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# Geomorphic response detection and quantification in a steep forested torrent

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Extreme events such as flash floods and debris flows are frequent phenomena that occur in steep torrential catchments; these kinds of events can cause notable geomorphic changes. Repeated terrestrial laser scanning (TLS) surveys were performed in a steep forested catchment of the Kuzlovec torrent (drainage area ~0.7 km$^2$) in central Slovenia, where a ~200-m long section of the torrent was scanned in 2013, 2014, and 2015. The main aim of this study was to perform the geomorphic response detection in the torrent due to hydro-meteorological events of different magnitudes. After applying several pre-processing steps, digital terrain models (DTMs) with a cell resolution of 5 cm were produced. The geomorphic change detection was performed using the DTM of Difference approach (DoD). Several above-average flow events occurred in the period from 2013 to 2015 (some of them can be regarded as floods). The 2014 August extreme flash flood that was initiated by the rainfall event with a return period exceeding 100 years, where maximum 1-minute rainfall intensities were up to 288 mm/h, led to erosion rates of an order of magnitude higher than average annual erosion rates. Moreover, the analysis of the geomorphic changes shows that the August 2014 flash flood caused intense sediment transport processes that resulted in the changes at the location of the main stream channel thalweg and reduced channel roughness. The unit stream power for the scanned section of the torrent was assessed to be approximately 500 W/m$^2$ during this extreme event. This is above the thresholds that were suggested to differentiate between the situations where significant geomorphic changes can occur and the situations where geomorphic changes are not notable.


## 1. Introduction

Extreme events such as flash floods and debris flows that are rainfall-triggered can cause large economic losses and even endanger human lives (e.g., Marchi et al., 2009; Mikoš et al., 2004; Rusjan et al., 2009). Severe hydro-meteorological events cause intense soil erosion, sediment transport and deposition processes (e.g., Lenzi and Marchi, 2000); such events occur in the Alpine catchments that were investigated in the scope of the SedAlp project (http://www.sedalp.eu/index.shtml).

Measurements of suspended load and bed load can be performed using various techniques. Some of these can be used for normal and extreme conditions, while other methods for measurements in extreme conditions are more complicated. Direct measuring techniques (e.g., bottle sampling or optical methods) are often used for suspended sediment measurements at catchments of different scales (e.g., Bezak et al., 2015a). In some situations some of these methods are not suitable for determining long-term sediment loads in small mountain catchments because the most extreme events can be missed (Carrivick et al., 2013). For example, manual bottle sampling is very difficult during extreme events. Measurements of bed material transport can often be complicated (e.g., Anderson and Pitlick, 2014), while sediment measurements using direct conventional methods can underestimate the long-term average rates (Carrivick et al., 2013; Kirchner et al., 2001). However, permanent measuring stations such as the Rio Cordon station (e.g., Lenzi and Marchi, 2000; Mao and Lenzi, 2007; Picco et al., 2012) yield valuable information about the long-term sediment budgets and can yield adequate measuring results under normal and extreme conditions. On the other hand, repeated topographic surveys can be used for indirect measurements of sediment transport (sediment budgets) (e.g., Blasone et al., 2014; Theule et al., 2012; Wheaton et al., 2010). Based on the gathered information, the short-term to long-term rates can be determined depending on the number of the surveys and their frequency (Lane et al., 1995; Brasington et al., 2003; Church, 2006). Using this method, various events of different magnitudes can be observed. Different methods such as aerial photogrammetry, airborne LiDAR, and airborne narrow-beam terrestrial-aquatic green can be applied to detect geomorphic changes (Croke et al., 2013; Grove et al., 2013; Mikoš et al., 2005; Tomczyk and Ewertowski, 2013; Wheaton et al., 2010). The selection of the technique depends on

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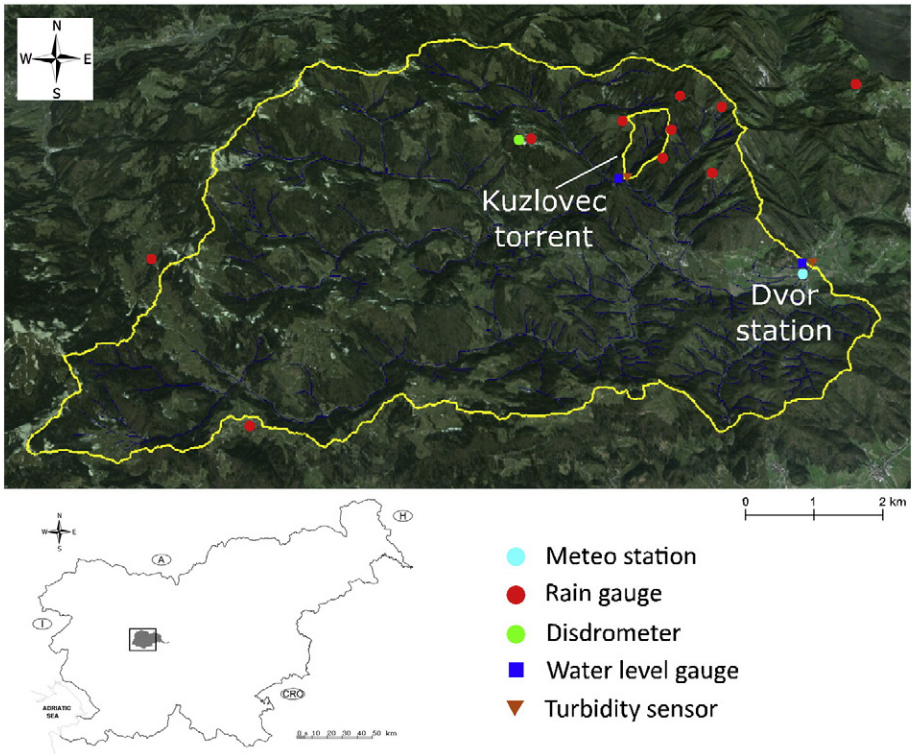


