Laharz volume/area approach

The original Laharz approach relies on statistics derived from empirical observations motivated by physical scaling considerations. Two volume/area equations are needed for the approach, one relating planimetric inundation area and the other vertical cross-sectional inundation area. Many researchers have shown that power-law relations between volume, V, and planimetric inundation area, B, reasonably represent empirical field observations for lahars from volcano flanks (Vallance and Scott, 1997; Iverson et al., 1998; Capra et al., 2002), debris flows (Crosta et al., 2003; Berti and Simoni, 2007; Griswold and Iverson, 2008; Scheidl and Rickenmann, 2010), and rock avalanches (Dade and Huppert, 1998; Legros, 2002; Griswold and Iverson, 2008). To delineate lahar inundation area in a digital landscape represented by a DEM, Laharz also needs an empirical power law for the maximum vertical cross-sectional area, A, inundated by the passing flow (Iverson et al., 1998).

Using volume and inundation area statistics from a worldwide database of debris flows of diverse sizes, Griswold and Iverson (2008) determined volume/area relations for different mass-flow processes, including lahars, debris flows, and rock avalanches. Their statistically derived predictive equations for debris flows are

$$A = 0.1\,V^{2/3} \tag{1}$$

for cross-sectional area, and

$$B = 20\,V^{2/3} \tag{2}$$

for planimetric area.

For physical scaling and statistical-fitting reasons (Iverson et al., 1998; Crosta et al., 2003), inundation area often scales with $V^{2/3}$. The volumes in these equations are considered independent variables and represent the maximum size of an event. Many of the debris-flow events used in the Griswold and Iverson (2008) analysis enlarged in volume as they traveled; any effects of volume growth are included in a specified V. Other researchers have identified similar relations with slightly different coefficients for observed debris flows, for example in Italy (Berti and Simoni, 2007) and Arizona (Magirl et al., 2010).

To utilize these volume/area relations in a DEM (at a scale appropriate for the phenomenon of interest), the Laharz approach requires locations for the start of inundation and estimates of total debris-flow volume. For each start location and specified volume, Laharz constructs inundation cross sections using Eq. (1) and proceeds downstream constructing additional cross sections until the total planimetric area for the given volume, defined by Eq. (2), is reached. Cross-sectional inundation area is assumed constant in this process.

For volcanoes where distal inundation may be of foremost interest, start location is often identified using the downslope end of a height/length (H/L) cone defining the change in slope at the base of the edifice (Iverson et al., 1998). Alternatively, start location may coincide with the landslide origin of a debris flow to delineate proximal inundation areas (Griswold and Iverson, 2008; Magirl et al., 2010). Uncertainties in total flow volume motivate the use of multiple scenarios with different volumes, potentially ranging over several orders of magnitude (Iverson et al., 1998; Vallance et al., 2004; Macías et al., 2008).

2.2. Integrating debris-flow growth throughout a drainage network

Instead of focusing on inundation effects from total debris-flow volume, as in Laharz, we map the consequences of volume growth using an empirically derived growth function that determines evolving volumes throughout a drainage network. At each DEM cell in the drainage network where growth can occur, debris-flow volume is computed as a function of a growth factor scaled by upslope contributing area or upstream channel length. Then, inundations at these locations are computed using the volume/area equations described above (Fig. 1). Because the precise growth processes may be unknown and are primarily occurring upstream of these locations, topography remains constant. This procedure is advantageous, as it uses the assumptions (e.g., maximum inundation at a cross section) and statistics underlying the Laharz equations. From a hazards perspective, this approach can be viewed as either forecasting inundation from a flow that systematically grows downstream or the aggregated inundation from a series of different sized flows originating at different locations along the drainage network.

We use a single, empirically derived debris-flow growth function to integrate all effects of growth processes acting in the landscape being analyzed. Debris-flow volumes for a given point in the drainage network scale using one of these growth functions:

$$V = c_1\,U \tag{3}$$

or

$$V = c_2\,L \tag{4}$$

where c_1 (L^3/L^2) and c_2 (L^3/L) are empirically derived growth factors for a given setting, U is the upslope contributing area, and L is the upstream channel length. Values for c_2 can be derived from growth either along horizontal channel length (corresponding to vertical erosion) or along true-channel length (corresponding to erosion normal to the channel