



Massive debris flow activity and connectivity shift in the 1980s deciphered by combined terrestrial and lacustrine record in a changing climate

Natalie Barbosa^{1,2,★}, Carolin Kiefer^{1,★}, Juilson Jubanski³, Florian Siegert^{2,3}, Michael Strasser⁴, and Michael Krautblatter¹

¹Chair of Landslide Research, Technical University of Munich, Arcisstraße 21, Munich, 80333, Germany

²GeoBio Center, Department of Earth and Environmental Sciences, Ludwig Maximilians University, Richard-Wagner-Str. 10, Munich, 80333, Germany

³3D RealityMaps GmbH, Landsberger Str. 314, Munich, 80687, Germany

⁴Department of Geology, University of Innsbruck, Innrain 52f, Innsbruck, 6020, Austria

★These authors contributed equally to this work.

Correspondence: Natalie Barbosa (natalie.barbosa@tum.de) and Carolin Kiefer (carolin.kiefer@tum.de)

Abstract. Recent climatic change affects sediment transfer in Alpine catchments beyond historical experience, increasing the need for robust quantification of sediment cascades to better anticipate the frequency and magnitude of future climate-driven natural hazards. Despite widespread projections of increased natural hazard activity, many studies lack quantitative volume estimates over more than a decade. Lake Plansee, located in the Northern Calcareous Alps (Tyrol, Austria), represents a quasi-closed geomorphological system in which previous studies have identified an increase in debris flow activity since the 1920s. Here, we revisit historical aerial imagery using recent photogrammetric techniques to quantify sediment transfer on 54 debris fans to the lake between 1952 and 2020, and to establish a first-order quantitative reconciliation between terrestrial sediment-transfer estimates and sediment accumulation inferred from the lacustrine sink archive within a common source-to-sink framework. Fans surrounding Plansee are grouped based on their connection to the lake inferred from the co-occurrence of active channel linkage to the lake and net sediment export (i.e., negative net change). Twenty-one debris flow channels are connected to the lake and actively deliver sediment. Sixteen channels indicate progression towards the lake and are expected to connect in the future. Rainstorm intensity analysis shows that, since 1980, the number of days with precipitation intensities capable of initiating debris flows ($>10 \text{ mm h}^{-1}$) has increased by 36 %, accompanied by a 12 % increase in total erosion volumes and a 47 % decrease in deposition volume at connected fans, suggesting an overall decrease in internal storage at the fans and enhanced sediment transport to the lake. The decadal response of sediment dynamics on the fans suggests that the increase in precipitation events results in an overall increase in sediment connectivity between catchments, fans, and the lake, driven by episodic events and diverse individual fan responses. These findings are reflected in land-cover changes: the increase in erosion is accompanied by an increase in non-vegetated areas on 70 % of the active fans after the 1980s. Event-layer deposition from the lacustrine record reveals a first-order debris flow volume estimate of $3.69 \pm 0.42 \times 10^5 \text{ m}^3$ deposited between 1952 and 2018. In comparison, a total of $3.42 \pm 0.43 \times 10^5 \text{ m}^3$ of sediment was transferred from the fans to the lake in the last seven decades. Here, we provide the first direct agreement between terrestrial sediment-volume estimates derived from



historical aerial imagery and lacustrine sediment-core reconstructions over multi-decadal timescales. While reconciliation of debris flow activity over time from sediment cores and terrestrial sediment dynamics is complex, both records agree on the overall increase of debris flow activity over the last decades coinciding with a shift in climatic conditions.

25 1 Introduction

Climate change in mountain regions is projected to increase the intensity and frequency of hydro-sedimentary extreme events like debris-laden flows (Turkington et al., 2016; Adler et al., 2022). Debris-laden flows (including debris flows and hyperconcentrated flows, hereafter "debris flows") are gravity-driven mixtures of water, soil, rock, vegetation, and debris with >40 % sediment by volume. They move down a slope or channel at speeds of up to $>60 \text{ km h}^{-1}$, and their flow behavior is controlled by the entrained sediment (Iverson, 2014). Debris flows occur in steep channels within mountain catchments and differ from other types of landslides because they occur periodically on established paths, usually gullies and first- or second-order drainage channels (Hungr et al., 2014). They are commonly triggered by a combination of rainfall intensity and duration (Caine, 1980; Guzzetti et al., 2008), but have proved sensitive to other climate variables such as snow-cover depth and duration (Bennett et al., 2013; Zimmerman, 1992). Their occurrence is controlled by the availability of erodible sediment in the basin and channel system (Bovis and Jakob, 1999), which, in turn, is indirectly influenced by changes in temperature and precipitation, as well as catchment parameters such as lithology, contributing surface area, the altitude of the rock wall (Jomelli et al., 2004) and the connectivity between the sediment source area and the channel network. Catchments where sediment transport is dominated by debris flows mobilize volumes that are two to three orders of magnitude larger than those mobilized by downstream processes (Mao et al., 2009). Future climatic conditions with increased extreme precipitation and temperatures might result in massive sediment delivery from Alpine catchments altering the sediment cascade and their associated risks and management.

A variety of methods have been used to investigate the temporal development of terrestrial debris flow activity. These include dating individual debris flow deposits with ^{14}C (Tipping, 2021), analyzing historical debris flow documentation (Tropeano and Turconi, 2004; Pavlova et al., 2014) and evaluating growth disturbances in century-old trees (van Steijn, 1996; Pelfini and Santilli, 2008; Stoffel, 2010; Jomelli et al., 2004). Other approaches use photointerpretation of historical aerial photographs to quantify debris flow frequency (e.g. Jomelli et al., 2004; Rom et al., 2023), planimetric areas (e.g. Rom et al., 2023; Dietrich and Krautblatter, 2017) and volumes (e.g. van Steijn, 1996; Stoffel, 2010; Bennett et al., 2012; Dietrich and Krautblatter, 2017). Most recently, terrestrial laser scanning has been used to investigate dynamic controls on erosion and deposition (Schürch et al., 2011; Stammberger et al., 2026). However, few studies have accomplished a spatiotemporal reconstruction of erosion and deposition patterns over more than a decade, which is necessary to establish a link between on- and offshore debris flow records.

Climatic analysis has shown a greater amplitude of temperature change in the European Alps than in Northern Hemisphere records and reconstructions over the last century (e.g. Casty et al., 2005). This trend is marked by intense warming in the twentieth century from the 1910s to the end of the 1940s and from the late 1960s to today (Büntgen et al., 2006) with peaks in the 1980s (e.g. Beniston et al., 1994), and exceptionally warm summers in 2003 (Büntgen et al., 2006) and 2022 (Esper



et al., 2025). Statistical analysis of the frequency of rare and extreme weather events indicates that intense precipitation events have become more frequent (e.g. Frei and Schär, 2001; Bongiovanni et al., 2026). Climate change does not primarily affect the dynamics of debris flows, but rather their triggering mechanisms and starting conditions (disposition) (Zimmerman, 1992; Pavlova et al., 2014, and references therein). Debris flow behavior has been analyzed in relation to the climatic shift in the 1980s, revealing a generally increasing trend in these events (e.g. Pelfini and Santilli, 2008; Kiefer et al., 2021; Dietrich and Krautblatter, 2017), that coincides with an increase in the number of extreme precipitation events (e.g. Rebetez et al., 1997) and a higher frequency of rainy days (e.g. Pavlova et al., 2014). A study in the French Alps exemplifies a change point, with debris flood frequencies doubling since the 1980s (Jomelli et al., 2011). Debris flow frequencies in 40 km distance to Plansee are dominated by short-term variations with an overall increasing trend, but the highest debris flow volumes occur in the 1990s (Rom et al., 2023).

An increase in Holocene debris flow activity in the Plansee catchment has been derived from lacustrine sediment cores by Kiefer et al. (2021). Debris flow-induced turbidite deposits in sediment cores covering 4000 years show a rapid frequency increase since the start of the 20th century. This sedimentary record is an aggregated signal from all contributing fans. The terrestrial record of debris flow rates of eight fans on the north slope of Plansee reveals a more than threefold increase between 1980 and 2014 compared to a reference period from the 1940s to the 1970s (Dietrich and Krautblatter, 2017).

Here we expand the spatial coverage of the terrestrial record to encompass all 54 debris fans surrounding Plansee. We address three key questions: (1) how much sediment is exported from the fan areas to the lake over decadal timescales and whether this export relates to debris flow sedimentation rates, (2) what is the sediment-dynamic response at the debris fans to the 1980s climatic shift, and (3) whether vegetation responds to changes in debris flow activity.

To address these questions, we quantify elevation and vegetation changes within the active debris channels of each fan between 1952 and 2020 on a decadal scale and we reanalyze debris flow-induced turbidite deposition rates from sediment cores. Sediment connectivity aims to describe the transfer of material between two zones (Bracken et al., 2015). Here, we use the sediment balance at each debris fan as a proxy for sediment connectivity, given the quasi-closed nature of the system, and we explore connectivity shifts based on the relative change in the net sediment balance.

2 Regional setting

Plansee is located in the Northern Calcareous Alps in the federal state Tyrol (western Austria) (Fig. 1). This inner-alpine lake has a surface area of 2.83 km^2 , a maximum depth of 78 m and a volume of 123.7 Mm^3 . At $976 \pm 5 \text{ m a.s.l.}$, the lake is the base level for more than 90 ephemeral streams that reach the lake through debris fans. It has two permanent inflows to the east and one outflow to the northwest. The highest peak in the 115.5 m^2 catchment area is Lichtbrenntjoch in the catchment of Fan 44 at 1960 m a.s.l. The annual mean precipitation in the region is 1700 mm with a pronounced summer-rainstorm peak (Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft, 2026).

The lithology around Plansee is intensely jointed (centimeter to decimeter scale) Upper Triassic lagoonal dolomite (Main Dolomite or Hauptdolomit), which produces a vast amount of loose sediment with short debris recharge times. Episodic grav-

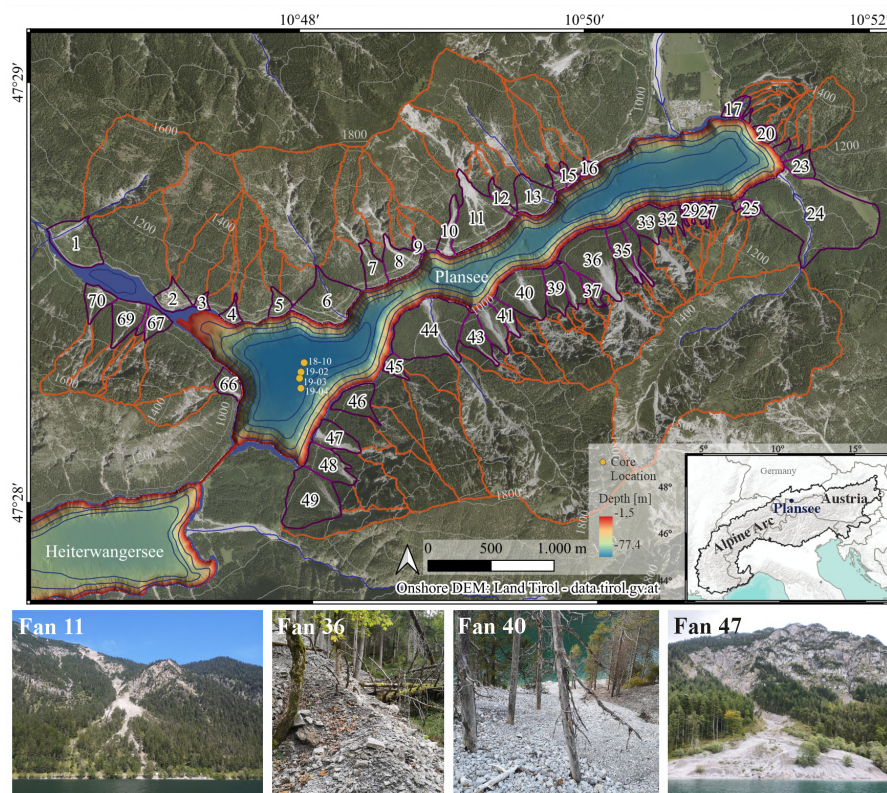


Figure 1. Location of Plansee and the 54 surrounding debris fans. Fans Nr. 1 to 16 are located on the northern slope; Nr. 18 to 23 are on the eastern slope, Nr. 35 to 49 are on the southern slope, Nr. 66 to 70 are on the western slope. Nr. 24 and 44 show ephemeral fluvial influence. Yellow dots represent the location of the sediment cores from Kiefer et al. (2021). The photographs below show characteristic fan morphologies with avulsion/lateral channel migration, debris-covered and uprooted trees, levee formation and incised channels. The lake base level elevation in 2010 was at 975 m a.s.l. Bathymetry: modified from P. Oswald and S. C. Fabbri in Kiefer et al. (2021), Onshore Orthophoto © Land Tirol (2010), reconstructed by JJ.

itational mass movements fed by the upper catchment areas propagate into fans and the lake. The debris material forms 54 conical fans of different evolutionary stages bordering the lake (Fig. 1). Their dynamic morphology reflects short-term extreme events with progressing depositional channels or incision into old deposits as well as the preserved long-term sedimentary strata and climatic changes over the Holocene. Underlying local glacial till deposits cover the glacially carved trough valley floor, which was eroded by over 400 m by ice flow from west to east (Hibler, 1921). The Heiterwangersee basin is separated from Plansee by the Pitzenbach fan. A 300 m long canal built in 1908 connects the two lake basins.



3 Data and methods

3.1 Delimitation of individual fans and source catchment

Fan area and source catchments are delimited based on a LiDAR (light detection and ranging) survey from 2019 acquired by Land Tirol. Fan areas are manually mapped based on a multi-direction hillshade while source catchments are automatically delimited by the hydrological toolbox in ArcGIS (Esri, 2026).

3.2 Reconstruction of fan sediment dynamics and routing from historical and digital aerial imagery

We photogrammetrically reconstructed five historical aerial imagery surveys (1952, 1971, 1979, 1987, and 2000) and two digital aerial imagery datasets (2010 and 2020), spanning 70 years at a decadal to bi-decadal frequency.

The historical aerial imagery was processed as a single multi-epoch photogrammetric block following Feurer and Vinatier (2018) using the software Metashape (Version 1.2.6) (Agisoft LLC, 2016). Prior knowledge of the camera calibration is retrieved from the scanned files provided by Land Tirol for each survey and is summarized in Table A1. We undistorted the scanned images using the automatic identification of fiducial marks in Metashape (Agisoft LLC, 2016), however, in some cases, manual identification was required. The undistorted images are later loaded into a multi-epoch block adjustment using the adjusted camera focal length and image position from the undistorted project. After successfully aligning all aerial photos, 20 invariant ground control points (GCPs) are used to georeference the multi-epoch block. The x, y, and z coordinates from the GCPs are obtained from the 2020 photogrammetric survey, which has a resolution of 0.2 m. An additional 20 control points were used to improve the matching between tiles and reduce distortions in the digital surface model (DSM). After optimization of the camera parameters, the camera models are saved individually to export the orthophoto, point cloud, and DSM for each survey. In contrast, the availability of precise aero-triangulation for digital aerial imagery allows the individual reconstruction of each survey using the software SURE (©2020 ESRI) following Barbosa et al. (2024).

Field observations in the Northern Calcareous Alps suggest that a few years after debris flow sedimentation, the color of the sediment darkens (Dietrich and Krautblatter, 2017). Therefore, we defined color thresholds to automatically map the active debris flow channels by segmenting the lighter areas in the orthophotos. We compared the automatic mapping with the manual mapping of selected areas and found the results to be consistent (Fig. 2), however, some surveys (e.g., the year 2000) are particularly affected by strong shadows that hamper automatic mapping. For these cases, we adjusted the active areas manually.

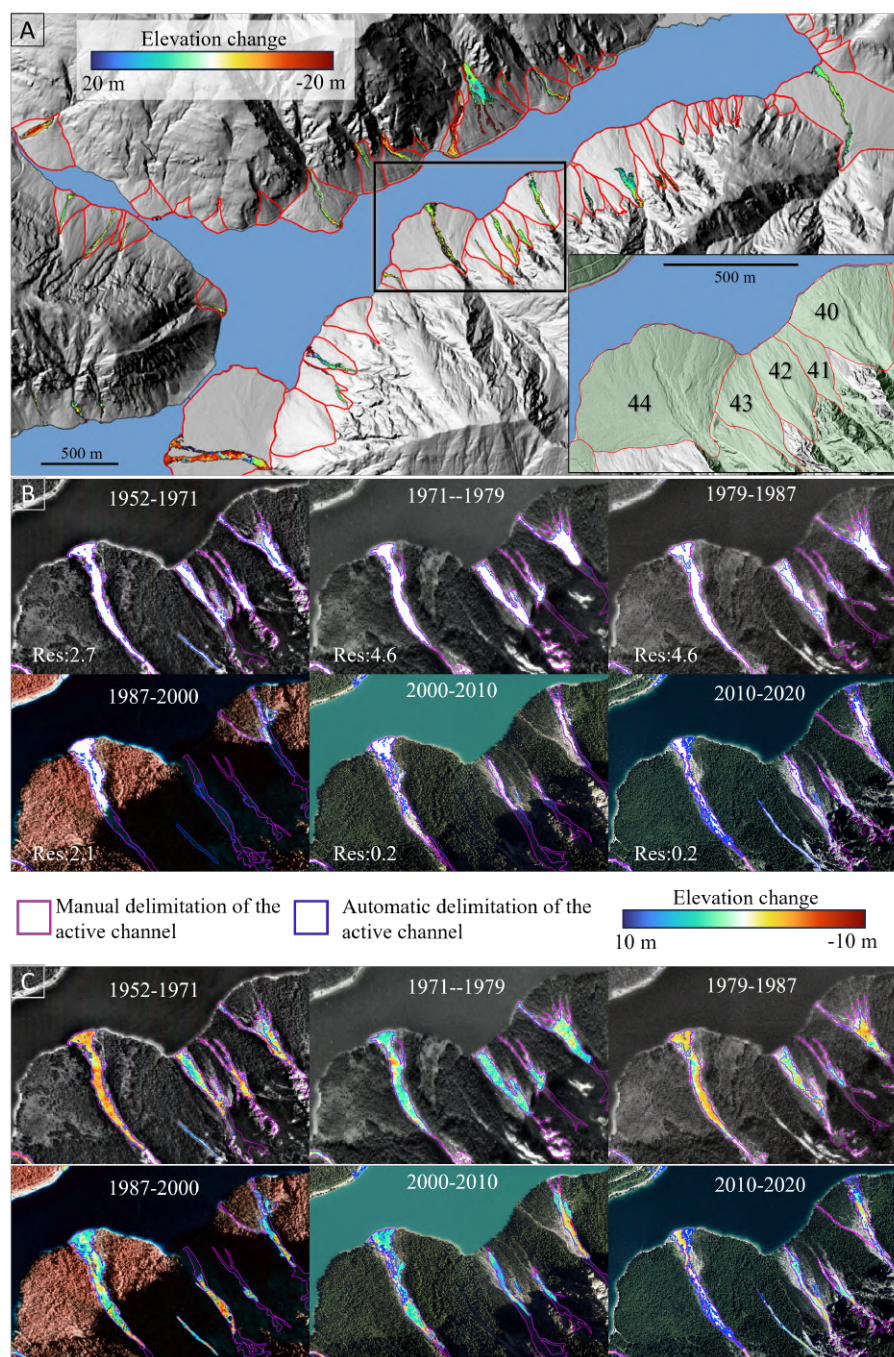


Figure 2. Reconstruction of fan sediment dynamics and routing from historical and digital aerial imagery. A). Cumulative elevation change in the last 70 years (1952-2020). The black rectangle indicates the location of Fan 40 to 44. Basemap hillshade ©Land Tirol (2019) B) Comparison of active channel manual delimitation and automatic delimitation. The base image is the most recent reconstructed orthophoto for each time interval C) Elevation change at the latest period active channel for each time interval.



