Decadal sediment yield from an Alpine proglacial zone inferred from reservoir sedimentation (Pasterze, Hohe Tauern, Austria)

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Abstract Reservoir sedimentation over more than five decades enabled the quantification of subrecent sediment yield from the glacierized Pasterze catchment, a 40-km^2 basin located in the Hohe Tauern Mountain range in Austria. Sediment yield is highly variable over an order of magnitude (1.5 to 16.7 × 10^4 t/year) with an average of ~ 6.3 ± 0.5 × 10^4 t/year resulting in a total sediment export of approx. 340 × 10^4 t of mainly fine grained sediment (D_{50} Ø coarse silt). This is equal to specific sediment yields (SSY) ranging from 0.4 to 4.2 × 10^3 t/km^2/year (Ø 1.6 ± 0.1 × 10^3 t/km^2/year) at a total of 85.6 × 10^3 t/km^2 in the 54 years studied. No significant correlation is found between annual data sets of sediment yield, discharge, glacial retreat and hydro-climate. Based on multi-temporal geomorphological mapping, a sandur (former proglacial lake) and a braid plain are identified as key landforms within the proglacial zone modulating sediment yield. It is assumed that sediment yield from proglacial zones will increase due to climate change which accelerates glacier melt. This study shows the impact of proglacial lakes on sediment yield which can reduce the connectivity between glacial sediment production and downstream sediment fluxes. The number of proglacial lakes within the Alps is expected to rise following accelerated glacial retreat. Three basins are located under the present tongue of Pasterze Glacier and further lakes will develop. It is assumed that sediment delivery from the Pasterze catchment will most likely be significantly altered in the near future. This will lead to changes in sediment yields with impacts on hydrology, river ecology and reservoir management.

Key words sediment yield; proglacial lake; glacier forefield; reservoir sedimentation; Pasterze Glacier

INTRODUCTION

Glacierized alpine catchments and the proglacial zones therein are among the most dynamic geomorphic systems. Glacial erosion produces large amounts of sediment temporarily stored in unconsolidated, loose and potentially unstable landforms like moraines. The amount of sediment available for reworking *within* and export *from* glacierized catchments greatly exceeds the background denudation rates, termed the “geological norm”, and significantly influences the downstream fluvial systems, as formalised in the concept of paraglacial sedimentation (Church & Ryder, 1972; Ballantyne, 2002). The area exposed since the Little Ice Age between the glacier snout and the terminal moraine is called the glacier forefield (Kinzl, 1929). This expanding zone of relatively bare ground is characterised by two types of landscape transformation processes: the paraglacial adjustment of unstable glacial deposits and the succession of primary vegetation (Moreau *et al*., 2008; Mercier *et al*., 2009). Paraglacial adjustment refers to processes, e.g. debris flows which erode glacial deposits until storages are either exhausted or stabilized by vegetation (Ballantyne, 2002; Mercier *et al*., 2009). Paraglacial adjustment has been reported to be the main evolutionary factor of drift-mantled slopes in ice marginal and proximal locations where relatively “young” surfaces are vulnerable to erosion and mobilization (Curry *et al*., 2006; Cossart & Fort, 2008). With increasing distance to the glacier, the activity decreases as the paraglacial adjustment is often completed leaving stabilized surfaces with proceeding plant colonization. Thus, glacier forefields reveal a short-lived form of paraglacial adjustment within a few decades (Ballantyne, 2002; Curry *et al*., 2006). The rapid removal of easily mobilized sediment leads to increased sediment yields originating from both glacial erosion and the (paraglacial) erosion of glacial and glaciofluvial storages (Orwin & Smart, 2004). Sediment yields from glacierized catchments therefore do not directly indicate rates of glacial erosion as temporal sediment storage and release in the proglacial zone can significantly control and modify the yields (Warburton, 1990; Harbor & Warburton, 1993). Nevertheless, quantification of sediment yields delivers insights towards the dynamic and (in)stability of glacierized catchments and is of great use for hydropower schemes as rates of reservoir sedimentation are directly linked with the upstream geomorphological development (Bogen, 1989; Einsele & Hinderer, 1997).

SCIENTIFC FRAMEWORK AND AIMS

This paper presents results of an ongoing research project within the ESF TOPO-EUROPE initiative SedyMONT. In this project, paraglacial landform adjustment since the Little Ice Age at the Pasterze landsystem in the Austrian Alps is investigated using the conceptual framework of the sediment budget. This requires the identification and quantification of sediment sources, temporal sediment storages and sediment transfer processes (Reid & Dune, 1996). The main targets here are: (1) to quantify the distribution and total amount of sediment yield from the Pasterze landsystem within the last five-and-a-half decades using annual reservoir sedimentation data; and (2) to determine the likely impact of the proglacial zone on sediment yield by means of time-series maps of the spatio-temporal evolution of sediment storages following glacial retreat. A qualitative discussion of the likely impact of accelerated glacial retreat on future sediment yield concludes the paper.

