Landslides
DOI 10.1007/s10346-019-01325-1
Received: 14 August 2019
Accepted: 13 November 2019

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An extreme May 2018 debris flood case study in northern Slovenia: analysis, modelling, and mitigation

Abstract Debris floods can cause large economic damage and endanger human lives. This paper presents an extreme May 2018 debris flood that occurred in northern Slovenia near the Krvavec ski resort and caused large economic damage. The debris flood was initiated by an extreme rainfall event with a return period of over 50 years. There were large differences in the measured rainfall amounts using different equipment. The estimated volume of the debris material during the event was 4000 m^3/km^2 for the Brezovški graben. In order to mitigate the risk due to future debris flood and debris flow events, a check is planned to be constructed. The part of the design process is presented in this paper. Additionally, RAMMS model was used to validate the empirical equations that were used in the process of the check dam stability design. The model was calibrated using information about the deposition area. Two adjacent torrents were modelled, and we were not able to find a common RAMMS parameter set that would yield adequate simulation performance in both cases.

Keywords Debris floods · Hyperconcentrated flows · Slovenia · RAMMS · Numerical modelling · Mitigation measures

Introduction

Slovenia is among the European countries where different types of mass movements such as debris flows, shallow landslides, or deep-seated landslides can occur relatively frequently (e.g., Mikoš et al. 2004; Mikoš et al. 2005; Sodnik and Mikoš 2006; Petkovšek et al. 2011; Jemec Auflič et al. 2016; Bezak et al. 2019a), and the density of active landslides in the Slovenian national database is more than three landslides per 10 km^2 (Herrera et al. 2018). Most often, this kind of mass movements in Slovenia is rainfall-induced, i.e., triggered by extreme rainfall events (e.g., Mikoš et al. 2004; Bezak et al. 2016; Jemec Auflič et al. 2016; Bezak et al. 2019a), and less frequent they are earthquake-induced (Mikoš et al. 2013). Extreme events can be either of short duration with very high rainfall intensities (e.g., Železniki case study) or of prolonged duration with smaller rainfall intensities where antecedent conditions are also important (e.g., 2000 Log pod Mangartom debris flow) (e.g., Bezak et al. 2016). Other triggering mechanisms are rarer. Short-duration storms with extreme intensities can also often lead to flash floods where sediment transport (i.e., bed and suspended load) is very intense (e.g., Bezak et al. 2017) and can similarly as in the case of debris flows or deep-seated landslides lead to large economic damage. A transitional process between water (i.e., flood) and debris flow is debris flood (Hungr et al. 2014) respectively hyperconcentrated flow (e.g., Pierson 2005; Calhoun and Clague 2018). Hungr et al. (2014) have updated the Varnes classification of landslide types, and in this modified classification, they defined, among other types, also "debris floods": "very rapid flow of water, heavily charged with debris, in a steep channel. Peak discharge comparable to that of a water flood." The term "hyperconcentrated" flow is more often used in torrential hydraulics and sediment transport theory, when the sediment concentration in a water flow exceeds a few percentages. Among other differences, debris flows may transport more sediments than water (e.g., more than 60% by volume), while in case of torrential floods, sediment concentrations are usually smaller than 4% by volume (Pierson 2005). In case that bed material begins to move together and coarse sediment becomes suspended, a torrential flood transforms into a hyperconcentrated flow (Calhoun and Clague 2018). This can occur when additional channel or hillslope erosion is significant during the flood initiated by extreme rainfall events (e.g., Pierson 2005). According to Pierson (2005), there are also other initiation mechanisms that are not very likely to occur in Slovene conditions, but in all cases, a supply of easily erodible material is crucial. It should be also noted that from the European perspective, Slovenia is one of the countries with the highest soil erosion rates (Panagos et al. 2015a), and especially extreme rainfall erosivity values are characteristic of some regions in Slovenia (Panagos et al. 2015b). This means that especially mountain areas could be prone to hyperconcentrated or debris flow occurrence (e.g., Sodnik and Mikoš 2006). Moreover, a debris flow can transform into a hyperconcentrated flow in case that certain conditions are fulfilled (e.g., Pierson 2005). Around the world, there are several locations where hyperconcentrated flows are frequent (e.g., Loess Plateau in China; Joingxin, 1999; Pierson 2005). Different types of measures can be used for the mitigation of hyperconcentrated and debris flows (e.g., Hübl and Fiebiger, 2005). Most often, different types of storage basins, check dams, and silt dams/barriers with vertical slits or similar measures are used for the mitigation (e.g., Hübl and Fiebiger, 2005). For the design of mitigation measures, modelling of the historical or future (i.e., scenario) debris or hyperconcentrated flow can be useful because based on the modelling results one can obtain flow velocity and pressure that are needed for structural design. Various modelling approaches and software used can be found in the literature (e.g., Chen et al. 2018; Cesca and D'Agostino 2008; Schneider et al. 2014). For example, Schneider et al. (2014) used Rapid Mass Movement Simulations (RAMMS; e.g., Christen et al. 2012) model, and Mergili et al. (2011) applied the FLO-2D model for debris floods simulations. Hungr et al. (2014) stated that: "The distinction between debris floods and debris flow surges is of great practical importance due to their different damage potential and also because of the widely different strategies that must be used to design protective structures." In the paper, the term debris flood is used as a synonym for hyperconcentrated flow. The main aim of this paper is to present the extreme debris flood that occurred in 2018 near the Krvavec ski resort in Slovenia (Europe) and to

Published online: 03 January 2020

illustrate the steps that were made to mitigate the risk due to possible future debris floods and debris flows. As part of the field investigation and countermeasures design, RAMMS model and its debris flow module (RAMMS-DF) were applied and used for post-event modelling of the 2018 event in order to calculate flow velocities and pressures during the debris flood. The results of the RAMMS model were used to additionally check (i.e., validate) the empirical procedure used for the check dam stability analysis. Additionally, by applying the debris flow module (RAMMS-DF) of the RAMMS model, we tested the applicability of this tool for numerical simulations of debris floods.

Data and methods

Case study description

Two torrents located below the Krvavec ski resort in north Slovenia (ski slopes from 1450 to 1971 m a.s.l., a part of the Kamnik-Savinja Alps) were investigated in this study. Figure 1 shows the location of the investigated case study on the map of Slovenia and the locations of the Krvavec cable car station and the Krvavec meteorological station, respectively. Basic characteristics of the Brezovški graben and Lukenjski graben torrents are shown in Table 1. Maximum elevation of the investigated area is above 1800 m a.s.l. Both torrents are characterized by steep slopes and have relatively similar characteristics (Table 1) where the main difference is that the slope of the Lukenjski graben torrent before the confluence with the Brezovški graben torrent is not as steep as in the case of the Brezovški graben. After the confluence of both torrents, the river is named the Reka torrent. Due to the torrential characteristics and supply of the material that is located in the upper part of the torrents, this area was to some extent regulated in the past, and some measures were taken in order to reduce the potential damage. However, the existing check dams' volume is relatively small, and in case of extreme events, it is not sufficient. Several events (either floods with intense sediment transport or debris floods) occurred in the last 30 years, for example, in 1990, 1991, 1994, 1995, 1996, 2007, and 2014 (e.g., Horvat 1995; Klaneček et al. 2008). Figure 2 shows a photo taken at the location of the cable car station after one of the past events. At the location of the Krvavec rainfall station, the Slovenian Environment Agency (ARSO) measures rainfall using a pluviograph and an optical disdrometer. Additionally, we also obtained rainfall radar measurements on the day of the investigated event. There are no discharge stations in place near the investigated torrents.

