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Linking landslide susceptibility to sediment yield at regional scale: application to Romania

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ABSTRACT

It is generally accepted that catchment sediment yield (*SY*, t km^{-2} y^{-1}) can be strongly influenced by landsliding. Nevertheless, due to data requirements, only few studies investigated this effect at a regional scale. The objective of this study is therefore to explore the potential of a landslide susceptibility map for explaining the spatial variation of *SY* in Romania. We selected 133 catchments in Romania for which *SY* was measured during a period of at least 10 years. For each catchment, we derived a variety of proxies that potentially explain *SY*, including several indicators of landslide occurrence. The latter were derived from a published landslide susceptibility map. Results show that *SY* is significantly correlated with mean landslide susceptibility ($r^2 = 0.30$). Estimates of average sheet and rill erosion rates showed a much weaker correlation with *SY* ($r^2 = 0.06$). Further analyses showed that the strong correlation between *SY* and landslide susceptibility is mainly attributed to regional variations in lithology and seismicity. Especially the latter may play a crucial role in understanding denudation rates at regional scales, e.g. by facilitating the occurrence of landslides. Using landslide proxies that also account for sediment connectivity did not result in stronger correlations. Overall, our results show that landslide susceptibility maps can be a highly useful tool to predict *SY* at regional scales, provided that they incorporate all relevant factors.

1. Introduction

Knowing the processes and factors controlling catchment sediment yield (*SY*, t/km^2/y) is essential to understand landscape denudation patterns and assess their impacts on biogeochemical cycles, river ecology and human infrastructure (Meybeck, 2003; Syvitski and Milliman, 2007; de Vente et al., 2013). Numerous studies have investigated which variables best explain observed variations in *SY* at regional, continental and global scales. Most studies focused on independent environmental variables (e.g.: Milliman and Syvitski, 1992; Verstraeten and Poesen, 2001; Rădoane and Rădoane, 2005; Vanmaercke et al., 2014a,b; Vanmaercke et al., 2015), rather than on the actual processes that feed rivers with sediment (e.g.: de Vente et al., 2006; Delmas et al., 2009).

Some recent studies revealed the importance of seismic activity as a factor controlling *SY*, even across continents with only a low to moderate degree of seismic activity, such as Africa and Europe (e.g. Vanmaercke et al., 2014a,c). Although the exact causes explaining this control remain poorly understood (e.g. Cox et al., 2010; Vanmaercke et al., 2014c), this relation is often explained by earthquake-induced landslides that contribute to *SY* (e.g.: Burbank et al., 1996; Dadson et al., 2004; Hovius et al., 2011). Nonetheless, most of the studies that investigate the link between landslides and *SY* focus on a single or a few catchments and on areas in highly active seismic regions (e.g. Pearce and Watson, 1986; Hovius et al., 1997; Dadson et al., 2004; Koi et al., 2008). Only few studies target regional or continental scales or less seismically active regions. Nevertheless, some research indicates that, also at regional or continental scales, landsliding can be highly relevant to *SY* (e.g.: de Vente et al., 2006, 2013; Delmas et al., 2009). The lack of studies that explicitly link landslides and *SY* reflects problems with landslide inventories: they are relatively scarce, usually unavailable for large regions, and often incomplete in space and time (Van Den Eeckhaut and Hervás, 2012; Guzzetti et al., 2012). Landslide susceptibility (*LSS*) maps offer a potential alternative. They can serve as a surrogate for actual landslide inventories, by extrapolating insights from discrete landslide inventories to continuous *LSS* coverage over larger regions (e.g. Guzzetti et al., 2006; Malet et al., 2009; Bălteanu

Abbreviations: SY, sediment yield; LSS, landslide susceptibility; PGA, peak ground acceleration.

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et al., 2010; Van Den Eeckhaut et al., 2012; Havenith et al., 2015). Nonetheless, only a few studies explored the potential of *LSS* as a predictor for *SY* (e.g., Ono et al., 2011).

Another difficulty in quantifying the contribution of landslides to *SY* is that not all landslides will effectively supply sediment to the river system. As is the case with other erosion processes (e.g. Van Rompaey et al., 2001; de Vente and Poesen, 2005), this contribution depends on sediment connectivity, which is influenced by a range of factors (e.g. topography, land use, distance to river). Over the past years, significant improvements have been made in quantifying this connectivity (e.g. Borselli et al., 2008; Cavalli et al., 2013). This opens additional opportunities to assess the importance of landsliding for *SY* at regional and continental scales.

Romania has long-term *SY* measurement records (e.g. Diaconu, 1969; Rãdoane and Rãdoane, 2005; Vanmaercke et al., 2011; Vanmaercke et al., 2014b) and a country-wide *LSS* map (Bălteanu et al., 2010). Although the country is also affected by other soil erosion processes (e.g. sheet, rill, gully and riverbank erosion; Motoc, 1983; de Vente et al., 2006, 2013), it can be expected that the contribution of landslides to *SY* will be significant (e.g. Bălteanu et al., 2010; Vanmaercke et al., 2014b). This makes Romania suitable to investigate relationships between landslides and *SY* at a country wide scale.