APPROACHES TO QUANTIFY SEDIMENT YIELD

Sediment yields are often calculated from direct measurements of discharge, suspended sediment concentration and bedload, enabling the computation of daily, seasonal and annual sediment yields (e.g. Warburton, 1990; Orwin & Smart, 2004). The rating curve method is frequently used to predict unmeasured sediment concentrations from discharge assuming that they are mainly controlled by discharge rather than by sediment supply. However, sediment supply is extremely variable as new sources at different locations become available while former sources have been exhausted. This is known to introduce a high degree of scatter in both bedload and suspended sediment rating curves (Bogen, 1980; Fenn *et al*., 1985). Improvements such as high resolution turbidity records or acoustic sensors have led to more accurate measurements and subsequent calculations of sediment loads. As pointed out by Orwin & Smart (2004), short-term geomorphological process studies provide insights into contemporary sediment transfer patterns, but cannot establish how these patterns might change over time. An accurate method to determine long-term sediment yields from a catchment is the direct measurement of sediment deposition in a reservoir (Einsele & Hinderer, 1997; Morris & Fan, 1998). This enables hierarchical analyses of annual to decadal variations of sediment yields. For the case of glacierized catchments, this can help to identify and indicate the likely future impacts of climate change on sediment fluxes with impacts on hydrology, river ecology and reservoir management.

STUDY SITE

The Pasterze landsystem is located in the northwestern part of the province of Carinthia, Austria, in the uppermost part of the Möll Valley at the foot of Austria's highest peak, the Großglockner (Fig. 1). The Pasterze is the longest glacier in Austria and the eastern Alps, and the source area of the Möll River that drains southwards into the Drava drainage network. The study site has a real surface basin area of approx. 39.7 km² (33.7 km² planimetric hydrological drainage area) with a relative relief of 1736 m, ranging from 2062 to 3798 m a.s.l. The lithology is dominated by metamorphic Mesozoic rocks of the Glockner nappe, mainly calcareous mica-schist, amphibolite and prasinite (Höck & Pestal, 1994). With a mean annual air temperature of 1.6° and precipitation of 909 mm measured close to the study site (Fig. 1), the landsystem is characterised by continental

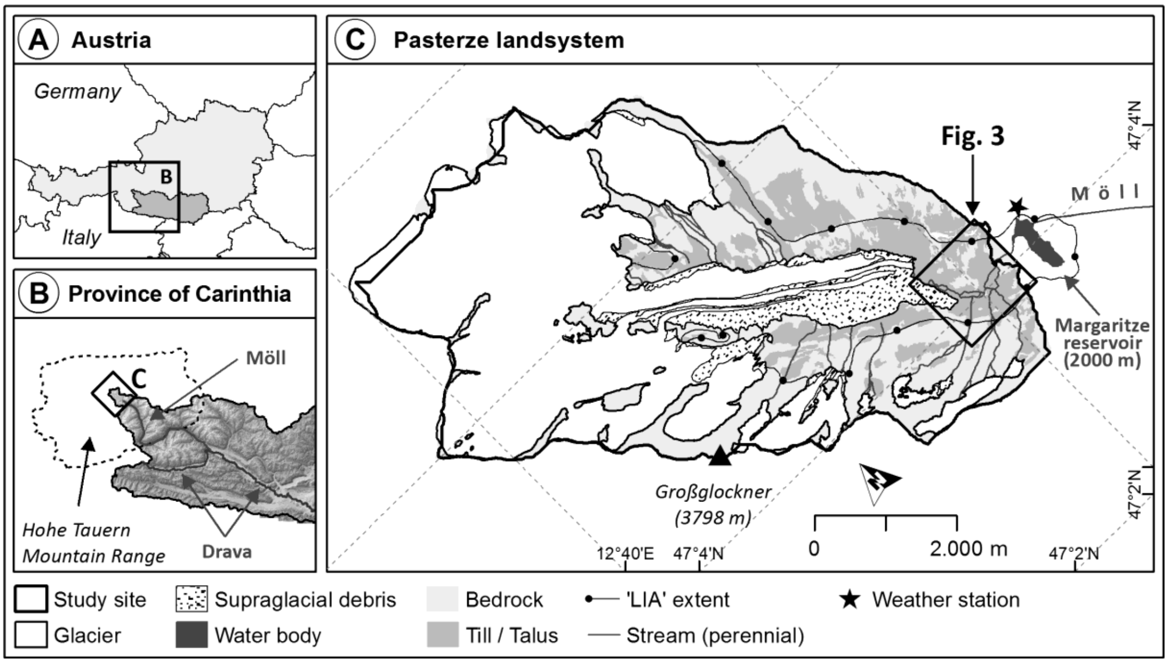

Fig. 1 Location and simplified geomorphological setting of the Pasterze landsystem with the spatial extent of Fig. 3 (Little Ice Age extent according to Nicolussi & Patzelt (2001)). The reservoir Margaritze is located approx. 500 m downstream of the catchment outlet.

climate conditions. Alpine meadows and dwarf shrubs characterise the vegetation that has developed continuously mainly beyond the Little Ice Age glacier terminus, with some sparse patches within the glacier forefield near the catchment outlet (Gewolf, 2011). During the last six decades an average annual glacial retreat of ~16 m/year has been measured, resulting in a cumulated frontal retreat of ~1 km (Patzelt, 1970, 1977, 2006). A typical landform assemblage is found: (i) talus and scree slope dominated areas beyond the modern drift limit of the Little Ice Age advance (Fig. 1), (ii) glacigenic sediment and glacial landforms within the drift limit, (iii) glaciofluvial storages in ice proximal locations and along recent and former meltwater channels, and (iv) reworked till accumulated in debris flow, avalanche and alluvial deposits at the base of incised drift-mantled slopes or stream tributaries. A distinct attribute of Pasterze Glacier is a pronounced supraglacial debris cover. A detailed description of the present geomorphological setting and the subrecent development of the proglacial zone will be given later. The Margaritze Reservoir (0.2 km²) is located at 2000 m a.s.l. approx. 500 m downstream of the catchment outlet and was constructed in the early 1950s (Fig. 1).