120 The time series of elevation changes consists of the geomorphic changes represented by the DEM of Difference (DoD) within
 the active debris flow channel of the later survey at 1 m spatial resolution. The elevation error between surveys is assumed
 to be uniformly distributed, and a signal-to-noise ratio is defined based on the ground surface distance (GSD) for each pair
 of surveys, individual image quality, and elevation differences across stable areas measured along topographic profiles (Fig.
 A2). Defining stable areas across the entire temporal series is challenging due to dense vegetation cover and anthropogenic
 125 changes in flat areas. We report mean erosion and deposition volumes and propagate the relative mean errors using standard
 error propagation. Despite its simplicity, the error of the mean is a conservative approach for quantifying decadal volumes
 over the last 7 decades. While quantification of topographic change at the catchment scale is highly inaccurate given the steep
 slopes, the smoother surface area of the debris flow fans allows for more reliable detection of topographic changes above the
 vertical error threshold of the aerial imagery. Therefore, erosion and deposition volumes at the active channel are reported for
 130 debris fans.

3.2.1 Fan-lake sediment routing and sediment budget as proxy for sediment export to the lake

The catchment-fan-lake geomorphic system of Plansee represents a simplified sediment routing cascade, with sediment pro-
 duction in the catchments, redistribution and temporary storage on debris fans, and eventual deposition in the lake at the
 subaqueous fan slope (coarse fraction) and the lake bottom (fine fraction). This study focuses on the sediment dynamics at the
 135 debris fans.

We acknowledge that the sediment budget of the fans is open on both ends; however, assuming limited sediment export
 beyond the lake over the study period, the system is treated as quasi-closed. This allows the use of net elevation changes on the
 debris flow fans as a proxy for the magnitude of sediment transfer to the lake. Net change is defined as the difference between
 gross erosion and deposition over a given time interval at the active channel of each fan.

140 Decadal sediment connectivity between the fan and the lake is inferred from the co-occurrence of active channel linkage to
 the lake and net sediment export (i.e., negative net change). We interpret net changes as proxies for the dominant process at the
 fans, which does not necessarily imply a lack of sediment transport to the lake during aggradation (i.e., a net positive sediment
 balance); rather, we refer to periods of positive net change as phases of reduced sediment transport, informing about sediment
 transport efficiency.

145 Following this framework, we classified the debris flow fans into three categories to describe sediment routing between the
 fans and the lake: 1) **connected fans**, where the active channel reaches the lake and sediment transfer (expressed as decadal
 net negative sediment balance) is measured during at least one time interval, 2) **disconnected fans**, which exhibits topographic
 change but lacks an active channel reaching the lake, and 3) **inactive fans** where no significant topographic change has been
 detectable over the past 70 years using photogrammetry, despite the existence of a channel.

150 For the disconnected fans, the DoDs were further analyzed to identify channel progression towards the lake. The time series
 begins in 1971, using 1952 as the reference year.

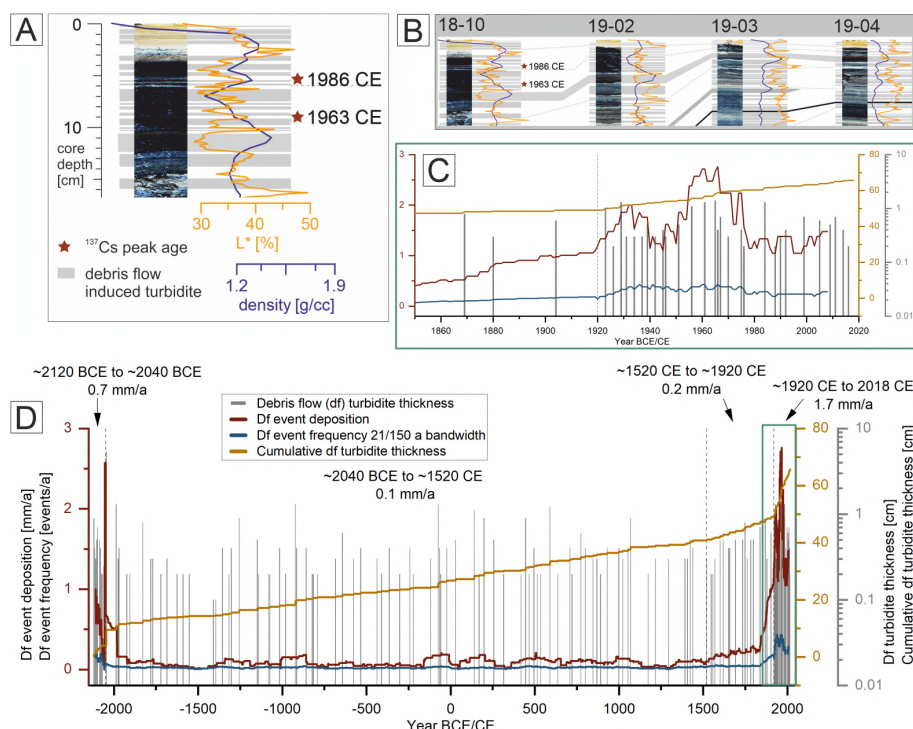


Figure 3. Debris flow frequencies and event magnitudes derived from dated sediment core transect (Kiefer et al., 2021). A) Dated master core section of the investigated time period, B) Event correlation across 4 cores from distal (18-10) to proximal (19-04) basin area, C) zoom of D) on the period since 1850, D) Debris flow turbidite thickness, event deposition rate, event frequency, and cumulative turbidite thickness over 4000 years. Background sedimentation is excluded. Core locations see Fig.1.

3.3 Historical record of debris flow events

Local newspaper and fire brigade archives provide a historical record of documented debris flows and flood events (Zunter - Das Außerfern-Archiv, 2026; Freiwillige Feuerwehr Höfen, 2026; Freiwillige Feuerwehr Reutte, 2026; Freiwillige Feuerwehr Breitenwang, 2026). From these sources, a inventory was compiled, detailing event date, event type, location, daily precipitation at Höfen (47° 26' N, 10° 44' E) and Berwang (47° 24' N, 10° 45' E), and recorded damages (Table B2).

3.4 Debris flow turbidite deposition rates from sediment cores

When sediment-laden flows from steep catchments or fan deltas enter the lake, they may plunge and/or transform into turbidity currents. Coarser sediment is preferentially deposited on proximal subaqueous slopes, delta fronts, or channel floors, whereas finer suspended sediment can be transported farther basinward within dilute, turbulent underflows. Under stratified conditions, part of this fine load may detach from the basal flow and intrude into the water column as an interflow before settling. In the deepest, flat basins, these processes can produce sharp-based, normally graded event beds overlain by a fine mud or clay



Table 1. Frequency of debris flow events from sediment cores for mean, minimum, and maximum age models across time periods between orthophotos, derived from Kiefer et al. (2021). Within the first period, the mean, min and max age models show 1, 3, and 1 event until 1960 and the rest after 1960.

Time interval	Mean Age	Min Age	Max Age
1952–1970	7	10	6
1971–1978	2	4	2
1979–1986	1	0	2
1987–1999	4	4	3
2000–2009	2	2	3
2010–2018	3	4	2

Mean age uncertainties are ± 6 years (1960–2018) and ± 19 years (1920–1959)

cap (Sabatier et al., 2022; Felix and Peakall, 2006; Irmeler et al., 2006; Sumner et al., 2009; Sletten et al., 2003; Blanckaert et al., 2024). In a previous study, event deposits in four sediment cores along a depocentre-to-subaqueous slope transect in the western main basin of Plansee (Fig. 1) were event-correlated, distinguished by geochemical and sedimentological means, and tied into a Bayesian age-depth model of combined radiocarbon and short-lived radionuclide (^{210}Pb and ^{137}Cs) ages (Kiefer et al., 2021). A total of 138 debris flow-induced turbidites were identified in the sedimentary succession over the last 4000 years (Fig. 3). Four phases with similar debris flow occurrence patterns were distinguished by change point analysis of the interevent times of debris flow-induced turbidites and correlated with four lithostratigraphic units in the core.

There is a significant shift in debris flow activity, with a sevenfold increase in frequency and a ninefold increase in event deposition rates between Phase 3 (1500–1920) and Phase 4 (1920–2018), see Fig. 3 and Kiefer et al. (2021). The decadal frequency since 1952 for the mean, minimum and maximum age models is displayed in Table 1.

A total of 89 % of the event layers in the sediment cores can be correlated across the investigated deep-basin core transect. In this study, we use the existing core transect from Kiefer et al. (2021) to derive a first-order lacustrine volume estimate, assuming that the cumulative fine-grained event-layer thickness measured in the investigated depocentre is representative of the effective depositional area considered in Eq.1. This assumption is likely most robust for source-to-sink pathways directly connected to the investigated deep basin, whereas greater uncertainty exists for catchments separated from the depocentre by bathymetric highs that may influence sediment-routing pathways. Suspended sediment from debris flows originating from eastern catchments is, nonetheless, expected to contribute to event layer deposition in the western part of the lake, as the suspension is transported farther toward the outflow (NW, Archbach).

The depocentre representative for the effective depositional area is mapped using contrasting backscatter signals, which distinguish fine- and coarse- grained deposits. Unterwater photographs provide evidence of a sharp transition between the coarse grain-size fraction deposited on the slope and the fine-grained sediment in the basin.



We also assume that a constant fine-to-coarse ratio can be used to convert fine-grained event-layer volumes into total debris
 185 flow volumes. The fine-grained fraction of debris flows is estimated to be 15-40 % (Pleskot, 2015; Yong et al., 2013; Hu
 et al., 2011). A local sieving analysis of Hauptdolomit fan sediments from Oberau (15 km east of our study site) shows that
 the Plansee debris flow material is likely at the lower limit of these estimates (P. Gewalt, oral communication). We therefore
 use a 20 % fine fraction value as a conservative first-order assumption to convert event-layer volumes into total debris flow
 volumes. This conversion assumes that the adopted fine-to-coarse ratio is representative of the effective depositional area
 190 considered in Eq. 1, despite potential spatial variability in sediment-routing pathways and depositional processes. Based on
 these premises, lake-wide debris flow volumes since 1952 are calculated from cumulative event-layer thicknesses extrapolated
 over the effective depositional area using Eq. 1 and 2.

$$V_{\text{fine}} = A \sum_{i=1}^n d_i \quad (1)$$

where V_{fine} is the volume (m^3) of fine-grained (clay to fine sand) debris flow material deposited in the sediment cores from
 195 the suspension cloud between 1952 and 2018 based on min, mean and max age-depth model from Kiefer et al. (2021), A is the
 flat depositional area of the lake (m^2), and d_i is the thickness (m) of the i^{th} debris flow turbidite layer.

$$V_{\text{tot}} = V_{\text{fine}} + V_{\text{coarse}} \quad (2)$$

where V_{tot} is the total debris flow volume (m^3) deposited between 1952 and 2018, V_{fine} is the Volume of coarse particles
 (larger than silt/fine sand) deposited on the subaquatic slope.

200 3.5 Controls on sediment dynamics and routing to Plansee

Sediment production, mobilization, and deposition are governed by both internal and external controls. Summer precipitation
 since 1942 is used as a proxy for external forcing on sediment dynamics, assuming a spatially uniform climatic influence.
 Internal controls are characterized by the geomorphometric properties of catchments and fans, along with vegetation dynamics
 and forest disturbance.

205 3.5.1 Rainstorm frequency

The meteorological station at Reutte, located c. 10 km west of Plansee, has been recording hourly precipitation since 1942,
 with gaps in the winter months between 1942 and 1979. In the Northeastern Alpine region, the annual cycle of precipitation
 peaks in summer due to convective events (Rajczak et al., 2013). Therefore, the rainstorm frequency analysis is carried out in
 the main period of debris flow activity from May to October (Pavlova et al., 2014).

210 Debris flows and hyperconcentrated flows are triggered by high-intensity, short-duration rainstorms (Stoffel et al., 2014).
 Identifying rainstorms that trigger sediment mobilization events remains challenging due to the individual properties of each



Table 2. Morphometric parameters used in this study, including their calculation and geomorphic interpretation.

Morphometric parameter	Calculation	Interpretation
Catchment and fan area (m ²)	Planimetric surface calculated from vector data	Large catchments collect more runoff
Fan–catchment relationship	$A_f = cA_d^n$	Larger basins supply greater amounts of sediment and thus create larger fans (Giles, 2010)
Catchment and fan slope (°)	Mean slope over planimetric surface	Steepness of terrain / sediment production potential
Terrain curvature	Second derivative from elevation values (DSM)	Degree of concavity/convexity perpendicular to direction of maximum slope
Stream power index (SPI)	$SPI = \ln(A \cdot \tan(\text{slope}))$	Proxy for transport and erosion power of stream – ability to move sediment
Melton ratio (Melton, 1965)	Difference between maximum elevation of catchment and elevation of fan apex at catchment outlet, divided by square root of catchment area	Predictor of debris flow catchments (de Haas et al., 2024)
Index of connectivity (IC) (Borselli et al., 2008)	$IC = \log_{10} \left(\frac{D_{up}}{D_{dn}} \right)$	How efficiently sediment can travel from hillslopes to fan
Channel profiles on fans	Calculated on 2019 DEM with Hydrology toolset in ArcGIS Pro	Slope and concavity

A is the upstream drainage area (i.e., flow accumulation at grid cell i multiplied by grid cell area). D_{up} is the upslope component, defined as $D_{up} = \bar{W} \bar{S} \sqrt{A}$, where $\bar{W}$ is the average weighting factor, $\bar{S}$ is the average slope gradient of the upslope contributing area, and A is the upslope contributing area (m²). D_{dn} is the downslope component considering the potential flow path length that sediment travels to reach the nearest target or sink, expressed as $D_{dn} = \sum_{i=1}^n (d_i / (W_i S_i))$, where d_i is the length of the flow path along the i^{th} cell and $W_i S_i$ are weighting factors. Slope statistics were calculated from 1 m segments along the profile. Channel profile curvature was classified into four groups using normalized quadratic curvature $y_n = ax_n^2 + bx_n + c$: convex ($a < -0.05$), linear ($-0.05 \leq a \leq 0.05$), lightly concave ($0.05 < a \leq 0.25$), and strongly concave ($a > 0.25$) (see Supplement).

catchment, including sediment availability and surface temperatures. For the rainstorm frequency analysis, we counted the number of days on which 10 mm h⁻¹ was exceeded (Hürlimann et al., 2019; Hirschberg et al., 2021) within the range of the acquisition dates of the aerial imagery.

215 3.5.2 Catchment and fan geomorphometry

The characteristics of debris flow catchments control the sediment dynamics of their associated depositional fans (e.g. Bull, 1964; de Haas et al., 2024). The morphometry of catchments and fans dominated by debris flows differs from those dominated by colluvial processes and floods, although considerable overlap exists (de Haas et al., 2024). We explored the characteristics of the catchments and fans around Plansee to hypothesize about the individual controlling factors that influence the sediment dynamics response of the fans to the post 1980s increase in precipitation. The morphometric parameters are calculated using a 20 m moving window to capture catchment-scale characteristics using Python (Python Software Foundation, 2026) and the



Whitebox Toolbox (Lindsay, 2026). The morphometric parameters used to discriminate fan groups within this study are listed in Table 2.

3.5.3 Vegetation response and disturbances

- 225 The time series of non-vegetated area on each of the connected fans was derived from the reconstructed orthophotos in ArcGIS Pro 3.1.3 ©2023 Esri. Object-based classification (maximum likelihood) was employed, including segmentation, accounting for color and shape characteristics when grouping pixels, and >20 training samples per class (non vegetated/vegetated). Shaded areas were delineated and classified manually. They were most pronounced on the southern shore in the orthophotos from 1979, 2000, and 2010. For comparison, changes within the investigated periods were normalized by time and fan area.
- 230 The European Forest Disturbance Atlas (Viana-Soto and Senf, 2025) was used to quantify vegetation changes in the catchment areas at 30 m resolution since 1985. A manual classification of non-vegetated areas in the catchments was not possible on the orthophotos due to shadows and debris flow channel coverage by the canopy.

4 Results

4.1 Fan-lake sediment transfer from sediment budgets

- 235 The block reconstruction of the historical aerial imagery resulted in a total error of 0.7 m in x, 1.3 m in y, and 0.7 m in z evaluated on 20 independent control points. In comparison, the reconstruction of the digital aerial survey resulted in errors of less than 0.2 m for all three components. The consecutive elevation profiles used to quantify the uncertainty in the elevation changes between surveys resulted in less than 2 m difference on unchanged areas within the active areas for the oldest aerial imagery (Fig. A2 and Table A2). The visual inspection of the resulting topographic changes allows for the identification of
- 240 both erosion and deposition at all time periods (Fig. 2).

Despite the high activity exhibited by most fans around Plansee, less than half have delivered sediment to the lake over the last 70 years (Fig. 4). Fans on the northern slopes predominately deliver sediment to the lake, whereas those on the southern slope mostly accumulate it. The decadal sediment balance indicates episodic transfer from the fans to the lake, with alternating decadal phases of net erosion and deposition.

- 245 Cumulative sediment transfer to the lake amounts to $(3.42 \pm 0.43) \times 10^5 \text{ m}^3$, with the majority of sediment export occurring during the 1950s, 1960s, 1980s, 1990s, and 2010s, and reduced sediment transfer during the 1970s and 2000s (Table 3). The decadal erosion and deposition volumes represent temporally aggregated sediment budgets from net elevation changes rather than gross sediment flux. As a consequence, these estimates should be interpreted as a lower bound of the total sediment transferred.

