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On predicting debris flows in arid mountain belts

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ABSTRACT

The use of topographic metrics for estimating the susceptibility to, and reconstructing the characteristics of, debris flows has a long research tradition, although largely devoted to humid mountainous terrain. The exceptional 2010 monsoonal rainstorms in the high-altitude mountain desert of Ladakh and Zanskar, NW India, were a painful reminder of how susceptible arid regions are to rainfall-triggered flash floods, landslides, and debris flows. The rainstorms of August 4–6 triggered numerous debris flows, killing 182 people, devastating 607 houses, and more than 10 bridges around Ladakh's capital of Leh. The lessons from this disaster motivated us to revisit methods of predicting (a) flow parameters such as peak discharge and maximum velocity from field and remote sensing data, and (b) the susceptibility to debris flows from catchment morphometry. We focus on quantifying uncertainties tied to these approaches. Comparison of high-resolution satellite images pre- and post-dating the 2010 rainstorm reveals the extent of damage and catastrophic channel widening. Computations based on these geomorphic markers indicate maximum flow velocities of 1.6–6.7 m s^{-1} with runout of up to ~10 km on several alluvial fans that sustain most of the region's settlements. We estimate median peak discharges of 310–610 m^3 s^{-1}, which are largely consistent with previous estimates. Monte Carlo-based error propagation for a single given flow-reconstruction method returns a variance in discharge similar to one derived from juxtaposing several different flow reconstruction methods. We further compare discriminant analysis, classification tree modelling, and Bayesian logistic regression to predict debris-flow susceptibility from morphometric variables of 171 catchments in the Ladakh Range. These methods distinguish between fluvial and debris flow-prone catchments at similar success rates, but Bayesian logistic regression allows quantifying uncertainties and relationships between potential predictors. We conclude that, in order to be robust and reliable, morphometric reconstruction of debris-flow properties and susceptibility requires careful assessment and reporting of errors and uncertainties.

1. Introduction

Earth's arid regions suffer significant deficits in their water balance by definition. Moreover, the water that does become available is often delivered erratically. This precipitation variability of arid regions is emblematic, and sudden rainstorms are major triggers of sporadic but nonetheless destructive flash floods, debris flows, and landslides. Precipitation patterns in the summer of 2010, the hitherto wettest year on record globally (World Meteorological Organization, 2011), triggered a number of disasters, including catastrophic flooding in Pakistan, numerous debris flows in NW China, and widespread flash floods and debris flows in the arid Transhimalaya, NW India (e.g. Hobley et al., 2012). There, monsoonal storm cells originating from south of the Himalayan divide impacted the region around Ladakh's capital of Leh, also a major international tourist destination, on August 4–6. The Geological Survey of India recorded ~12 mm of rainfall within 30 min near the most affected region of Sabu (11 km east of Leh), where water levels rose by up to ~4.5 m during this period (Thayyen et al., 2013; Figs. 1–3).

Multiple rainstorms during these days triggered dozens of flash floods and debris flows, damaging 1235 houses, and destroying 688 streets and 29 bridges, thus affecting more than 9000 people in 52 villages; the overall death toll in the region amounted to 217. The communities of Choglamsar, Sabu and Leh were affected the most, with 182 dead, 400 missing, and 607 houses destroyed (Geological Survey of India, 2010). Parts of the region's major traffic arteries, such as the Manali-Leh Highway, were destroyed, remaining impassable for several days. Wrecked bridges and high flood levels left hundreds of international tourists stranded for days on cut-off trekking routes in remote mountainous terrain.

These tragic incidents motivated us to revisit the current state-of-the-art of reconstructing and predicting from geomorphometric parameters the characteristics of, and susceptibility to, debris flows in (semi-) arid mountain belts. Much of this line of research on debris flows comes

