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Debris flooding magnitude estimation based on relation between dendrogeomorphological and meteorological records

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ABSTRACT

Debris floods are mass movement events which are usually triggered by intense short duration rainfall events. They often occur on alluvial fans in an alpine environment. Due to their sever geohazard potential they pose a serious threat to infrastructure and human life. To minimize their threat understanding of their past magnitude occurrence is crucial. Dendrogeomorphology has proven to be a highly useful method in studies of past slope mass movements. However, establishing magnitudes of past events has so far been based on indirect indicators, such as: spatial distribution of affected trees, characteristics of tree injures and sedimentological records. In this study we present a method that directly estimates the magnitudes of past debris flood events on an alluvial fan using dendrogeomorphological and meteorological data sets. The studied dendrogeomorphological data set is based on tree-ring series from 105 sampled trees (*Picea abies*, *Abies alba* and *Larix decidua*) growing on an active alluvial fan in a typical alpine environment of the Julian Alps in NW Slovenia. Based on sudden growth suppression thirteen debris flood events since 1903 were dated. Meteorological data from a nearby meteorological station was used to determine the exact triggering meteorological event for ten events. Comparing the I_t index of affected trees and calculated return period of an individual triggering meteorological event established the magnitude of debris flooding. We showed that more trees are affected at high return period/intensity of the triggering meteorological event and therefore higher magnitudes of debris floods. This research presents the first combined use of dendrogeomorphological and meteorological data sets for magnitude estimation of historic debris flood events which could be successfully applied in similar environments.

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1. Introduction

In the Alpine environments the majority of sediment supply on alluvial fans is mobilised during major rainfall events (Harvey, 2012). Depending on different geological setting, sediment is transported by different transport processes; e.g. fluvial sediment transport, debris flows or debris floods and deposited in form of fans and cones (Hungr et al., 2001; Hungr, 2005; Rickenmann and Scheidl, 2012; Hungr et al., 2014). In the case of populated areas these events often pose a serious threat not only to infrastructure but also to human life. In order to minimize the debris flood hazard risk data on their past magnitude, timing and location is needed. Such information can be used in hazard mapping and spatial planning, as it can provide potential flow directions of future debris floods, areas of possible channel avulsions, and areas vulnerable to debris flood events (Jakob and Bovis, 1996; Skermer and VanDine, 2005; Bowman, 2019). This is quite problematic, because historic data and human memory are usually incomplete, inaccurate or lack sufficient spatial or/and temporal length and scale (Skermer and VanDine, 2005), therefore several other research methods and techniques of dating and spatial analysis need to be applied in order to better understand transport processes in an alluvial fan environment (Jakob, 2005; Schneuwly-Bollschweiler et al., 2013).

Dendrogeomorphology is a very successful method for dating geomorphological events based on growth anomalies in tree rings (Alestalo, 1971; Shroder, 1978, 1980). The method proves to be efficient in studies of mass movement events on fans and cones, such as debris flows and debris floods, regarding their spatial, temporal and frequency distribution (Mayer et al., 2010; Schneuwly-Bollschweiler and Stoffel, 2012; Ouellet and Germain, 2014). Magnitudes of past mass movement events however, can be determined only on the basis of stratigraphic records of deposited lobes (i.e. their thickness), the spatial distribution of affected trees and the height or dimension of growth disturbances on stems (Bollschweiler and Stoffel, 2010; Schraml et al., 2013). Therefore, the need for additional methods of magnitude estimation regarding past debris flood events on alluvial fans is crucial to fully understand their occurrence (Bovis and Jakob, 1999; Stoffel, 2010).

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Here we present a method approach based on pairing multi data to estimate magnitudes of past debris flooding events. It is based on the relation between the calculated dendrogeomorphic I_t index and return periods of potential triggering meteorological events. To test this method, we choose the area of the Julian Alps in NW Slovenia (Fig. 1) because of: (i) frequent occurrences of mass movement events, which pose threat to infrastructure and human life (Mikoš et al., 2004; Zorn and Komac, 2004; Mikoš et al., 2006a; Mikoš et al., 2006b; Komac and Zorn, 2007; Komac, 2009; cf. Komac et al., 2009); (ii) incomplete historic records, which cover only very recent and most catastrophic events based predominantly on human memory and do not include minor mass movement events (Zorn and Komac, 2004; Zorn et al., 2006; Komac and Zorn, 2007; Komac, 2009); (iii) very detailed meteorological records that cover a period of almost sixty years.

The aim of this research is to determine magnitudes of past debris flood events on an active alluvial fan in a typical Alpine environment. In order achieve this we: (i) reconstructed spatio-temporal occurrence of past debris flood events on an alluvial fan in the Julian Alps in Slovenia (Fig. 1) using dendrogeomorphological methods, (ii) related dendrogeomorphological data with meteorological records in order to determine exact meteorological events which triggered debris floods and (iii) estimated the magnitude of debris flood events based on dendrogeomorphological dating and return periods of triggering meteorological events. Additionally, this study represents one of the few dendrogeomorphological studies from the Southern Alps and its broader area (Mayer et al., 2010; Oven et al., 2019).

1.1. Study sit

The research was carried out in the Planica Valley located in the Julian Alps in the north-western Slovenia. The valley is orientated in the north-south with an entrance close to the Rateče village (864 m a. s. l.) (Fig. 1a, b). We chose this valley because of (i) proximity to the Rateče meteorological station (Fig. 1b, c), (ii) high debris flooding activity, (iii) type of vegetation and (iv) vicinity of the newly built ski-jumping infrastructure. Ski-jumping facilities, first built in the 1930s and recently rebuilt and enlarged in 2010s, are becoming a major tourist attraction and are built in direct vicinity to the Rančev graben (RG) alluvial fan (Figs. 1b, 2), where our research was conducted.

The valley is a typical mountainous glacial valley bounded by steep slopes composed mainly of Upper Triassic carbonates (Ramovš, 1981; Ogorelec, 1984; Jurkovšek, 1987a, 1987b; Celarc, 2004; Celarc and Placer, 2006; Celarc et al., 2013; Gale et al., 2015). The physical erosion of steep carbonate slopes produces relatively large quantity of coarse-grained material, which is transported by different sedimentary processes to the valley floor, where they form different unconsolidated Holocene sedimentary bodies (Bohinec, 1935; Popit et al., 2013; Zupan, 2013; Šmuc et al., 2015; Novak et al., 2018). Sediments transported by debris floods are forming alluvial fans, which represent one of the largest and most common sedimentary bodies in the Planica Valley. Due to the high porosity of Holocene sediments there are no permanent surface water streams (Novak et al., 2018). Consequently, the deposition of sediments onto alluvial fans in the Planica Valley is related only to sporadic short-duration heavy precipitation events in autumn and spring and to a lesser extent to rapid snowmelt in spring. Heavy rain mobilises sediment from the catchment area and transport it via active torrential feeder channels and distributary channels on the middle and distal part of the fan. Here the sediment is deposited in the form of sedimentary lobes and sheets composed of carbonate sub-angular to sub-rounded clast-supported moderately sorted gravels and sands. Lobes and sheets therefore represent episodic debris flooding depositional events (Novak et al., 2018).