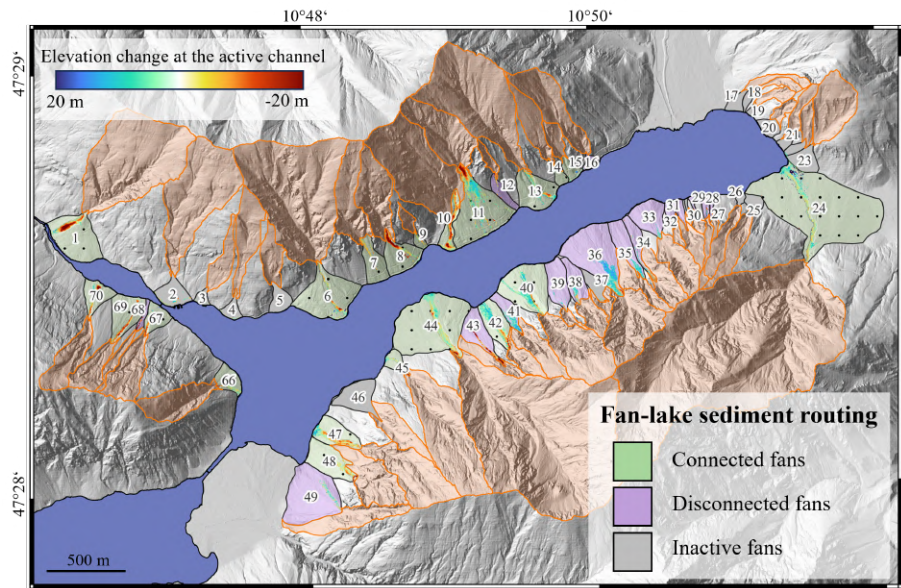


Figure 4. Classes of fan-lake sediment routing based on whether their active channel reached the lake and recorded a negative net change, interpreted as sediment delivery, for at least one time interval over the last 70 years. Base map hillshade ©Land Tirol (2019).

Table 3. Decadal sediment balance at connected fans to Plansee.

Decade	Time Interval	Erosion (m ³)	Deposition (m ³)	Net (m ³)
50/60	1952–1971	349 304 ± 11 992	259 148 ± 11 100	−90 156 ± 23 092
70	1971–1979	81 949 ± 5 049	223 682 ± 6 443	141 733 ± 11 493
80	1979–1987*	151 492 ± 4 984	50 150 ± 2 573	−101 343 ± 7 558
90	1987*–2000	233 436 ± 4 795	183 890 ± 5 755	−49 545 ± 10 551
2000	2000–2010	133 896 ± 3 918	186 730 ± 6 060	52 833 ± 9 978
2010	2010–2020	136 402 ± 741	35 386 ± 1 030	−101 016 ± 1 772

The net change (m³), calculated as the difference between erosion and deposition volumes in the active channel for the time intervals 1952–1971, 1979–1987, 1987–2000, and 2010–2020, was added to quantify the total amount of sediment transferred to the lake over the last 70 years. *The orthophoto from 1987 contains strong shadows on the southern slope of Plansee, which decreases the accuracy of the volume calculation.

250 **4.2 Sediment-core observations and volumetric reconstruction**

The cumulative thickness of debris flow-induced turbidites in the sediment cores between 1952 and 2018 derived from Kiefer et al. (2021) is 0,111 m/ 0,126 m/ 0,010 m (mean/min/max age model). Assuming a fine-to-coarse ratio of 20:80, the total debris flow volume is $(3.69 \pm 0.42) \times 10^5 \text{ m}^3$ (Table 4).



Table 4. Subaquatic debris flow volume between 1952 and 2018 assuming 20 % fine-grain fraction, derived from turbidite deposition in sediment cores from Kiefer et al. (2021).

Age model	Cumulative turbidite thickness (m)	Debris flow volume (m ³)
Mean	0.111	362 245
Min	0.126	411 202
Max	0.100	326 351

Total basin area (flat, low backscatter signal): 652 702 m². Cumulative turbidite thickness 1952-2018 derived from Kiefer et al. (2021).

4.3 Decadal variability of terrestrial sediment dynamics at the fan scale

Despite the assumed spatial uniformity of climatic forcing across all catchments, individual fans exhibit pronounced decadal variability in sediment patterns and net export rates to the lake (Fig. 5), highlighting the episodic and spatially heterogeneous nature of sediment dynamics at the fan scale. Notably, 18 of the 21 connected fans exhibit a negative net sediment balance during the most recent decade (2010-2020), indicating predominant sediment delivery to the lake, and 10 fans have shown sustained negative net sediment balance since the 2000s (i.e., two consecutive decades). Only three fans show persistent sediment transfer to the lake (i.e., a negative net balance) over the last three decades, and two extend this pattern back to the 1980s.

Thirteen connected fans show new channel formation or reactivation of dormant channel sections over the investigated period. This process starts in 1971 (Fans 10, 11, 42, 44), 1979 (Fans 8, 67), 1987 (Fans 7, 13, 14, 40, 69, 70) and 2010 (Fan 48) and lasts until 2020 for most fans. Fans 11 and 42 show progression over all periods. Fan 11 shows by far the largest stretch of newly formed or reactivated channel sections, with a total length of 1 200 m, followed by Fan 7.

Sediment dynamics at disconnected fans – where active channels do not reach the lake – are critical for constraining future sediment transfer rates to the lake. Among the 16 disconnected fans, approximately half exhibit little to no activity between the 1970s and the 2000s, followed by a reactivation after 2010. This reactivation, characterized by mostly positive net changes (Fig. 5), reflects the recent deposition of debris on downslope forested areas. In total, 15 fans have active channels that progressed towards the lake between 1971 and 2020, with progression rates ranging between 0.6 myr⁻¹ and 32 myr⁻¹ (Table 5). Each decade exhibits a high degree of variability among fans, with high progression rates in some channels and very low rates in others. Five channels showed progression prior to 1980 (Fig. 6, Fig. E1). Notably, these correspond to neighboring channels 34 to 39 (excl. inactive channel 37). Of the 10 channels that initiated progression after 1980, two are located on the northern shore (Fan 12, 16), one on the western shore (Fan 68), and 7 on the southern shore (Fan 27, 28, 29, 32, 33, 41, 43). Since 1980, the cumulative rate of channel progression across all advancing channels has increased from 1 myr⁻¹ (1979-1987) to 50 myr⁻¹ (2010-2020), see Table 5. The mean annual progression rate is 2.1 myr⁻¹, reaching up to 10 myr⁻¹ on Fan 36, where three independently advancing channels have formed. Fans 12, 41, 43, and 68 also show high channel progression rates (2 – 5 myr⁻¹).

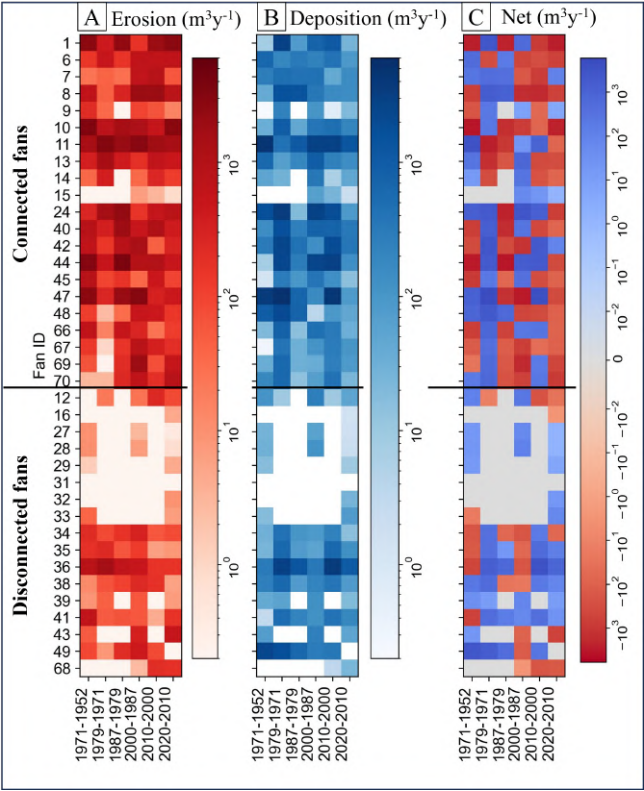


Figure 5. Sediment dynamics at the individual fans represented by A) erosion volume per year, B) deposition volume per year, C) net volume per year as the difference between erosion and deposition volumes used as proxy for sediment delivery to the lake

Table 5. Cumulative yearly channel progression on disconnected fans by decade.

Decade	Time interval	No. of channels	Progression range (m.yr ⁻¹)	Cumulative progression (m.yr ⁻¹)
1970	1971–1979	5	16.7 ± 16.1	49.5
1980	1979–1987	1	0.9	0.9
1990	1987–2000	4	9.7 ± 8.4	27.0
2000	2000–2010	3	9.4 ± 5.6	28.9
2010	2010–2020	9	7.3 ± 6.7	50.7

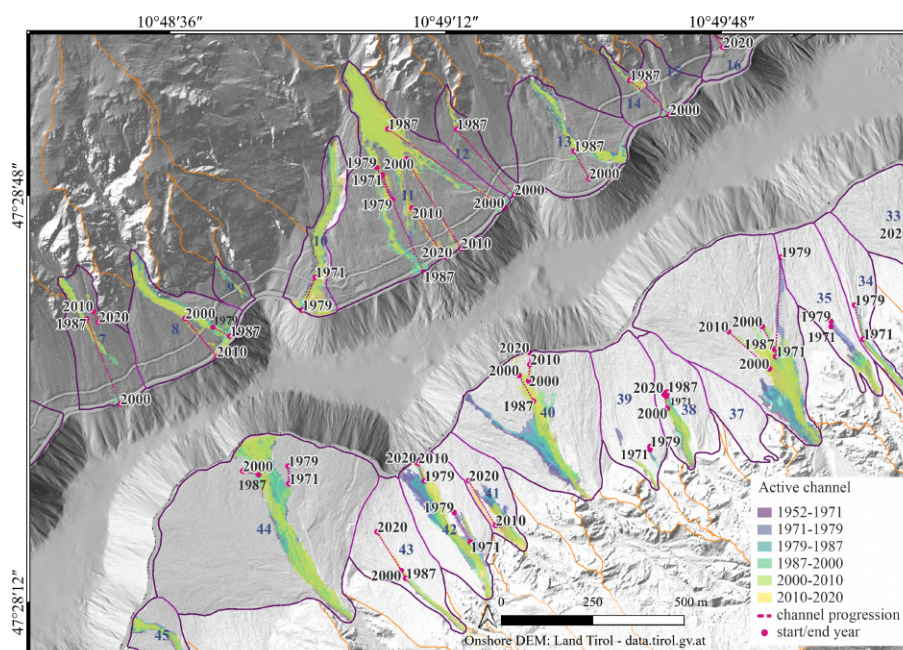


Figure 6. Active channel progression since 1952. Pink lines show the cumulative channel progression with marked positions of start and end year between 1971 and 2020. Channel progression and new channel formation occurs on both connected and non-connected fans. The linear channel profiles of Fans 7 and 11 show the strongest channel progression within connected fans. The disconnected Fans 34–39 have started progressing before 1980, the 10 remaining disconnected fans started progressing after 1980. The rate of progression is increasing on all fans since, with up to 10 m yr^{-1} on Fan 36. Note that active areas on the south shore shifted to the east in recent decades. Base map hillshade ©Land Tirol (2019).



4.4 Response of sediment regimes to rainstorm intensity

Rainstorm intensity is considered a key control on sediment transport and debris flow triggering. The mean rainfall intensity at Plansee over the past 70 years is 0.205 mm h^{-1} . Over this period, decadal mean precipitation intensity ranged between 0.194 and 0.224 mm h^{-1} , showing relatively low variability. In contrast, maximum rainfall intensities show greater variability, ranging from 28 mm h^{-1} in the 1950s–1960s to a peak of 47 mm h^{-1} in the 1980s. While mean intensities remain stable, maximum intensities indicate periods of enhanced extreme rainfall events, particularly during the 1980s and 2000s (Table 6). Similarly, the frequency of events exceeding the 10 mm h^{-1} threshold increases by 36 % after 1980 compared to the reference period starting in 1945 (Fig. 7B). In total, this threshold was exceeded 191 times over the last 70 years, occurring on 172 different days, with some events lasting for more than one consecutive hour.

Documented debris flows in the Plansee region were analyzed in relation to the corresponding rainfall recorded at nearby meteorological stations. Since 1952, 25 debris flow events have been recorded ($< 40 \text{ km}$ from Plansee), eight of which were located directly at Plansee or Heiterwangersee. They occurred in June 1987, July 2008, July 2010, October 2011, August 2012, June 2013, July 2014 and August 2016 (Fig. 7 and Table B2). The 5 events since 2011 were accompanied by heavy rainfall events ($30\text{--}90 \text{ mm day}^{-1}$) on the same day or within the preceding week. For the three events occurring before 2011, rainfall totals of $10\text{--}20 \text{ mm day}^{-1}$ was recorded on the event day.

Mean erosion volumes across the lake show an increase of 7 % after 1980, with a more pronounced increase observed on connected fans (12 % , Fig. 7C). In contrast, deposition volumes on all fans decrease about one-third after 1980 (32 %), indicating a shift towards more negative net sediment balance and enhanced sediment transfer to the lake.

There is a positive correlation between erosion volumes and mean precipitation values (Fig. C1), but the relationship may be non-linear, indicating that erosion rates do not scale proportionally with increased precipitation.

At the fan scale, erosion and deposition rates can be grouped in three main categories based on each fan's response to the increase in rainstorm intensity since the 1980s (Fig. 8): **A)** Fans that shift from predominantly depositional to predominantly erosional behavior, resulting in the **onset of sediment delivery to the lake**, indicated by decades of net negative mass balance (Fan 7, 24, 47, 48, 70). **B)** Fans that exhibit an increase in the magnitude of net negative mass balance that resulting in **enhanced sediment delivery** to the lake (Fan 1, 6, 8, 10, 15, 40, 42, 67, 69). **C)** Fans that show a decrease in the magnitude of net negative mass balance or a shift to net positive mass balance, resulting in **reduced sediment delivery** to the lake (Fan 9, 11, 13, 14, 44, 45, 66).

The observed sediment dynamics derived from decadal erosion and deposition patterns in the active channels indicate that after the 1980s, increased erosion is typically expressed as discrete erosional pulses characterized by high decadal erosion volumes occurring in one or more, often consecutive, time intervals rather than following a linear or constant trend over time. For example, Fan 69 exhibits a single erosional pulse between 1987 and 2000, while Fan 7 shows two consecutive time intervals with increased net erosion between 1987 and 2010, resulting in a shift in the net sediment balance and the onset of net sediment transfer to the lake after the 1980s (Fig. 8Bb). In contrast, Fan 47 shows a decrease in both erosion and deposition rates, with a sharper drop in deposition after the 1980s, which resulted in a shift towards a net negative sediment balance (Fig. 8Ba). This

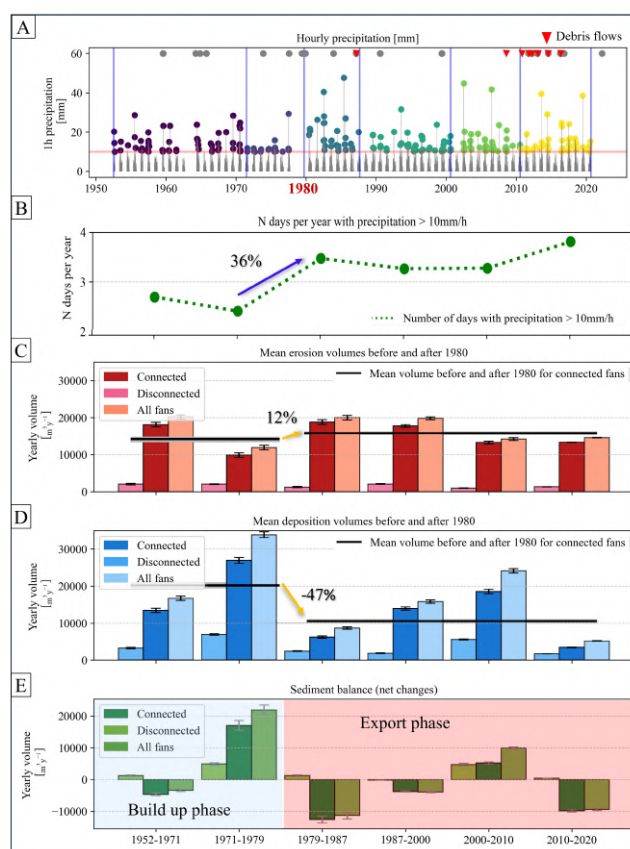


Figure 7. Response of sediment regime to changes in rainstorm intensity. A) Hourly precipitation at the rainfall station at Reutte and historical record of debris flow events. The precipitation was segmented in decades based on the aerial imagery acquisition dates (vertical blue lines). Grey circles show rainfall events that caused floods. B) Number of days with precipitation intensity above the 10mm/h threshold per decade. C) and D) Normalized erosion and deposition volumes at connected, disconnected, and all Plansee fans. Mean volumes at connected fans before and after 1980s are shown by the black line. E) Decadal sediment balance. Decades of enhanced net positive are measured before the 1980s promoting fan build up. Consecutive decades of net negative are measured after the 1980s favoring massive sediment transfer from the fans to the lake.

exemplifies how, on highly active fans, the decadal erosion and deposition volumes may partially cancel each other out due to ongoing sediment redistribution, leading to an underestimation of the net sediment budget while preserving the dominant geomorphic signal.

315 A change of sediment routing is also visible after the 1980s. On fans with enhanced sediment transfer to the lake (Group B), erosion is mainly concentrated at the fan base before 1980 (e.g., Fan 6 - Fig. 8Bb), whereas after 1980 it is mostly observed at the fan apex or along the entire active channel, with less intermediate deposition (Fig 8).



Table 6. Temporal variation in mean and maximum precipitation intensity from 1952 to 2020 by decade.

Decade	Time interval	Mean precipitation (mm h^{-1})	Maximum intensity (mm h^{-1})
1950s/1960s	1952–1971	0.224	28
1970s	1971–1979	0.194	29
1980s	1979–1987	0.206	47
1990s	1987–2000	0.204	31
2000s	2000–2010	0.199	44
2010s	2010–2020	0.205	39

Fans with reduced sediment transport to the lake (Group C) exhibit diverse sediment dynamics. Overall decreases in erosion rates lead to decreases in sediment transfer rates to the lake (e.g., Fan 9, 13). However, the most interesting cases are Fan 11 and 44 (Fig 8Bc). Both experience a dramatic shift from a net erosional to a net depositional regime. They experience aggradation after the 1980s, evidencing channel avulsion (new channel carries over 50 % of the discharge from the previous channel) and the formation of multiple channels.