DATA AND METHODS

Reservoir sedimentation and sediment yield calculation

The sediment volume accumulated within the reservoir has been determined by annual bathymetric surveys since 1956. In general, reservoir re-surveys are a common way to detect the thickness of sediment deposition resulting from total sediment loads with a high degree of accuracy (Morris & Fan, 1998). The annual volumetric units of sediment input were converted into tonnes of dry material using a conversion factor of 1.35, as commonly used for fine grained material such as clay and silt (Einsele & Hinderer, 1997). Discharge, air temperature and precipitation data and grain size distributions of sediment samples taken in the reservoir were provided by the Verbund AG, which operates the Margaritze Reservoir. Glacial retreat has been determined by an annual surveying programme coordinated by the Austrian Alpine Club (published annually, e.g. Patzelt, 2006; earlier data summarized, e.g. in Patzelt, 1970, 1977).

The most critical point and prevalent source of error in our study is the conversion of annual volumetric units of sediment input into tonnes of dry material. At the Margaritze, silt was the average mean diameter (D_{50}) of 13 samples of sediment entering the reservoir in 2003. We therefore hypothesize that the conversion factor used corresponds to the natural conditions. This is supported by comparing a calculated yield with an independent data set published by Hartmeyer *et al.* (2007). Within their study carried out at the Pasterze in 2006, a yield of 50 000 t was calculated from direct measurements of discharge and suspended sediment concentrations (n = 90) using the rating curve method. This is somewhat lower than the yield of ~57 100 t calculated from the reservoir data (Fig. 2(A)). However, Hartmeyer *et al.* (2007) mentioned that they probably underestimated the yield as they missed the elevated suspended sediment concentrations during the period of snow melt and the early ablation-season "flushing" of subglacial suspended sediment stores. It is therefore considered that the yield calculated from the reservoir data is in good agreement with that estimated by Hartmeyer *et al.* (2007). It is consequently assumed that the conversion factor used was suitable, but we are very aware of the limited availability of comparative data. In any case, an error potentially associated with the volume-to-mass conversion will affect the absolute values of sediment yield, but not the relative differences in annual variability.

Multi-temporal geomorphological mapping

Detailed geomorphological field mapping was carried out in 2009 and sediment storages, transfer processes, hydrological and glaciological features were mapped at the catchment scale (Geilhausen *et al*., 2012a,b). These data represent the present inventory of the geomorphological system. The subrecent development of the proglacial zone was mapped based on orthophotos and aerial images dating back to the early 1950s. Four dates of small- to medium-scale historical vertical aerial images (1953, 1962, 1974, 1979) and subsequent orthophotos (1998, 2003, 2006, 2009) were interpreted. Aerial images were digitally obtained at high scanning resolutions (14 µm) and the photogrammetric processing of orthorectification was done using the Leica Photogrammetry Suite 2010 (LPS) within ERDAS Imagine software. The interior orientation of each image frame was calculated using camera calibration specifications, including camera type, focal length and the location of fiducial marks. The exterior orientation was determined by triangulation from ground control points (GCP) and automatically generated match points on overlapping imagery (image tie points). The LPS makes use of a bundle block adjustment algorithm to determine the best estimates for the perspective centre and the rotation angles of each image in a single least square solution (ERDAS, 2010). Natural features like stable boulders or flat and structured bedrock areas were found to be effective GCPs and were used in all four time series to ensure relative accuracy (Kääb & Vollmer, 2000). Coordinates of the GCPs were obtained from 2009 orthophotos with a pixel resolution of 25 cm, and elevations derived from 2009 airborne laser scan data (vertical accuracy of approx. ±5 cm). A hierarchical stereo correlation based image matching algorithm with a 5 × 5 correlation window was used to extract the DEMs which were then used to resample the aerial images to orthophotos (ERDAS, 2010).

The photogrammetric processing of aerial images resulted in average RMS errors of the interior orientation of 2.4 ± 1.4 pixels. The horizontal control point RMS errors achieved by triangulation were less than 25 cm in latitude and longitude for all aerial image series, which delivered final orthophoto resolutions of 18–43 cm. Both the RMS error and pixel resolution are considered to be sufficient for the mapping purposes of this study.

RESULTS AND DISCUSSION

Sediment yield

The calculated sediment yields (SY) are illustrated in Fig. 2(A). In the period 1956 to 2009, sediment yields were in the range of 1.5 to 16.7 × 10^4 t/year with a mean yield of 6.3 ± 0.5 × 10^4 t/year. Approximately 340 × 10^4 t of sediment were exported from the Pasterze landsystem within