Historic documentations of various mass movements and debris flood events induced by heavy or extreme rainfall in the Planica Valley and its immediate surroundings are rare. Only a few extreme and catastrophic, but no minor mass movements and debris flood events have been documented, and described or analysed for the period of the last two decades. Such an event is a debris flow caused by a record breaking monthly precipitation in November 2000 under the slopes of Mount Ciprnik in the Planica Valley (Zorn and Komac, 2004; Komac and Zorn, 2007; Komac, 2009; Šmuc et al., 2015). In August 2003 intense three-day precipitation event caused floods and landslides in the Rateče village and its wider area (Dolinar, 2004; Zorn et al., 2006). Similarly, an intense rainfall event occurred in June 1996 in the upper part of the Fella river basin in Italy approximately 20 km away from our research area, causing several debris flows and debris floods (Paronuzzi et al., 1998). On the basis of meteorological records, there have been several rainfall events in the past few decades that could potentially trigger debris flooding events. An example of such an event is a short, but intense rainfall event in October 2008 (ARSO, 2018a). However, there are no records whether or not such recorded precipitation events actually triggered debris floods or any other mass movement events. The studies mentioned above do not include dendrogeomorphological dating. These relatively short-term observations and descriptions of singular mass movements miss several older and undocumented events. As such they cannot provide enough information on the past complex spatio-temporal occurrence of debris floods in an area with high human and mass movement activity.

Vegetation in the Planica Valley is diverse and depends on elevation and stage of the succession. Mixed forest of European beech *Fagus sylvatica* L., subalpine Norway spruce *Picea abies* (L.), European silver fir (*Abies alba*), Dwarf mountain pine *Pinus mugo* L., and various shrub communities are predominant in this area (Dakskobler, 2015).

2. Material and methods

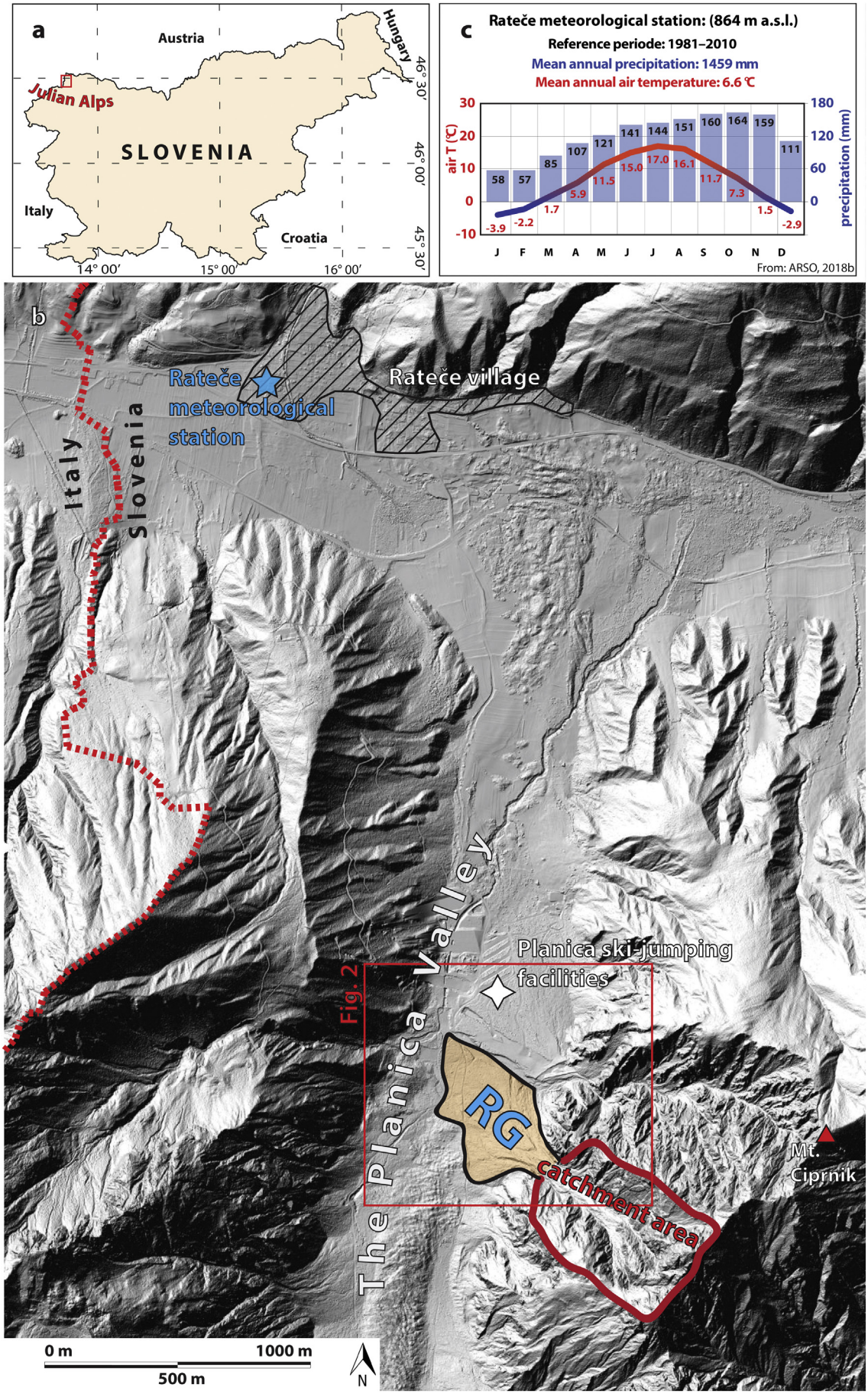
2.1. Meteorological characteristics of the research area

The meteorological data and calculations of rainfall return periods we used in this study are obtained from and calculated by the Slovene Environmental Agency (ARSO). A permanent meteorological station is located in the Rateče village (Fig. 1b) and is collecting data since 1. 1. 1961 (ARSO, 2018a). The mean annual precipitation value for the Rateče meteorological station is 1459 mm, with the annual precipitation maximum in autumn (ARSO, 2018b; Fig. 1c). According to the Slovenian Environment Agency, intense rainfall is defined as a 24-hour precipitation event that exceeds 50 mm of precipitation (ARSO, 2006). On average such events occur six to eight times per year at the Rateče meteorological station and eight to ten times at the Planica Valley (ARSO, 2006; ARSO, 2018b, 2018c). Based on the precipitation values, measured at the Rateče meteorological station, return periods of extreme 24-hour rainfall events are calculated by ARSO based on Gumbel's method and cover the period between 1975 and 2012 (ARSO, 2006; ARSO, 2009; ARSO, 2018d) and are shown in Table 1.