Despite the fact that no actual debris flow events occurred at this area in the last 30–50 years, it is possible that the future situation will lead to the occurrence of a debris flow due to the large amount of sediments in the upper part and steep slopes of the torrents. Intensive erosion process started during the May 2018 event, and large amounts of sediment are potentially "available" for debris flows. Therefore, along with debris floods, debris flow occurrence was also considered in the process of the check dam design (section 2.3). Moreover, we estimated the potential magnitude of the debris flow using the Takei (1984), Ceriani et al. (2000) for debris flows, and Marchi and D'Agostino (2004) equations:

$$M = 13,600 * A^{0.61} \tag{1}$$

$$M = 1,000 * k * A^{1.0} * M_b{}^{0.8} * S_{cl\_c}{}^{1.0} * I\_F^{-2} \tag{2}$$

$$M = 65,000 * A^{1.35} * S^{1.7} \tag{3}$$

where M is the debris flow magnitude [m^3], A is the catchment area [km^2], k is the empirical coefficient (i.e., 5.4 for debris flow and 3 for debris flood/bed load), M_b is the Melton number [–], S_{cl_c} is the gradient of the torrential channel on the fan [%], I_F is the landslide index [–] (i.e., $I\_F = 1$ for the presence of large active or reactivable landslides within the drainage network, $I\_F = 2$ for the presence of landslides on the slopes of the basin, not directly along the drainage network, and $I\_F = 3$ for the absence of significant landslides), and S is the average gradient of the torrential channel [m/m]. The Melton number is defined as (Melton 1965):

$$M_b = (H_{MAX} - H_{MIN}) * A^{-0.5} \tag{4}$$

where H_{MAX} [km] and H_{MIN} [km] are the highest and the lowest points of the torrential watershed. Additionally, we also wanted to calculate bed load rates using Rickenmann and Recking (2011) and Smart and Jäggi (1983) equations, but the torrent's slope was not in the range of the equations' limits.

RAMMS and HEC-HMS

To model the debris flood that occurred in 2018 in the investigated area, we used the RAMMS software and its debris flow module RAMMS-DF, which is generally used for modelling debris flows, but it has also been used to model hyperconcentrated events (e.g., Schneider et al. 2014). Depth-averaged shallow water equations for granular flows are used in the single-phase model (RAMMS 2018). RAMMS uses the Voellmy-fluid friction model in order to simulate debris flow movement (RAMMS 2018). This friction model uses two parameters, μ parameter that represents the dry-Coulomb friction and ξ parameter that represents the viscous-turbulent friction (RAMMS 2018). Newer RAMMS versions use a modification of the Voellmy equation that also considers cohesion (RAMMS 2018). These two parameters are kept constant during the simulations. Additional information about the modelling approach used by RAMMS can be found in RAMMS (2018). In this paper, we determined both Voellmy parameters in the process of model calibration using information about the extent and height of the deposited material after the 2018 event. Moreover, we also calibrated the stop parameter (i.e., percentage of total momentum). As an input to the RAMMS software, we used hydrographs, which is a preferred way of modelling in case of channelized topography (RAMMS 2018). Publicly available LIDAR data were used to represent the topography of the investigated area (1-m cell size was used). The LIDAR data were measured before the May 2018 event (i.e., in years 2014 and 2015). In order to determine the runoff hydrograph of the 2018 event, we applied the

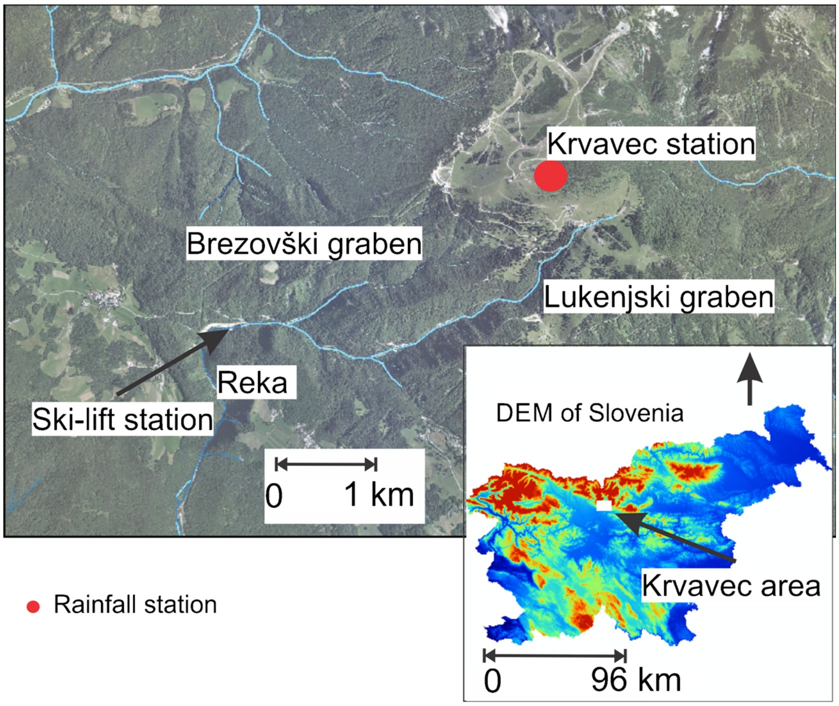

Fig. 1 Location of the May 2018 debris flood in the Krvavec catchment on the map of Slovenia (source: Atlas okolja, 2019)

hydrological HEC-HMS software (HEC-HMS, 2019). The rainfall loss was calculated using the Soil Conservation Service (SCS) curve number (CN) method, and transformation from rainfall to runoff was modelled using the SCS unit hydrograph method that uses the lag-time parameter (HEC-HMS, 2019). In order to determine the CN parameter for the investigated area, information about land-use and the soil hydrologic group (e.g., A, B, C, or D) was used (HEC-HMS, 2019). In order to determine the design discharge values needed for dam design, the frequency storm method (HEC-HMS, 2019) was used to define the design hyetograph where information about intensity-duration-frequency (IDF) curves (at station Kamniška Bistrica; ARSO (2019)) and catchment time of concentration was used. Some additional information about the application of the HEC-HMS software for the hydrological modelling and design discharge determination can be found in Šraj et al. (2010) or Bezak et al. (2018).