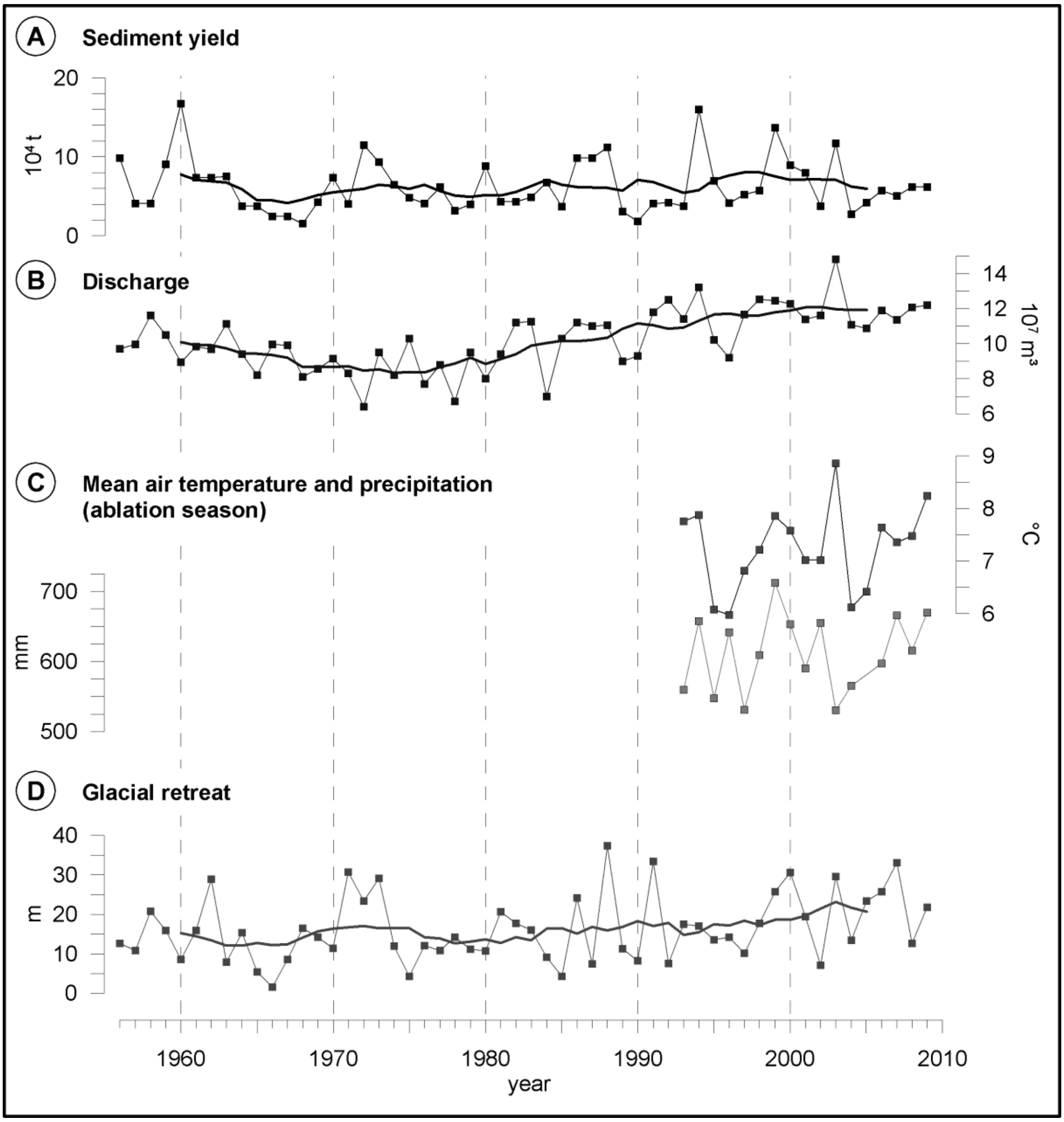

Fig. 2 Calculated sediment yield (A), discharge (B), climate data (C) and glacial retreat (D) during the period 1956–2009, bold lines represent 9 years running averages. Climate data are limited to the period from 1993 to 2009 with average air temperature and precipitation given for the ablation season. Please note lack of precipitation data for 2005, due to missing data for two months.

54 years. The highest yield occurred in 1960 and eight years later the lowest yield was observed. Using the study site basin area of 39.7 km², this corresponds to specific sediment yields (SSY) ranging from 0.4–4.2 × 10^3 t/km^2/year (Ø 1.6 ± 0.1 × 10^3 t/km^2/year) with a total of 85.6 × 10^3 t/km^2 in 54 years. Using the basin area (i.e. the real surface area) is a crucial consideration as the planimetric area underestimates the real surface area of steep alpine catchments. However, it is the real surface area of the relief, and not its horizontal projection, where geomorphological processes take place. Taking a rock density of 2.6 t/m^3 is assumed to be realistic for the rock types found at the Pasterze landsystem (prasinite, amphibolite and calcareous mica-schist), a conversion factor of 0.385 (Einsele & Hinderer, 1997) was used to calculate the mechanical denudation rates (DR_{me}) from the SSYs. This would result in a total mechanical denudation of ~33 mm within the 54 years of investigation with DRs in the range of 0.2–1.6 mm/year.

Although there were periods of relatively low inter-annual differences (e.g. 1961–1963 or 1981–1983, cf. Fig. 2), a considerable temporal variability within the data is found. Linking the yields with discharge (Fig. 2(B)) gives a limited explanation. For example, the highest sediment yield (16.7×10^4 t) was reached at an annual discharge of 8.95×10^7 m^3 in 1960, whereas the unusually warm summer 2003 caused the highest discharge of 14.82×10^7 m^3, but only ~2.9×10^4 t of sediment export. Furthermore, variability in both sediment yield and discharge has been different. The coefficient of variation (CV) was calculated that expresses the ratio of the standard deviation to mean, thus giving a measure of the normalised variability. The sediment yield CV of 0.5 is 2.5 times greater than that of discharge (CV = 0.2). Consequently, discharge does not seem to be the only parameter controlling sediment yield, which is not surprising as briefly discussed above.