2.2. Sampling sites and sampling methods

Our research was performed on Rančev graben alluvial fan (RG) (Figs. 1b, 2), which is a typical sheetflood fan (cf. Collinson, 1996; cf. Nichols, 2009). The fan is located under the slopes of Mountain Ciprnik in the proximity of the Planica ski-jumping facility. The fan covers an area of approximately 15 ha and has a catchment area of approximately 28 ha. From the catchment area two distributary channels marked as torrential channels **A** and **B** (Fig. 2) are emerging. Both channels have a short

Fig. 1. a) Location of the Planica Valley in the Julian Alps, NW Slovenia. b) Location of the Rančev graben (RG) alluvial fan in the Planica Valley. c) Meteorological diagram with the climatic characteristics of the research area recorded at the Rateče meteorological station.


a
Austria
Hungary
Julian Alps
SLOVENIA
Italy
Croatia
46° 30′
46° 00′
45° 30′
14° 00′
15° 00′
16° 00′
c
Rateče meteorological station: (864 m a.s.l.)
Reference periode: 1981–2010
Mean annual precipitation: 1459 mm
Mean annual air temperature: 6.6 ℃
air T (℃)
precipitation (mm)
30
20
10
0
-10
180
120
60
0
58 57 85 107 121 141 144 151 160 164 159 111
-3.9 -2.2 1.7 5.9 11.5 15.0 17.0 16.1 11.7 7.3 1.5 -2.9
J F M A M J J A S O N D
From: ARSO, 2018b
b
Italy
Slovenia
Rateče meteorological station
Rateče village
Planica ski-jumping facilities
Fig. 2
The Planica Valley
RG
catchment area
Mt. Ciprnik
0 m
500 m
1000 m
N

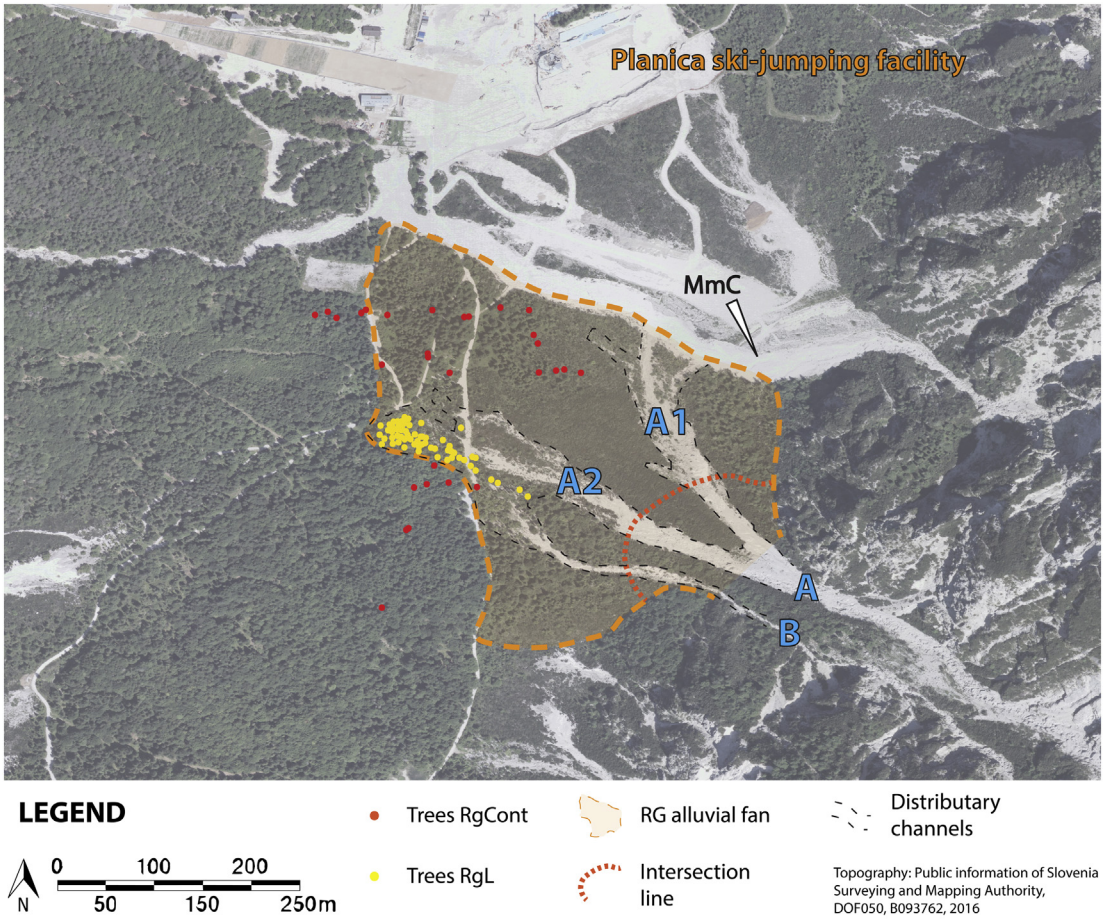


Fig. 2. Locations of the sampled trees on the Rančev graben (RG) fan. The trees are divided into a sampling group (RgL – yellow dots) and a control group (RgCont – red dots). Distributary channels are marked with corresponding letters. Partially manmade channel (MmC) is indicated with white arrow.

runoff and begin to widen and deposit the sediment after the intersection line. Channel **A** splits further into two channels, which we marked as **A1** and **A2**. Channel **A1** discharges into a partially manmade channel, which is part of the neighbouring alluvial fan. Channel **A2** merges with channel **B**, which terminates at the valley's floor in a fan shaped lobe (Fig. 2).

The research follows the methodology of the field tree sampling, sample preparation and sample analysis described by several authors done in a similar research setup (Wilford et al., 2005; Stoffel et al., 2010; Gärtner and Heinrich, 2013; Stoffel et al., 2013; Stoffel and Corona, 2014). Samples were collected between September and November 2015 from the partially buried trees growing on the surface of Rančev graben alluvial fan and the area in its immediate vicinity (Fig. 2). Only coniferous trees were sampled, mainly Norway spruce (*Picea abies*) with addition of six Silver firs (*Abies alba*) and three European larches (*Larix decidua*). The Sample collection is composed of cores from 105 sampled trees divided into a group of affected trees (76 sampled trees) and a group of control tree (29 sampled trees, only Norway spruce species) (Fig. 2). The group of affected trees, marked as a RgL group, was sampled at the left flank of the alluvial fan at the terminal parts of torrential channels **A2** and **B**. There the sediment is deposited in a minor fan shaped lobe covering an area of 0.41 ha (app. 130 m long and up to 40 m wide) with a gradient of approximately 10°. The trees at this site are partially buried (from a few tens of centimetres to one-metre-high) by unconsolidated carbonate gravel and sand. According to the research of Strunk (1997) and Kogelnig-Mayer et al. (2013) such trees are suitable for debris flooding dating. A control group of unaffected trees marked as RgCont was sampled to build a reference chronology. These trees were sampled outside and within the area of the alluvial fan and not affected by debris flood events or any other type of mass movements (Fig. 2). Four cores per tree were taken perpendicular to each tree's stem direction at a breast height. The diameter at the breast height was measured with tape and the position of the tree was acquired with a handheld GPS device. From 105 trees, altogether 391 samples were measured and analysed with the CooRecorder and CDendro programs respectively (Cybis Dendrochronology, 2019). The reference chronology was built from undisturbed Norway spruce cores sampled at the RgCont site. These were visually and statistically synchronised and crossdated using statistical analysis with the Student's *t*-test. The growth curves of individual core samples of affected trees (group RgL) were visually and statistically cross-dated to the reference chronology curve to identify missing tree rings and/or growth disturbances (e. g. Schweingruber, 1996). In the course of visual crossdating, identification of missing rings, and disturbances we examined each sample under the stereomicroscope.

Table 1
Return period of extreme rainfall events for the Rateče meteorological station for the period between 1975 and 2012 (data acquired from ARSO, 2009; ARSO, 2018d).

Return period in years	1[a]	2	5	10	25	50	100	250
24-hour rainfall in mm	48[a]	87	116	135	160	178	196	219

[a] Value acquired from ARSO (2009).

2.3. Dating of events based on dendrogeomorphological data

The dating of debris flood events is based on the number of growth disturbances recorded in the tree rings of the affected trees. We were

specifically searching for severe growth surpressions indicating tree burial by sediment transported by debris floods. Growth suppressions were determined by at least a 50% reduction in the tree-ring width in comparison to previous growth rings in an individual sample. To fully attribute growth suppressions to debris flooding the suppression must have had continued for at least four consecutive years. The suppressions were determined on a growth curve based on tree-ring width as well as visual observation of the samples. The growth of the affected trees was also compared with the reference curve to fully confirm the debris flood event and to exclude the possibility of other environmental influences.

