

Dendrogeomorphic reconstruction of flash floods in the Patagonian Andes



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ABSTRACT

Flash floods represent a significant natural hazard in small mountainous catchments of the Patagonian Andes and have repeatedly caused loss to life and infrastructure. At the same time, however, documentary records of past events remain fairly scarce and highly fragmentary in most cases. In this study, we therefore reconstruct the spatiotemporal patterns of past flash flood activity along the Los Cipreses torrent (Neuquén, Argentina) using dendrogeomorphic methods. Based on samples from *Austrocedrus chilensis*, *Pseudotsuga menziesii*, and *Nothofagus dombeyi*, we document 21 flash flood events covering the period A.D. 1890–2009 and reconstruct mean recurrence intervals of events at the level of individual trees being impacted, which varies from 4 to 93 years. Results show that trees tend to be older (younger) in sectors of the torrent with gentler (steeper) slope gradients. Potential triggers of flash floods were analyzed using daily temperature and precipitation data from a nearby weather station. Weather conditions leading to flash floods are abundant precipitations during one to three consecutive days, combined with temperatures above the rain/snow threshold (2 °C) in the whole watershed.

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1. Introduction

Flash floods periodically cause serious risk to life and destruction of buildings and infrastructure (Gaume et al., 2009). These natural hazards typically occur in ungauged watersheds not larger than a few hundred square kilometers (Ruiz-Villanueva et al., 2010) where heavy precipitation events may lead to a sudden and often massive increase in (peak) discharge (Borga et al., 2007). In mountainous areas, abundant rainfall (often in combination with rapid snowmelt) has been described as the main trigger of flash floods. These may then travel downvalley to reach populated areas with no or only limited time for warning. In such areas, the documentation of past as well as the characterization of potential future events, also including those with low probability of occurrence but associated high damage potential, is important, also in view of the mitigation of related risks using specific land planning tools (Merz et al., 2009; Canelli et al., 2012).

Historical records of past flash floods are in general short, scarce, and fragmentary (Cook, 1987). In some cases, records cover several centuries, although information on peak discharge and affected areas often tends to remain uncertain for the oldest records (Payrastre et al., 2005). Mountainous regions with expanding infrastructure, as is the case in the Patagonian Andes of South America, are particularly exposed to flash floods as a result of the meteorological and orographic characteristics of the Andes. Moreover, largely lacking records or systematic data on previous events hinders the application of effective mitigation measures. As a consequence, and in view of increasing land needs for construction, additional sources are needed to supplement the limited available records.

Dendrogeomorphology is an accurate method to reconstruct spatial and temporal patterns of past torrential processes (Alestalo, 1971; Shroder, 1978; Stoffel and Bollschweiler, 2008). The analysis of growth rings of trees affected by flash floods can provide valuable information on past events (Yanosky and Jarrett, 2002; Zielonka et al., 2008), mostly with yearly, but sometimes even with seasonal precision (Stoffel, 2008). Classical (flash) flood reconstructions included (i) the dating of scars in the trees (McCord, 1996), (ii) determination of the age of sprouts resulting from trunk tilting or crown damage (Sigafos, 1964), and (iii) the inference of event dates based on ages of trees colonizing the

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new surfaces after catastrophic flooding (Costa, 1978). More recent studies focused on anatomical responses of trees to flash floods, including conifers (Mayer et al., 2010; Ruiz-Villanueva et al., 2010; Procter et al., 2012) and broad-leaved trees (Arbellay et al., 2010; Ballesteros et al., 2010). Dendrogeomorphic indicators in combination with one-dimensional (Corriell, 2002) and two-dimensional (Ballesteros Cánovas et al., 2011) hydraulic models have also been implemented to estimate flash flood discharge.

In this study, we reconstructed the spatiotemporal patterns of flash floods in a torrent located in the Patagonian Andes using 58 samples from *Austrocedrus chilensis*, *Nothofagus dombeyi*, and *Pseudotsuga menziesii* trees covering the period A.D. 1795–2008. The tree-ring based chronology of events was used to determine potential triggers of flash floods in the torrent through the analysis of regional climatic data.

2. Study area

The sampling was conducted at Los Cipreses torrent in the Neuquén Province, Patagonian Andes, Argentina (40°56'00" S., 71°24'45" W.; Fig. 1). The catchment area and the torrent length are ~7.5 km² and 4.9 km, respectively. The elevational range between the highest summit (Cerro Alto Bonito; 1963 m asl) and Lago Nahuel Huapi (768 m asl) is close to 1200 m. The torrent crosses National Road 231, an important international connection between San Carlos de Bariloche (Argentina) and Osorno (Chile) at an elevation of 792 m asl. Stream gauge stations do not exist in this or its neighboring torrents.