Therefore, this study explores to what extent a *LSS* map and indicators for sediment connectivity can explain regional patterns of *SY* in Romania. The specific objectives are: (1) to explore relationships between landslide susceptibility and *SY* at regional scale; (2) to investigate the importance of sediment connectivity in assessing the contribution of landslides to *SY*; and (3) to compare the potential of *LSS* maps for explaining regional variation in *SY* with that of sheet and rill erosion rates and other independent environmental variables.

2. Study area

Romania is located in Southeastern-Central Europe and covers an area of 238,391 km^2 (Fig. 1). A vast fraction of the territory (28%) consists of the Carpathian Mountains (altitude range: 800 to 2500 m), which are composed of crystalline formations, volcanic rocks and sedimentary successions with flysch and molasse (Bălteanu et al., 2010). They are part of the Alpine fold-and-thrust belt and were mainly formed during the late Cenozoic as a result of convergent activity of several micro-plates with the Eurasian plate (Airinei, 1977; Linzer, 1996; Bălteanu et al., 2010). At intermediate altitude, the hills and plateaus bordering the Carpathian chain together with the Transylvanian Depression, cover 42% of the territory. The upper sediments in this depression consist of detritic terrestrial rock, volcanic tuffs, salt formations, clays and marls. The Subcarpathian hills mainly consist of molasse associated with folds and faults (Bălteanu et al., 2010). The remainder of the territory at the lowest altitude (30%) consists of plains (Bălteanu et al., 2010). Current subduction of the Black Sea micro-plate under the Carpathians (Sandulescu, 1988), makes the Vrancea region, as part of the Bend Carpathians and Subcarpathians, one of the most seismically active regions in Europe (Bălteanu et al., 2010; Fig. 1).

The climate of the Carpathians is cool and humid with annual precipitation ranging between 1000 and 1400 mm. The climate in the hilly regions and plains is continental-temperate with oceanic influences in west- and central Romania, Mediterranean in the south and continental in the east. Annual precipitation in these regions ranges between 400 and 600 mm (Bălteanu et al., 2010). Annual and monthly rainfall variability in Romania is high. The highest precipitation occurs during the warm season, with a stronger torrential rainfall regime in the east of the country (Bălteanu et al., 2010). Weak lithological units, a high degree of neotectonic uplift and high rainfall intensities make the Bend Subcarpathians most prone to landsliding with as much as 60% of the slopes covered by landslides (Bălteanu et al., 2010; Fig. 2) and total soil erosion rates up to 3000 to 4500 t km^{-2} y^{-1} (Motoc, 1983). Other regions with large areas (10–30%) prone to landsliding are the hills of the Transylvanian Depression, the Moldavian Plateau in the east and the Eastern Carpathians (Bălteanu et al., 2010).

3. Materials and methods

3.1. Sediment yield dataset

Observations on *SY* were selected from a previously constructed *SY* database (Vanmaercke et al., 2011). All *SY* measurements were either derived from runoff and suspended sediment concentration measurements at gauging stations or from sedimentation rates in reservoirs. Sampling frequency at gauging stations was high. Runoff discharge was generally recorded at least twice a day. Suspended sediment concentration measurements were mostly taken on a flow-proportional

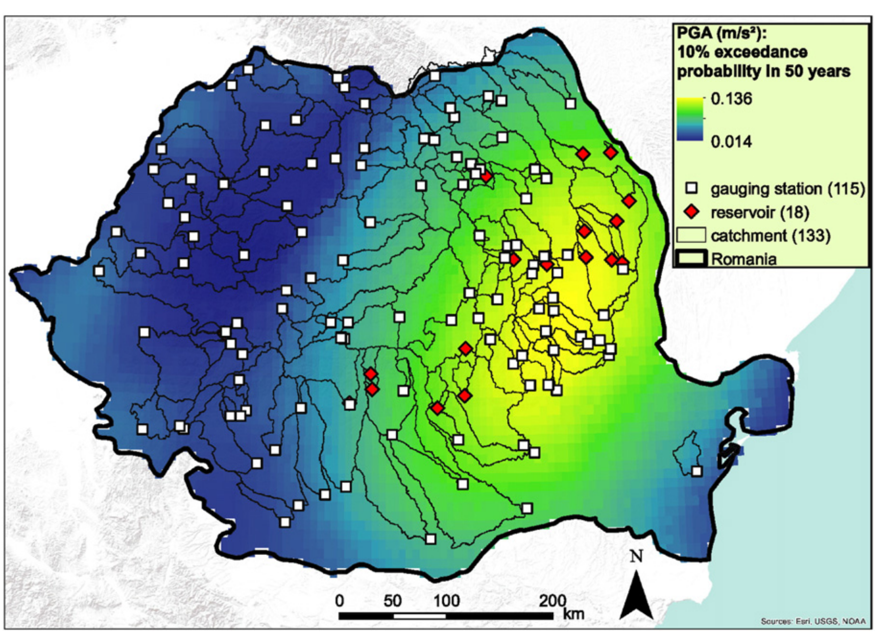

Fig. 1. Map of Romania showing the peak ground acceleration (*PGA*) with an exceedance probability of 10% in 50 years based on Giardini et al. (2013). The location of the 133 catchments and their outlets, for which *SY* data was used in this study, are also indicated.