During sampling prominent tilting and scars were rarely detected in the sampled trees. Nevertheless, we have also paid attention to the possible presence of other growth disturbances in the core sample collection, such as rows of traumatic resin ducts, reaction wood, and abrupt growth releases. These growth disturbances could be attributed to the influences of debris floods. Scares caused by the transport of sediment (gravel) could be later overgrown (closed), leaving only traumatic resin ducts indicating past tree injuries. Similarly, tree tilting could have occurred in earlier decade due to the accumulation of the debris lobes, but tilt could appear less pronoun during sampling, making reaction wood only indicator of debris flood events. Abrupt growth releases could occur due to elimination of competition at the undisturbed neighbouring trees. Growth releases were additionally compared with the reference curve to confirm that the release was linked to geomorphic processes and not to climate.

Debris flood events were dated based on the replication concept, which states that only the years in the tree-ring record with growth disturbances registered by significant number of trees are considered as event years. We dated the debris flood events based on the number of growth suppressions in sample trees alive at the same year, sample depth and growth site of trees. Based on the number of trees showing growth suppression and sample depth we calculated the I_t index value following the concepts of Shroder (1978) and Butler and Malanson (1985):

$$I_t = \left(\sum_{i=1}^{n} R_t / \sum_{i=1}^{n} A_t \right) \times 100\%$$

Here R is defined as the number of trees showing growth suppression as a possible response to a debris flood in the year t, and A is defined as the total number of sampled trees alive in the year t. Years with the I_t index value for growth suppressions exceeding the 9.00% minimum threshold were considered as debris flood event years. Since growth suppressions are the best expressed and most abundant growth disturbances in our study, other disturbances (growth release, traumatic resin ducts and reaction wood) were used to corroborate debris flood events expressed by growth suppressions. We used the I_t threshold of 9.00% as the minimum threshold to successfully date the event. Research done by other author (Mayer et al., 2010; Lopez-Saez et al., 2012; Lopez-Saez et al., 2014) states the minimum threshold of affected trees is between 4 and 5%. However, our research was not conducted on a large alluvial fan surface, but on relatively small and localized areas of an individual fan. To avoid overestimation of events, we chose a more conservative approach and adopted a twice-higher minimum threshold, since growth disturbances with smaller threshold could be attributed to effects of human activity, primary to road repairs after debris flood events and forest management. To further avoid overestimation of events we confirmed only the events where there were >50% alive affected trees based on RgL group sample depth.

2.4. Determination of the meteorological triggering event and magnitude estimation of debris flood event based on comparison of dendrogeomorphological and meteorological data

Estimation of debris flooding event magnitude is based on comparison of the I_t index of affected trees (Shroder, 1978; Butler and Malanson, 1985) and return periods of potential triggering meteorological events. Based on the I_t value in our dendrogeomorphological data set we determined the magnitude of debris flood events by categorizing them into events with low tree response i.e. low magnitude debris flood event (9.0% to 18.0% I_t index value), moderate tree response i.e. moderate magnitude debris flood event (18.1% to 27.0% I_t index value) and high tree response i.e. high magnitude debris flood event (≥27.1% I_t index value). Such categorisation follows the two and three times multiple of our chosen minimum threshold.

Dendrochronologically dated debris flood event years were later compared with the precipitation data in order to find possible debris flooding triggering meteorological events. We set the precipitation threshold for a debris flood triggering meteorological event at 50 mm of rainfall in 24 h, which is a slightly higher threshold compared to other studies (Paronuzzi et al., 1998; Guzzetti et al., 2007; Guzzetti et al., 2008), but it corresponds to the ARSO (2006) definition of an intense 24-hour rainfall event. In addition, we included rainfall sums for various longer periods (48, 72, 168, 336 h), which accompany potential 24-hour triggering events. This was done in order to take in consideration low intensity long duration events as possible meteorological triggering events (cf. Caine, 1980; Guzzetti et al., 2007; cf. Guzzetti et al., 2008). High precipitation events at the study site occur mainly in autumn, which is out of the growing season of sampled trees. Since the tree response to a geomorphological event, occurring out of the growing season is delayed (Shroder, 1978), meteorological data was also analysed for a year preceding the year of growth disturbance recorded in a tree-ring set.

The magnitude of meteorological triggering events is established based on the calculated return periods of intense 24-hour rainfall events by ARSO (2009). Intense 24-hour rainfall events were categorised as events with 1, 2, 5, 10, 25, 50, 100 or 250 year return periods, depending on the rainfall amount. For the purpose of this study, we categorised events with a return period from 1 to 5 years as low magnitude meteorological events, 10 to 50 year return period as moderate magnitude meteorological events, and events with 100 to 250 year return period as high magnitude meteorological events.

The final result is the dendrogeomorphological and meteorological categorisation of the event, which estimates the magnitude of the debris flooding. This derives from a comparison between the value of categorised calculated I_t index and categorised return period of 24-hour precipitation triggering meteorological event.

3. Results

Debris flood events at Rančev graben alluvial fan usually affect trees by partially burying them in the middle and distal parts of the fan. Prominent tilting, scars, exposed roots and decapitations caused by debris floods were only very rarely observed.

3.1. Growth disturbances in the RgL group

Growth suppressions are the strongest growth disturbance indicators for a debris flood event in our sample collection and have the I_t index calculated. The number of sampled trees available for the analysis (sample depth) at a given year and the number of trees affected by growth suppressions for the RgL group are present in the Fig. 3. Rows of traumatic resin ducts occur in only up to four trees per year, while there are two major growth releases in the years 1940 (14 trees) and 1983 (11 trees). Compression wood was documented predominantly in the juvenile stage of the tree growth (first 20 years of growth) and only a number of trees having compression wood out of that stage are presented in the Appendix. Trees in the RgL group affected by different growth disturbances in the same year are presented in the Appendix.

Based on sample depth, tree location and the I_t Index in the RgL group we can determine events with a sufficient degree of confidence for the period from the year 1903 onwards since there are >50% affected trees alive and available for dating (Fig. 3). Types of growth disturbances