The torrent flows through Los Machis outcrops primarily composed of granodioritic rocks, together with tonalites and quartz monzonites

(Servicio Geológico Minero Argentino, 1995). Total annual precipitation and mean annual temperature (1914–2011) recorded at San Carlos de Bariloche airport, located 33 km to the SE (41°09'02" S., 71°09'24" W.; 840 m) of Los Cipreses torrent, are 955 mm and 8 °C, respectively (Fig. 2). A large proportion (60%) of the precipitation occurs in late fall and winter (May, June, July, and August); at elevations above 1000–1100 m asl, precipitation occurs commonly as snow.

The study reach, with a length of 560 m and an area of ~7000 m², is located on the alluvial fan of Los Cipreses torrent. Abundant evidence of flash flood activity in the torrent is provided by depositional forms of past flash floods in the form of lobate deposits and abandoned channels, as well as through broken, bent, and uprooted trees growing on the fan (Fig. 3). In many cases, channel wall erosion has partially exposed root systems (Stoffel et al., 2012). Historical records of past flash floods do not exist for the torrent, but newspaper articles (Lanación.com, 2004) and eyewitness reports (Gustavo Villarosa, *verbatim*) allude to a heavy precipitation event in winter 2004 and related flash flood occurrences causing casualties and damage to infrastructure in the area. The study area is only affected by flash floods; signs of other geomorphic processes, such as snow avalanches or rockfalls, are clearly missing at the study site.

3. Material and methods

3.1. Sampling procedure

The main tree species growing in Los Cipreses torrent are Chilean cedar (*A. chilensis* (D. Don) Florin et Boutelje), Southern coihue beech (*N. dombeyi* (Mirb.) Oerst.), and Douglas-fir (*P. menziesii* (Mirb.)

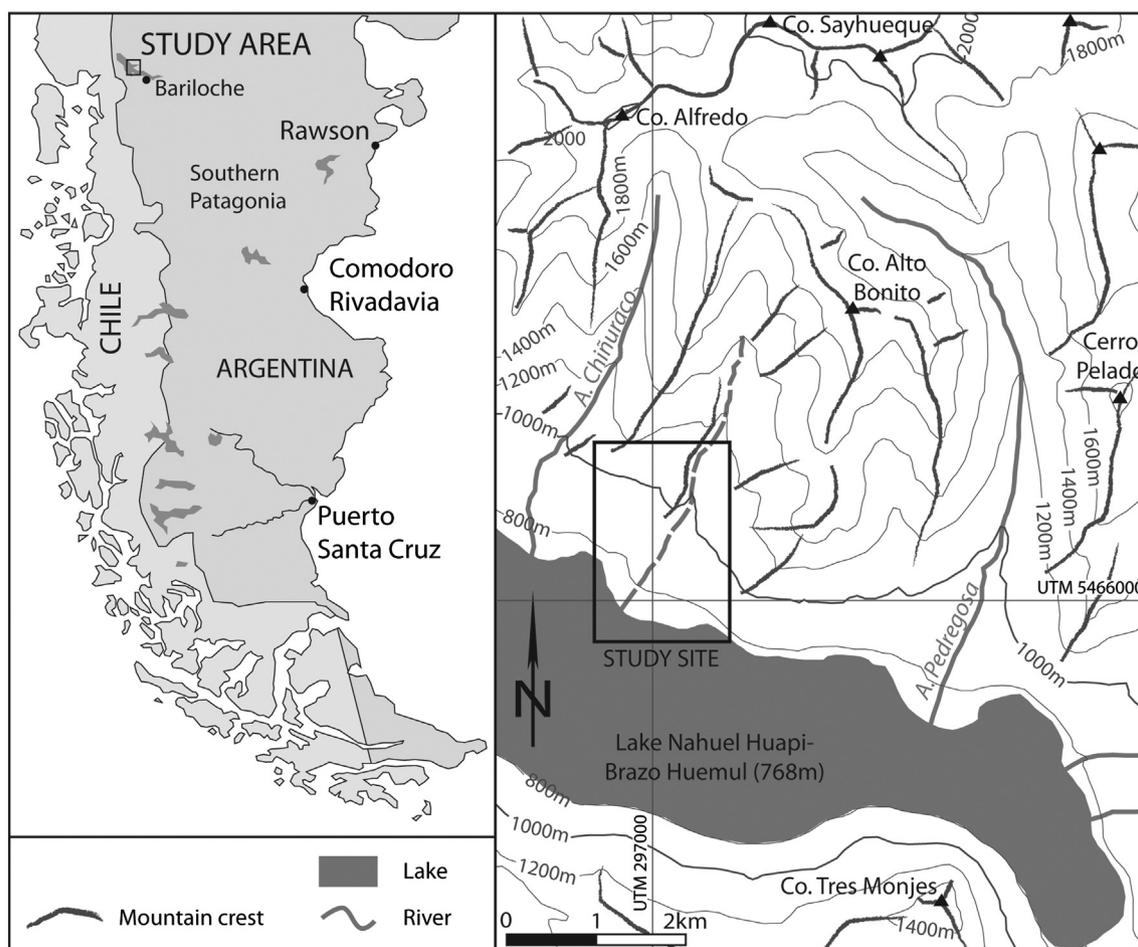


Fig. 1. Study area (rectangle) located in the province of Neuquén, Argentina. The Los Cipreses torrent has a catchment area of 7.5 km² and a channel length of 4.9 km. The torrent enters Nahuel Huapi Lake at 768 m asl. The elevational range spans ~1.2 km.