4.5 Catchment-fan morphology as a "static" controlling factor

The 54 catchments surrounding Plansee range from 0.004 km^2 to 1.6 km^2 , while fan areas range from 0.003 km^2 to 0.4 km^2 . Mean catchment and fan area differ significantly between connected and disconnected/inactive fans (Fig. 9A and B). Connected catchments and their associated fans are larger than those in the disconnected and inactive groups. Catchment-area regression follows a significant law scaling ($k = 0.64$, $p < 0.0001$) showing that an increase in catchment size produces a smaller proportional increase of fan size (Fig. D4). In contrast, the mean fan-catchment area ratio statistically distinguishes between connected and disconnected fans, with disconnected fans exhibiting higher ratios than connected ones (Fig. D5).

Catchment surface curvature statistically differentiates among the connected, disconnected and inactive groups. Notably, catchments linked to disconnected fans show a pronounced negative plan curvature promoting flow convergence (Fig. 9E), paired with high profile curvature, indicating enhanced flow acceleration (Fig. 9C). These morphometric characteristics suggest favorable conditions for enhanced sediment transport and increased susceptibility to debris flows. Conversely, the catchments linked to connected fans show a more heterogeneous morphometry, suggesting a less uniform response to climatic forcing.

The normalized quadratic curvature classification shows that, across all fan groups, most fan channel profiles are classified as strongly concave (Table D2 and Fig. D1, SD2, SD3). This dominance of concave profiles is consistent with conditions favoring sediment deposition. However, most fans showing an onset of sediment delivery after the 1980s (Group A) are characterized by lightly concave channel profiles. Only few fans exhibit linear or convex channel profiles (Fan 7, 11, 19, 23, 38), making them more susceptible to sediment reworking and reduced deposition potential; however, they do not correspond to any of the proposed fan groups. Fans 7 and 11 are connected fans that exhibit the greatest channel progression, while the disconnected Fan 38 is wedged between neighboring fans, constraining its channel path.

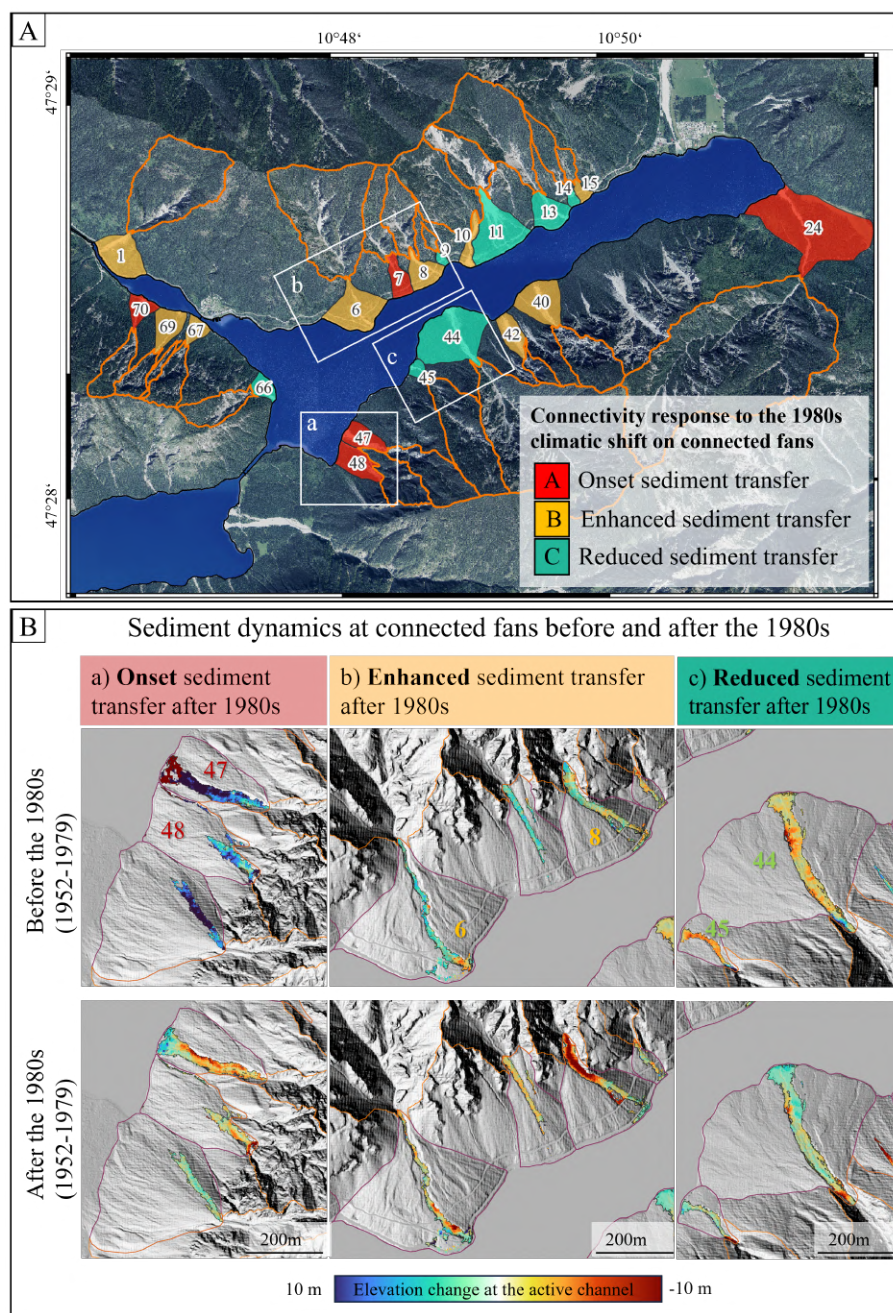


Figure 8. A) Spatial distribution of connected fans grouped by their response to increased rainstorm intensity since the 1980s. Orthophoto © Land Tirol (2020), reconstructed by JJ. B) Changes on sediment dynamics at each fan group expressed by cumulative net elevation change on the active channel before 1980s (DoD 1952-1979) and after 1980s (DoD 1979-2020). Note the predominance of positive elevation changes at the active channel (aggradation at the fan) for groups A and B before the 1980s and the shift to dominant negative elevation changes (channel erosion and incision) after the 1980s. Fans with reduce sediment transfer (group C) show the opposite shift. Base map hillshade ©Land Tirol (2019).



The other explored morphometric parameters do not reveal statistically significant differences among the fan response groups following the 1980s climatic shift, although qualitative differences remain indicative.

Catchments associated with fans showing an onset of sediment transfer after the 1980s (Group A) are characterized by the
 345 smallest catchment areas among the connected fans, slope angles ranging from 37° to 39° (Fig. 9G), narrowly distributed plan
 curvatures close to zero and profile curvature around 1. These catchments also exhibit the the highest connectivity index values
 (Fig. 9I) but the lowest stream power index values (Fig. 9J). In contrast, the corresponding fans (Group A) show a wide range
 of stream power index values with the highest mean among the groups (Fig. 9J) and predominantly positive plan curvatures
 (Fig. 9F). The combination of catchment and fan morphometry suggests a system characterized by catchments with higher
 350 susceptibility to debris flow generation and depositional conditions on the fan surfaces.

Catchments linked to connected fans that exhibit enhanced sediment transfer after the 1980s (Group B) show the highest
 mean catchment slope (Fig. 9G) and a wider distribution of stream power index values values (Fig. 9J). The corresponding fans
 (Group B) are among the steepest within the connected group (Fig. 9H), and exhibit predominantly negative plan curvature
 (Fig. 9F). This combination of catchment and fan morphometry suggests a high sediment production potential in the catchments
 355 and sediment routing and redistribution on the fan surfaces.

Catchments associated with fans that reduced sediment transfer after the 1980s (Group C) are characterized by the lowest
 mean slope values (Fig. 9G) and lower profile curvatures (Fig. 9C), indicating reduced gravitational forcing. In contrast, they
 exhibit relatively high stream power index values (Fig. 9J), suggesting runoff concentration and high hydrological and hydraulic
 potential. Corresponding fans display a wide range of plan curvatures from positive to negative, and slopes from 10° to 35°,
 360 indicating spatially variable sediment storage and reworking conditions.

The fan-to-catchment ratio of disconnected fans is the highest, with catchments characterized by the smallest size (Fig.
 9A), high profile curvatures (Fig. 9C), highly negative plan curvatures (Fig. 9E), and the steepest slopes (Fig. 9G). These
 catchments also exhibit low stream power index values (Fig. 9J) and a lower percentage of connectivity index above one (Fig.
 D5). In contrast, the associated disconnected fans show a high mean positive plan curvature (Fig. 9F) and the steepest slopes
 365 (Fig. 9H). This configuration suggests catchments with efficient, convergent routing pathways but limited overall hydrological
 connectivity, associated with fans that favor sediment storage.

Finally, catchments linked to inactive fans are characterized by the lowest mean slope (Fig. 9G) and negative plan curvatures
 (Fig. 9E). In contrast, the corresponding fans are the smallest in area (Fig. 9B), and exhibit the most pronounced negative
 (concave) profile curvature (Fig. 9D), a wide range of slopes (Fig. 9H) and a very low stream power index (Fig. 9F). This
 370 configuration suggests catchments with low gravitational forcing and limited sediment production potential.

4.6 Fan and Catchment response to vegetation changes

The fans are dominated by montane/subalpine mountain pine forest and spruce-fir woodlands, while the catchments are char-
 acterized by dwarf pine scrub. The northern and southern catchments show distinctive vegetation-coverage characteristics.
 Larger catchments overall exhibit greater forest coverage compared to smaller catchments. Southern catchments are dominated
 375 by exposed bedrock (forest coverage <40 % on catchments 33-43), while larger catchments in the south (forest coverage

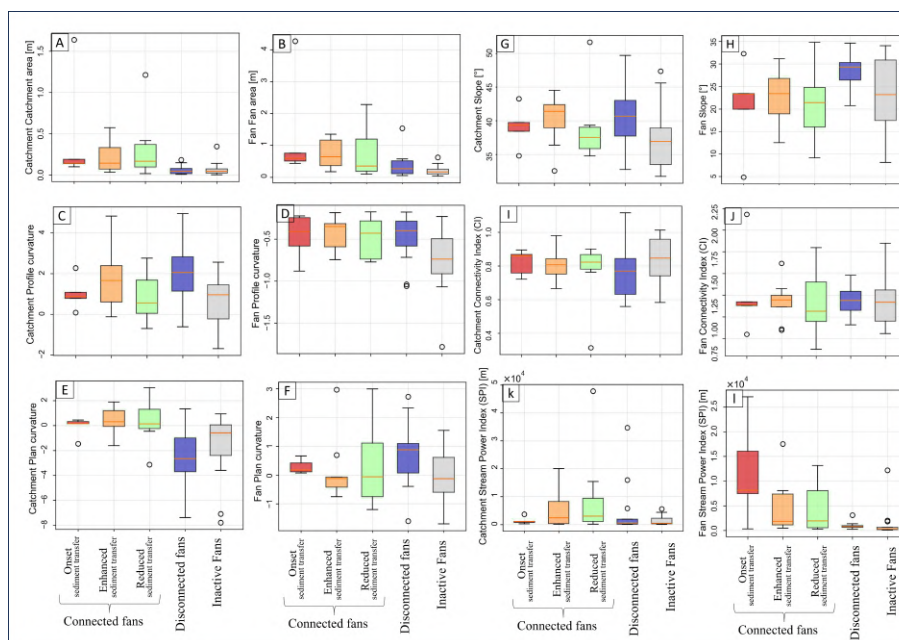


Figure 9. Summary statistics of catchment and fan morphology grouped by classes of fan-lake sediment routing and response to increased rainstorm intensity since the 1980s.

>60 % e.g. catchments 1-5, 24-26, 44-45) and northern catchments show debris-filled channel networks that reach the top of the catchments.

Field observations reveal that laterally eroding channels (e.g., Fan 44) have uprooted entire trees (see Fig. 1). Simultaneously, living trees were found to be damaged and buried by up to 2 m by newly created debris flow deposits in several lobes (e.g., Fan 36, 40).

Fig. 10 shows the yearly change in non-vegetated fan area over the decades for each fan. The yearly increase and decrease of non-vegetated area on individual fans ranges from -2 to +2 %, with some fans (Fan 9, 10, 42, 16, 19, 31, 37) showing greater variability than others. The differences between individual fans are substantial; for example, within the group of inactive fans, there are some of the highest vegetation changes but half of the inactive fans show no change over the whole period.

In the first two decades (1952-1971), 15 % of all fans show an increase in non-vegetated area, followed by a progressive loss of vegetation up to 2000: 37 % (1971-1979), 41 % (1979-1987) and, 69 % (1987-2000). The 2000-2010 decade is an exception, where only 24 % of fans show an increase in non-vegetated area, followed by 50 % in 2010-2020.

Overall, the first three decades are followed by a system shift after 1979, in which 63 % of fans changed from an increase to a decrease in non-veg. area, or vice versa. The next two decades (1979-2000) present the period with the most consecutive vegetation loss over the entire studied timeframe. After 2000, another a shift occurs, with 61 % of the fans changing sign, mostly from an increase to a decrease in non-vegetated area.



As groups, the connected and disconnected fans show similar decadal vegetation trends. The non-vegetated area increases in 70 % of all active fans after the 1980s (13 connected and 13 disconnected). In total, 15 fans show a decrease in non-vegetated area after the 1980s, while three fans (Fans 21-23) show no significant change (Fig. 10). Notably, 10 inactive fans exhibit an increase in non-vegetated area after the 1980s.

Ten fans show a positive correlation between erosion volume and non-vegetated area over the entire studied period. Fans 9 and 36 show a statistically significant positive correlation between an increase in non-vegetated area and erosion volumes (Table F1). Fans 10, 40, 28, and 35 show a strong but not statistically significant positive correlation. Fans 14, 32, 1, and 7 show a moderate positive correlation.

The forest disturbance atlas (Fig. F2) shows that the northern catchments are most affected by harvest (Catchments 2-16), followed by windthrow and bark beetle outbreaks (Catchments 1, 2, 7-10, 13, 15). There are no wildfire disturbances documented in the forest disturbance atlas between 1985 and 2020. Two recorded wildfires happened in June 2020 and March 2024 on the northern shore of Plansee (Freiwillige Feuerwehr Heiterwang, 2026). On the south shore, mostly larger catchments (24, 44-48) are affected by a mixture of harvest, windthrow, and bark beetle outbreaks. For the majority of catchments, the most substantial disturbance happened after 2000. Most areas are only affected once by disturbances. Repeated forest disturbance (> 3 events) at the same location can be observed on catchments 6 and 8-10 (Fig. F1).

Catchments associated to connected fans show a higher disturbance rate between 1987 and 2020 compared to the group of disconnected and inactive fans (Fig. F3). Catchments linked to connected fans exhibit an overall decreasing trend in forest disturbance between 1987 and 2020. The catchments of disconnected fans show most forest disturbances in the first period (1987-2000). Catchments of inactive fans are also affected by forest disturbances, with an increasing trend between 1987 and 2020.

5 Discussion

5.1 Uncertainties and Measurement Errors of Terrestrial and Lacustrine Volumes

Photogrammetric reconstruction of historical aerial imagery poses multiple challenges regarding data quality and accuracy, and few have achieved an elevation resolution that allows for the quantification of geomorphic change over decades (e.g. Bennett et al., 2012; Micheletti et al., 2015; Heisig and Simmen, 2021). Given the spatial resolution of the historical aerial imagery, erosion and deposition patterns that create a vertical signal of less than 1 m cannot be reliably detected. Nevertheless, our approaches have proved sufficient for identifying sediment patterns (erosion and deposition) through time.

Vegetation coverage on the fans is dense, but a clear delineation of the active debris flow area at each time interval was possible. However, sediment transport by minor events might be under-observed if they do not alter vegetation coverage. For example, Fan 36 was observed to be active and to deliver sediment to the lake over the last decade; however, the active channel at the fan toe is covered by dense forest and is therefore not visible for the photogrammetric approach. Furthermore, road and hiking path construction on the northern shore led to changes that could not be distinguished from sediment transport;

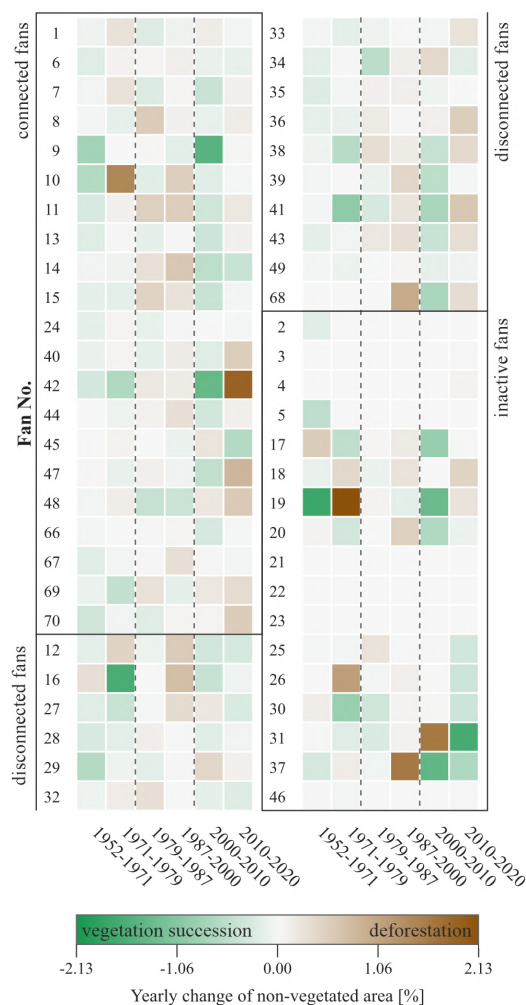


Figure 10. Yearly change in non-vegetated fan area grouped by fan type (first group: connected fans, second group: disconnected fans, third group: inactive fans). Brown colors: increase in non-vegetated area, green colors: decrease in non-vegetated area. The non-vegetated area increases on 70 % of active fans in the period after 1980. Note the shift in most fans at 1979 and 2000 and the lack of vegetation change in 50 % of the inactive fans.

therefore, the connection to the lake could no longer be verified for certain fans (e.g., Fans 10 and 16). As a result, the present
 425 sediment transfer rates from connected fans to the lake are likely underestimated.

