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Process type identification in torrential catchments in the eastern Alps

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ABSTRACT

Torrential hazards are omnipresent in the alpine regions, as it frequently causes damage to infrastructures. In some cases, even people's lives are endangered. The classification of these processes takes place according to factors like sediment concentration and flow behaviour and ranges from fluvial process types, including water floods and fluvial sediment transport processes, to fluvial mass movements such as debris flows. Following the hypothesis of this study, a context exists between basic geomorphological disposition parameters and potential dominant flow process types in a steep headwater catchment.

Thus, examined catchments were selected based on a historical event documentation of torrential events in the Austrian Alps. In total, 84 catchments could be analysed, and 11 different morphometric parameters were considered. To predict the dominant torrential process type within a catchment, a naive Bayes classifier, a decision tree model, and a multinomial regression model was trained against the compiled geomorphological disposition parameters. All models as well as their combination were compared. Based on bootstrapping and complexity, we present the classification model with the lowest prediction error for our data that might help to identify the most likely torrential process within a considered catchment.

1. Introduction

Torrential processes are part of living in mountainous regions. Event documentations show that floods, fluvial sediment transports or debris-flow-like processes can endanger mankind and human achievements at all times. Such hazardous events differ in transport mechanism, sediment concentration and density as well as in grain sizes (Costa, 1984; Phillips and Davies, 1991; Anderson and Anderson, 2010). They further show diverse response to rainfall or other triggering events and to the disposition conditions within the catchment (e.g. Berti et al., 2000; Stoffel et al., 2005; Guthrie, 2009; Johnson et al., 2008). For this reason hazard assessment of torrential processes is a complex task and needs fundamental knowledge about the effective process type within a catchment, especially if the dominant transported medium differs from pure water flow. This contribution will help to identify the most likely torrential process within a considered catchment, supporting the hazard assessment in finding accurate tools for delineating endangered areas or the design of mitigation measurements in an early stage of planning.

In practice, torrential process types are often classified on the basis of geomorphologic expertise (e.g. Costa, 1988; Hübl et al., 2002). Several publications compared debris flow and fluvial catchments by morphometric analysis for mountainous regions in Europe, Canada, and New Zealand (e.g. Marchi et al., 1993; Wilford et al., 2004; Rowbotham et al., 2005; de Scally et al., 2010; Welsh and Davies, 2011). To distinguish torrential processes, the relationship between Melton's ruggedness number (Melton, 1957) and the alluvial fan gradient has first been stated by Melton (1965) and (Church and Mark (1980). Kostaschuk et al. (1986) as well as (Jackson et al. (1987) identified debris flows by Melton's ruggedness and fan slope in the Canadian Rocky Mountains. Threshold lines for different torrential process types were stated by Marchi and Brochot (2000) and Bardou (2002) and Berti and Simoni (2007) and applied by Scheidl and Rickenmann (2010) for events in the Austrian and Swiss Alps. Bertrand et al. (2013) recently compiled data sets from 620 catchments to predict fluvial and debris flow response for the above-mentioned regions by analysing Melton's ruggedness number and channel or fan slope.

In this study we classify torrential processes based on geomorphological parameters. We distinguish between pure water processes (*WFL*), fluvial sediment transport processes (*FST*), and debris flow processes (*DBF*). In general, water floods (*WFL*) show higher runoff than on average, involving only suspended load. Contrary, fluvial sediment transport processes (*FST*) may have a volumetric sediment concentration of up to 20% (ONR-24800, 2009). The term debris flow (*DBF*) refers to the classification proposed by Hungr et al. (2014), defining debris flow as a very rapid to extremely rapid surging flow of saturated debris in a steep channel with strong entrainment of material and water from the flow path.

A database of torrential events in Austria (Hübl et al., 2008c) is used to sample prototypical catchments for all defined process types (*WFL*, *FST*, and *DBF*). Based on catchment-scale morphometrics, we determine

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several parameters that (i) might control the range of torrential flow characteristics and (ii) describe only the basic disposition in order to ensure the comparability and resist short-time changes of an environment—not susceptible to short-term variations. Here, we focus on dynamic entities with corresponding periods of about 10^2 years, defined by Schumm and Lichty (1965) as a graded time scale. Knighton (1998) noticed that over the intermediate or graded time scale and corresponding to that mean state, equilibrium channel forms may be expected to develop, adjusted to average discharge of water and sediment delivered from the upstream catchment, and dependent on the valley characteristics inherited from a longer time period.

The compiled parameters are further related to relief and shape-dependent catchment factors, showing their relevance for the dominant process type identification. By using a naive Bayes classifier, decision tree analyses and a multinomial regression approach for the relief-related, shape-related, and whole parameter set, we train multiple classifier models to predict the dominant process type. Based on bootstrapping and complexity of the resulting models, we finally present the classification model with the lowest prediction error for our data.