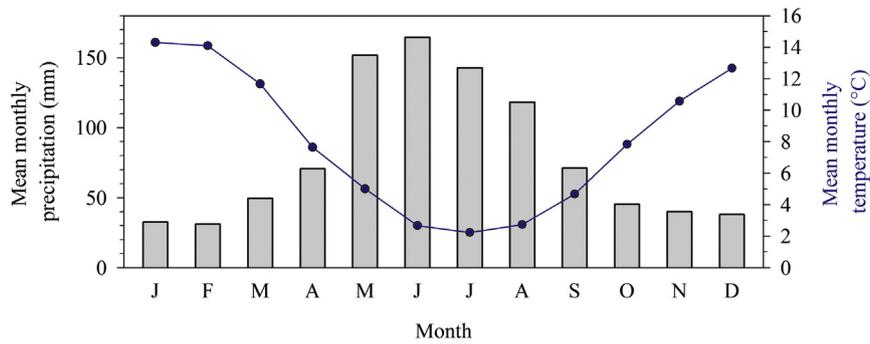


Fig. 2. Mean monthly precipitation and temperature records (1914–2011) registered at San Carlos de Bariloche airport. Source: Servicio Meteorológico Nacional of Argentina.

Franco), with the latter being introduced in the 1970s and currently expanding into native forests (Schlichter and Laclau, 1998).

A total of 43 trees have been selected in the field (Table 1) based on their position with respect to geomorphic evidence of past flash flood occurrence, as well as regarding the presence of scars, exposed roots, tilted, broken, and/or buried stems (Stoffel and Corona, 2014). Sampling was designed in a way to cover a large surface including all channel sectors along the present-day flow path. Cross sections (i.e., transverse cuts) were taken from all *P. menziesii* trees and from severely damaged *A. chilensis* and *N. dombeyi* individuals, whereas increment cores (Phipps, 1985) were extracted from *A. chilensis* and *N. dombeyi* trees with less severe damage induced by flash floods. In most cases, cross sections were obtained at various stem heights to maximize the tree-ring evidence of past disturbances. Increment cores were extracted typically in two directions: parallel and perpendicular to the flow direction. For each tree, data on the nature and intensity of the damage, height, diameter at breast height (DBH; i.e., 1.3 m above ground), social position of the tree (i.e., dominant, co-dominant, regular, oppressed), tree morphology (i.e., single or multiple stems), and presence of deposits around the stem base were recorded. Photographs and GPS (± 5 m accuracy) positions for each tree, in addition to several sketch maps along the torrent, complemented the field survey. A regional reference chronology of *A. chilensis* was used to compare the growth patterns of trees growing along the torrent with those not affected by flash floods.

3.2. Tree-ring analyses and flash flood reconstruction

Samples were prepared following standard dendrochronological techniques (Stokes and Smiley, 1968) and subsequently dated following



Fig. 3. Overview of the Los Cipreses torrent showing recent transported material and trees affected by past flash floods. The surfaces affected by recent activity can be clearly distinguished in the image.

Schulmans (1956) convention for the Southern Hemisphere, assigning to each tree ring the year in which the radial growth started. Ring widths were measured using a Velmex UniSlide traversing table connected to a Metronics Quick-Check QC-1000 digital counter (accuracy: 0.01 mm). To detect dating errors (i.e., missing or false rings), the cross-dating quality was evaluated using COFECHA (Holmes, 1983).

Growth disturbances (GD) were identified on the tree-ring series including injuries (Mears, 1975), changes in stem eccentricity (Schweingruber, 1996), tangential rows of traumatic resin ducts (TRD) formed next to wounds (Bollschweiler et al., 2008), abrupt growth suppressions and releases (Rayback, 1998), and reaction wood (Timell, 1986). The determination of event years was based on (i) the number of samples synchronically showing GD; (ii) signal intensity, i.e., weak, medium, or strong (Kogelnig-Mayer et al., 2011; Stoffel and Corona, 2014); and (iii) the spatial distribution of damaged trees along the torrent (Schneuwly-Bollschweiler et al., 2013). In the case of continuous reactions over several years, particularly in the case of TRD and reaction wood, only the first occurrence of the GD was taken into account. In addition, we limited the flash flood reconstruction to the period A.D. 1890–2009, for which we have a sample replication of at least 10 trees. Following Stoffel et al. (2012), two types of events were identified: events were considered possible (probable) as soon as 6–10% ($\geq 10\%$) of all living trees showed simultaneous reactions. The seasonality of flash floods was determined via the location (i.e., earlywood, latewood, and dormancy) of injuries and TRD within tree rings (Stoffel et al., 2006).