Decadal sediment mass balance must be interpreted with caution, particularly when quantifying sediment transfer. The decadal erosion and deposition volumes represent temporally aggregated sediment budgets from net elevation changes, therefore, estimates should be interpreted as a lower bound of total sediment transfer. First, this method does not resolve intra-decadal sediment reworking as only net topographic change between successive decadal DEMs is available. Second, periods of



430 net positive mass balance are interpreted as fan aggradation periods, but it does not imply the lack of sediment transfer to the lake. For these periods, fan sediment transfer is significantly underestimated. Observed sediment dynamics at debris flow fans indicate sediment mobilization occurring in pulses or waves on annual to biennial timescales (Barbosa et al., 2024), leading to the partial cancellation of deposition and erosion signals, which results in an underestimation of total sediment throughput. Finally, sediment passing through the system without causing any elevation change is not captured. This occurs either when
 435 sediment is transferred directly from the catchment to the lake, or when erosion and deposition balance each other out over the decade. However, if the drainage area source of the sediment is well-defined and sediment loss at the outlet is neglected, sediment mass balance on fans enables the determination of the mean sediment yield (Einsele and Hinderer, 1997).

Besides the photogrammetric approach, debris flow deposits on Fans 6-11 were previously studied by Dietrich and Krautblatter (2017) using an empirical approach from Rickenmann and Scheidl (2013) to derive debris flow volumes from active
 440 channel areas mapped on orthophotos. The study suggests increasing active areas on the fans between 1947 and 2000 for all 6 fans, followed by a slight decrease until 2014, corresponding to an approximately threefold increase in deposition volumes after the 1980s, compared to the preceding period. Our analysis of all 54 fans shows a similar spatial pattern, with increasing active area on the fans between 1979 and 2010, followed by a decrease until 2020. Despite both studies relying on similar aerial imagery, the volumetric estimates presented here are systematically lower. This difference is expected because Dietrich and
 445 Krautblatter (2017) estimated deposition volumes based on the extent of the active channel area, whereas this study directly quantifies erosion and deposition from measured decadal elevation changes. Our results show that the increase of the active channel area after the 1980s for most of the connected fans is associated with channel incision and sediment redistribution. For few of the fans with reduced sediment transfer (Group C) new channels are formed due to channel avulsion (Fan 13 and 44) or channel diversion (Fan 11).

450 The lake-wide debris flow volumes presented in this study should be interpreted as first-order volumetric estimates. While the uncertainty of the sediment core age-depth model (mean ages 1960-2018 ± 6 yrs) is propagated to the calculation of the subaqueous debris flow volumes, two limitations remain unresolved: the erosion of older event deposits by subsequent events, and turbidite deposits thinner than 1 mm. The lake-sediment volume estimates correspond to an uncertainty envelope of 24% (approximately -10% to $+14\%$ relative to the mean age model estimate).

455 The calculations assume that the investigated deep-basin sediment cores are representative of the effective depositional area considered in Eq.1. A bathymetric high in the centre of the lake (60 m depth), as well as density contrasts and lake stratification, influence how suspended particle flows progress westward towards the lake depocentre and outflow. Because of this, the thickness of turbidite deposits originating from debris flows in eastern catchments likely underestimates their corresponding terrestrial volumes. A sensitivity analysis of the assumed effective depositional area indicates that reasonable variations due
 460 to a stronger concentration of sediment in the depocentre or a broader depositional area including more shallow basin areas result in a volume variation of $\pm 15\%$. The calculations assume that the adopted fine-to-coarse ratio is spatially constant and representative for converting fine-grained lacustrine event-layer deposits into total debris flow volumes. However, because sediment-routing pathways and flow transformation vary across the lake, this ratio may also vary spatially. A 5% reduction of fine particle content to 15:85 increases the calculated deposition volume by 33%, whereas a 5% increase to 25:75 decreases it



465 by 20%. The combined sensitivity analysis of depositional area and fine-to-coarse ratio result in a deposition volume range of $4.01 \pm 1.55 \times 10^5 \text{ m}^3$.

Despite the discussed errors and limitations inherent to both techniques, the independently derived estimates for lake-wide debris flow volumes and the terrestrial transfer volumes to the lake over the last seven decades are broadly consistent within the uncertainty associated with both approaches. The new onshore and reanalyzed offshore frequency-magnitude records show
 470 that the overall increase in debris flow activity since 1920 is not linear, but is marked by distinctive phases possibly controlled by changes on rainstorm frequency or extreme precipitation events.

5.2 System response to enhanced rainfall intensity after the 1980s

The precipitation analysis reveals that maximum rainfall intensity exhibits greater temporal variability than mean precipitation, with pronounced peaks during the 1980s and 2000s. This pattern is consistent with observations from more than 800 Austrian
 475 climate stations, which report a persistent increase in hourly heavy rainfall of 15 % since the 1980s accompanied by a 25 % increase in floods in small catchments (Haslinger et al., 2025).

At Plansee, the increased frequency of days with rainfall events exceeding the debris flow-triggering threshold (10 mm h^{-1}) after the 1980s, relative to the 1952-1979 reference period, coincides with a moderate increase in erosion volumes (+12 %) but a much more pronounced decrease in deposition (-47 %) on connected fans. This pattern suggests reduced internal storage on
 480 the fans, leading to enhanced sediment transport to the lake, most likely through more frequent or higher-magnitude debris flow events. These observations are consistent with previous studies identifying the 1980s and the subsequent decades as a period of enhanced debris flow activity across the Alps, associated with more frequent and intense precipitation events (e.g. Haeberli et al., 1990; Rebetez et al., 1997; Jomelli et al., 2004; Bennett et al., 2013; Pavlova et al., 2014; Turkington et al., 2016). Yet, the disproportionate shift in deposition volumes indicate a nonlinear system response to increased precipitation.

485 The temporal evolution of the sediment budget (Fig. 7) indicates that the fan response to increased rainstorm frequency is not uniform through time but evolves over decadal timescales. Overall, mean deposition rates remain lower after the 1980s than before the 1980s. However, post 1980, deposition increases gradually to a local maximum during the 2000s before declining again. In contrast, erosion rates remain relatively constant throughout the post 1980 period. This bi-decadal pattern coincides with changes in non-vegetated area, the exceptionally warm summer of 2003 and a slightly higher frequency of number of
 490 rainfall events exceeding the debris flow triggering threshold. Together, these observations suggest that the Plansee system adjusts to changes in climatic forcing over one to two decades, although they may also reflect the onset of a new climatic phase after 2000.

The climatic shift of the 1980s coincides with an increase in non-vegetated area on most fans, with a persistent increase of non-vegetated area until the 1990s. The two general shifts in 1979 and 2000 highlight where most fans changed their
 495 vegetation pattern. Their timing correlates with increasing erosion rates, deposition rates exceeding erosion rates and periods of pronounced maximum precipitation peaks. The 1980s and 1990s exhibit the most consecutive loss in vegetated area over the entire studied period, supporting the hypothesis of multi-decadal system response times.



5.3 Implications on sediment connectivity

We observe contrasting fan responses to increased frequency of rainstorm intensities after the 1980s. Generally, smaller fan sizes show higher sediment fan-lake connectivity by the onset or intensification of sediment transfer (Group A and B). On the other hand, the biggest fans respond with predominant aggradation, which decreases sediment transfer to the lake (Group C). The later response does not contradict increased debris flow activity at the catchment. Measurements at debris fans (De Haas et al., 2018) as well as experimental models (Leenman and Eaton, 2022) suggest that channel diversion, avulsion, and an overall increased deposition on the fan surface are the main mechanisms driving debris fan formation under enhanced sediment supply conditions. Therefore, a remaining key question addresses the mechanisms that increase erosion at the fan and promote sediment connectivity.

We hypothesize that catchment and fan morphology control - up to a certain extent- the response to a climatic shift. Catchment-fan systems in Group A, representing the onset of sediment delivery to the lake after the 1980s, are characterized by catchments with a low stream power index which likely reflects their small catchment size. Increased precipitation events, such as those observed after the 1980s, may lead to a temporary increase in catchment stream power, likely resulting in higher-magnitude debris flows with enough energy to pass through the fans and reach the lake (Fig. 8). As a result, sediment connectivity between catchment, fan, and lake is established, driven by episodic debris flow activity.

Fans with enhanced sediment transfer to the lake after the 1980s (Group B) show sediment dynamics with sustained high erosion rates over multiple decades, while only few exhibit single decade peaks (e.g., Fan 67). We hypothesize that increased rainfall events lead to increased debris flow activity in these catchments due to two primary mechanisms: critical runoff and/or shallow slope failure, which result in a high heterogeneity of sediment transport patterns. Group B exhibits decadal-scale internal sediment redistribution, with some fans aggrading at the apex and eroding at the base (e.g., Fig.8; Fan 6), while others show erosion concentrated at the apex and deposition at the toe (e.g., Fig.8; Fan 8). Both sediment dynamics have been documented as different stages of sediment transfer following slope failure (De Haas et al., 2018; Barbosa et al., 2024). As a result, sediment connectivity between the fan and the lake is enhanced by faster sediment redistribution across the fan surface, reducing sediment residence times on decadal timescales.

Disconnected fans also show enhanced debris flow activity after 1980s expressed by sediment remobilization within the fans and longer runouts. The pre-1980 period is characterized by aggradation within the active channels, with little erosion at the apexes (Fan 36, 41), while the post-1980 period exhibits active channels dominated by erosion (Fan 68, 43, 12, 31, 29) and progression (Fig. E1). Spatiotemporal characteristics such as channel progression toward the lake (Fan 34-39), the shifting of the active channel toward the east (Fan 36-42) and channel activation during the last decade (Fan 27 to 33), suggest a shift toward higher sediment input from the catchment to the fan, implying enhanced sediment connectivity.

The individual sediment transport response of each fan to climatic change appears to be nonlinear. The connectivity between the catchment, fan and lake is influenced by the extent of local rainfall cells, weathering and recharge times, intermediate storage and the local morphology. A nearby study in the Horlachtal (40 km distance from Plansee) also suggests that changes in debris flow patterns are not linear, but rather governed by activity peaks. Specifically, Rom et al. (2023) reveal a peak in



debris flow frequency between 1950 and 1970, followed by a low-frequency phase until 1990. The next frequency peak occurs from 1990 to 2009, with additional single peaks in the 2010s. In comparison, the Plansee sediment core archive shows peaks in the 1930s and 1960s, followed by an increasing frequency trend after 2000.

535 **5.4 Vegetation response to debris flow activity**

Larger Plansee catchments have a higher percentage of forest coverage but store more sediment compared to smaller catchments. The catchment vegetation is considered a protective forest, where the forest plays a key role in stabilizing loose material, buffering hydrological extremes and reducing erosion inside and outside the channels through root activity. This protective capacity can be lost due to windstorms, bark beetle outbreaks, and wildfires (Moos et al., 2023). Forest disturbances in the catchment are mostly caused by harvest and windthrow, being most pronounced in the northern catchments. The area of forest disturbance peaked between 1987 and 2000 and shows an overall decrease over time, with the most affected areas being located outside of channelized debris flow catchments. We hypothesize that these forest disturbances do not immediately enhance the sediment transport and storage, but rather create more erodible areas that, over longer timescales, connect to the existing channel network within the catchments. The resolution of the forest disturbance map is insufficient to show lateral erosion cutting off vegetation at the edge of the embankments of incised channels, which is considered a major factor in increased sediment mobilization.

Although documented fires are rare in the area they are expected to become more frequent under a warming climate and can have long-lasting effects on the slope stability, thereby increasing debris flow susceptibility (Moos et al., 2023).

The evolution of the non-vegetated area on the fans shows individual patterns for each fan, with a general trend toward more non-vegetated area in recent decades. Most channels in the transfer area between the catchment and the fan are deeply cut into the terrain with steep embankments that protect the surrounding vegetation from being affected by debris flows. Changes occur due to retrogressive erosion of these embankments, progressing downslope deposition, or avulsion and the lateral creation of new channels. Avulsion – where a new dominant channel forms and causes severe changes in vegetation cover – occurs on fans with several channels (Fan 11) but also on fans with single straight channels (Fan 47), where higher shear stresses lead to channel bank erosion, followed by bed infilling and eventual avulsion (Vincent et al., 2022).

Most decades (except for 2000-2010) display an increase in non-vegetated area for all fan types. These results confirm the previously documented increasing trend in non-vegetated area on Fans 6–11 (Dietrich and Krautblatter, 2017) for all Plansee fans. The 10 fans that show a positive correlation between erosion and non-vegetated fan area are mostly located in the central basin where the highest morphological changes occur. This likely reflects the direct influence of rainfall on erosion, followed by changes in the vegetation cover on the fans, even though the vegetation on each fan reacts individually, and we generally observe bi-decadal response times and two distinct shifts in vegetation patterns. Morphological controls like straight vs curved catchment/fan geometry, as well as the height and stability of embankments, also influence changes in the vegetation cover and have not been investigated in this study.

Overall, the increasing erosion after the 1980s coincides with an increase in non-vegetated area on the fans, mostly due to bank erosion and channel progression. Catchment vegetation could not be mapped in the same manner as on the fans, but



shows decreasing human-induced and natural forest disturbances since 1987, which is contradictory to the increase in sediment transfer to the lake. Consequently, the increase in erosion is likely attributed to promoting factors such as changes in rainstorm frequency and intensity, whereas human activities and natural forest disturbances exert only a minor effect.

5.5 Implications for future source-to-sink reconstructions

570 While this study establishes the fan-to-lake connectivity, a comprehensive analysis of the catchment-to-fan connectivity and subaqueous sediment-routing pathways is required to understand the relationship between terrestrial debris flows and the character of their subaquatic deposits.

Sediment supply from the catchment to the fan could be quantified using photogrammetric analysis, however, the uncertainties of reconstruction from historical imagery are high. Therefore, future research should focus on sediment supply from the
 575 catchment over the last two decades (high resolution images).

We provide a practical framework for a first-order quantitative comparison between terrestrial sediment-transfer estimates with sediment accumulation inferred from the lacustrine archive. The observed mismatch in event frequencies between the two records may be linked to complex flow transformations at the terrestrial to subaquatic transition and hydrodynamic filtering. As highly deformable debris flows cross the shoreline, they undergo rapid and efficient flow transformation, generating significant
 580 spatial and temporal variations in current velocity and sediment concentration. The efficiency and extent of this process depend on the initial viscosity and density of the incoming flow. High-viscosity, high density flows experience minor transformation at the lake surface, whereas low-viscosity, low density flows are churned up entirely upon entry, transforming into a fully turbulent turbidity current (Felix and Peakall, 2006). This highly dynamic behavior complicates the reconstruction of event magnitudes within the sedimentary record, especially since debris flows may consist of multiple surges.

585 The stratification of the water column also strongly influences subaquatic flow dynamics, redirecting sediment pathways and partitioning material based on grain size. Under stratified conditions, interflows can form within the metalimnion (at 5-20 m depth in Plansee). This is driven by intense plunging mixing when entering the lake, which rapidly reduces the density excess of the inflow (Blanckaert et al., 2024).

It remains an open question to what degree interflows progress basin-wide and drive inter-basin dispersion of the fine-grained
 590 fraction. Furthermore, it is unclear what percentage of fine particles is carried by the interflow versus the percentage retained within the dilute turbulent underflow. Ultimately, deposition in the deepest basin represents a complex overprinting of fallout from waxing and waning dynamics of a basal underflow and suspended sediment settling from the dispersed interflow.

Subaquatic sediment routing is also influenced by interactions with the lake bottom and pre-existing bathymetric boundaries. Where underflows encounter subaquatic gullies, the lateral confinement restricts and accelerates the flow, enabling the
 595 entrainment of previously deposited sediment. Additionally, the wide range and likely varying grain size distributions within the debris flows result in complex, stacked, and asymmetric fan morphologies rather than idealized lobes (Tsunetaka et al., 2022; Kiefer et al., 2021). These effects influence the basin stratigraphic record. Plansee features a central narrow area constricted by progradation of the underwater fans. To fully decipher how this bathymetric barrier impacts sediment redirection and event preservation, future research must combine the spatial correlation of event layers from both basins with real-time



600 monitoring of flow behavior under changing lake stratification using, for example, sediment traps and cameras. We suggest that future connectivity studies focus on the fans and subaquatic deposition in the central part of the lake between the two basins, where the highest volume transport and channel progression have occurred recently.

Observed changes in sediment connectivity in response to the climatic shift of the 1980s also raise questions about future cascading risks in other Alpine regions. An increase in the intensity of harmful precipitation events, which can trigger gravitational mass movements, is expected in the future for the Alpine region (Gobiet and Kotlarski, 2020). Until the end of this century (2070-2099), modeled extreme precipitation events in the wider study region, expressed as 5-year return values of 1-day precipitation events, will increase in winter, spring, and autumn by 5–20 %, compared to the years 1970–1999 (Gobiet et al., 2014; Rajczak et al., 2013). Increased temperature and precipitation events may activate currently dormant, outsized debris fan systems, causing massive sediment waves in Alpine rivers and affecting strategic infrastructure such as power dams, aquatic life and water quality. This further stresses the need for representative studies on future frequencies and magnitudes.

6 Conclusions

Fan sediment dynamics at Plansee provide evidence of the geomorphic responses to the increased frequency of rainstorms since the 1980s. Reanalysis of historical aerial imagery and sediment cores shows that:

1) A minimum of $(3.42 \pm 0.43) \times 10^5 \text{ m}^3$ of sediment has been transferred from the fans to Plansee over the last seven decades by debris flow events. Conversely, a first-order estimate from sediment cores suggests that $(3.69 \pm 0.42) \times 10^5 \text{ m}^3$ have been deposited in the lake, presenting the first steps toward integrating and reconciling lacustrine millennial sediment records with terrestrial decadal sediment dynamics. Both investigations suggest an overall increase of erosive activity since 1920, with phases possibly reflecting sediment supply cycles controlled by precipitation changes.

2) The debris fan systems respond to increased frequency of rainstorms since the 1980s with a shift from an overall fan-buildup phase to an export phase, characterized by greater sediment connectivity between the fans and the lake. Four fans shift from predominantly depositional to predominantly erosional behavior, marking the onset of sediment delivery; nine fans increased their magnitude of sediment delivery; and four fans reduced sediment delivery due to channel avulsion and active channel progression toward the lake. These responses reflect changes in sediment dynamics driven by amplified catchment sediment supply and/or increased runoff, which promoted greater debris flow activity.

3) Even disconnected fans provide evidence for increased activity since the 1980s, represented by active channel progression toward the lake, the formation of new channels and avulsion. Greater activity is observed after 2010 where six fans reactivate.

4) Fans at Plansee have increased their non-vegetated area since the 1980s but also exhibit a shift in 2000, supporting an additional climatic change at that time with implications for the sediment dynamics of the fans.

5) At Plansee, we show for the first time, a generally coherent lacustrine and terrestrial record, indicating massive sediment transport and connectivity increases over the last few decades.