Dam design

To mitigate risks due to possible future debris floods or debris flows, a check dam (i.e., barrier) with a vertical slit and a trapezoidal weir is planned to be constructed just downstream of the confluence of the Brezovški graben and Lukenjski graben torrents in order to check both torrents. To determine the size of the vertical slit, we applied the equation proposed by (Zollinger, 1983; cited in Piton and Recking 2015):

$$Q = \mu_p * w * 0.66 * d^{3/2} * \sqrt{2g} \quad (5)$$

where μ_p is the slit coefficient (taken as 0.65 by Zollinger (1983)), w is the slit width [m], d is the water depth over the slit bottom [m], g is the acceleration due to gravity, and Q is discharge [m^3/s] (Piton and Recking 2015). Slit dimensions were determined so that the slit can convey design discharge with a 20-year return period. Additionally, to determine the relative opening, the following equation was used (Piton and Recking 2015):

$$\text{Relative Opening} = \frac{\text{Opening size}}{\text{Material size}} = \frac{n_o}{D_{MAX}} \quad (6)$$

Table 1 Basic characteristics of the investigated torrents

Torrent	Area [km^2]	Mean slope of the catchment area [%]	Slope of the torrent [%]	Slope of the torrential channel on the fan [%]	Hydraulic length of the catchment [km]	Land-use
Brezovški graben	1.91	58.6	Approx. 32	Approx. 28	3.3	Forest 74%, agricultural area 26%
Lukenjski graben	2.44	57.3	Approx. 25	Approx. 17	4.2	Forest 76%, agricultural area 24%

Fig. 2 Historical event at the Krvavec ski-resort, photo shows the situation after the 1991 event at the location of the cable car station (adopted from Horvat 1995)

where D_{MAX} is maximal sediment diameter and n_o is the shortest dimension of the opening (Piton and Recking 2015). In order to carry out the grain-size analysis, BASEGRAIN software was used where several photos of the deposited material after the 2018 event were analyzed (BASEGRAIN 2019). Both criteria (discharge and relative opening) were considered for determining the final width of the slit.

Weir design was carried out using information about design discharge with a 100-year return period and additional freeboard.

For the structural design (stability analysis) of the check dam, the following three cases were taken into consideration:

– The check dam is empty; the debris flow impacts the lower half of the check dam.

– The check dam is half-full, the debris flow impacts the upper half of the check dam.

– The check dam is full (filled with debris) and the debris flow is flowing over the dam (drag force).

Based on the analysis of the sediment diameter size in the catchment area, the boulder impact in the check dam was not considered in the structural design of the check dam.

For the calculation of the debris flow impact on the dam, the ONR 24801 standard (i.e., Protection works for torrent control – Actions on structures) was used (e.g., Scheidl et al. 2013; Hübl and Nagl 2018):

$$p_{peak} = 5^{*}\rho^{*}v^{0.8*}(g^{*}h)^{0.6} \tag{7}$$

where p_{peak} is the maximum debris flow impact pressure [Pa], ρ is the bulk density [kg/m^3], h is the flow height [m], v is the debris flow velocity [m/s], and g is the acceleration due to gravity [m/s^2]. Other details about structural design are not given in this paper since this is not the main aim of this study.

Results and discussion

May 2018 event

The extreme debris flood occurred on May 30, 2018, in the afternoon. Figure 3 shows the measured rainfall at the location of the Krvavec rainfall station. The Slovenian Environment Agency (ARSO) measured rainfall using a pluviograph and an optical disdrometer. Additionally, Fig. 3 shows hourly rainfall radar images that were determined based on the measurements of two rainfall radars that are operated by ARSO. One can notice that there are large differences in the measured rainfall amount by the pluviograph (i.e., 55 mm) and optical disdrometer (i.e., 92 mm). Furthermore, during the most intense rainfall (i.e., about 15 min), the optical disdrometer detected hail. Several studies have indicated that optical disdrometers tend to overestimate the drop velocities, which also affects the calculated rainfall amount (e.g., Tokay et al. 2014). Moreover, there also exist relatively large differences among various disdrometer models (e.g., Tokay et al. 2014; Angulo-Martínez et al. 2018). However, in most studies, the reported differences were not as large as in the case of the Krvavec case study, but some examples can be found in the literature (e.g., Tokay et al. 2014; Angulo-Martínez et al. 2018). For example, Angulo-Martínez et al. (2018) have shown that for a high-intensity event, the Thies Clima disdrometer, which is also used by ARSO, measured around 35 mm, while OTT Parsivel measured 21 mm of rainfall. Because no other rainfall measurements were available while the rainfall radar indicated that hourly rainfall intensities in this area could be around 100 mm/h (Fig. 3), we decided to use the measurements of both instruments (i.e., of the pluviograph and the optical disdrometer) in further steps of this study (i.e., lower and upper bounds). Additionally, we also estimated the return period of the rainfall event according to the closest rainfall station that has IDF curves available (i.e., Kamniška Bistrica station; ARSO 2019). For the 30-min rainfall measured using the pluviograph, the return period was between 50 and 100 years, while for the optical disdrometer case, the return period was much larger than 250 years. Moreover, this rainfall station is located more than 1000 m below the Krvavec station that was used in this study. Thus, one could expect that the actual return period is somewhat smaller. However, in 2018, the Krvavec and Kamniška Bistrica stations measured 1835 mm and 1777 mm, respectively.

The extreme rainfall event caused intense erosion processes that lead to the debris flood. Figure 4 shows photos taken at different locations in the Brezovški graben and Lukenjski graben torrents after the May 2018 event. The main source of the material that was deposited at the wider area of the cable car station was the Brezovški graben where in the upper part there is still a lot of potential material located in or near the channel (Fig. 4). In the lower part of the torrent, the slope is relatively high (approx. 0.4 m/m) and not much of deposition occurred in this area. Moreover, one of the photos also shows a cross section that was full during the event. It was estimated that the cross section at this place is at least 4.5 m wide and 2.3 m high (an area of more than 10 m^2). Most of the material from the Brezovški graben was deposited near the cable car station where the maximum deposition height was up to 3–4 m (Fig. 4). The estimated volume of debris material was between 7000 and 10,000 m^3. The deposited material consisted of sediments with a diameter from few mm up to boulders with a diameter of 1 m. Additionally, a fair amount of woody debris was detected in the deposition area. However, a field survey after the event revealed that some material was also transported further downstream from the cable car station. For the Lukenjski graben, also the main source is in the upper part of the torrent where also some landslides were observed during the field survey after the event (Fig. 4). However, most of the sediments that were transported during the event were deposited upstream of the confluence with the Brezovški graben and did not reach the cable car station (Fig. 4). The estimated volume was similar as in the case of the Brezovški graben (i.e., approx. 8000 m^3).

After the event, a geological survey of the entire area was also carried out in order to evaluate the situation in the torrent, as shown in Fig. 5. General characteristics of the event source area, transport of the material, and lithological characteristics of accumulated material suggested that event characteristics are more typical for the hyperconcentrated event (i.e., debris flood) than for the typical debris flow event. In the deposited sediment, coarse-grained carbonate gravel prevails, while the fine fraction (e.g., clay and silt) is not present in significant quantities. In addition, the source area of the material is not one individual landslide area but rather a longer section of the Brezovški graben torrent where erosion and smaller landslides occurred. Based on the field survey and intense erosion processes in the torrents, it was estimated that events of similar magnitude could occur in the future.

HEC-HMS modelling results

Hydrological modelling using HEC-HMS software was carried out in order to estimate the input hydrograph for the RAMMS software. As an input, rainfall data measured using a pluviograph and an optical disdrometer were used. The soil hydrology group according to the SCS classification was determined to be equal to B class for the investigated torrents. Based on the land-use map (Table 1) of the area and the soil hydrology group, we also estimated the CN parameter (i.e., 68). Based on the CN parameter and by using the SCS method, we also estimated the lag-time parameter that is needed to determine the synthetic unit hydrograph. Lag time was estimated to be 20 min for both torrents. Table 2 shows modelling results using the pluviograph and optical disdrometer data. Notably, the values shown in Table 2 are only a rough estimation of the peak discharge values and runoff volume during the event. Therefore, according to the field survey (Fig. 4), the input hydrograph that is used in the RAMMS software was additionally modified, to be on the safe side from the design perspective. Therefore, for the Brezovški graben, the peak discharge was increased to 32 m^3/s and 8.5 m^3/s for the optical disdrometer and the pluviograph, respectively, the volume was not changed, and the hydrograph duration was shortened in order to obtain the volume.