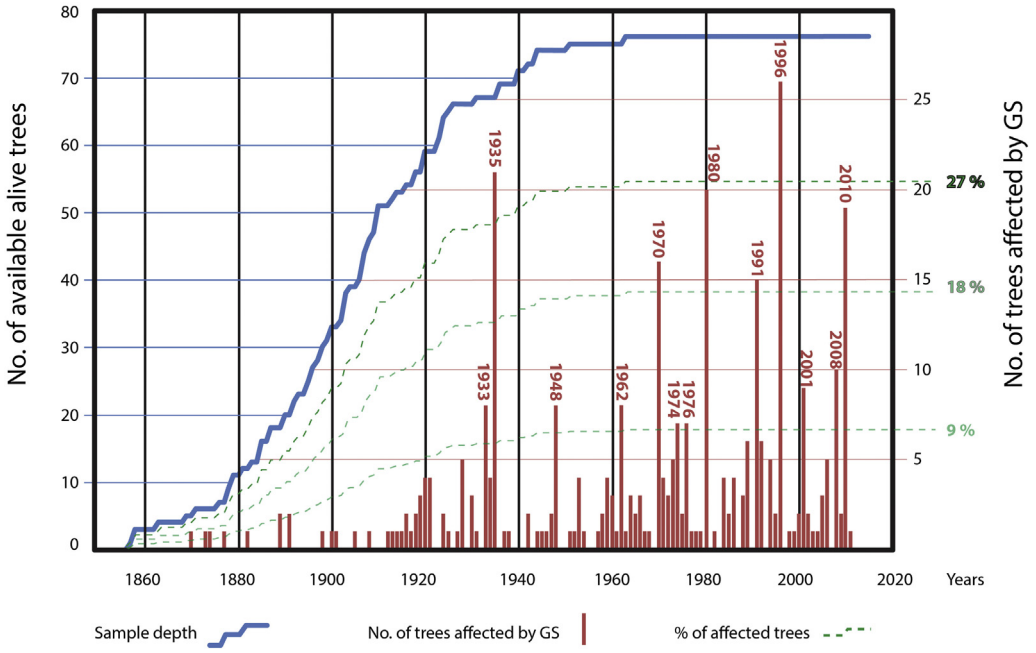


Fig. 3. Number of sampled trees available for the analysis (sample depth, blue curve) and number of trees affected by growth suppressions (GS) per year (red columns) for the RgL group. Additionally, magnitude thresholds (9, 18 and 27%) are marked (green dashed curves).

such as growth suppressions and growth releases are well expressed and numerous, while rows of traumatic resin ducts and reaction wood are rare (Appendix). Growth suppressions which exceed the threshold of 9.00% are found in the years 1933, 1935, 1948, 1962, 1970,1974, 1976, 1980, 1991, 1996, 2001, 2008 and 2010 (Fig. 3), indicating burial of trees with sediment transported by debris flood events.

3.2. Relating the I_t index with meteorological data and event magnitude estimation

Relating events exceeding the 9.00% I_t threshold with meteorological data, primary with 24-hour precipitation values, determined the exact triggering meteorological events. The potential triggering meteorological events and their precipitation values are presented in Fig. 4. Based on the value of the calculated I_t index and the return period of a 24-hour precipitation triggering meteorological event the magnitudes of debris flooding events were determined. The temporal sequence of debris flood and meteorological events along with magnitudes of debris flood and meteorological events for the RgL group are represented on the timeline in Fig. 5.

Because the meteorological data has been gathered from 1. 1. 1961 onwards, we could not relate it with growth suppressions in the years 1933, 1935 and 1948. Values of I_t indexes for the years 1933 and 1948 are 11.49% and 10.81% respectively, marking those debris flood events as low magnitude events. The I_t index for the year 1935 is 31.34%, marking this a high magnitude debris flooding event.

3.2.1. Year 1962

An I_t index of 10.67% marks the year 1962 as a low magnitude event year. Five 24-hour precipitation events that could trigger debris flood happened on the 8th (59.3 mm), 18th (70.4 mm) and 19th (86.7 mm) of October 1961, 13th (59.6 mm) of November 1961 and on the 14th (89.2 mm) of May 1962 (Fig. 4). These five rainfall events with a return period of one to two years (Table 1) are low magnitude rainfall events occurring at the beginning or out of the growth season and are potential triggers of a low magnitude debris flood event. A prolonged 48-hour precipitation between 18th and 19th of October with 157.1 mm of rainfall makes this event the most likely meteorological trigger of debris flood.

In addition to the 24-hour and 48-hour events, few notable long-term precipitation events occurred (Fig. 4), most notable ones are, 336-hour precipitation between 2nd and 15th November (184.8 mm), which exceeds the values of the average monthly precipitation and above average monthly precipitation in October 1961 (266.1 mm) and May 1962 (297,1 mm). The latter monthly precipitations twice exceed the monthly precipitation, although the greater proportion of rainfall occurred in short-term precipitation periods, which makes them the more likely triggers.

3.2.2. Year 1970

Growth suppressions in the year 1970 have an I_t index of 21.02% which indicates a moderate magnitude event. Three 24-hour precipitation events that could trigger debris floods happened on the 22nd August (137.6 mm), 14th (143.2 mm) and 15th November (60.1 mm) 1969 (Fig. 4). All three events happened late or outside the growth season of previous year (year 1969), which makes these precipitation events the most likely triggering meteorological events. According to return period values, the events of the 22nd August and 14th November fall into the category of an event with a 10 to 25 year return period (Table 1), making them moderate meteorological triggering events. The rainfall event on the 15th of November has a one to two year return period, making it a low magnitude event.

An intense 48-hour rainfall event, which exceeds the average monthly precipitation occurred between the 14th and 15th November 1969. Although additional sums of long-term periods accompanying short-duration rainfall add-up to above average monthly precipitation, the majority of the precipitation happened in the short-period (24- and 48 h) events. Since these events occurred late or outside of the growing season of 1969 it is most likely that a moderate amount of growth suppressions in 1970 were caused by moderate magnitude debris flood events, triggered, in particular, by moderate rainfall events on 22nd August and/or 14th November 1969.

3.2.3. Year 1974

Growth suppressions in the years 1974 have an I_t index of 9.21% indicating to be a low magnitude event. In the year 1974 there were no precipitation events exceeding the threshold of 50 mm, however, four