2. Morphometric parameters

To determine the dominant *flow* process types for steep headwater catchments (*WFL*, *FST*, *DBF*), we analysed morphometric parameters that are contingently connected to flowing. The used parameters, which are related to the basic disposition, are characterised by the slope and form–roughness of a torrential catchment, reasonably influencing torrential flowing processes. Hassan et al. (2005) stated that sediment transport regime in steep headwater catchments is dominated by episodic sediment supply from adjacent slopes rather than the hydraulic conditions. For this reason we further considered sediment connectivity and a parameter describing the channel-bed morphology. The basic sample for this study consists of 11 morphometric parameters, either based on relief gradients (reflecting the slope influence within a catchment) or on catchment shape (reflecting the form–roughness). All parameters meet the requirements of being metric and dimensionless.

2.1. Parameters related to relief gradients

Relief classified parameters, used in this study, are the average channel slope (*S*), the Melton ratio (*Mr*) (Melton, 1957), the ruggedness number (*Rn*) (Strahler, 1952), the relief ratio (*Rr*) (Schumm, 1954), and the elevation relief ratio (*Err*) (Wood and Snell, 1960). To characterise the channel bed morphology we also applied a roughness index (*RI*) proposed by (Cavalli et al., 2008).

The relationship between *S* and torrential processes is evidenced by several studies (e.g. Jakob, 1996; Marchi and D'Agostino, 2004; Scheidl and Rickenmann, 2010). The Melton ratio has been used to differentiate between process types by drawing it against the average fan slope (e.g. Marchi and Brochot, 2000; Bardou, 2002; Berti and Simoni, 2007; Scheidl and Rickenmann, 2010). The ruggedness number specifies the dynamics of basin evolution and has already been used to differentiate process types in mountain torrents (Church and Mark, 1980). High ruggedness numbers occur in mountain catchments with debris flow response, small values indicate fluvial process types (Slaymaker, 2010). The relief ratio increases for smaller catchments with higher relief. Schumm (1954) examined 35 drainage basins with different lithology in the U.S. and stated a relationship between annual sediment loss per unit area and relief ratio, where loss exponentially increased with increasing relief ratio. Evans (1972) used the elevation relief ratio to describe the degree of landscape dissection. Pike and Wilson (1971) showed that the elevation relief ratio equals the hypsometric integral, which can be related to catchment form and process (Schumm, 1956; Strahler, 1964). Cavalli et al. (2008) reported that the roughness index can be used as an indicator of the local variability of the elevation and slope and allows us to distinguish different channel-bed morphologies such as riffle–pool and step-pool reaches—the latter typically formed by sediment transport processes.

2.2. Parameters related to catchment shape

The selected parameters for this study, related to catchment shape, include parameters describing the channel system of a catchment, the sediment connectivity, and the catchment form. Here, we considered the weighted bifurcation ratio (*wBr*) proposed by Strahler (1953) as a representation of the density of streams per unit area.

The sediment connectivity index (*IC*), first described by (Borselli et al., 2008), acts as an indicator for the sediment transfer at catchment scale. The *IC*-value applied in this study was proposed by Cavalli et al. (2013) and has been proved to be very promising for the characterization of sediment dynamics in the complex morphological settings of Alpine headwaters.

Parameters addressing the catchment form are the circularity ratio (*Cr*) (Miller, 1953), elongation ratio (*Er*) (Schumm, 1956), and form factor (*Ff*) (Horton, 1932).

3. Methods

The modelling procedure for this study consists of data acquisition, pre-processing of the data, fitting four different classification models, and measuring their performance via bootstrapping. The model based on the best performance measures is finally selected. A detailed overview of the modelling procedure is given in Fig. 1.

3.1. Collection of prototypical catchments

The sampling of catchments, assigned to the defined process types, is based on a historical event documentation of all recorded events in Austria (Hübl et al., 2008c). It contains records from the Austrian Torrent and Avalanche Control Service and includes also the *Brixner Chronicle*, which is a handwritten manuscript dealing with floods and torrential devastations, landslides, debris flows, and rockfalls in Tyrol and Vorarlberg up to 1891. Detailed information about data acquisition of the used event database can be found in Hübl et al. (2008a), Hübl et al. (2008b), Hübl et al. (2008c), and Hübl et al. (2011). For this study we only considered events recorded from 1900 to the most recent entry, dated from 2013.

We identified those catchments showing the highest number of identical process types for the considered period. The criterion to assign a certain catchment to a defined process type (*WFL* or *FST* or *DBF*) was based on a frequency analysis as a result of two assumptions. First, we selected only catchments where at least one of the defined process types has a minimum annual mean occurrence probability of 0.1. This means that we only counted catchments with high event-frequencies of one of the defined process types. And second, 80% of all recorded events within a catchment needed to be of the same process type. This second assumption eliminated intermediate catchments, showing more than one of the defined process types—where a clear assignment is not possible. Based on this methodology, 42 catchments were assigned to the process water flood (*WFL*), 17 to fluvial sediment transport (*FST*), and 25 to debris flow (*DBF*). Fig. 2 shows an overview of the assigned torrential-catchments to a defined process type across Austria.

3.2. Determination of morphometric parameters

All 11 morphometric parameters were determined for each of the 84 catchments based on a GIS analysis (ESRI). The delineation of the catchments, the channel segments as well as values for area and elevation originate from a digital elevation model (DEM) with a resolution of 5 × 5 m. All streams, including intermittent ones, were analysed; and