RAMMS modelling results

The RAMMS-DF model was used to model the May 2018 event. The main aim of the model's use was to obtain estimates of the flow pressure and velocity. These numbers were used to validate the results of Eq. 7 used in the process of the check dam stability analysis. Therefore, the main aim was to calibrate the model for the more extreme scenario shown in Table 2. Based on the field survey after the event, we determined the RAMMS release area and the polygon of the deposition area. In the first step, the RAMMS model was calibrated using information about the deposition area. In the calibration process, the stop parameters, μ and ξ parameters, were changed with the aim to obtain the best visual fit between the model deposition and the actual deposition during the May 2018 event. In the first step, we calibrated the model using the input hydrograph with a peak discharge of 32 m^3/s and a hydrograph volume of 48,000 m^3 (i.e., triangular shape of the hydrograph was used). The best fit in terms of deposition extent/area was obtained using the following set of parameters: stop parameter = 10%, μ = 0.13, and ξ = 400 m/s^2. Other parameters that are used by RAMMS (e.g., Hcutoff, density) were set to default values that are used in the RAMMS software. According to the RAMMS manual (RAMMS, 2018), values of ξ between 200 and 1000 m/s^2 should represent mud flow (i.e., fluid-like) situation. Moreover, Schneider et al. (2014) used μ = 0.04 and ξ = 500 m/s^2 in order to model a 2010 debris flood. Moreover, Dietrich and Krautblatter (2019) used μ = 0.16 and ξ = 200 m/s^2 parameters for debris flow modelling in Germany. Additionally, μ parameter value is in the range of the possible values that could be suitable for the alpine environment (e.g., Bezak et al. 2019b). Figure 6 shows results of the simulation (i.e., deposited material) using a calibrated set of parameters. Moreover, one can notice that also the modelled deposition height is slightly higher than the actual deposition height that was observed during the filed survey. In the next step, we repeated the modelling procedure using the smaller input hydrograph that corresponds to the pluviograph measurements (i.e., 8.5 m^3/s and 12,600 m^3). Using the calibrated set of parameters from the previous step, the RAMMS model simulated that most of the material is transported downstream from the cable car station and the actual deposition area during the May 2018 debris flood as indicated in Fig. 6.

Additionally, we were interested if the calibrated set of parameters (stop parameter = 10%, μ = 0.13, and ξ = 400

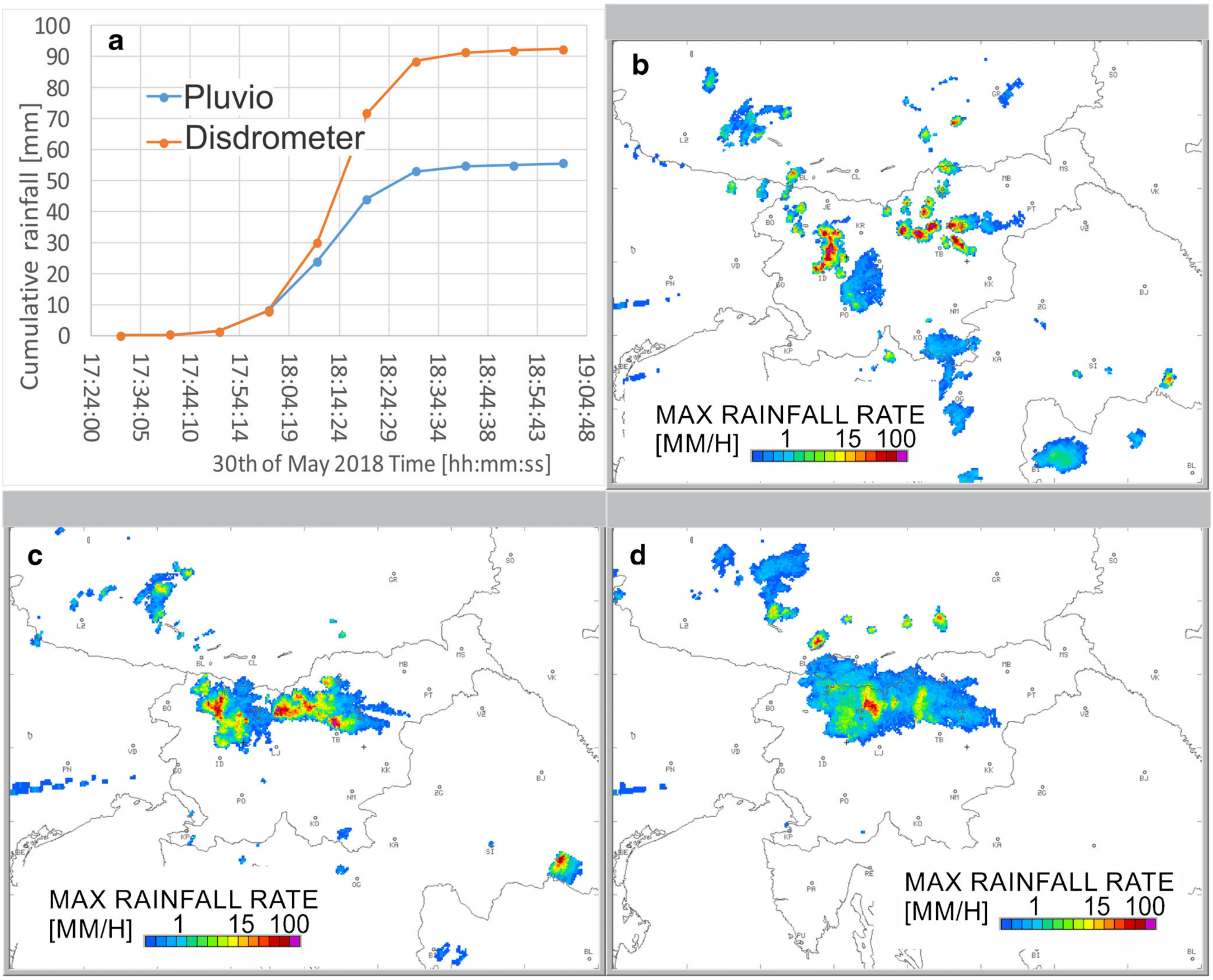

Fig. 3 Rainfall during the May 2018 event measured/estimated using the pluviograph and the optical disdrometer (a) and the rainfall radar (b) from 17:00 until 18:00, (c) from 18:00 until 19:00, and (d) from 19:00 until 20:00)

m/s²) that was used for the Brezovški graben also yields good results for the Lukenjski graben. Similarly, as for the Brezovški graben, we defined the release and deposition areas based on the field survey after the event. The same input hydrograph was used as in the case of the Brezovški graben. As already indicated, the deposition area of the Lukenjski graben was before the confluence with the Brezovški graben. Using the same set of parameters, the material was not deposited at the area of actual deposition but was mostly transported downstream to the cable car station. Thus, we repeated the calibration procedure for the Lukenjski graben. The following set of parameters, i.e., stop parameter = 10%, μ = 0.2, and ξ = 900 m/s^2, yielded the best results (i.e., deposition occurred before the confluence with the Brezovški graben). Because torrents are located next to each other and have similar characteristics in terms of area, slope, land-use, and material characteristics, and as we can also assume that rainfall properties were similar during the event, one could expect that calibrated parameters would be the same for both cases. However, this was not the case in the presented study. One could argue that a possible reason could be in the location of the release area that could be only roughly estimated based on the field survey after the event. Thus, if we included the release area position and the size in the calibration procedure, we could determine the same set of calibrated parameters for both torrents. Additionally, model's sensitivity regarding the roughness and slope at which the material is deposited could also be one of the reasons why the same set of parameters did not yield equally satisfactory results for both torrents. For the Lukenjski graben torrent, the deposition area reached almost the confluence with the Brezovški graben torrent. This could indicate that a slightly higher slope