As a product of sediment concentration and discharge, sediment yield exhibits greater variability than streamflow (Morris & Fan, 1998) due to daily, seasonal and annual variations in sediment concentrations. These in turn are caused by variations in sediment supply from: (i) the early season flushing and late season exhaustion effects, (ii) transient flushes of sediment from the glacier in the absence of corresponding discharge variations, (iii) variable sediment supply from local proglacial sources, and (iv) sediment supply dynamics associated with rainfall-induced flow events (Bogen, 1980; Fenn *et al*., 1985). Thus, precipitation and the development of the proglacial zone need to be considered to determine sediment supply and storage. However, precipitation data are available as monthly sums since 1993 (Fig. 2(C)) and the data record accounts for ~31% of the sediment yield record. The data coverage and resolution enable limited statements because it is the intensity and frequency of rainfall events within a month, rather than the total precipitation of the month, that leads to elevated sediment supply from extra-channel sources. Due to the poor explanatory power of monthly sums, precipitation is consequently excluded from the subsequent discussion.

The annual rates of glacial retreat (Fig. 2(D)) determine the area exposed within the proglacial zone, but provide no information on the characteristics and relief structure of the deglaciated terrain, e.g. the percentage of sediment or bedrock coverage of the area exposed. Consequently, glacial retreat seemed to be an insufficient surrogate for temporal sediment release and storage in the proglacial zone. Therefore, the proglacial zone was mapped for eight different years on the basis of orthophotos resulting in time series maps of sediment storage development following glacial retreat. These are used to determine and discuss the likely impact of the proglacial zone on sediment yield. As a consequence, the further analysis and discussion will be primarily performed on a decadal scale. We are aware of the fact that the causes of singular annual peaks in sediment yield would remain unexplained. However, a general trend of controlling factors within the proglacial zone can be deduced using a multi-temporal mapping approach.

Geomorphological development of the proglacial zone

The development of the proglacial zone is illustrated in Fig. 3(A–H) with the spatio-temporal evolution of sediment storages since 1953 within the deglaciated terrain. In 1953, the Pasterze covered the entire valley floor with the snout located at the outlet of the study site close to the Möll gorge (A). The continuous retreat exposed a natural basin that was initially filled with glaciofluvial outwash sands (B). The basin expanded and a proglacial lake developed having an area of approx. 110×10^3 m^2 in 1974 (C). The glacier formed ~160 m of the lake’s southeastern shore line and a meltwater channel draining from northwest led to the development of an alluvial fan propagating into the lake. Around 1979, the maximum lake area of ~122×10^3 m^2 was reached (D). An area of 67×10^3 m^2 was exposed within the period 1974–1979 and the retreat and surface lowering of the glacier led to the redirection of meltwater channels decoupling the fan from the sediment transport system. Since the late 1970s, the Pasterze receded from the lake and an area of >352×10^3 m^2 was exposed by 2009 (D–H). At the valley floor, a braid plain (depicted as number 2 in Fig. 3(H)) developed with changing channel threads and a chaotic pattern of irregular hummocks and hollows with dead/stagnant ice bodies melting out. This has been reported to be a