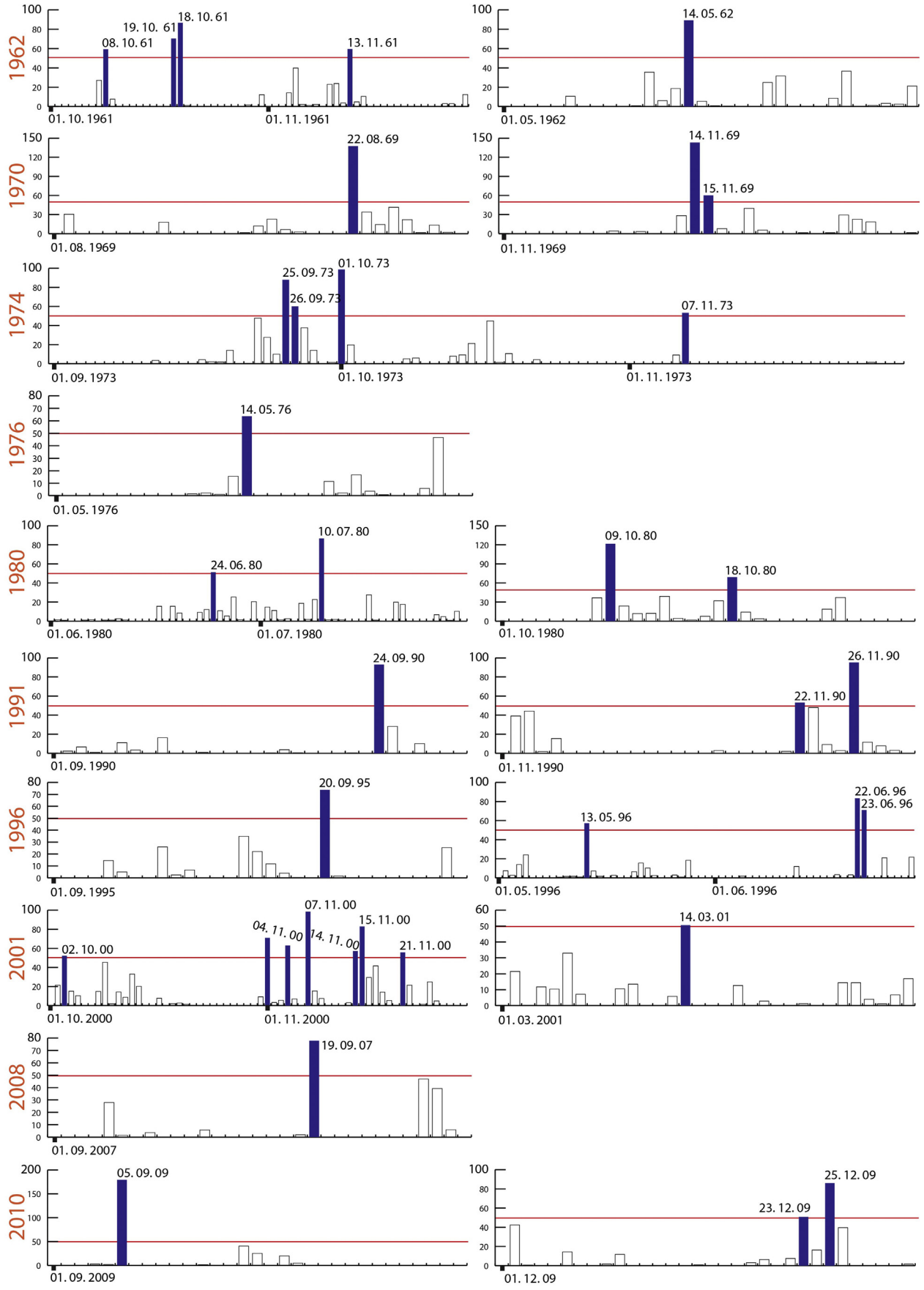


Fig. 4. Potential triggering meteorological events (blue columns) which exceed the 50 mm threshold (red line) for each event year.

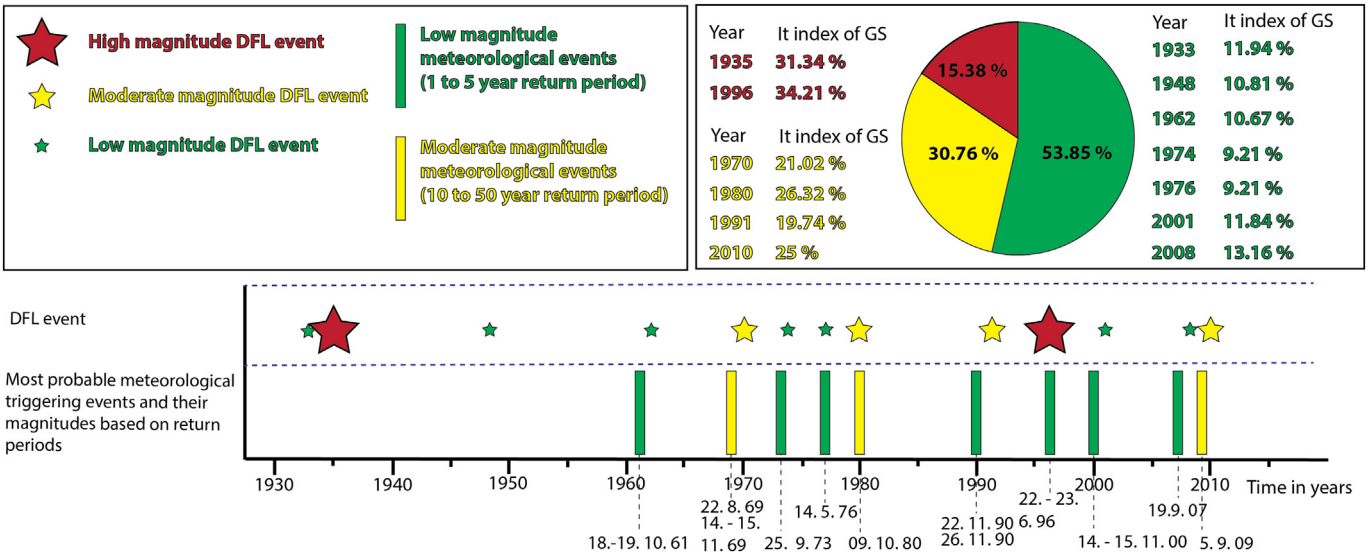


Fig. 5. Timeline of debris flood events dated based on growth suppressions. Dated debris flood events are paired to the most probable meteorological triggering events, for which magnitudes are based on their return periods. There is a relation between the I_t index based magnitude of debris flood event and magnitude of the triggering meteorological event based on its return period.

events on the 25th (87.9 mm) and 26th (60.1 mm) of September, 1st of October (98.8 mm) and 7th of November (53.3 mm) 1973 exceed the threshold (Fig. 4). These rainfall events with return periods of one to two and two to five years (low magnitude triggering meteorological events, Table 1) occurred out of the growing season and are the most likely triggers of low magnitude debris flood events. The most prominent is a 48-hour rainfall event between 25th and 26th September, which is the most likely meteorological triggering event. Although sums of long-term 168- and 336-hour precipitation periods in late September, which exceed the average monthly precipitation more than twice, are notable, the rainfall peak occurred in short-term 24- and 48-hour precipitation events.

3.2.4. Year 1976

Growth suppressions in the year 1976 have an I_t index of 9.21% indicating them to be low magnitude event responses. Only one precipitation event exceeds the 50 mm threshold on the 14th of May 1976 (Fig. 4), when 63.6 mm of rainfall occurred at the beginning of the growth season, making it a low magnitude triggering event with a return period of one to two years (Table 1). This low magnitude meteorological event is the most likely trigger of a low magnitude debris flood event. Sums of various longer precipitation periods do not show any potential meteorological triggering event, since they not exceed average monthly precipitations and are interrupted by several dry periods.

3.2.5. Year 1980

With an I_t index of 26.32% this is considered a year with a moderate magnitude event. In the year 1979 there were no high 24- or 48-hour precipitation events exceeding 50 mm threshold that could potentially trigger a debris flood. Possible meteorological triggering events occurred on the 24th June (51.2 mm), 10th July (86.6 mm), 9th (121.6 mm) and 18th (69.3 mm) of October 1980 (Fig. 4). Events in June, July and 18th October have a one to two year return period, making them low magnitude meteorological events, while the event on the 9th October is a moderate magnitude meteorological event with a return period of 5 to 10 years. The events occurred at the peak or out of the growing season making them difficult to link with growth suppressions in 1980. However, based on meteorological data, average monthly temperatures in March, April, May and July in 1980 were up to 2 °C colder than average (ARSO, 2018a). In addition, 1980 was on average the second coldest year since the beginning of meteorological measurements. A relatively colder beginning of growth season could postpone the sprout of sampled trees, which were later buried by debris flood in June, July and October. It is possible, that growth suppressions in 1980 were caused by combination of a relatively cold beginning of the growth season and continued by partial burial caused by moderate magnitude debris flood event, most likely triggered by moderate triggering rainfall on the 9th of October 1980.

3.2.6. Year 1991

With an I_t index of 19.74% this is a year with a moderate magnitude debris flood event. There were no high precipitation events in the year 1991, which could cause a debris flood. However, three events exceed the threshold in 1990. These occurred on the 24th of September (93 mm), 22nd of November (53.2 mm) and 26th of November (95.2 mm) 1990 (Fig. 4). All three meteorological events are low magnitude meteorological events with a one to two or two to five year return period. The sums of long-term precipitation in September and November 1990 (168- and 336-hour precipitations) do not show a possible triggering event, since they do not exceed average monthly precipitation. Additionally, all of the long-term precipitation events have interruptions with more than one 24-hour dry period. Most notable is a 72-hour precipitation event between the 22nd and 24th November, followed by intense 24-hour rainfall on the 26th of November. This four-day event with 208.3 mm of rainfall is the most probable meteorological triggering event. These events occurred out of the growing season and are best candidates for triggering moderate debris flood, which later on caused growth suppressions in 1991.