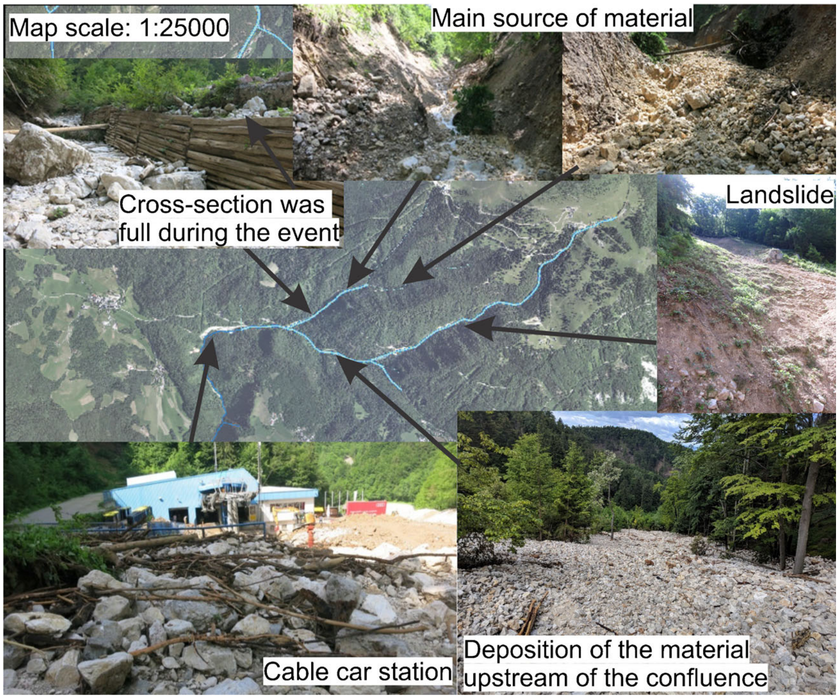

Fig. 4 Situation in the Reka torrent and the Brezovški graben and the Lukenjski graben torrents after the May 2018 event

or smaller roughness would lead to the case where material would be transported downstream of the confluence.

Mitigation measures

In order to mitigate further risk due to debris floods and debris flows in the investigated area, a check dam is planned to be constructed at the confluence of the Brezovški graben and the Lukenjski graben torrents. The Melton number (Melton 1965) for the Brezovški and Lukenjski graben using Eq. 4 is 0.64 and 0.53, respectively. Because debris flows could also occur in this area, we also used equations proposed by Takei (1984), Ceriani et al. (2000), and Marchi and D'Agostino (2004) in order to estimate the magnitude of a possible debris flow event (k = 5.4 and I_F = 3 was used for Eq. 2). For the Brezovški graben, the estimates were 20,000 m^3, 22,500 m^3, and 22,500 m^3 using the aforementioned empirical equations, respectively. For the Lukenjski graben, the estimates were 23,500 m^3, 15,000 m^3, and 20,500 m^3 using the aforementioned empirical equations, respectively. Thus, these magnitudes also indicate that both torrents have similar characteristics. However, this kind of an event would be extreme, especially if we also take into consideration the volume of material that was transported during the May 2018 event (i.e., 7,000–10,000 m^3). These numbers are in accordance with Eq. 2 in case that k = 3 is used, which corresponds to the debris flood case. Additionally, these numbers are in the range of possible debris flow volumes for northeastern Italy (Marchi et al. 2019). For the catchment area of around 2 km^2, a possible range of debris flow volumes is between approx. 70 m^3 (2%) and approx. 100,000 m^3 (98%) with a median (50%) value of approx. 4,000 m^3 (Marchi et al. 2019). Thus, our estimated volume is higher than the median value reported by Marchi et al. (2019), which somehow confirms that the May 2018 event was extreme. Based on these numbers and considering actual space availability, the check dam was designed for maximum possible capacity, which is 14,000 m^3. A larger sediment trap would bring even more extensive measures and larger costs, which would be hardly justified considering the relatively low damage potential in the downstream area. The designed dam height is 5 m and the dam width is 57.3 m. Construction of the dam will require several additional hydro-technical structures to be built, and other works (e.g., material excavation) will be necessary; some of these are shown on Fig. 7. Transversal and longitudinal cross section of the dam is also shown in Fig. 7. The procedure described in section 2.3 was used for the dam design. BASEGRAIN analysis using Fehr's (1987) method indicated that d_{30}, d_{50} , and d_{90} are 14 mm, 98 mm, and 318 mm, respectively. Therefore, for the slit design, D_{MAX} = 40 cm was used. Based on the procedure described in section 2.3, the width of the slit was determined to be 0.8 m. Weir dimensions were determined so that the weir can convey 60 m^3/s. For the dam stability, three cases were considered (section 2.3). Using Eq. 7 and a velocity of 6 m/s, the debris flow impact is estimated to be equal 290 kPa (density of 2000 kg/m^3). RAMMS modelling results for the case presented in Fig. 6 indicated that the modelled maximum flow pressure at the location of dam is 200 kPa. For the case with a smaller peak discharge and hydrograph volume, the calculated maximum flow pressure