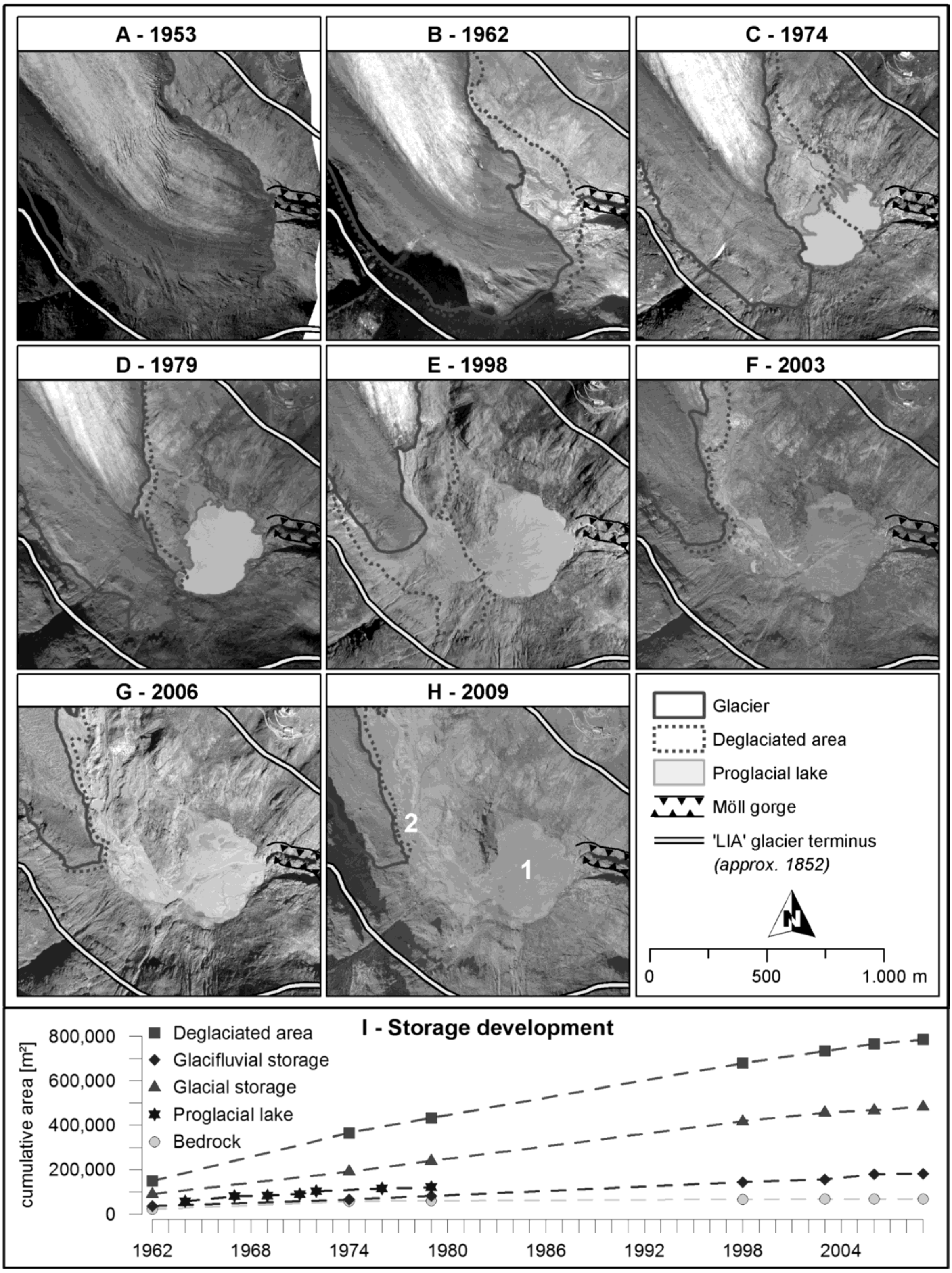

Fig. 3 Time series maps of the development of the proglacial zone (A–H) and cumulative areas of sediment storages, bedrock and water bodies in the area deglaciated (I). The numbers in map H label the dominant areas of sedimentation found with 1 = sandur and 2 = braid plain.

typical assemblage for receding glacier margins (Hubbard & Glaser, 2005). The kettle holes found seem to be quickly covered by glaciofluvial deposition as they often disappeared on subsequent imagery. Flat topped kame terraces following the limits of hummocky moraine deposits in ice marginal locations were found. The proglacial lake was filled up by glaciofluvial sedimentation, appearing as an almost plain and circular sandur, probably since the early 1990s (E–H). The sandur now has an area of ~120×10^3 m^2 and a length of more than 400 m (depicted as number 1 in Fig. 3(H)). The eastern limit of the sandur is built by a small gravel-dominated former delta that is currently buried by fine grained sediment. As typical of sandurs, grain sizes decrease from sand and gravel at the beginning to silt and clay at the margin in the vicinity of the catchment outlet (Möll gorge). Geophysical surveys carried out in 2006 delivered a mean sediment thickness of approx. 6.2 m, resulting in a calculated sediment volume of ~744×10^3 m^2 stored in this landform (Geilhausen & Schrott, 2011).

Since 1953, an area of more than 785×10^3 m^2 has been exposed in the proglacial zone, of which 23% accounts for storages in the glaciofluvial domain of the valley floor. The debris covered part of the Pasterze has exhibited minor retreat and shrinkage rates as compared to the clean ice part due to reduced ablation. As a consequence, the slope gradient of the glacier tongue covered by debris has increased within the mapping period. The southwestern hillslope in the proglacial zone is characterized by a remarkable till coverage due to the dumping of supraglacial debris. Paraglacial reworking seems to be limited to a few active debris flows, avalanche and meltwater paths transferring sediment downslope and propagating onto valley floor storages. However, active hillslopes are mainly decoupled from the glaciofluvial transport system. The valley floor exposed within the last five decades is characterized by a generally low gradient, indicating a reduced transport capacity of the meltwater channel for coarser sediment potentially available in ice proximal and marginal locations.

Towards a qualitative explanation

Sediment flux is considered to operate in a cascade of two coupled subsystems in which sediment output from the subsystem “glacier” is transformed into the sediment input of the subsystem “proglacial zone”. Glaciers serve as a source of sediment washed out by subglacial streams, but the subglacial drainage system has been known to exhibit temporal and spatial variations in the course of the ablation season and from one year to the next (Hubbard & Glaser, 2005). Consequently, the quantity of sediment exported from the glacier is variable. It is assumed that the variability of sediment yield is to a certain extent a consequence of variable sediment output from the glacier due to changing subglacial drainage systems. The function of the proglacial zone and in particular the valley floor within the sediment cascade is considered to be both a temporal source and sink. Based on the proglacial landform evolution obtained from multi-temporal geomorphological mapping, dominant phases are derived and a set of interpretations is established (Fig. 4(B)).