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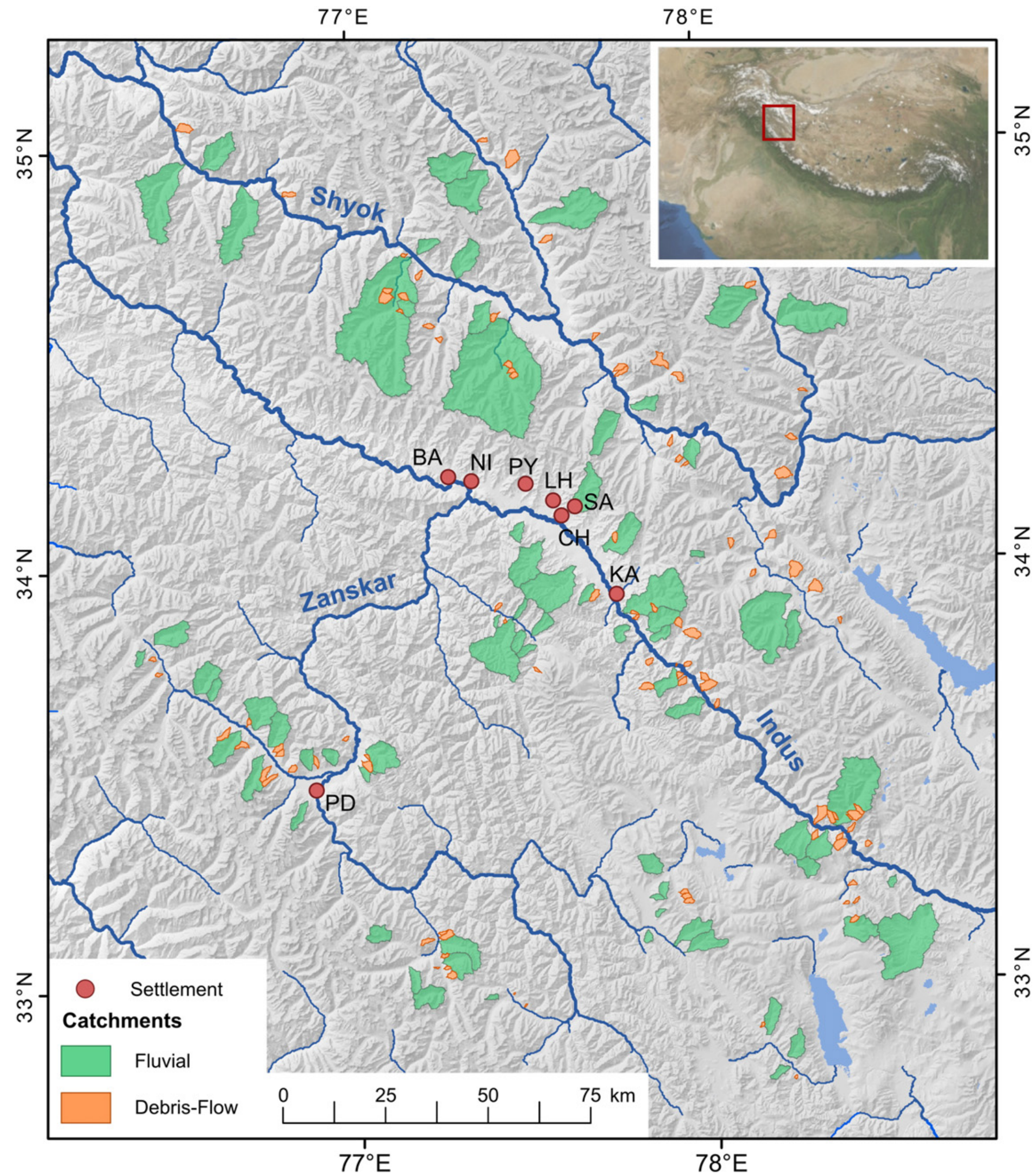

Fig. 1. Overview map of study area. Location of 171 catchments used for morphometric prediction of regional debris-flow susceptibility. Major settlements and study sites: BA — Basgo, NI — Nimu, PY — Phyang, LH — Leh, SA — Sabu, CH — Choglamsar, KA — Karu, PD — Padum. Background image is shaded relief of SRTM90 data (www.viewfinderpanoramas.org) and the image source of inset a Blue Marble MODIS composite (www.visibleearth.nasa.gov).

from humid mountainous terrain (Hungr et al., 1984; Kostaschuk et al., 1986; Crosta and Frattini, 2004; De Scally and Owens, 2004; Wilford et al., 2004; Volker et al., 2007; Kovanen and Slaymaker, 2008). Conversely, much remains to be elucidated about the hazard potential of such events in the drier rain shadows of major mountain belts. Arid regions in general experience sporadic debris-flow episodes (e.g. David-Novak et al., 2004; Harvey et al., 2005; Vargas et al., 2006; Magirl et al., 2010). Still, the enormous bandwidth of literature on debris flows has largely overlooked the role of uncertainties about topography as a potential predictor of debris flow susceptibility. We set out by reviewing selected recent studies before presenting our results on reconstructing from geomorphic field evidence the flow characteristics of debris flows in three catchments affected by the 2010 Ladakh rainstorms. We proceed with a regional analysis of catchment morphometry in order to test the predictability of debris flows from selected catchment characteristics. We discuss the feasibility of these methods, particularly zooming in on the underlying uncertainties, and the model parameterisation, which largely derives from data in humid mountainous terrain, before concluding with a number of recommendations for future research.

2. Previous work

The linking of form and process boasts a long-standing research tradition when it comes to reconstructing mass wasting phenomena, including debris flows. Terrestrial debris flows are highly mobile gravity-driven mass movements with a high sediment–water ratio, and initiate at the interface of rainfall (or at least high pore-water pressures), steep terrain, and sediment availability (Iverson, 1997; Bovis and Jakob, 1999). In mountainous terrain, debris flows occur mostly on hillslopes as a consequence of landslides or along steep channels that debouch onto fans at tributary junctions (see Harvey et al., 2005;