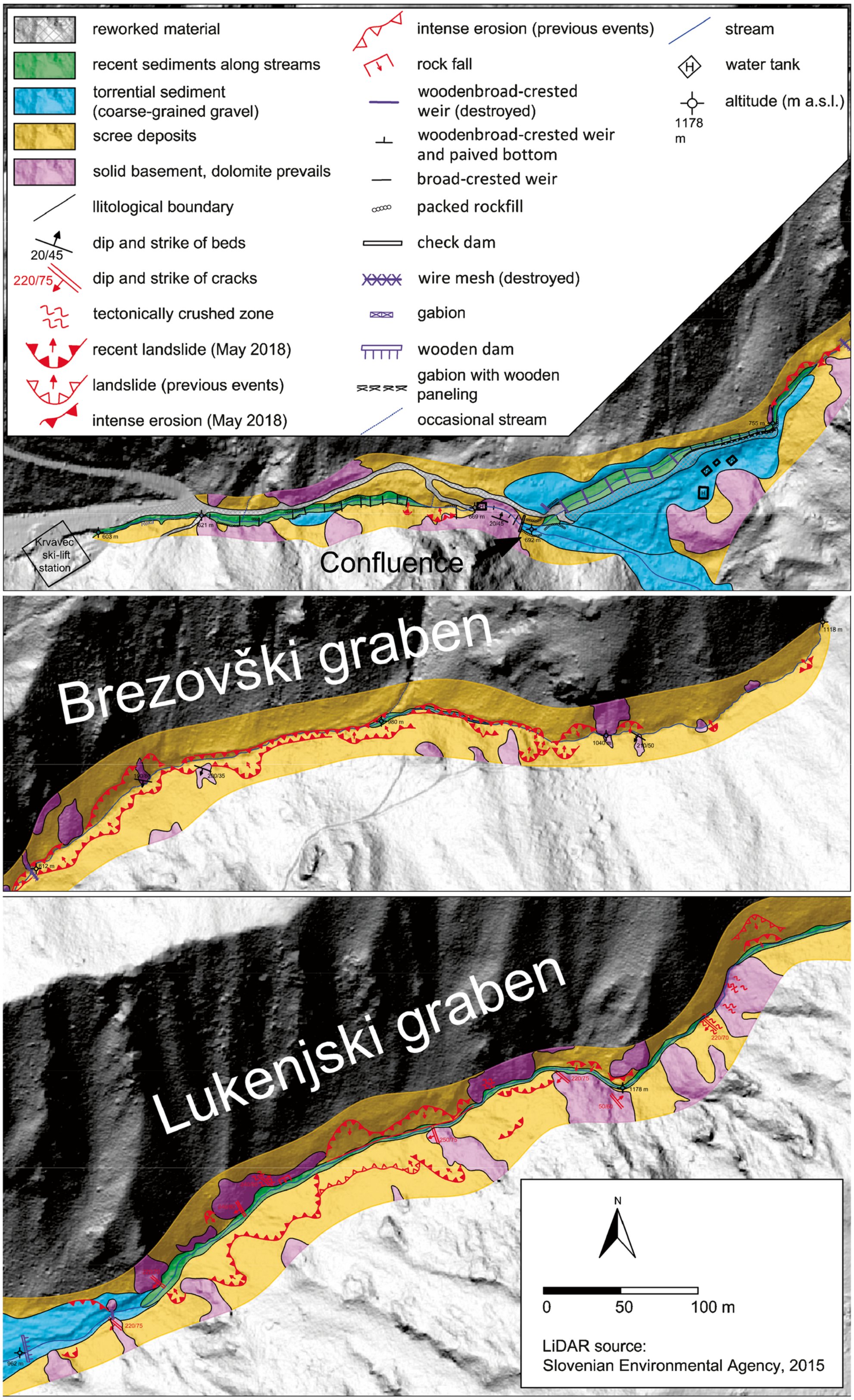

Fig. 5 Geological map of the area after the May 2018 event

Table 2 Hydrological modelling results using the pluviograph and optical disdrometer data

Torrent	Rainfall data	Peak discharge [m^3/s]	Volume [m^3]	Hydrograph duration [h]
Brezovški graben	Optical disdrometer	22	48,000	1.2
Brezovški graben	Pluviograph	5.7	12,600	1.2
Lukenjski graben	Optical disdrometer	27.6	59,800	1.3
Lukenjski graben	Pluviograph	7.1	16,000	1.3

at the dam location was below 130 kPa. Moreover, also for the Lukenjski graben, the maximum flow pressure at the dam location is around 180 kPa (for the case where material is transported downstream of the confluence and deposited at the cable car station). This indicates that the design debris flow impact values that were used for the structural design are on the safe side regarding the RAMMS modelling results.

Conclusions

This study presents the extreme debris flood that occurred in May 2018 below the Krvavec ski resort in northern Slovenia. Rainfall measurements during the event using various sensors are presented. The situation after the event in the Brezovški graben and the Lukenjski graben torrents is shown. Because a lot of debris material is still available in sediment sources in the upper parts of the torrents, a check dam with a vertical slit is planned to be constructed at the confluence of both torrents. Among others, the RAMMS model is used to verify the assumptions made during the structural design process in order to take into consideration the potential debris flow impact on the planned check dam. Based on the presented results, the following conclusions can be drawn:

– The differences in the measured rainfall amounts during the extreme event using the different equipment were relatively large. For example, the 30-min rainfall return period was between 50 and 100 years for the pluviograph and more than 250 years for the optical disdrometer. During the extreme event, the estimated volume of the transported debris material was 4000 m^3/km^2 for the Brezovški graben torrent.

– The simulations using the RAMMS-DF model that was calibrated using the information about the deposition area yielded meaningful results that validate the empirical approach that was used for the dam stability design.

– Even though two adjacent torrents were investigated, the calibration procedure indicated that we were not able to find a common parameter set that would yield good simulation performance for both torrents.

– Even though the RAMMS-DF model is dedicated to debris flow modelling, it was successfully applied for debris flood modelling.

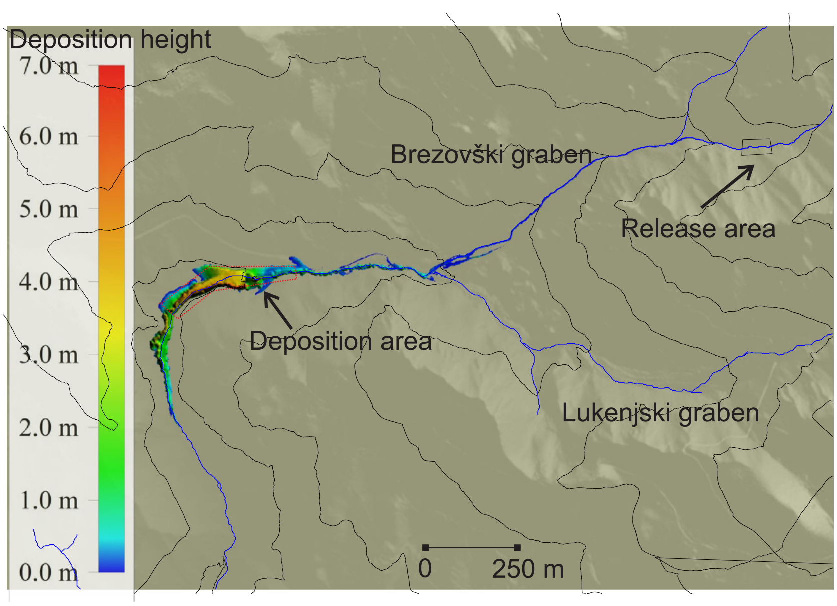

Fig. 6 RAMMS modelling results (i.e., legend shows material deposition) using the calibrated set of parameters for the Brezovški graben for the 32 m^3/s peak discharge and a hydrograph volume of 48,000 m^3. Spacing between contour lines is 100 m