3.2.7. Year 1996

With an I_t index of 34.21% this year contains a high magnitude debris flood event. Four events exceeding the threshold occurred on the 20th September (73.8 mm) 1995, 13th May (57.3 mm) 1996, 22nd (83.4 mm) and 23rd (71.0 mm) June 1996 (Fig. 4). All four events have a return period of one to two years making them low magnitude meteorological triggering events. However, a combined 48-hour precipitation event between the 22nd and 23rd of June 1996 had 154.4 mm of rainfall, which presents almost 10% of all rainfall in the year 1996. At the same time, severe debris flooding events triggered by intense torrential rain happened in north Italy in the Fella river basin not far from our research area (Paronuzzi et al., 1998). Since the 48-hour event occurred at the peak of the growing season, it is most likely that growth suppressions were

caused by high magnitude debris flood events triggered by a meteorological event in that period. Sums of long-term precipitation do not show a possible triggering event, because larger proportions of rainfall occurred in short-term events. Additionally, sums of long-term precipitation events were interrupted by one or more 24-hour dry periods (Fig. 4).

3.2.8. Year 2001

Growth suppressions in the year 2001 have an I_t index of 11.84% making the debris flood event a low magnitude event. Eight potential triggering meteorological events exceed the threshold of 50 mm of rainfall in 24 h and all of them have a return period of one to two years (Fig. 4). One occurred on the 2nd October 2000 (52.2 mm) and one in 14th March 2001 (50.6 mm), while all the rest happened in November 2000 (1st (71 mm), 4th (63 mm), 7th (98.5 mm), 14th (57.2 mm) and 15th (82.9 mm)). All of these events have return periods from one to two or two to five years, making them low magnitude events. Notable events occurred on the 14th and 15th November 2000, which combined have 140.1 mm of rainfall in 48 h. Meteorological data shows that long-term record-breaking rainfall events occurred in November 2000 (613.6 mm), which triggered a debris flow and a complex landslide in the Planica Valley (Zorn et al., 2006; Komac and Zorn, 2007; Zupan, 2013; Komac, 2009; Šmuc et al., 2015). However, based on the amount of growth suppressions at the site of the Rančev graben alluvial fan only a low magnitude debris flood event occurred. As these potentially triggering meteorological events took place outside the growing season, predominantly in the year 2000, growth suppressions recorded in the tree-ring record of 2001 can be attributed to the causes of the low magnitude debris flooding in autumn 2000.

3.2.9. Year 2008

With an It index of 13.16% this is a low magnitude event year. Only one low magnitude meteorological event exceeds the precipitation threshold of 50 mm. It occurred on the 18th of September 2007 (77.9 mm) and has a one to two year return period (Table 1, Fig. 4). The sum of long-term precipitation does not show a possible triggering event, since monthly precipitation values are not above average and all of the long-term precipitation events have interruptions with more than one 24-hour dry period. Because the tree response is low and the rainfall event has a low magnitude, it is most probable that growth suppressions were caused by a low magnitude debris flood event induced by low magnitude rainfall in September 2007.

3.2.10. Year 2010

With an It index of 25% this is an event year with a moderate tree response. There are three precipitation events exceeding the 24-hour precipitation threshold, which occurred on the 5th of September (179.5 mm), 23rd (50.8 mm) and 25th (86.1 mm) December 2009 (Fig. 4). Event in September is a moderate magnitude event with a return period of 50 years (Table 1) as well as the highest 24-hour amount of rainfall ever recorded at the Rateče station. Events in December are low magnitude meteorological events with return periods of one to two years. Since the events occurred out of the growing season and there were no potential events in the year 2010 it is most likely that growth suppressions in 2010 were caused by a moderate debris flood event triggered by a moderate magnitude rainfall event in September 2009. The sums of long-term precipitations show above-average precipitations, but the majority of rainfall occurred in short term precipitation events. In the case of December 2009, some of the precipitation occurred as snow and is excluded as potential triggering precipitation.

There is a relation between the magnitude of the debris flood event based on the I_t index and the magnitude of the most probable triggering meteorological event in case of eight years (1962, 1970, 1974, 1976, 1980, 2001, 2008 and 2010) and partial relation in the years of 1991 and 1996 (Fig. 5). Based on comparison of the two data sets there is significant relation between the relative magnitudes of meteorological triggers ("event"), the I_t index of affected trees ("response") and the relative magnitude of debris flood events ("process"). From 1903 onwards at our study site 53.85% of debris flood events were low magnitude events, 30.76% were moderate magnitude events and 15.38% were high magnitude events (Fig. 5).

4. Discussion

By dating debris flood events based on growth suppressions, we related the dendrogeomorphologically dated debris flood events with the most likely triggering meteorological event (precipitation above 50 mm in 24 h) from the year 1961 onwards. We proved that both sets of data can be successfully paired and the magnitudes of debris flood events can be estimated, since the number of affected trees (I_t index) relates well with the return periods of triggering meteorological events. The lesser the number of affected trees the lower is the return period/intensity of a meteorological event and vice versa. However, we detected some variations, which are predominantly conditioned by site specifics.

4.1. Tree responses to debris flood events

Dating of debris flood events in our study is primary based on growth suppressions, because they clearly dominate in the collected samples. In addition to the growth suppressions, we detected other growth disturbances, which are present in our sample collection in a far lesser extent (Appendix; Section 3.1). Growth release is present in the RgL group in the years 1940 and 1983, shortly after two growths suppressions in the years 1935 and 1980 (Appendix). The growth suppressions in 1935 and 1980 are indicating high and moderate debris flood events respectively. Since both growth disturbances occurred in separate trees, we tentatively interpret the growth release as a response of the unburied trees, which benefited from buried-related weakening or death of the neighbouring trees. We tentatively base this interpretation on field observation and comparison of growth rates to other trees. Additionally, the growth release could also be related to non-geomorphic influences, such as forest management. However, our conclusions are in line with previous studies (Alestalo, 1971; Strunk, 1991; Strunk, 1997; Gärtner et al., 2003; Stoffel et al., 2006; Bollschweiler and Stoffel, 2010) and follow the general explanation on how trees react to burrowing (Stoffel and Corona, 2014).

Occurrences of rows of traumatic resin ducts are in general very low and they do not temporally correlate with growth suppressions related to the debris flood events. Since all the sampled trees are located away from the valley's cliffs and slopes, traumatic resin ducts are unlikely to be formed by rock falls. We attribute the causes of tree injures to several other factors (forest management, animal activity …). Similarly, compression wood does not temporally correlate with debris flood events, which indicates that trees were not tilted by transported debris. This is also corroborated by the fact that the sampled trees did not show any obvious signs of tilting in the field. Compression wood was only present in the juvenile period, when tree trunks were not very thick and when the formation of reaction wood could easily be caused by other processes (forest management), rather than debris flood events. Since traumatic resin ducts, scars, and reaction woods do not correlate in time with growth suppressions and therefore not with debris floods, their absence can be attributed to the nature of the relatively low impact force of debris floods (Hungr et al., 2014; Stoffel and Corona, 2014).