3.3. Climatic analyses

Daily precipitation was used in combination with minimum, mean, and maximum air temperature records from San Carlos de Bariloche airport to identify potential triggers of past flash flood events. Daily climate data cover the period 1962–2010. As a majority of precipitation in the region occurs during late Southern hemisphere falls and winters, a temperature threshold was used to distinguish between rainfall events at the meteorological station (at 840 m asl) and snowfalls in the watershed of Los Cipreses torrents, or at least in its upper parts.

Temperatures defining snowline precipitation was estimated for (i) the highest peaks (1963 m asl), (ii) at 1664 m asl (i.e., defining a contribution from 75% of the catchment), and (iii) at 1365 m asl (50% of the catchment). Considering a lapse rate of $0.65\text{ }^{\circ}\text{C } 100\text{ m}^{-1}$, temperature differences between these three elevations and Bariloche airport are $-7.3\text{ }^{\circ}\text{C}$, $-5.5\text{ }^{\circ}\text{C}$, and $-3.7\text{ }^{\circ}\text{C}$, respectively.

Days with snowfalls below 1365 m asl were excluded as predictors, and periods in which only part of the basin could contribute to runoff were considered less susceptible in terms of flash flood triggering than days with temperatures well above $0\text{ }^{\circ}\text{C}$ at the summits of the catchment. Maximum daily, 3-day, 5-day, and 10-day precipitation totals were successively tested as predictors. Relationships between climatic variables and flash floods were further explored using logistic regressions (Aldrich and Nelson, 1984; Hebertson and Jenkins, 2003; Lopez Saez et al., 2013). This method establishes the relationship

Table 1
Overview of the samples collected in the field.

| Species | Trees (number) | Samples (number) | Mean age (y) | Mean diameter (cm) |
|-------------------------------|----------------|------------------|---------------|--------------------|
| <i>Austrocedrus chilensis</i> | 33 | 41 | 105 (SD 45.7) | 19 (SD 11.6) |
| <i>Nothofagus dombeyi</i> | 2 | 2 | 58 (SD 14.1) | 5 (SD 5.0) |
| <i>Pseudotsuga menziesii</i> | 8 | 15 | 34 (SD 26.7) | 5 (SD 5.0) |
| Total | 43 | 58 | 88 (SD 50.7) | 18 (SD 10.6) |

between a dichotomous response variable (the presence/absence of a flash flood event in our case) and a set of continuous climatic data. The logistic regression estimates the probability of occurrence of an event by fitting data to a logistic curve. The logit is simply the log odds ratio of mean flash flood triggering probability:

$$\text{logit}(p_i) = p_i / (1 - p_i) \tag{1}$$

where p is the probability of an event year for i years (1890–2009 herein) modeled as a linear function:

$$\text{logit}(p_i) = \beta_0 + \beta_1 \chi_1 + \dots + \beta_k \chi_k \tag{2}$$

with an equivalent formulation:

$$p_i = 1 / (1 + \exp^{-(\beta_0 + \beta_1 \chi_1 + \dots + \beta_k \chi_k)}) \tag{3}$$

where χ_k represents the k climatic factors used as regressors for year i , β_0 the intercept, and β_k the regression coefficients. The unknown parameter β_j is usually estimated by maximum likelihood using a method common to all generalized linear models.

4. Results

4.1. Dating of past events

Tree-ring analyses of 58 samples from 43 trees yielded a total of 236 GD (Table 2) related to past flash floods. The years of occurrence of past flash floods in the torrent were determined mainly via growth decreases (27.1%), which most frequently occurred in *A. chilensis* and as a response to reduced tree vitality. Injuries, formed after mechanical damage of cambial tissues by flash flood material, were present in one-fourth of the cases (25.8%). The TRD have been recorded less frequently (18.6%), primarily because they only form in *P. menziesii* but not in the other species analyzed. Growth increases after the elimination of neighboring trees (14.0%) and reaction wood, induced as a reaction to tilting (11.9%), were less frequent. A minor proportion of trees (2.5%) exhibited stem eccentricity variations, which are also linked to changes in tree stability. Fig. 4 shows an *A. chilensis* tree heavily affected by flash floods at Los Cipreses and associated injuries, growth changes, reaction wood, and variations in stem eccentricity.