Appendix A: Quantification of sediment budgets and connectivity shift from aerial imagery

A1 Photogrammetric reconstruction

The photogrammetric reconstruction of historical and digital aerial imagery allows the quantification of elevation changes over the last 7 decades. The workflow is summarized on Figure A1. Five historical aerial surveys and two digital aerial surveys from Land Tirol were selected to reconstruct the sediment dynamics at the fans. Generalities are summarized on Table A1. Land Tirol provided scanned historical aerial imagery and camera calibration files. This information is used as initial parameters on the block reconstruction. The digital aerial imagery is associated to an Aerialo-Triangulation file used for the individual reconstruction. Given the different reconstruction characteristics, we process the digital imagery separated.

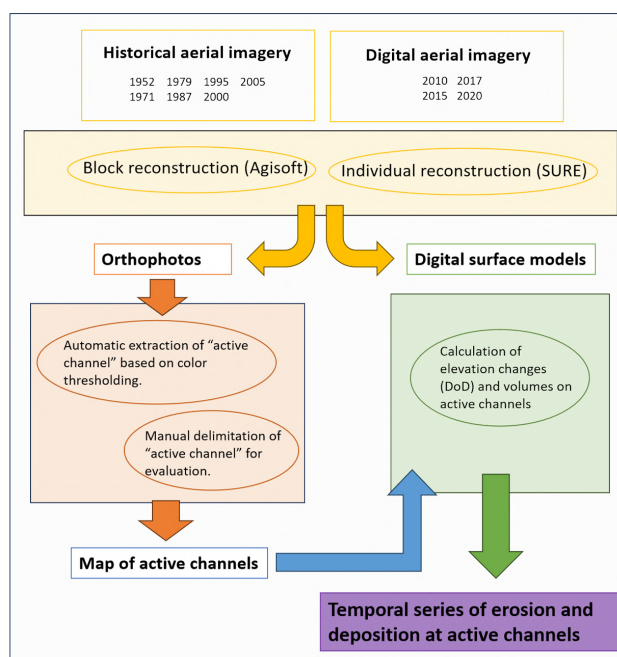


Figure A1. Workflow followed to reconstruct the temporal series of erosion and deposition at active channels, quantify sediment budgets and define sediment connectivity between the fans and the lake.

A2 Uncertainty analysis

The area of study is characterized by a dense vegetation cover and human intervention on flat areas, therefore, identifying stable surfaces through time is challenging. We quantified the elevation uncertainty between surveys (DoD) on two ways. First, we identified 14 areas with minimal vegetation change over the years and calculate its mean elevation change and standard deviation. The areas are located on diverse terrane surfaces with slope angles between 4 to 38°. Stable surfaces on the flat terrain are challenging to identified due to human intervention and vegetation coverage. The volumetric computation is performed only



Table A1. Characteristics and metadata of the aerial photogrammetric surveys.

Photogrammetric block	Date	Images	Format (cm)	Overlap (%)	Focal length (mm)
Forest survey A (1952 001)	01.07.1952	191	23 × 23	–	210
Overall flight Tyrol/1971 (1971 067)	10.07.1971	198	23 × 23	–	209.48
REV OEK-85-86, 115-116 (1979 015)	17.09.1979	48	23 × 23	60	152.59
KF 84-86 (1987 009), KF 115-116 (1987 012)	21.09.1987, 31.08.1987	38	23 × 23	60	150
Ausserfern/2000 CIR (2000 501)	20.08.2000	134	23 × 23	60	305.084
Reutte_Soelden (2010 880)	08.01.2010	292	–	80	–
Imst (2020 260)	07.08.2020	187	–	80	–

Table A2. Summary of photogrammetric reconstruction and elevation uncertainty for topographic change analysis.

Year	Error in Z (m)	DoD	RMSE _z (m)	95 % confidence interval (m)
1952	0.70	–	–	–
1971	0.70	1952–1971	2.00	±1.94
1979	0.70	1971–1979	1.00	±1.94
1987	0.70	1979–1987	1.00	±1.94
2000	0.70	1987–2000	1.00	±1.94
2010	0.40	2000–2010	1.58	±1.58
2020	0.20	2010–2020	0.40	±0.80

The Digital Surface Model (DSM) resolution is estimated by Agisoft Metashape from camera model parameters.
 The limit of detection (LoD) threshold is defined following a conservative approach based on topographic profiles across active channels and imagery quality. The elevation uncertainty is propagated from photogrammetric errors.

645 at the active area of the debris fan, characterized by low angle surfaces, therefore, we used topographic profiles on the fan areas
 to determine the minimum detectable change from noise (LoD) within the active channel by measure the elevation difference
 on areas where no change is observed on the Orthophotos (i.e., outside the active channel). An example of the topographic
 profiles is presented in Figure A2). For all the fans, LoD calculated as the 95% confidence interval of the elevation uncertainty
 is less than 2 m. This is consistent with the observation on the topographic profiles. For individual surveys and fans lower LoD
 650 is observed.

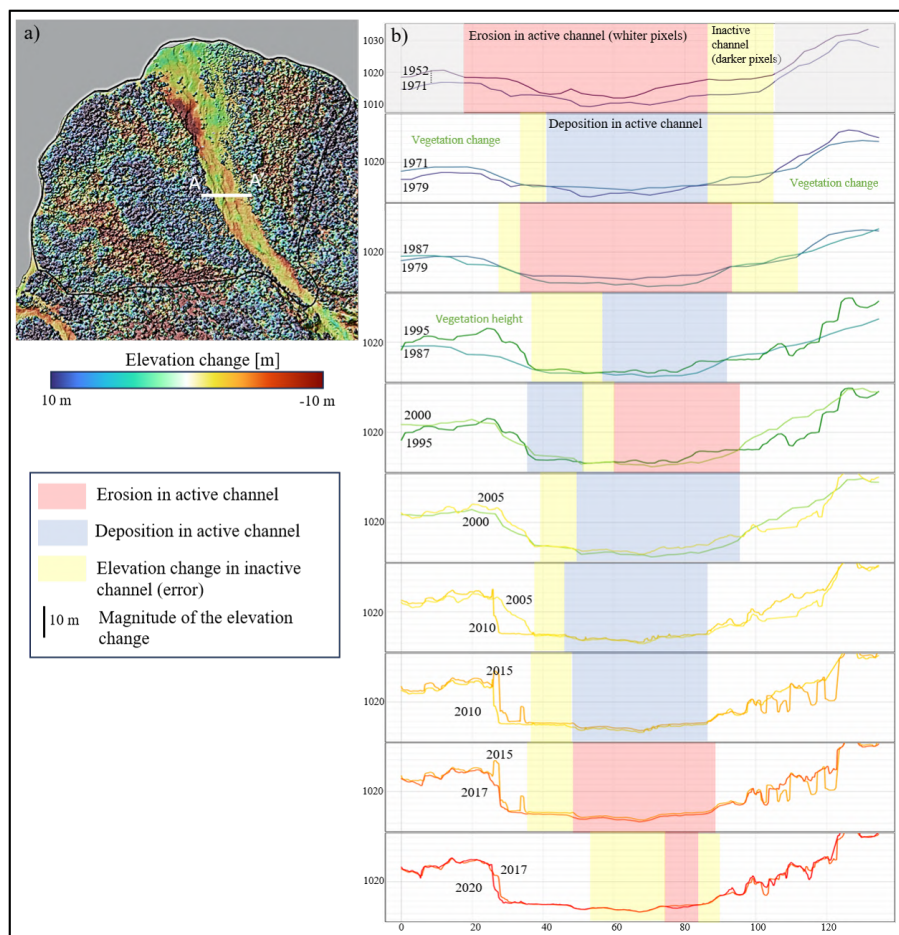


Figure A2. Temporal evolution of erosion and deposition at Fan 44. a) Total elevation change between 1952 and 2020. b) Example of the topographic profiles used to quantify the signal-to-noise ratio between elevation surveys. The active channels in profile A-A' have changed through time allowing the quantification of the magnitude of the elevation change in areas considered 'stable'. Red and blue areas are identified as part of the active channel based on the color of the Orthophotos, while yellow areas highlight ground areas with darker colors (stable).



Appendix B: Historical event record



Table B1. Historical debris flow and flood events recorded in the region, including concurrent daily rainfall precipitation at Berwang, Höfen and Griesen as well as details on rainfall/damages are recorded Sources: municipality archive www.zunter.net, fire brigades Reutte, Berwang and Höfen, ehyd.gv.at.

Year	Event type	Location	Distance to Plansee (km)	Precip. (mm/day)			Precip. Griesen	Details
				Höfen	Berwang			
15.08.1952	debris flow	Elmen	25	51.2	32		–	3000 km2
30.07.1953	debris flow	Lechtaler Alpen	40	22.2	25.8		–	several debris flows, 3 tourists die
08.08.1959	rainfall	Außerfern	–	16	21.8		–	street damage
04.05.1964	rainfall	Tannheim	22	70.9	40		–	137 mm Tannheim 3.5.64
17.11.1964	rainfall	Lechtal	–	61	42		–	November. 310 mm rain Lechtal
08.06.1965	debris flow	Musau	12	26.6	34.2		–	–
10.06.1965	rainfall	Höfen/Berwang	9	133	123		–	up to 175 mm Lechtal
1967	debris flow	Winkl/Holz	10	–	–		–	–
09.08.1970	debris flow	Lechtal	–	83.4	91.5		–	8.8 150-200 mm Lechtal
15.11.1973	rainfall	Allgäu/Lechtal	–	54.5	47		–	up to 170 mm Lechtal/Allgäu
x.x.1975	debris flow	Höfen	9	–	–		–	–
30.06.1975	rainfall+debris flow	Höfen/Berwang	9	49.5	60		–	–
04.07.1975	debris flow	Tannheim	22	7	12		–	Houses destroyed
31.07.1977	rainfall	Lechtal	–	87	91		–	flood
11.03.1979	rainfall	Höfen/Berwang	9	36.5	40.6		–	–
12.03.1979	rainfall	Tannheimer Tal	22	27.2	13.3		–	185 mm Tannheimer Tal
17.06.1979	rainfall	Höfen/Berwang	9	73.2	72.2		–	176mm Reutte
06.11.1979	rainfall	Lechtal	–	52	38.2		–	140 mm Lechtal
06.08.1982	debris flow	Höfen	9	21.5	25.4		–	Houses destroyed
x.x.1983	debris flow	Höfen	9	–	–		–	–
26.11.1983	rainfall	Außerfern	–	16.4	26.2		–	165 mm
27.11.1983	rainfall	Höfen/Berwang	9	55	33.5		–	–
02.05.1986	debris flow	Höfen	9	0	0		–	fields destroyed
27.02.1987	rainfall	Außerfern	–	38.8	24.2		–	streets blocked
03.07.1987	debris flow	Planseestraße	0	17.5	4		–	–
x.x.1988	debris flow	Höfen	9	–	–		–	–
29.07.1990	debris flow	Bach	39	0	0		–	fields destroyed
30.07.1990	rainfall	Höfen/Berwang	9	60.8	29		–	–
21.05.1999	rainfall	Höfen/Berwang	9	169	180.2		–	–
23.05.1999	rainfall	Pflach	8	0.3	0.3		–	flood

Distance is measured to the center of Lake Plansee.



Table B2. Historical debris flow and flood events recorded in the region, including concurrent daily rainfall precipitation at Berwang, Höfen and Griesen as well as details on rainfall/damages are recorded Sources: municipality archive www.zunter.net, fire brigades Reutte, Berwang and Höfen, ehyd.gv.at. Continued.

Year	Event type	Location	Distance to Plansee (km)	Precip. (mm/day)		Precip. Berwang	Precip. Griesen	Details
				Höfen	–			
2002	debris flow	Lechtal	no specific location	–	–	–	–	streets flooded
22.08.2005	debris flow	Außerfern	no specific location	130.1	130.8	101.4	101.4	worst flood in Außerfern ever
30.07.2008	debris flow	Planseestraße	0	10.3	8.2	3.7	3.7	–
11.07.2010	debris flow	Planseestraße	0	6.2	16.4	14.4	14.4	–
10.10.2011	rainfall	Höfen/Berwang	9	26.4	31.4	30.1	30.1	–
11.10.2011	debris flow	Plansee biggest fan separating lakes	0	0	0	0	0	–
04.07.2012	rainfall	Heiterwang	6	20	13.1	7.1	7.1	–
04.08.2012	debris flow	Planseestraße and Heiterwangersee	0	5	39.5	32.3	32.3	–
01.06.2013	rainfall	Heiterwang	6	84	85.6	60.2	60.2	–
02.06.2013	debris flow	Heiterwang	6	48	47.5	29.4	29.4	B179 road
30.07.2014	rainfall	Höfen/Berwang	9	42.2	47.5	43.5	43.5	–
31.07.2014	debris flow	Planseestraße	0	2.7	2.7	2.1	2.1	–
19.09.2014	debris flow	Ammerwald	6	4.2	1.6	0.1	0.1	2,5 km from German/Austrian Border
25.06.2016	rainfall	–	0	31	28.3	data gap	data gap	flood/Verklaussung kleiner Plansee
11.07.2016	rainfall	–	–	18.6	49	data gap	data gap	flood
04.08.2016	rainfall	Höfen/Berwang	9	50	48.7	data gap	data gap	–
05.08.2016	debris flow	Plansee biggest fan separating lakes	0	26.5	39.2	data gap	data gap	–
21.05.2019	debris flow	Ammerwald	6	33.6	24.7	19.4	19.4	–
17.07.2021	debris flow	Reutte	7	93.3	76.6	36.4	36.4	B179 Katzenberg Fernpassstraße
04.07.2022	rainfall	Heiterwang	6	13.9	31.7	7.8	7.8	flood

Distance is measured to the center of Lake Plansee.

Appendix C: Response of general sediment regimens to rainstorm intensity

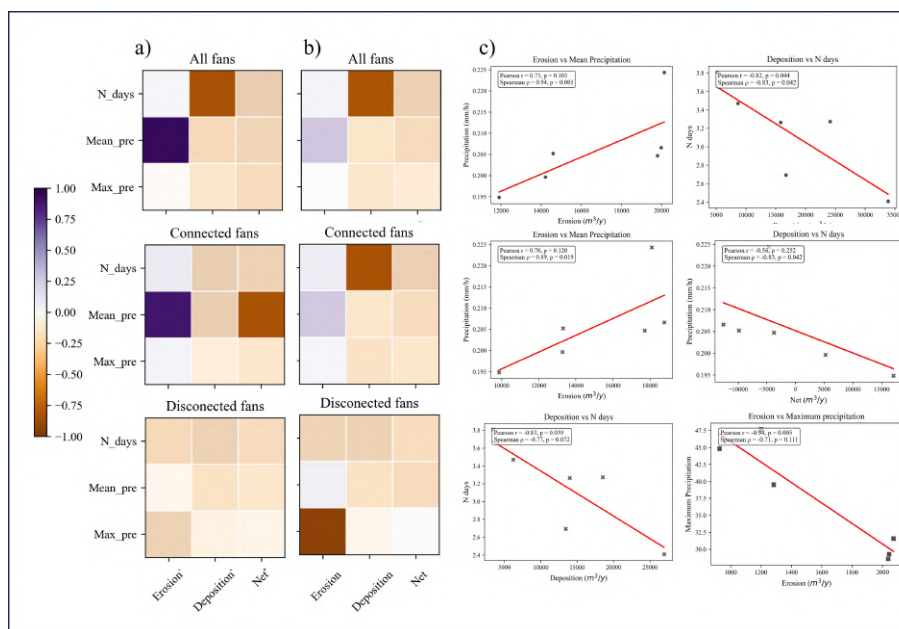


Figure C1. Statistical correlation between erosion, deposition, and net volumes and precipitation descriptive variables: mean precipitation (mm/h), maximum precipitation (mm), and number of days (N days) exceeding the 10mm/h threshold. a) Spearman correlation coefficient. Color transparency indicates significance. Darker colors highlight correlations with $p > 0.05$. b) Pearson correlation coefficient. Color transparency indicates significance. Darker colors highlight correlations with $(p > 0.05)$. c) Scatter plots for variables with significant correlation coefficients. Dots are volumes for all fans, x are volumes for connected fans, and squares are volumes for disconnected fans. The red line shows the linear trend.

We tested statistical correlation between volumes of erosion, deposition, and net volumes, and precipitation descriptive variables like mean precipitation (mm/h), maximum precipitation (mm), and number of days (N) exceeding the 10mm h^{-1} threshold. We evaluate linear correlation by Pearson correlation coefficient that measures the strength and direction of a straight-line pattern between two continuous variables (Fig. C1b). We acknowledge that the number of samples is small therefore their significance is limited (Fig. C1c and d), however, some trends can be drawn from the scatter plots. Landscape response to changes in climatic conditions has been observed to be non-linear, therefore, we used the Spearman correlation coefficient, that evaluates how well one variable increases or decreases as the other variable increases, regardless of whether that relationship is a straight line, to test for monotonic trends (Fig. C1a).

There is a positive correlation between erosion volumes and mean precipitation values (Fig. C1), but the relationship may be non-linear, indicating that erosion rates do not scale proportionally with increased precipitation.



Appendix D: Morphometric analysis

D1 Fan channel profiles

665 Fan channel profiles are extracted from the DEM ©Land Tirol (2019) using the hydrology toolset in ©ArcGIS Pro.

Table D1. Channel slope statistics for connected, disconnected, and inactive fans. Slopes are derived from channel profile analysis.

Status	Min. slope (°)	Max. slope (°)	Mean slope (°)	SD (°)
Connected	4	33	19	7.3
Disconnected	15	37	25	5.4
Inactive	6	36	23	8.6

D2 Fan profile curvature classes

The normalized quadratic curvature classification shows that over all fan types, the majority of channel profiles on fans are classified as strongly concave, followed by fans that are lightly concave. Only for the channels on connected fans that started sediment delivery after 1980 the majority are lightly concave. The convex Fan 38 is wedged in between the neighboring fans.

670 Fans 11, 7, 19 and 23 show linear channel profiles.

Table D2. Number of fans by channel profile category: $a < -0.05$ (convex), $-0.05 \leq a \leq 0.05$ (linear), $0.05 < a \leq 0.25$ (slightly concave), and $a > 0.25$ (strongly concave).

Fan type	Convex	Linear	Slightly concave	Strongly concave
Conn. red. ST aft. 1980	0	1	2	4
Conn. enh. ST aft. 1980	0	0	4	5
Conn. onset ST aft. 1980	0	1	3	1
Disconnected	1	0	6	9
Inactive	0	2	5	10

ST stands for sediment transport; Conn., red., and enh. stand for connected, reduced, and enhanced, respectively.