Growth suppressions did present some difficulties in determining the exact year of an event. In some samples the suppressions were not abrupt but rather gradual, which is contrary to the cases in studies done by Mayer et al. (2010), Kogelnig-Mayer et al. (2013) and Schraml et al. (2015). Our interpretation is that gradual growth suppression might be caused by the sedimentological characteristics of deposited material, which is composed of sands and gravels, but lacks fine-grained sediment (silt and clay). Such type of sediment has an open framework which does not compresses tree trunk as much as it would with fine-grained material (Strunk, 1991, 1997; c.f. Kaczka and Morin,

2006). Consequentially the suppression is not as abrupt as in the above-mentioned cases.

4.2. Meteorological triggers of debris flood events and site specifics

Based on the correlation of dendrogeomorphological and meteorological data we established that debris flood events on the studied alluvial fan were primary triggered by short and intense rainfall events, specifically by 24- and 48-precipitation events, rather than long-term low intensity precipitation events. Reasons for this are in specific geological and geomorphological characteristics, namely morphology of the catchment area and high porosity (open framework) and thickness of the Holocene carbonate sediments forming the alluvial fan. Due to sedimentological characteristics, water quickly infiltrates underground. Therefore, the alluvial fan sediment never gets saturated enough by long-term low intensity rainfall events to trigger a debris flood. The sediment can only be transported by an intense and high amount of rainfall in a relatively short time period (i.e. torrential rainfall). This is in line with studies by Guzzetti et al. (2007), who states that slope failure in mountain areas of mid-latitude regions is more conditioned by rainfall intensity, rather than duration. Similar cases are reported in studies by Paronuzzi et al. (1998). In addition, morphological characteristics of the studied fan and its corresponding catchment area also contribute to the intensity of individual event. The catchment area has a high relative altitude difference between its highest and lowest parts (more than 500 m). Additionally, significant parts of the catchment area are a bare surface without a vegetation. Such morphology works as a funnel, which increases the speed of water that emerges from a catchment area via distributary channels onto the fan's surface.

4.3. Undetected historic mass movement events

Based on meteorological data and other research, three extreme meteorological events (years 2000, 2003 and 2008) happened in the study area, but we encountered no or very little response to those events in our samples. On November 2000 record breaking monthly precipitation event triggered a debris flow and mass movements in the Planica Valley (Zorn et al., 2006; Komac and Zorn, 2007; Komac, 2009; Zupan, 2013; Šmuc et al., 2015). However, on our study location trees at the RgL site have a very low response (11.84%, Appendix, Fig. 4, Section 3.2 of this paper) for those meteorological events. Similarly, two events in 2003 and 2008 with high 24-hour precipitation and documented damage on infrastructure occurred in the Rateče village. The first occurred in the period from the 29th to 31st of August 2003 with a cumulative precipitation of 287 mm of rainfall (Dolinar, 2004; Zorn et al., 2006) and the second on the 30th of October 2008 (149.7 mm; ARSO, 2018a). However, we have not found a sufficient number of growth disturbances in RgL group, which would indicate any mass movement activity on Rančev graben alluvial fan for these periods.

We attribute the low detection to be interlinked to the site specifics of the fan, more specifically sediment starvation in the catchment area due to previous events. For the case of the year 2001, we assume that despite of a record breaking meteorological event in 2000, only a low magnitude debris flood was triggered and detected as growth suppressions for two reasons. The first reason is attributed to the open framework and thickness of the Holocene sediments and lack of thick soil. Despite the record-breaking long-term precipitation events in November 2000, the precipitation was distributed over a longer period of time and it quickly infiltrated under the surface of porous sediment and therefore unable to trigger a debris flood. The second reason is the insufficient amount of sediment in the fan's catchment area, which was removed by the two previous debris flood events (1991; moderate magnitude event and 1996; high magnitude event). Due to these events the catchment area was probably relatively starved of sediment which could be transported in a debris flood event later on. Similar occurrences were also observed in studies by Bovis and Jakob (1999), Procter et al. (2011) and Schraml et al. (2015). In similar fashion the potential meteorological triggering events in August 2003 and October 2008 did not cause debris flood due to an insufficient amount of sediment in the catchment area of the Rančev graben alluvial fan because of the previous three debris flood events (1990 detected in tree rings of 1991, 1996 and 2000 detected in tree rings of 2001). Comparably, our study suggests that the two moderate and high debris flood events recorded in tree-ring data set (events in 1991 and 1996) were triggered by low and moderate magnitude meteorological events. This can be again attributed to the sediment availability in the catchment area, since the preceding debris flood event in 1980 occurred a decade before the two events. In such a time gap a large amount of sediment could be deposited in the catchment area and later on transported by low and moderate magnitude meteorological events. Despite these variances, relating the two data sets is possible by which magnitudes of slope mass movements can be estimated.

4.4. Accuracy of past debris flood magnitude estimations based on the two datasets

The magnitudes of past debris floods are estimated based on the relation between dendrogeomorphological and meteorological datasets. We demonstrate that analysing only one dataset is not enough to fully estimate the magnitude of past debris flooding events, since there can be divergence. Estimations of magnitudes solely based on the I_t index can overestimate the triggering event, which can be demonstrated in the cases of the years 1991 and 1996. In both years we detected moderate to high tree response, however the triggering meteorological events were low magnitude meteorological events. Tree-ring data can therefore successfully be used in dating and determining spatial extent of individual events, however to determine the causal event they need to be paired with meteorological records. Similarly, estimation of debris flooding magnitudes cannot be based solely on meteorological events as is clearly presented in the case of the events from 2000, 2003 and 2008. Although mass movements occurred at those meteorological events, very little or none of them occurred at our studied fan. Due to specific site conditions complementary usage of the two datasets is needed in order to accurately estimate the magnitudes of past debris flooding.

4.5. Natural hazard threat on Rančev graben alluvial fan

Tree-ring evidence indicates that the past debris floods leading form channels B and A2 (Fig. 2) did not travel closer to today's location of ski-jumping facilities than 350 m. Based on century long tree-ring records and surface morphology we estimate there is relatively low chance for channels B and A2 to affect ski-jumping infrastructure. Based on this research we estimate that the road leading further up the Planica valley is most prone to the debris flood effects. Such effects are exhibited as burrowing of the road and damages on road surface. However, the potential threats of the channel A1 (Fig. 2) are unknown. Currently this channel discharges into partially manmade channel, which is part of the neighbouring alluvial fan on which some of the ski-jumping facilities are located. Based on current data it is not possible to make firm estimations of the channel A1 natural hazard threat potential.

5. Conclusion

We were able to successfully estimate the magnitudes of past debris flood events by comparing the number of affected trees with the return period of potential triggering meteorological events. Firstly, we built a century long chronology which enabled us to detect past thirteen debris flood events on a typical alpine alluvial fan, using growth suppressions from partially buried trees. Secondly, the comparison of dendrogeomorphological data with the precipitation values of the nearby meteorological station allowed the determination of the most

likely debris flood triggering meteorological event, often with a daily precision. We show that debris flood events triggered by rainfall events of larger return period affect a larger number of trees. Finally, the comparison of the I_t index and the return periods of triggering meteorological events has successfully demonstrated that the magnitude of individual past debris flood event can be determined. Our research approach in debris flood magnitude estimation, serves as powerful tool for future dendrogeomorphological research into the effects of debris flooding in alpine environment. Additionally, our study represents one of the first dendrogeomorphological studies in the region of Southern Alps.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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