Table 2
Growth disturbances used to infer years of past flash flood events in the torrent.

| Growth signature | <i>Austrocedrus chilensis</i> | <i>Nothofagus dombeyi</i> | <i>Pseudotsuga menziesii</i> | Total | Percent |
|------------------------|-------------------------------|---------------------------|------------------------------|-------|---------|
| Injury | 41 | 1 | 19 | 61 | 25.8 |
| TRD ^a | – | – | 44 | 44 | 18.6 |
| Growth increase | 29 | 0 | 4 | 33 | 14.0 |
| Growth decrease | 59 | 0 | 5 | 64 | 27.1 |
| Reaction wood | 20 | 0 | 8 | 28 | 11.9 |
| Eccentricity variation | 5 | 1 | 0 | 6 | 2.5 |
| Total | 154 | 2 | 80 | 236 | 100.0 |

^a TRD: tangential rows of traumatic resin ducts; dashes = not present.

The oldest tree sampled at Los Cipreses attained sampling height in A.D. 1795, whereas for the youngest tree it was reached in A.D. 1993. Mean tree age was calculated to be 88 years, with a standard deviation (SD) of 50.7 years (Table 1). The annual synchronicity in the occurrence of GD, together with the spatial distribution along the study reach, allowed reconstruction of 21 flash flood events over the period A.D. 1890–2009 (Fig. 5). Three of these events (i.e., 1947, 1966, and 1975) were considered possible as a result of the somewhat limited replication of GD, whereas the remaining 18 events (i.e., 1893, 1900, 1903, 1920, 1925, 1942, 1949, 1955, 1962, 1971, 1977, 1989, 1993, 1995, 1999, 2002, 2004, and 2006) were considered probable events with ≥ 10% of the sample showing simultaneous reactions.

4.2. Spatial reconstruction of events and return periods

A spatial interpolation of maximum individual tree ages (using the method of inverse distance weighting) shows that older trees are growing in those sectors of the torrent where slope gradients are gentler and flow energies are presumably less important (Fig. 6). In contrast, trees are younger in the steepest sectors of the torrent where flows are likely to be more turbulent.

Return periods of events were determined by dividing individual tree ages by the number of GD associated with the 21 reconstructed events, yielding values between 4 and 93 years with a mean and SD of 37.4 and 27.2 years, respectively. An interpolation of event return periods suggests that trees in (or following) steep channel sectors are more frequently (or intensively) affected by flash floods, whereas samples taken from trees growing in areas with more gentle slope gradients exhibited larger return periods.

4.3. Seasonality and meteorological triggers of events

Wood anatomical analyses of the intra-annual position of injuries and TRD within tree rings indicate that a high proportion of events (58.2%) occurred during dormancy, i.e., disturbance responses are located at the very beginning of tree rings. A lower proportion of events occurred during the growing season of the trees: 29.1% and 12.7% for earlywood and latewood, respectively.

Analyses of maximum daily to 10-day precipitation totals show the significant role of intense rainfalls in triggering flash flood events, in particular for the temperature threshold of – 7.3 °C for which the entire catchment will contribute to runoff (data not presented here). In addition, the most parsimonious logistic regression models after backward elimination involve 3-day precipitations (Table 3) with the general form:

$$\text{logit}(p_i) = \beta_0 + \beta_k(3\text{-day max rainfall}). \tag{4}$$

The likelihood ratio test, significant at $p > 0.001$ indicates that the logit model is better than a null model and predicts correctly flash flood triggering probability. The model provides parameter estimates of – 1.88 for β_0 and 0.027 for β_j ; and β_j indicates that the probability of a flash flood was estimated to increase by 0.05 with a respective 10-mm increase in maximum 3-day rainfall. The probability of a flash flood is 20% for 17 mm (median of the distribution of 3-day rainfalls) and 44% for 60-mm 3-day rainfall totals, which corresponds to the 90th percentile threshold for 3-day precipitation (Fig. 7).