The development of the proglacial lake to its maximum extension in the late 1970s (depicted as “increasing lake” in Fig. 4(B)) seemed to have a great influence, at least in the period 1961–1968 when the lowest sediment yield occurred. The subsequent period of lake aggradation involved a reduction of storage capacity leading to reduced and variable sediment trapping. It is considered that the quantity of sediment deposited was controlled by the flow velocity within the lake. The flow velocity in turn should increase with decreasing lake volume leading to lower rates of deposition. Furthermore, flow velocity increases as discharge rises which could be an explanation for the three consecutive peaks of 1986–1988 because these were years of higher discharge. In the early 1990s, Krainer & Poscher (1992) observed a specific seasonal pattern of erosion and deposition on the recently developed sandur. During periods of high flow conditions (summer) the meltwater was dammed up to a very shallow lake flooding the sandur (backwater situation) and >50% of suspended sediment was deposited. With decreasing discharge in autumn the lake surface was lowered and the backwater disappeared leading to partial erosion of sediment deposited during summer. This is supposed to be the dominant influence of the sandur today as the shallow lake has been found during field work within the last years. Within the last five-and-a-half

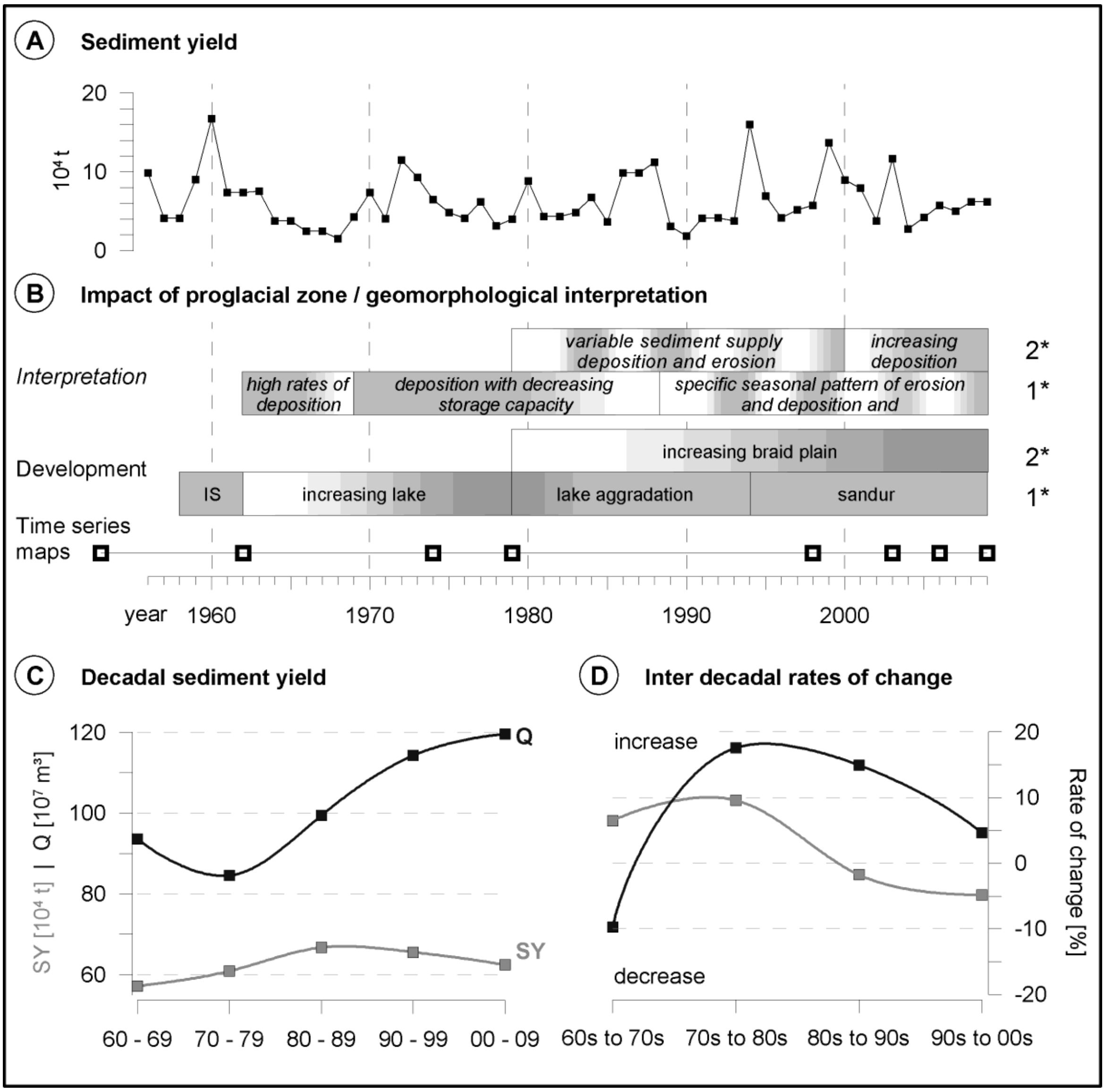

Fig. 4 Calculated sediment yield (A), geomorphological interpretation of the impact of the proglacial zone on sediment yield derived from multi-temporal surface mapping (B), decadal sediment yield (grey) and discharge (black) (C) and inter-decadal rates of change in sediment yield and discharge (D) (IS = initial sandur, * numbers correspond to Fig. 3 and refer to the dominant deposition areas within the proglacial zone: 1 = sandur and 2 = braid plain).

decades, the lower part of the proglacial zone shifted its function from a sink (proglacial lake) to a landform of sediment throughput (sandur) with accentuated periods of sediment input exceeding output (summer) and *vice versa* (autumn). Hartmeyer *et al.* (2007) found higher suspended sediment concentrations at the sandur outflow sampled synchronously with the inflow on 26 May 2006. This is generally in good agreement with the result by Krainer & Poscher (1992) as the high flow conditions tend to develop from June onward. In addition to the natural development of the lower proglacial zone, the outlet was twice dammed artificially, in 1969 and 1982, both of which seemed to have minor impacts on sediment yield of the following years (Fig. 4(A)). Since the early 1990s, the sandur is the last major landform having a key position within the sediment cascade. We therefore conclude that the sandur plays a significant role in modulating the proglacial sediment yield.