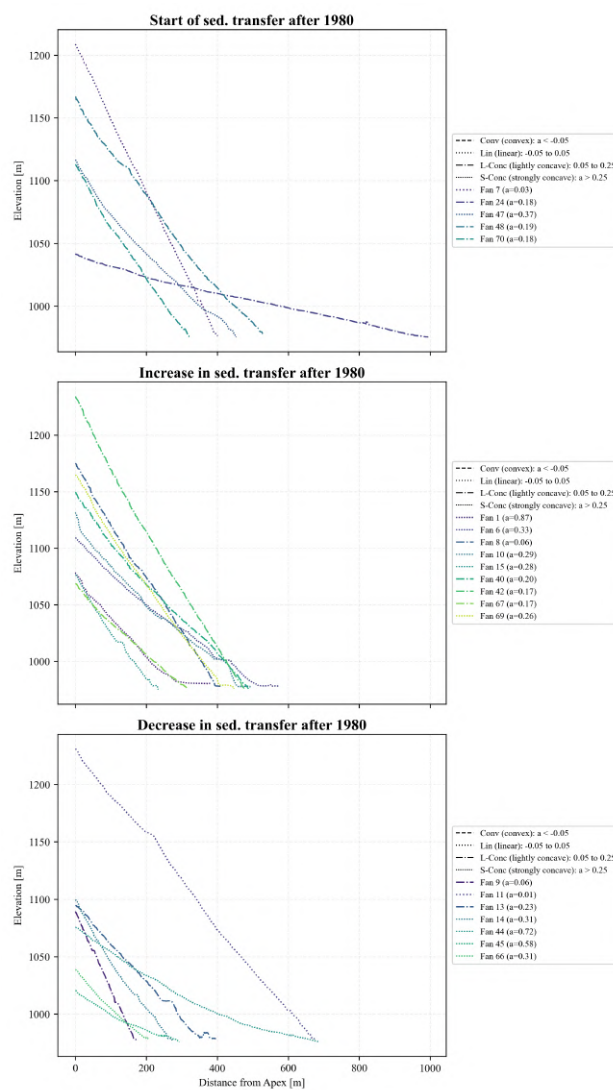


Figure D1. Channel profiles on three subgroups of connected fans.

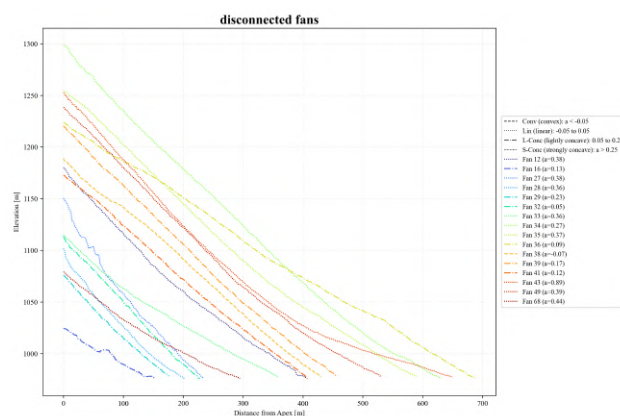


Figure D2. Channel profiles on disconnected fans.

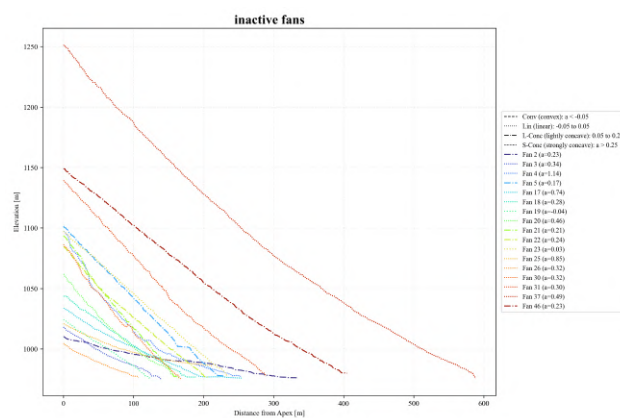


Figure D3. Channel profiles on inactive fans.

D3 Fan to catchment area ratios

Fan/Catchment ratio regression results in a k coefficient less than 1 for all fan groups, suggesting that an increase in catchment size produce a smaller proportion of increase of fan size. This reflects the high activity of the fans at Plansee, that respond with channelized transport, efficiently delivering the sediment to the lake, and only for few fans, deposition is concentrated on the

675 fans.

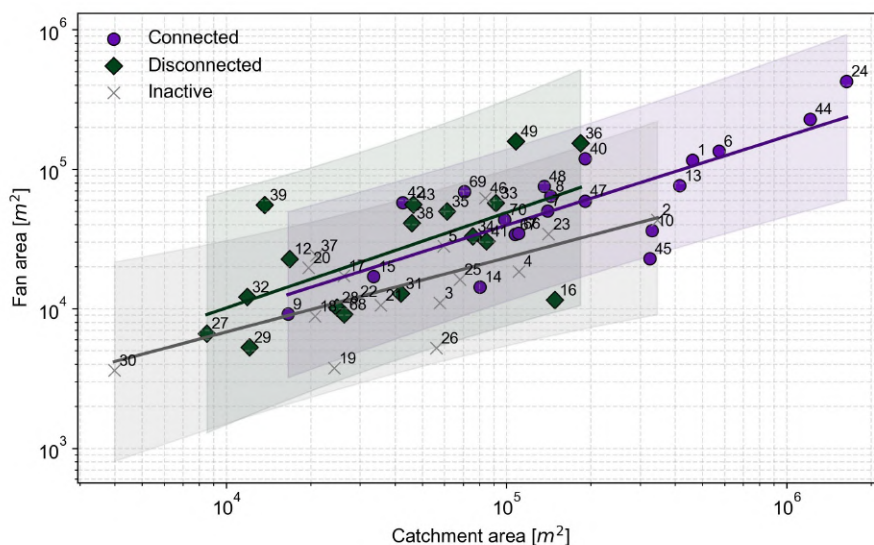


Figure D4. Fan/Catchment area regression for each fan group. Connected fans: $F_a = C_{25}^{0.63}$, Disconnected fans: $F_a = C_{18}^{0.68}$, Inactive fans: $F_a = C_{50}^{0.53}$

D4 Additional morphometric parameters

Fan-Catchment ratio, Melton index and thresholds of Slope and connectivity index show variations among the fan classes. Disconnected fans show the highest fan-catchment ratio. Fans with an onset on sediment transfer after the 1980s show the less variability on steep slope angle ($>30^\circ$) at the catchment. Fans with reduced sediment transfer show the most narrow distribution

680 on index of connectivity higher than 1.

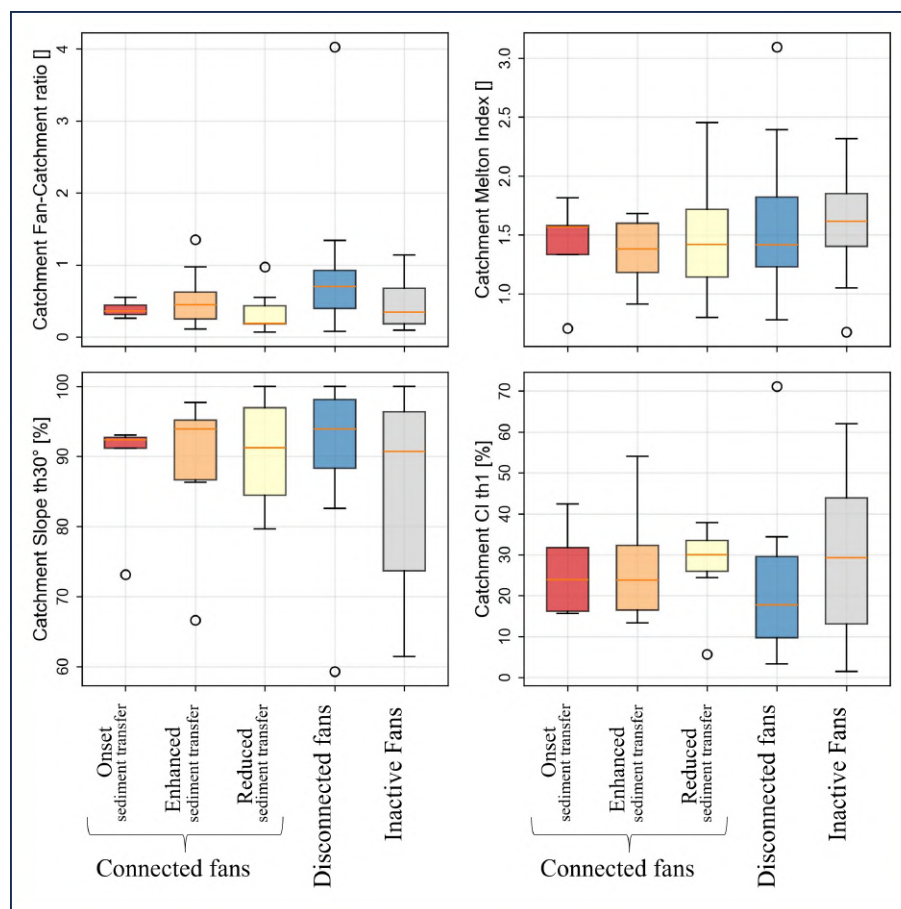


Figure D5. Additional Morphometric parameters.



Appendix E: Channel progression on disconnected fans

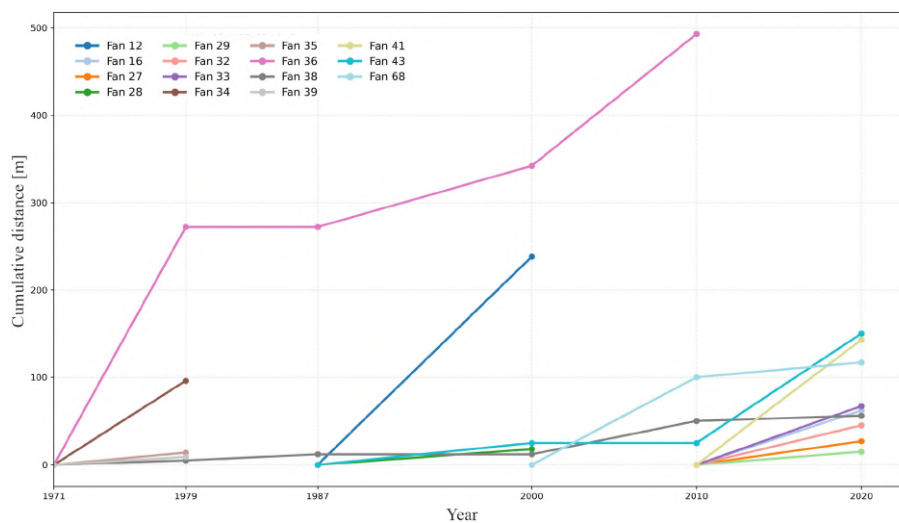


Figure E1. Cumulative channel progression on disconnected fans since 1971 (reference year 1952).



Appendix F: Vegetation analysis

F1 Correlation between erosion and non-vegetated area

10 fans show a positive correlation between erosion volumes and non-vegetated fan area (Table F1).

Table F1. Fans with positive correlation between changes in non-vegetated area and erosion volumes.

Fan ID	Pearson r	Pearson p	Spearman ρ	Spearman p
36	0.86	0.03	0.83	0.04
9	0.68	0.14	0.89	0.02
40	0.78	0.07	0.77	0.07
10	0.77	0.08	0.26	0.62
28	0.71	0.12	0.27	0.60
35	0.67	0.14	0.20	0.70
14	0.56	0.24	0.60	0.21
32	0.53	0.28	0.65	0.16
1	0.46	0.35	0.20	0.70
7	0.43	0.40	0.26	0.62

685 F2 Disturbed forest area

The number of disturbances and the disturbance agent in the catchments are displayed in Figures F1 and F2.

The percentage of disturbed forest area in the catchment decreases for each fan group between 1987 and 2020, except for inactive fans (Fig. F3). The number of catchments affected by forest disturbances also decreases over time.

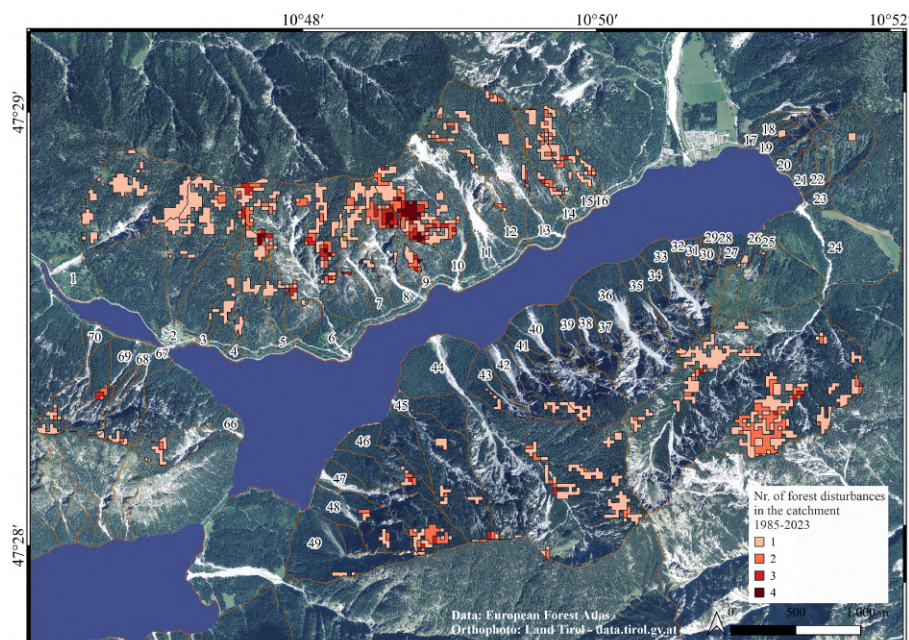


Figure F1. Number of disturbances in the fan catchments 1985-2023. Data ©European Forest Atlas and (Viana-Soto and Senf, 2025). Orthophoto ©Land Tirol (data.tirol.gv.at).

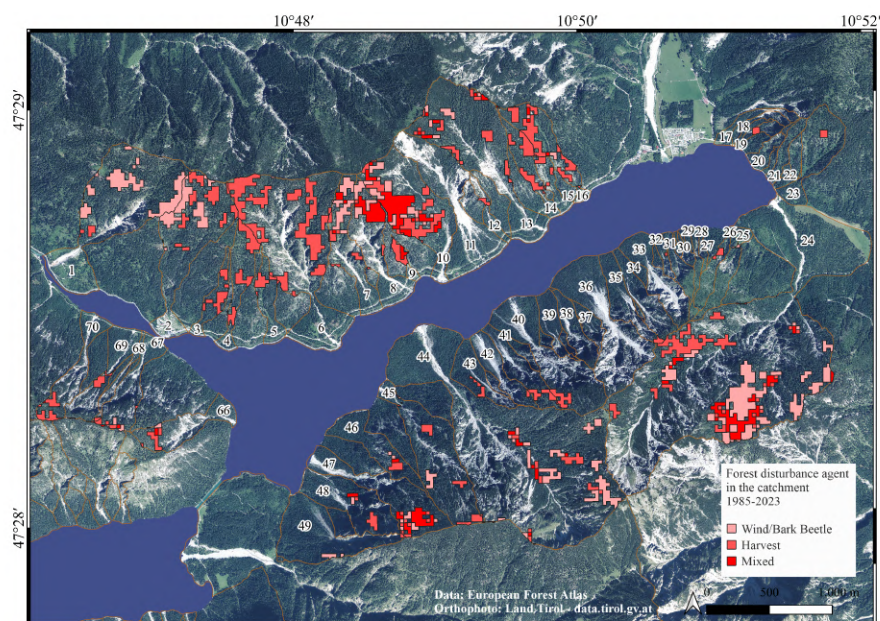


Figure F2. Forest disturbance agent 1985-2023. Data ©European Forest Atlas and (Viana-Soto and Senf, 2025). Orthophoto ©Land Tirol (data.tirol.gv.at).

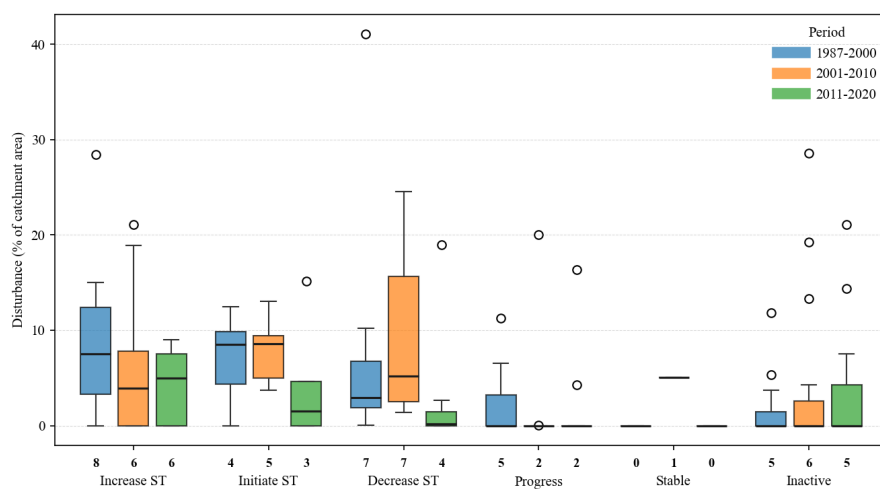


Figure F3. Disturbed forest area as percentage of total combined catchment and fan area by group and period. Number of affected catchments is noted on x-Axis Viana-Soto and Senf (2025).



690 *Data availability.* Orthophotos can be visualized in <https://lba.tirol.gv.at/public/karte.xhtml>. Shapefiles and elevation changes at the active channels are available upon request.

695 *Author contributions.* NB, CK and MK designed the study. NB and JJ reconstructed the aerial imagery. NB estimated sediment mass balances from consecutive DEMs and conducted the precipitation and morphometry analysis. CK re-examined the sediment cores, analyzed vegetation, channels and historical documentation and previous Plansee studies. NB and CK co-created the draft and visualization with the input of all co-authors. FS and MK provided guidance and funding. All authors revised the manuscript and contributed to the ideas developed in this study.

Competing interests. One author is member of the editorial board of *Earth Surface Dynamics*.

Acknowledgements. We thank 3D RealityMaps GmbH for the support with data visualization. We are grateful for comments on the draft by P. Gewalt and C. Mayr. We also thank Karlheinz Eberle and the Seenverwaltung Tirol as well as the Municipality Heiterwang and Bezirkshauptmannschaft Reutte for providing their historical documentation and access to the lake.