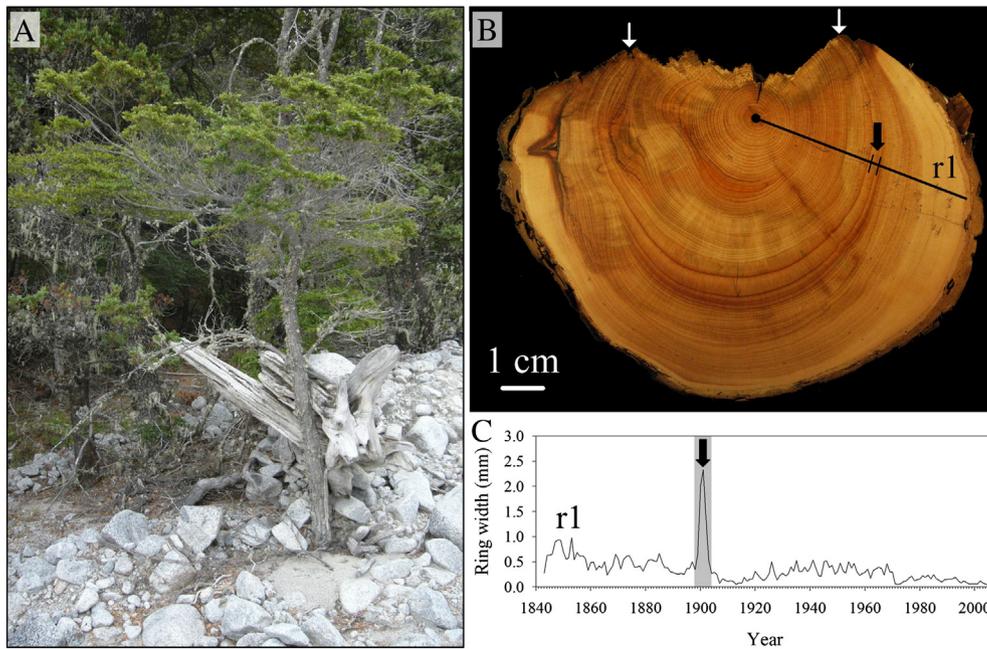


Fig. 4. (A) *A. chilensis* impacted by flash floods: wood and debris still remain on the upstream side of the tree, indicating recent activity. (B) Cross section obtained from the same tree showing multiple signs of flash flood disturbance. The white arrows point to a scar formed in 1901. (C) The radius $r1$ measured on the cross section shows an abrupt growth increase at a certain distance from the cambial damage indicating the presence of an injury.

5. Discussion and conclusions

In the study presented here, flash flood activity has been reconstructed in the Los Cipreses torrent (northern Patagonian Andes) with dendrogeomorphic approaches and for the period A.D. 1890–2009. The species analyzed in this study (*A. chilensis*, *N. dombeyi*, and *P. menziesii*) have been used only rarely for dendrogeomorphic purposes in the past, but demonstrated here to yield extensive and valuable information on mass-movement processes in a region that has been largely neglected in terms of hazard and risk assessments so far.

Tree roots of the same species were analyzed by Stoffel et al. (2012) to infer channel wall erosion in the same torrent. Although the number of events reconstructed in the channel wall erosion study largely coincides with the results of the present study in absolute terms, we realize that several years with reconstructed events also differed between the two data sets. From a total number of 21 events recorded in both reconstructions, flash flood dates coincide in 10 events.

Based on the analysis of spatial patterns involved in individual events in both reconstructions and the number of samples recording

the events, we deduce that smaller events might have been restricted to sectors where trees were not present on the alluvial fan or where the channel was too deep for flash flood material to affect trees growing on the channel banks. At the same time, we realize that those trees growing in the lowermost portions of the fan (and shortly before the torrent enters Lago Nahuel Huapi) have been affected more often by flash floods than were the trees growing on the channel banks. The inclusion of trees growing in this depositional environment may thus allow reconstruction of events that would have been missed if sampling was restricted to the channel banks and/or to roots of exposed trees from the channel walls.

Despite the fact that roots will only survive as long as their tips are still in the ground, the reconstruction based on root evidence was longer than that based on stem analyses (starting in A.D. 1870 and 1890, respectively). Possibly channel wall erosion is less severe and less harmful to tree survival in this particular environment than is the sedimentation on the fan, with the consequence that trees grow older along the banks than in the lowermost depositional area of the flash flood system. As a consequence, and in view of the results obtained in both studies, we call for the combination of stem and root sample

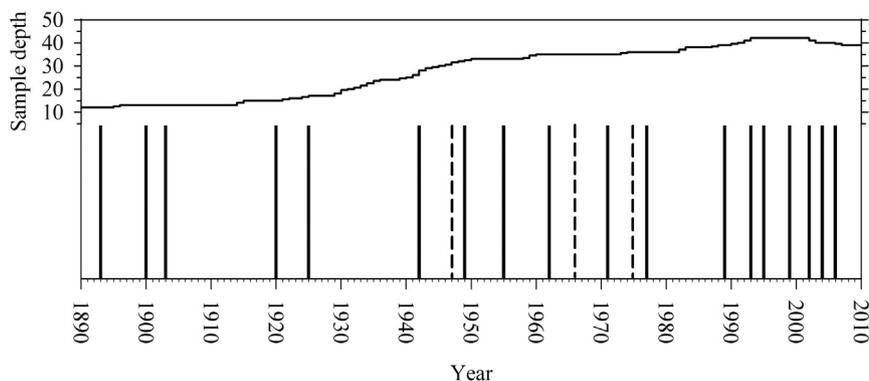


Fig. 5. Tree-ring based chronology of flash floods at Los Cipreses covering the period A.D. 1890–2009. The 18 bold vertical lines represent events with synchronous reactions in $\geq 10\%$ of the trees, whereas dashed lines correspond to events with synchronous reactions in 6–10% of all trees living in that specific year. The sample size is indicated with the upper solid line, limiting the reconstruction to a minimum of 10 available trees (earlier part of the reconstruction not shown).