The impact of the braid plain exposed since the late 1970s on sediment yield is somewhat more difficult to derive because distinct periods of landform evolution were hardly identified by multi-temporal geomorphological mapping as compared to the lower proglacial zone. In general, the undulated and hummocky relief with kettle holes and melting dead ice bodies is considered to supply sediment, rather than to cause significant deposition. However, the elevation difference between the present day glacier snout and the end of the braid plain at the transition to the sandur is 3 m over a distance of approx. 1000 m. This results in a very low channel gradient with many shallow water courses, indicating a reduced transport capacity of the stream which is assumed to reduce sediment yields.

The general system response is deduced from decadal sediment yields (sum of all annual yields per decade) and discharge and is shown in Fig. 4(C and D), where plot C illustrates the decadal yield (SY) and discharge (Q) and plot D depicts the rates of change in SY and Q between the decades. Remarkable differences in the shapes of the SY and Q curves are noticed (Fig. 4(D)). Discharge dropped from 93.7×10^7 m^3 (1960–1969) to 84.6×10^7 m^3 (1970–1979) but then increased to 119.6×10^7 m^3 (2000–2009, with 99.4×10^7 m^3 in the period 1980–1989 and 114.27×10^7 m^3 in the decade 1990–2000). The lower Q in the 1970s was caused by cooler climate conditions when numerous glaciers in Austria advanced, although a substantial advance of the Pasterze was not observed due to its delayed response (Wakonigg & Lieb, 1996). The significant increase in discharge since the 1980s is in good agreement with higher temperatures observed. In contrast, sediment yield increased from 57.2×10^4 t (1960–1969) to 66.7×10^4 t (1980–1989), but since then dropped to 62.4×10^4 t (2000–2009). The lowest yields of the decade 1960–1969 are explained by the proglacial lake significantly trapping sediment. The subsequent increase could be a consequence of reduced sediment trapping and deposition due to continuous lake aggradation. The subsequent SY decrease is assumed to be the result of the decreasing transport capacity of the meltwater stream and the lower sediment delivery ratio- (SDR) of the braid plain.

CONCLUSIONS AND PERSPECTIVES

Subrecent sediment yields from the Pasterze catchment were calculated using a 54-year record of reservoir sedimentation. Volumetric units of annual sediment input were converted into tonnes of dry material using a factor of 1.35 according to Einsele & Hinderer (1997). Sediment yields (SY) are highly variable over an order of magnitude (1.5 to 16.7×10^4 t/year) with an average of ~$6.3 \pm 0.5 \times 10^4$ t/year. Approximately 340×10^4 t of mainly fine grained sediments have been exported (D_{50} Ø coarse silt). This is equal to specific sediment yields (SSY) ranging from $0.4–4.2 \times 10^3$ t/km^2/year (Ø $1.6 \pm 0.1 \times 10^3$ t/km^2/year) with a total of 85.6×10^3 t/km^2 over the 54 years. No significant correlation between the annual data sets of sediment yield, discharge, glacial retreat and hydro-climate was found. Multi-temporal aerial images and orthophotos were used to produce time-series maps of the geomorphological development of the proglacial zone. A former proglacial lake that was silted up to a sandur and a subsequent braid plain, were identified as key landforms modulating sediment yields. On the decadal scale, sediment yield and discharge are characterised by an inverse relationship. With the exception of the 1970s, discharge has continuously increased, whereas SY has decreased slightly since the 1990s. This is explained by variable deposition processes and a reduced transport capacity of the main meltwater stream, both resulting in lower sediment delivery ratios (SDR) of the proglacial zone.

It is assumed that climate change and accelerated glacier melt lead to an increase in sediment yields from proglacial zones (e.g. Stott & Mount, 2007). We address the topography of the recently deglaciated terrain as another important factor. If glacial retreat, accelerated by climate change, exposes natural basins, the topographical conditions meet the development of proglacial lakes that can have great influence on the downstream hydrological and geomorphological systems due to discharge modifications, sediment trapping, decoupling effects and long-term sediment storage. Our study indicates the impact of a proglacial lake and subsequent lake aggradation on sediment yield that has significantly reduced the connectivity between glacial sediment production and downstream sediment fluxes. It is expected that the number of proglacial lakes will rise within the Alps following accelerated glacial retreat (Tsutaki *et al*., 2011). Ice-thickness measurements at the Pasterze showed that three further basins are located under the glacier tongue (Span *et al.*, 2005; Fischer *et al.*, 2007). Further glacial retreat will expose these basins and will lead to the development of proglacial lakes. It can therefore be assumed that sediment delivery from the Pasterze catchment will most likely be significantly altered in the near future, which will lead to changes in the sediment yields with impacts on hydrology, river ecology and reservoir management.

Acknowledgements This paper emanates from an individual project of the University of Salzburg within the collaborative research project SedyMONT (Timescales of Sediment Dynamics, Climate and Topographic Change in Mountain Environments, ESF TOPO-EUROPE programme, cf. www.sedymont.eu). We would like to express our thanks to the Verbund Austria AG for providing data on reservoir sedimentation, discharge and climate. Financial support provided by the Austrian Science Fund (FWF): Projektnummer I 157-N19 is gratefully acknowledged.

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