**Fig. 1.** The location of the Kuzlovec torrent in the Gradaščica River catchment and the measuring equipment.

the scale and properties of the investigated area, such as slope and vegetation cover. The identification of the geomorphic changes at the catchment scale can be performed using terrestrial laser scanning (TLS) (e.g., Blasone et al., 2014; Carrivick et al., 2013; Lisenby et al., 2014; Picco et al., 2013; Vericat et al., 2014).

The main aim of this study was to detect geomorphic changes in the torrent following the hydro-meteorological events of different magnitudes. The specific aims of this study were as follows: (i) production of the DTM based on the repeated topographic surveys using terrestrial laser scanning (TLS); (ii) calculation of the DTM of Difference (DoD) maps with the consideration of uncertainty; (iii) analysis of the hydro-meteorological events that caused the largest percentage of changes in the DoD maps; (iv) investigation of the geomorphic changes in the steep forested torrent.

## 2. Data and methods

### *2.1. Case study description*

Repeated topographic surveys were performed in 2013, 2014, and 2015 in the steep and forested Kuzlovec torrent, which is part of the Gradaščica River catchment in central Slovenia. Fig. 1 shows the location of the investigated Gradaščica River catchment down to the Dvor gauging station, and the location of this catchment on the map of Slovenia. In the investigated Kuzlovec torrent (Fig. 1), several hydro-meteorological processes are being observed since 2013 (Bezak et al., 2013). Precipitation is recorded at 7 locations around the Kuzlovec torrent using tipping bucket rain gauges. Water level depths and turbidity are measured at the outlet of the Kuzlovec torrent, and an optical disdrometer (Črni Vrh; Fig. 1) is used for observing rainfall characteristics such as raindrop size distribution; the measured rainfall amounts are available in real time online (http://ksh.fgg.uni-lj.si/avp/DisCrniVrh/). Rainfall data measured by the meteorological radar (the spatial resolution of the radar data is 1 km$^2$) and the rain gauge, which are located at the Črni Vrh nad Polhovim Gradcem and are operated by the Slovenian Environment Agency, were also used in this study. The distance between the Črni Vrh nad Polhovim Gradcem and the Kuzlovec torrent is about 4 km.

**Table 1**
Basic characteristics of the investigated Kuzlovec torrent.

| Characteristic/catchment | Kuzlovec |
|---|---|
| Catchment area [km$^2$] | 0.71 |
| Elevation range (min; max; mean) [m.a.s.l.] | 394; 847; 631 |
| Slope (max; average) [°] | 46.5; 27.3 |
| Length of the main stream [km] | 1.3 |
| Mean channel slope [%] | 23.5 |
| Dominant land-use type | Mixed forest (38%) and broad-leaved forest (44%) |
| Dominant soil type (FAO type) | Rendzic Leptosol |

Table 1 shows some basic characteristics of the investigated Kuzlovec torrent; forest is the dominant land-use type, and steep slopes predominate for the greater part. The relief in the Gradaščica catchment has been shaped predominantly by fluvial erosion; narrow valleys and steep slopes can be found in the headwater parts (north and northwestern parts of the watershed), whereas towards south and southeast the valley widens and the area has prevailing lowland topographical characteristics. The Kuzlovec experimental catchment is located in the headwater, mountainous part of the Gradaščica catchment. Both fluvial and karstic morphologic features can be found in the area. The elevation in the Gradaščica catchment (Fig. 1) ranges from 340 to 1020 m. a.s.l. Valley bottoms are covered by medium to thick layers of alluvial deposits.

Position of the Gradaščica catchment in the Alpine-Dinaric barrier is responsible for high rainfall amounts (yearly averages between 1600 and 1800 mm of rainfall). The highest rainfall totals are observed in autumn and high rainfall amounts are also observed during summer. The Gradaščica River and the Kuzlovec torrent have a rain–snow regime