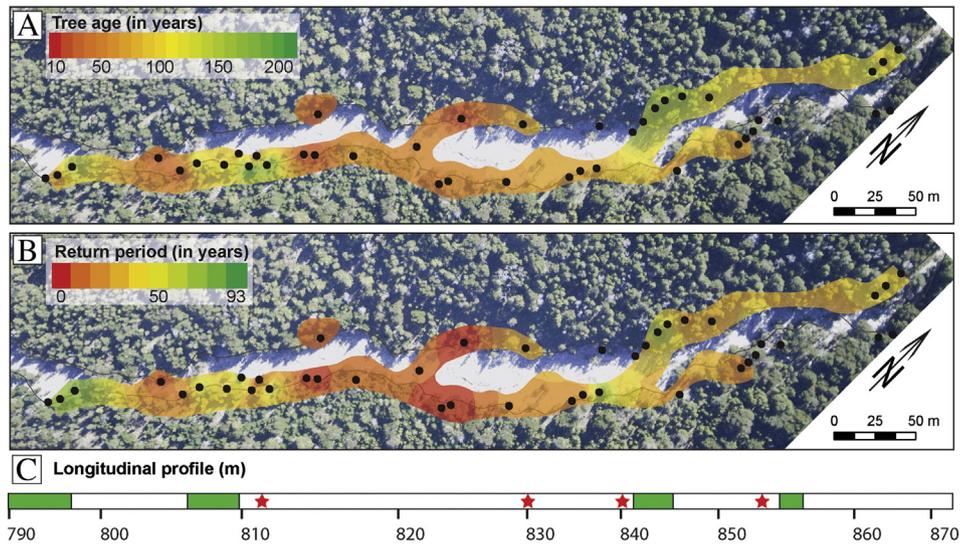


Fig. 6. Spatial interpolations of (A) maximum tree age and (B) return periods of reconstructed events. (C) The longitudinal profile shows that interpolated ages are higher in sectors of the torrent with more gentle slope gradients (green surfaces) as compared to sectors following steps and pools (red stars), where turbulence is expected to increase. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

analyses in erosive fan environments, as this can indeed increase the number of reconstructed events (from 21 to 32 in our case) and reduce the recurrence periods of events at the level of the study site from 5.7 (21 events between 1890 and 2009) to 4.3 (32 events between 1870 and 2009) years.

The reconstruction presented in this study also clearly points to a variety and different expression of GD in the species analyzed for flash flood detection. Sudden growth increases and decreases represented the most common signature used for flash flood reconstruction but were mainly limited to *A. chilensis*. Injuries to the cambial tissue, commonly used in the past as a reliable tree-ring signature for spatiotemporal reconstruction of various geomorphic processes (Strunk, 1991; Stoffel and Perret, 2006; Arbellay et al., 2010), were in contrast much more present in *P. menziesii* and might thus point to differences in spatial occurrence of this invasive plant and/or to different bark thickness and associated probability for debris to inflict wood-penetrating wounds (Trappmann and Stoffel, 2013). A combined analysis of injuries and TRD has been confirmed in this study to represent a valuable tool for the determination of event seasonality (Stoffel et al., 2006; Bollschweiler et al., 2008). In the case of flash floods in the Los Cipreses region, events are mostly limited to the dormant season of trees, i.e., to the months of May, June, July, and August, which is in agreement with the seasonality of heavy precipitation events in the wider study region. These findings are in agreement

with the consulted climatic records, which show that most precipitation in the region occurs between late fall and early spring, i.e., outside the growing period of trees. A direct coupling of flash flood with precipitation data is for this reason not possible. The inclusion of tree-ring data from further torrents in the area and further analyses of climatic records from a broader geographic environment might provide more consistent relationships between climate and the occurrence of flash floods.

Tree ages along the torrent show a large variation, which is partly explained by the inclusion of young and recently introduced *P. menziesii*. However, and in view of the channel topography, younger trees (and mostly so *P. menziesii*) are located in the steeper segments of the torrent where vegetation is removed more frequently by flash floods. Interpolated ages of trees are also in concert with root ages along the same stream (Stoffel et al., 2012) and thereby confirm the findings of this study. Steeper gradients are expected to induce larger

Table 3

Parameters used for the logistic regression models of flash flood triggering; for each regression involving the maximum 3-day rainfalls according to different temperature thresholds, the *p* value, its significance, the intercepts (*a*) and slopes (*b*) are given (**p* < 0.05, ***p* < 0.01, ****p* < 0.001).