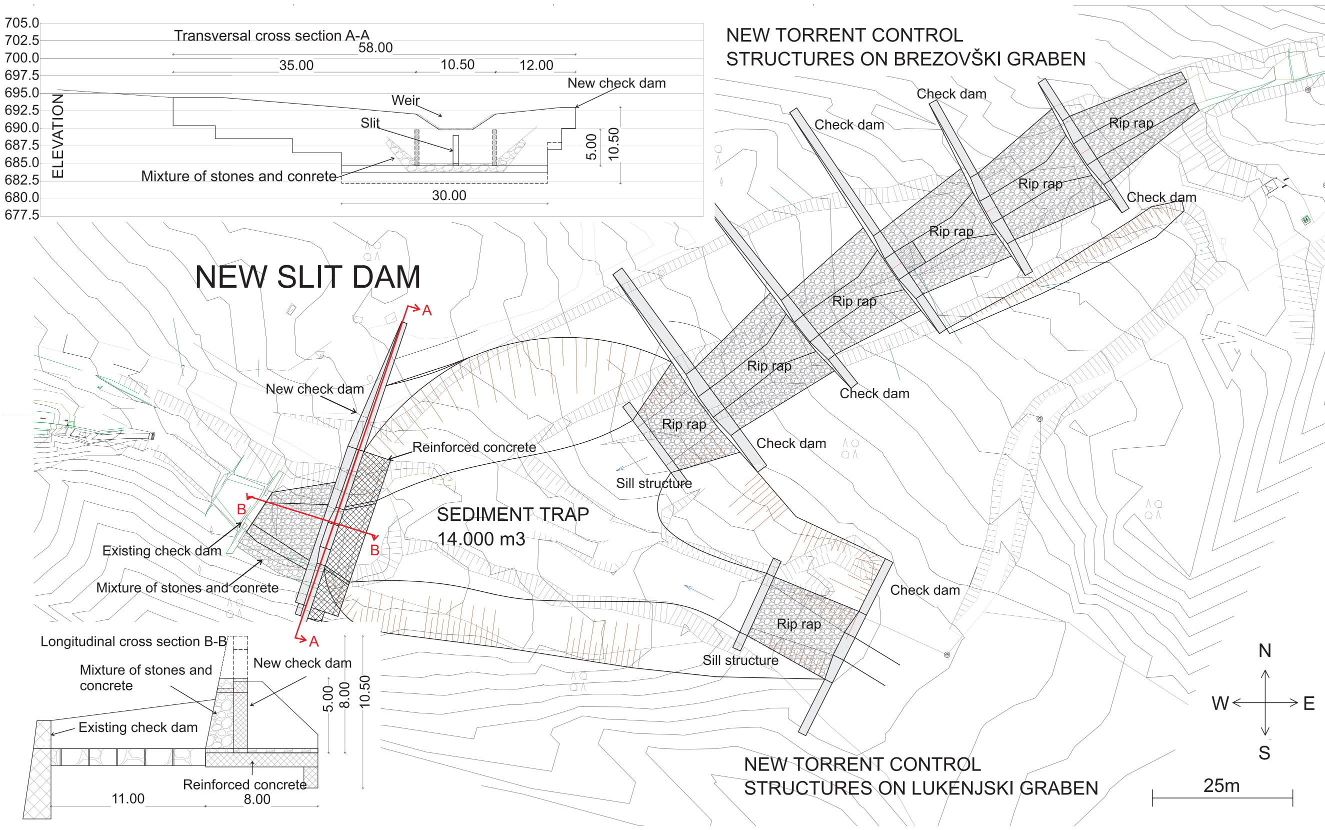

Fig. 7 Graphical presentation of the dam location and its main characteristics with the transversal and longitudinal cross section of the dam. Spacing among contour lines is 2 m. Additional structures that are to be built are also shown in the figure (e.g., several sill structures)

– A check dam that is planned to be constructed in the investigated area will be able to trap sediments transported during future extreme events similar to the one that occurred in May 2018.

Funding information

The results of this study are part of the research projects J7-8273 "Recognition of Potentially Hazardous Torrential Fans Using Geomorphometric Methods and Simulating Fan Formation" and J1-8153 "Studying Landslide Movements from Source Areas to Zone of Deposition using a Deterministic Approach" that are financed by the Slovenian Research Agency (ARRS). Both projects were approved by the International Programme on Landslides (IPL) as the IPL-225 and IPL-226 Project, respectively (http://iplhq.org/category/iplhq/ipl-ongoing-project/). We would like to thank the Slovenian Environment Agency (ARSO) for data provision. The check dam design and design of other mitigation measures were financed by the Slovenian Water Agency. We would like to thank anonymous reviewer and editorial board members for their insightful comments that improved the quality of the manuscript.

References

Angulo-Martínez M, Beguería S, Latorre B, Fernández-Raga M (2018) Comparison of precipitation measurements by OTT Parsivel2 and Thies LPM optical disdrometers. Hydrol Earth Syst Sci 22:2811–2837. https://doi.org/10.5194/hess-22-2811-2018

ARSO (2019) IDF curves. Available online: https://meteo.arso.gov.si/met/sl/climate/tables/precip_return_periods_newer/. (Accessed on 9 July 2019).

Atlas Okolja (2019) Available online: http://gis.arso.gov.si/atlasokolja/profile.aspx?id=Atlas_Okolja_AXL@Arso. (Accessed on 9 July 2019).

BASEGRAIN, 2019. Available online: https://basement.ethz.ch/download/tools/basegrain.html. (Accessed on 9 July 2019).

Bezak N, Šraj M, Mikoš M (2016) Copula-based IDF curves and empirical rainfall thresholds for flash floods and rainfall-induced landslides. J Hydrol 541(A):272–284

Bezak N, Grigillo D, Urbančič T, Mikoš M, Petrovič D, Rusjan S (2017) Geomorphic response detection and quantification in a steep forested torrent. Geomorphology 291:33–44

Bezak N, Šraj M, Mikoš M (2018) Design rainfall in engineering applications with focus on the design discharge. In Engineering and Mathematical Topics in Rainfall; InTech Press: London, UK, ISBN 978-953-51-5562-1.

Bezak N, Jemec Auflič M, Mikoš M (2019a) Application of hydrological modelling for temporal prediction of rainfall-induced shallow landslides. Landslides 16(7):1273–1283

Bezak N, Sodnik J, Mikoš M (2019b) Impact of a random sequence of debris flows on torrential fan formation. Geosciences 9(2):64. https://doi.org/10.3390/geosciences9020064

Calhoun NC, Clague JJ (2018) Distinguishing between debris flows and hyperconcentrated flows: an example from the eastern Swiss Alps. Earth Surf Process Landf 43:1280–1294

Ceriani M, Crosta G, Frattini P, Quattrini S (2000) Evaluation of hydrogeological hazard on alluvial fans. In : Interpreavent 2000 – Villach, Tagungspublikation, Vol. 2., 213-225, http://www.interpraevent.at/palm-cms/upload_files/Publikationen/Tagungsbeitraege/2000_2_213.pdf.