700 *Financial support.* This research is funded by the Bavarian State Ministry of the Environment and Consumer Protection (StMUV) (Grant No. TUS01UFS-76976 and TUS01UFS-77318) and the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - 558963977. The aerial imagery was acquired and process in the framework of the project “AlpSenseRely” – Alpine remote sensing of climate-induced natural hazards: Reliability of multi-method hazard prediction in a changing climate (Teilprojekt for LMU). Writing and publication is done in the framework of the project "AlpSenseAdapt"



705 References

- Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G., Morecroft, M. D., Muccione, V., and Prakash, A.: Cross-Chapter Paper 5: Mountains, in: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., and Rama, B., pp. 2273–2318, Cambridge University Press, Cambridge, UK and New York, NY, USA, <https://doi.org/10.1017/9781009325844.022>, 2022.
- 710 Agisoft LLC: Agisoft PhotoScan Professional, <http://www.agisoft.com/downloads/installer/>, 2016.
- Barbosa, N., Leinauer, J., Jubanski, J., Dietze, M., Münzer, U., Siegert, F., and Krautblatter, M.: Massive sediment pulses triggered by a multi-stage 130 000 m³ alpine cliff fall (Hochvogel, DE-AT), *Earth Surface Dynamics*, 12, 249–269, 2024.
- Beniston, M., Rebetez, M., Giorgi, F., and Marinucci, M.: An analysis of regional climate change in Switzerland, *Theoretical and applied*
 715 *climatology*, 49, 135–159, 1994.
- Bennett, G., Molnar, P., McARDell, B., Schlunegger, F., and Burlando, P.: Patterns and controls of sediment production, transfer and yield in the Illgraben, *Geomorphology*, 188, 68–82, 2013.
- Bennett, G. L., Molnar, P., Eisenbeiss, H., and Mcardell, B. W.: Erosional power in the Swiss Alps: characterization of slope failure in the Illgraben, *Earth Surface Processes and Landforms*, 37, 1627–1640, 2012.
- 720 Blanckaert, K., Vinnå, L. R., Bouffard, D., Lemmin, U., and Barry, D. A.: Field Observations Reveal How Plunging Mixing and Sediment Resuspension Affect the Pathway of a Dense River Inflow Into a Deep Stratified Lake, *Water Resources Research*, 60, e2023WR036813, <https://doi.org/https://doi.org/10.1029/2023WR036813>, 2024.
- Bongiovanni, G., Napoli, A., Matiu, M., Crespi, A., Majone, B., and Zardi, D.: Air temperature and precipitation trends in the Extended European Alpine Region over 1961–2020 from a dense network of surface weather stations, *Climatic Change*, 179, 121, 2026.
- 725 Borselli, L., Cassi, P., and Torri, D.: Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment, *Catena*, 75, 268–277, 2008.
- Bovis, M. J. and Jakob, M.: The role of debris supply conditions in predicting debris flow activity, *Earth surface processes and landforms*, 24, 1039–1054, 1999.
- Bracken, L. J., Turnbull, L., Wainwright, J., and Bogaart, P.: Sediment connectivity: a framework for understanding sediment transfer at
 730 multiple scales, *Earth surface processes and landforms*, 40, 177–188, 2015.
- Bull, W. B.: *Geomorphology of segmented alluvial fans in western Fresno County, California*, US Government Printing Office, 1964.
- Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft: Hydrographisches Jahrbuch von Österreich digital (eHYD WebGIS-Portal), Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft (BML), Wien, Österreich, <https://ehyd.gv.at>, last access: 26. Juni 2026, 2026.
- 735 Büntgen, U., Frank, D. C., Nievergelt, D., and Esper, J.: Summer temperature variations in the European Alps, AD 755–2004, *Journal of Climate*, 19, 5606–5623, 2006.
- Caine, N.: The rainfall intensity-duration control of shallow landslides and debris flows, *Geografiska annaler: series A, physical geography*, 62, 23–27, 1980.
- Casty, C., Wanner, H., Luterbacher, J., Esper, J., and Böhm, R.: Temperature and precipitation variability in the European Alps since 1500,
 740 *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 25, 1855–1880, 2005.



- De Haas, T., Densmore, A., Stoffel, M., Suwa, H., Imaizumi, F., Ballesteros-Cánovas, J., and Wasklewicz, T.: Avulsions and the spatio-temporal evolution of debris-flow fans, *Earth-Science Reviews*, 177, 53–75, 2018.
- de Haas, T., Lau, C.-A., and Ventra, D.: Debris-flow watersheds and fans: Morphology, sedimentology and dynamics, *Advances in debris-flow science and practice*, pp. 9–73, 2024.
- 745 Dietrich, A. and Krautblatter, M.: Evidence for enhanced debris-flow activity in the Northern Calcareous Alps since the 1980s (Plansee, Austria), *Geomorphology*, 287, 144–158, 2017.
- Einsele, G. and Hinderer, M.: Terrestrial sediment yield and the lifetimes of reservoirs, lakes, and larger basins, *Geologische Rundschau*, 86, 288–310, 1997.
- Esper, J., Reinig, F., Torbenson, M., del Castillo, E. M., Kunz, M., Arzac, A., Carrer, M., Chen, F., Kadioglu, A. K., Kirdyanov, A. V., et al.:
750 Pan-alpine summer temperatures since 742 CE, *Dendrochronologia*, 94, 126–143, 2025.
- Esri: Hydrology Toolset (Spatial Analyst, ArcGIS Pro), <https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/an-overview-of-the-hydrology-tools.htm>, tools include Flow Direction, Flow Accumulation, Watershed, Fill, etc., 2026.
- Felix, M. and Peakall, J.: Transformation of debris flows into turbidity currents: mechanisms inferred from laboratory experiments, *Sedimentology*, 53, 107–123, <https://doi.org/10.1111/j.1365-3091.2005.00757.x>, 2006.
- 755 Feurer, D. and Vinatier, F.: Joining multi-epoch archival aerial images in a single SfM block allows 3-D change detection with almost exclusively image information, *ISPRS journal of photogrammetry and remote sensing*, 146, 495–506, 2018.
- Frei, C. and Schär, C.: Detection probability of trends in rare events: Theory and application to heavy precipitation in the Alpine region, *Journal of Climate*, 14, 1568–1584, 2001.
- Freiwillige Feuerwehr Breitenwang: Operational Log and Incident Reports, Voluntary Fire Department Breitenwang-Mühl, Tyrol, <http://feuerwehr-breitenwang.at>, accessed: 26 June 2026, 2026.
- 760 Freiwillige Feuerwehr Heiterwang: Operational Log and Incident Reports, Voluntary Fire Department Heiterwang, Tyrol, <http://www.feuerwehr-heiterwang.at/>, accessed: 26 June 2026, 2026.
- Freiwillige Feuerwehr Höfen: Operational Log and Incident Reports, Voluntary Fire Department Höfen, Bavaria, <https://feuerwehren.bayern>, accessed: 26 June 2026, 2026.
- 765 Freiwillige Feuerwehr Reutte: Operational Log and Incident Reports, District Fire Department Headquarters Reutte, Tyrol, <https://feuerwehr-reutte.at>, accessed: 26 June 2026, 2026.
- Giles, P. T.: Investigating the use of alluvial fan volume to represent fan size in morphometric studies, *Geomorphology*, 121, 317–328, 2010.
- Gobiet, A. and Kotlarski, S.: Future Climate Change in the European Alps, *Oxford Research Encyclopedia of Climate Science*, <https://doi.org/10.1093/acrefore/9780190228620.013.767>, 2020.
- 770 Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., and Stoffel, M.: 21st century climate change in the European Alps—A review, *Science of The Total Environment*, 493, 1138–1151, <https://doi.org/10.1016/j.scitotenv.2013.07.050>, 2014.
- Guzzetti, F., Peruccacci, S., Rossi, M., and Stark, C. P.: The rainfall intensity–duration control of shallow landslides and debris flows: an update, *Landslides*, 5, 3–17, 2008.
- Haeberli, W., Rickenmann, D., Zimmermann, M., and Rösli, U.: Investigation of 1987 debris flows in the Swiss Alps: general concept and
775 geophysical soundings, *IAHS publication*, 194, 303–310, 1990.
- Haslinger, K., Breinl, K., Pavlin, L., Pistotnik, G., Bertola, M., Olefs, M., Greilinger, M., Schöner, W., and Blöschl, G.: Increasing hourly heavy rainfall in Austria reflected in flood changes, *Nature*, 639, 667–672, <https://doi.org/10.1038/s41586-025-08647-2>, 2025.



- Heisig, H. and Simmen, J.-L.: Re-engineering the past: countrywide geo-referencing of archival aerial imagery, *PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 89, 487–503, 2021.
- 780 Hibler, I. J.: *Der Plansee und seine Umgebung: eine glazial-geologisch-besiedlungs-wirtschafts-und kulturgeschichtliche Abhandlung*, Universitätsverlag Wagner, 1921.
- Hirschberg, J., Badoux, A., McArdell, B. W., Leonarduzzi, E., and Molnar, P.: Evaluating methods for debris-flow prediction based on rainfall in an Alpine catchment, *Natural Hazards and Earth System Sciences*, 21, 2773–2789, 2021.
- Hu, K., Wei, F., and Li, Y.: Real-time measurement and preliminary analysis of debris-flow impact force at Jiangjia Ravine, China, *Earth*
 785 *Surface Processes and Landforms*, 36, 1268–1278, <https://doi.org/10.1002/esp.2155>, 2011.
- Hung, O., Leroueil, S., and Picarelli, L.: The Varnes classification of landslide types, an update, *Landslides*, 11, 167–194, 2014.
- Hürlimann, M., Coviello, V., Bel, C., Guo, X., Berti, M., Graf, C., Hübl, J., Miyata, S., Smith, J. B., and Yin, H.-Y.: Debris-flow monitoring and warning: Review and examples, *Earth-Science Reviews*, 199, 102981, 2019.
- Irmeler, R., Daut, G., and Mäusbacher, R.: A debris flow calendar derived from sediments of lake Lago di Braies (N. Italy), *Geomorphology*,
 790 77, 69–78, <https://doi.org/10.1016/j.geomorph.2006.01.013>, 2006.
- Iverson, R. M.: Debris flows: behaviour and hazard assessment, *Geology Today*, 30, 15–20, <https://doi.org/10.1111/gto.12037>, 2014.
- Jomelli, V., Pech, V., Chochillon, C., and Brunstein, D.: Geomorphic variations of debris flows and recent climatic change in the French Alps, *Climatic Change*, 64, 77–102, 2004.
- Jomelli, V., Pavlova, I., Utasse, M., Chenet, M., Grancher, D., Brunstein, D., and Frédéric, L.: Are Debris Floods and Debris
 795 Avalanches Responding Univocally to Recent Climatic Change A Case Study in the French Alps, ISBN 978-953-307-419-1, <https://doi.org/10.5772/23916>, 2011.
- Kiefer, C., Oswald, P., Moernaut, J., Fabbri, S. C., Mayr, C., Strasser, M., and Krautblatter, M.: A 4000-year debris flow record based on amphibious investigations of fan delta activity in Plansee (Austria, Eastern Alps), *Earth Surface Dynamics*, 9, 1481–1503, <https://doi.org/10.5194/esurf-9-1481-2021>, 2021.
- 800 Land Tirol: tiris Geodaten: Laser- Luftbildatlas Tirol, <https://www.tirol.gv.at/data/>, open Government Data (CC BY 4.0). Accessed: 2026-06-12.
- Leenman, A. S. and Eaton, B. C.: Episodic sediment supply to alluvial fans: implications for fan incision and morphometry, *Earth Surface Dynamics*, 10, 1097–1114, 2022.
- Lindsay, J. B.: Whitebox Next Generation, <https://docs.csc.fi/apps/whiteboxtools/>, 2026.
- 805 Mao, L., Cavalli, M., Comiti, F., Marchi, L., Lenzi, M. A., and Arattano, M.: Sediment transfer processes in two Alpine catchments of contrasting morphological settings, *Journal of Hydrology*, 364, 88–98, 2009.
- Melton, M. A.: The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona, *The Journal of geology*, 73, 1–38, 1965.
- Micheletti, N., Lane, S. N., and Chandler, J. H.: Application of archival aerial photogrammetry to quantify climate forcing of alpine land-
 810 scapes, *The photogrammetric record*, 30, 143–165, 2015.
- Moos, C., Stritih, A., Teich, M., and Bottero, A.: Mountain protective forests under threat? an in-depth review of global change impacts on their protective effect against natural hazards, *Frontiers in Forests and Global Change*, 6, <https://doi.org/10.3389/ffgc.2023.1223934>, 2023.
- Pavlova, I., Jomelli, V., Brunstein, D., Grancher, D., Martin, E., and Déqué, M.: Debris flow activity related to recent climate conditions in
 815 the French Alps: A regional investigation, *Geomorphology*, 219, 248–259, <https://doi.org/10.1016/j.geomorph.2014.04.025>, 2014.



- Pelfini, M. and Santilli, M.: Frequency of debris flows and their relation with precipitation: A case study in the Central Alps, Italy, *Geomorphology*, 101, 721–730, <https://doi.org/10.1016/j.geomorph.2008.04.002>, 2008.
- Pleskot, K.: Sedimentological characteristics of debris flow Deposits within ice-cored moraine of Ebbabreen, central Spitsbergen, *Polish Polar Research*, 36, 125–144, <https://doi.org/10.1515/popore-2015-0006>, 2015.
- 820 Python Software Foundation: Python Programming Language, <https://www.python.org/>, 2026.
- Rajczak, J., Pall, P., and Schär, C.: Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine Region, *Journal of Geophysical Research: Atmospheres*, 118, 3610–3626, <https://doi.org/10.1002/jgrd.50297>, 2013.
- Rebetez, M., Lugon, R., and Baeriswyl, P.-A.: Climatic change and debris flows in high mountain regions: the case study of the Ritigraben torrent (Swiss Alps), *Climatic change*, 36, 371–389, 1997.
- 825 Rickenmann, D. and Scheidl, C.: Debris-Flow Runout and Deposition on the Fan, in: *Dating Torrential Processes on Fans and Cones*, edited by Schneuwly-Bollschweiler, M., Stoffel, M., and Rudolf-Miklau, F., pp. 75–93, Springer, https://doi.org/10.1007/978-94-007-4336-6_5, 2013.
- Rom, J., Haas, F., Heckmann, T., Altmann, M., Fleischer, F., Ressler, C., Betz-Nutz, S., and Becht, M.: Spatio-temporal analysis of slope-type debris flow activity in Horlachtal, Austria, based on orthophotos and LiDAR data since 1947, *Natural Hazards and Earth System Sciences*, 23, 601–622, <https://doi.org/10.5194/nhess-23-601-2023>, 2023.
- 830 Sabatier, P., Moernaut, J., Bertrand, S., Van Daele, M., Kremer, K., Chaumillon, E., and Arnaud, F.: A Review of Event Deposits in Lake Sediments, *Quaternary*, 5, 34, <https://www.mdpi.com/2571-550X/5/3/34>, 2022.
- Schürch, P., Densmore, A. L., Rosser, N. J., and McArdell, B. W.: Dynamic controls on erosion and deposition on debris-flow fans, *Geology*, 39, 827–830, 2011.
- 835 Sletten, K., Blikra, L., Ballantyne, C., Nesje, A., and Dahl, S.: Holocene debris flows recognized in a lacustrine sedimentary succession: Sedimentology, chronostratigraphy and cause of triggering, *Holocene*, 13, 907–920, <https://doi.org/10.1191/0959683603hl673rp>, 2003.
- Stammberger, V., Katharina, B., and Michael, K.: Channel position-dependent erosivity of steep debris flows combining gravitational and erosive processes: Towards predictive modeling, *Engineering Geology*, 371, 108919, <https://doi.org/10.1016/j.enggeo.2026.108919>, 2026.
- 840 Stoffel, M.: Magnitude–frequency relationships of debris flows—A case study based on field surveys and tree-ring records, *Geomorphology*, 116, 67–76, 2010.
- Stoffel, M., Tiranti, D., and Huggel, C.: Climate change impacts on mass movements – Case studies from the European Alps, *Sci. Total Environ.*, 493, 1255–1266, <https://doi.org/10.1016/j.scitotenv.2014.02.102>, 2014.
- Sumner, E. J., Talling, P. J., and Amy, L. A.: Deposits of flows transitional between turbidity current and debris flow, *Geology*, 37, 991–994, <https://doi.org/10.1130/g30059a.1>, 2009.
- 845 Tipping, R.: Radiocarbon dating of a composite multi-period debris cone stratigraphy in the Lochan na Lairige, Ben Lawers, *Scottish Journal of Geology*, 57, sjg2021–008, <https://doi.org/10.1144/sjg2021-008>, 2021.
- Tropeano, D. and Turconi, L.: Using Historical Documents for Landslide, Debris Flow and Stream Flood Prevention. Applications in Northern Italy, *Natural Hazards*, 31, 663–679, <https://doi.org/10.1023/B:NHAZ.0000024897.71471.f2>, 2004.
- 850 Tsunetaka, H., Hotta, N., Sakai, Y., and Wasklewicz, T.: Effect of debris-flow sediment grain-size distribution on fan morphology, *Earth Surf. Dynam.*, 10, 775–796, <https://doi.org/10.5194/esurf-10-775-2022>, eSurf, 2022.
- Turkington, T., Remaître, A., Ettema, J., Hussin, H., and van Westen, C.: Assessing debris flow activity in a changing climate, *Climatic Change*, 137, 293–305, <https://doi.org/10.1007/s10584-016-1657-6>, 2016.



- van Steijn, H.: Debris-flow magnitude—frequency relationships for mountainous regions of Central and Northwest Europe, *Geomorphology*,
 855 15, 259–273, 1996.
- Viana-Soto, A. and Senf, C.: The European Forest Disturbance Atlas: a forest disturbance monitoring system using the Landsat archive,
Earth System Science Data, 17, 2373–2404, <https://doi.org/10.5194/essd-17-2373-2025>, 2025.
- Vincent, L., Eaton, B., Leenman, A., and Jakob, M.: Secondary geomorphic processes and their influence on alluvial fan morphology, channel
 behavior and flood hazards, *Journal of Geophysical Research: Earth Surface*, 127, e2021JF006 371, 2022.
- 860 Yong, L., Xiaojun, Z., Pengcheng, S., Yingde, K., and Jingjing, L.: A scaling distribution for grain composition of debris flow, *Geomorphol-*
ogy, 192, 30–42, <https://doi.org/10.1016/j.geomorph.2013.03.015>, 2013.
- Zimmerman, M.: Climatic change and debris flow activity in high-mountain areas: A case study in the Swiss Alps., *Catena Suppl.*, 22, 59–72,
 1992.
- Zunter - Das Außerfern-Archiv: Digital Historical Chronicle and Regional Archive of Reutte, Zunter Online Platform, <https://zunter.net>,
 865 accessed: 26 June 2026, 2026.