| Regressor | a | b | <i>p</i> Value | Significance |
|---------------------------------------|----------------|-----------------|----------------|--------------|
| 3-Day precip/max temp (°C) | 0.01241 | -2.34049 | 0.03281 | * |
| 3-Day precip/max temp - 7.3 °C | 0.01379 | -2.15390 | 0.02656 | * |
| 3-Day precip/max temp - 5.5 °C | 0.02671 | -3.51179 | 0.00263 | ** |
| 3-Day precip/max temp - 3.7 °C | 0.01857 | -2.86920 | 0.00835 | ** |
| 3-Day precip/min temp (°C) | 0.01641 | -2.54866 | 0.01405 | * |
| 3-Day precip/min temp - 7.3 °C | 0.02720 | -1.87901 | 0.00055 | *** |
| 3-Day precip/min temp - 5.5 °C | 0.02225 | -1.93218 | 0.00225 | ** |
| 3-Day precip/min temp - 3.7 °C | 0.02287 | -2.42853 | 0.00499 | ** |
| 3-Day precip/mean temp (°C) | 0.01442 | -2.51909 | 0.02122 | * |
| 3-Day precip/mean temp - 7.3 °C | 0.03358 | -2.65110 | 0.00148 | ** |
| 3-Day precip/mean temp - 5.5 °C | 0.02953 | -2.96222 | 0.00265 | ** |
| 3-Day precip/mean temp - 3.7 °C | 0.01760 | -2.60544 | 0.00807 | ** |

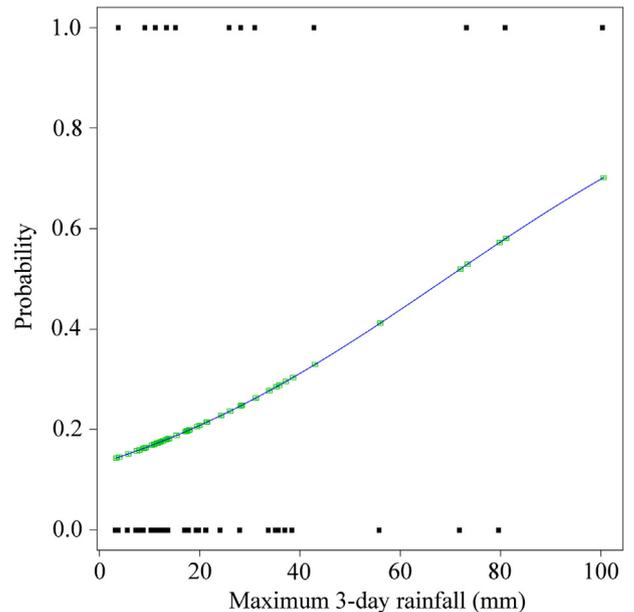


Fig. 7. Maximum 3-day rainfall values and predicted probabilities of flash flood triggering at the Los Cipreses torrent. Black squares with probability = 1 represent the maximum 3-day rainfalls associated to an event, whereas black squares with probability = 0 represent the maximum 3-day rainfalls during years without events.

flow turbulence, which results in larger probabilities for trees to be damaged and consequently in lower tree ages. Interpolated tree ages and the spatial distribution of return periods of flash floods are intercorrelated, indicating that larger tree mortality is associated with larger flash flood recurrence.

Intense precipitation events over three consecutive days (>60 mm) result in high probabilities (>40%) of occurrence of flash floods. Yet the most significant relationships are observed when precipitation occurred in its liquid form over the entire catchment (i.e., with 100% of the catchment contributing to runoff). To determine above and below snowline precipitations, a lapse rate of $0.65\text{ }^{\circ}\text{C } 100\text{ m}^{-1}$ has been included to translate the temperatures recorded at San Carlos de Bariloche airport to the situation in the Los Cipreses catchment. The measurement records considered in this study are the only long and complete series existing in the region, and the results obtained are consistent with the flash flood activity reconstructed at the torrent. We recognize, however, that the weather station used is located relatively far away (33 km) from the study area and that the comparison of precipitation with flash flood data can be affected by this limitation, as shown recently for the Swiss Alps and for smaller distances between the recording meteorological stations and debris-flow sites (Schneuwly-Bollschweiler and Stoffel, 2012). In addition, it would be valuable to include information on the presence of accumulated snow in the catchment prior to the occurrence of rain events (i.e., rain-on-snow events; Butler and Walsh, 1994), but such data does not exist for the study region.

Despite all the limitations discussed above, the use of dendrogeomorphic techniques has been demonstrated here to represent a valuable tool for the investigation of the spatial and temporal occurrences of flash floods in an environment for which instrumental records and archival data are largely missing. The inclusion of new species has contributed significantly to the quality of the results, and we call for more studies in this unique environment where torrential processes can be studied with very limited anthropogenic disturbance. Last but not least, the coupling of tree data with information from roots (Stoffel et al., 2012) has proven most useful and has added almost one-third of events and subsequently resulted in a significant reduction of calculated return periods.

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