Cesca M, D'Agostino V (2008) Comparison between FLO-2D in RAMMS in debris-flow modelling: a case study in the Dolomites. WIT Trans Eng Sci 60:197–206

Chen C, Lin Y, Chung H, Hsieh T, Yang J, Lu J (2018) Modelling of hyperconcentrated flow in steep-sloped channels. J Hydraul Res 56(3):380–398

Christen M, Bühler Y, Bartelt P, Leine R, Glover J, Schweizer A, Graf C, Mc Ardell BW, Gerber W, Deubelbeiss Y, et al. (2012) Integral hazard management using a unified software environment: Numerical simulation tool "RAMMS" for gravitational

natural hazards. In Proceedings of the 12th Congress INTERPRAEVENT, Grenoble, France, 23–26 April 2012; Koboltschnig, G., Hübl, J., Braun, J., Eds.; pp. 77–86.
Dietrich A, Krautblatter M (2019) Deciphering controls for debris-flow erosion derived from a LiDAR-recorded extreme event and a calibrated numerical model (Roßbichelbach, Germany). Earth Surf Process Landf 44:1346–1361
Fehr R (1987) Geschiebeanalysen in Gebirgsflüssen (Grain Size Analysis in Torrents), Mitteilung Nr. In: 92, Versuchsanstalt für Wasserbau. Zürich, Hydrologie und Glaziologie (VAW), ETH Zürich (in German)
Hungr O, Leroueil S, Picarell L (2014) The Varnes classification of landslide types, an update. Landslides 11(2):167–194
Jemec Auflič M, Šinigoj J, Krivic M, Podboj M, Peternel T, Komac M (2016) Landslide prediction system for rainfall induced landslides in Slovenia (Masprem). Geologija 59(2):259–271
Joingxin X (1999) Erosion caused by hyperconcentrated flow on the Loess Plateau of China. Catena 36:1–19
HEC-HMS (2019) Reference Manual. Available online: http://www.hec.usace.army.mil/software/hec-hms/documentation/HEC-HMS_Users_Manual_4.2.pdf. (Accessed on 9 July 2019).
Herrera G, Mateos RM, García-Davalillo JC, Grandjean G, Poyiadji E, Maftei R, Filipciuc T-C, Jemec Auflič M, Jež J, Podolszki L, Trigila A, Iadanza C, Raetzo H, Kociu A, Przyłucka M, Kułak M, Sheehy M, Pellicer XM, McKeown C, Ryan G, Kopačková V, Frei M, Kuhn D, Hermanns RL, Koulermou N, Smith CA, Engdahl M, Buxó P, Gonzalez M, Dashwood C, Reeves H, Cigna F, Liščák P, Pauditš P, Mikulėnas V, Demir V, Raha M, Quental L, Sandić C, Fusi B, Jensen OA (2018) Landslide databases in the Geological Surveys of Europe. Landslides 15(2):359–379
Horvat A (1995) Urejanje hudourniških in erozijskih območij. Ujma 9:243–248 (In Slovenian)
Hübl J, Fiebiger G (2005) Debris-flow mitigation measures. In: Jakob M, Hungr O (eds) debris-flow hazards and related phenomena. Springer, Berlin, pp 445–487
Hübl J, Nagl G (2018). Austrian Standard Regulations for the design of check dams under impact by torrential processes. Proceedings of the 5th IAHR Europe Congress – New Challenges in Hydraulic Research and Engineering, Trento.
Klaneček M, Zupančič A, Sušec-Šuker V, Ilc U, Podobnikar I, Globokar T (2008) Poplave 2007 – intervencijski ukrepi, predhodni sanacijski in sanacijski program. Mišičev vodarski dan 2008:196–210 (In Slovenian)
Marchi L, D'Agostino V (2004) Estimation of debris-flow magnitude in the eastern Italian Alps. Earth Surf Process Landf 29:207–220
Mergili M, Schneider D, Worni R, Schneider J (2011) Glacial lake outburst floods in the Pamir of Tajikistan: challenges in prediction and modelling. In: Genevois, R; Hamilton, D L; Prestininzi, A. 5th international conference on debris-flow hazards mitigation: mechanics, prediction and assessment. Padua: Università La Sapienza, 973-982.
Marchi L, Brunetti MT, Cavalli M, Crema S (2019) Debris-flow volumes in northeastern Italy: relationship with drainage area and size probability. Earth Surf Process Landf 44:933–943
Melton MA (1965) The geomorphic and paleoclimatic significance of alluvial deposits in Southern Arizona. J Geol 73(1):1–38
Mikoš M, Četina M, Brilly M (2004) Hydrologic conditions responsible for triggering the Stoze landslide. Slovenia Eng Geol 73(3–4):193–213
Mikoš M, Fazarinc R, Pulko B, Petkovšek A, Majes B (2005) Stepwise mitigation of the Macesnik landslide. N Slovenia Nat Hazards Earth Syst Sci 5(6):947–958
Mikoš M, Jemec M, Ribičič M, Čarman M, Komac M (2013) Earthquake-induced landslides in Slovenia: historical evidence and present analyses. In: Ugai K, Yagi H, Wakai A (eds) earthquake induced-landslides. Springer, Berlin, pp 225–233
Panagos P, Borrelli P, Poesen J, Ballabio C, Lugato E, Meusburger K, Montanarella L, Alewell C (2015a) The new assessment of soil loss by water erosion in Europe. Environ Sci Pol 54:438–447
Panagos P, Ballabio C, Borrelli P, Meusburger K, Klik A, Rousseva S, Tadić MP, Michaelides S, Hrabalíková M, Olsen P, Aalto J, Lakatos M, Rymszewicz A, Dumitrescu A, Beguería S, Alewell C (2015b) Rainfall erosivity in Europe. Sci Total Environ 511:801–814. https://doi.org/10.1016/j.scitotenv.2015.01.008
Petkovšek A, Fazarinc R, Kočevar M, Maček M, Majes B, Mikoš M (2011) The Stogovce landslide in SW Slovenia triggered during the September 2010 extreme rainfall event. Landslides 8(4):499–506
Pierson TC (2005) Hyperconcentrated flow; transitional process between water flow and debris flow. In: Jakob M, Hungr O (eds) debris-flow hazards and related phenomena. Springer, Berlin, pp 159–202
Piton G, Recking A (2015) Design of sediment traps with open check dams. I: hydraulic and deposition processes. J Hydraul Eng 142(2):04015045
RAMMS (2018) User Manual v1.7.0 Debris Flow. 2018. Available online: http://ramms.slf.ch/ramms/downloads/RAMMS_DBF_Manual.pdf. (accessed on 9 July 2019).
Rickenmann D, Recking A (2011) Evaluation of flow resistance in gravel-bed rivers through a large field data set. Water Resour Res 47(7):W07538
Schneider D, Huggel C, Cochachin A, Guillen S, Garcia J (2014) Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru. Adv Geosci 35:145–155
Scheidl C, Chiari M, Kaitna R, Mullegger M, Krawtschuk A, Zimmermann T, Proske D (2013) Analysing debris-flow impact models, based on a small scale modelling approach. Surv Geophys 34(1):121–140
Smart GM, Jäggi MNR (1983) Sediment transport on steep slopes, Mitt. 64, pp. 89–191, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich, Zurich, Switzerland.
Sodnik J, Mikoš M (2006) Estimation of magnitudes of debris flows in selected torrential watersheds in Slovenia. Acta geogr Slov 46(1):93–123
Šraj M, Dirnbek L, Brilly M (2010) The influence of effective rainfall on modeled runoff hydrograph. J Hydrol Hydromech 58:3–14
Takei A (1984) Interdependence of sediment budget between individual torrents and river-system. Interpreavent 1984 – Villach, Vol. 2. Villach.
Tokay A, Wolff DB, Petersen WA (2014) Evaluation of the new version of the laser-optical disdrometer, OTT Parsivel. J Atmos Ocean Technol. https://doi.org/10.1175/JTECH-D-13-00174.1
Zollinger F (1983) "Die Vorgänge in einem Geschiebeablagerungsplatz (ihre Morphologie und die Möglichkeiten einer Steuerung) [Processes in debris detention basins for torrent control (A morphology and the possibilities of control)]." Ph.D. thesis, ETH Zürich, Zurich, Switzerland (in German).

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