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Research Article

Effects of Alpine hydropower dams on particle transport and lacustrine sedimentation

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Abstract. The effects of high-alpine hydropower damming on lacustrine sedimentation and transport of solid particles were investigated in the glaciated Grimsel area and in downstream Lake Brienz, providing quantitative denudation rates and sediment yield on a source-sink basis. A total of 271 kt/yr of solid particles entered the Grimsel reservoirs on average in the last 71 years, mostly by turbiditic underflows that focused sedimentation in depocenters upstream of obstacles such as bedrock ridges, submerged moraines, or dams. This is equivalent to a sediment yield of 2430 t/(km^{2}yr) in the catchment (111.5 km^2) or a denudation rate of 0.94 mm/yr. A total of 39 kt/yr of the fine fraction (<~4 μm) leave the reservoirs and are transported to downstream Lake Brienz, while 232 kt/yr of mostly coarse particles are retained, reducing total sediment input of the River Aare into Lake Brienz by two thirds. Modeling the particle budgets in the Aare with and without dams indicates that the fine fraction budgets are only slightly affected by damming, but that the reservoirs cause a shift in seasonal runoff timing resulting in increasing and decreasing particle transport in winter and summer, respectively. Thus, hydrodamming alters mostly deltaic sedimentation in Lake Brienz, where the coarse fraction is deposited, whereas fine grained distal sedimentation and varve formation on lateral slopes are less affected. All varved records of the reservoirs and Lake Brienz that provide sediment rates and grain size records on an annual basis indicate that climate is the main control on these proxies, while, for instance, the onset of pump storage activity in the reservoirs did not impose any significant change in lacustrine sedimentation pattern.

Key words. Sediment yield; reservoir lakes; lacustrine sedimentation; particle transport; erosion rates.

1. Introduction

Sediment yield, particle transport, and deposition in source-sink systems are sensitive to factors such as climatic conditions (e.g. temperature and precipitation), bedrock lithologies, topographic relief, and

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Table 1. Characteristics of the three reservoirs in the Grimsel area.

	Maximum elevation (m asl)	First flooding (yr AD)	Maximum water-volume (10^6 m^3)	Maximum length (m)	Maximum width (m)	Maximum depth (m)
Oberaarsee	2303	1953	57	~2500	~600	85
Grimselsee	1909	1929	95	~6000	~500	87
Räterichsbodensee	1767	1950	25	~1000	~700	56
All three lakes:			177			
All KWO reservoirs			196			
Lake Brienz	566	Postglacial	5120	~14,500	~2500	260

tectonic processes (Hinderer, 2001; De Vente and Poesen, 2005; and references therein). These particle fluxes may be altered by anthropogenic impact, such as by hydropower dam construction that form artificial sediment sinks acting as manmade sediment traps. Operation of such reservoirs is thus affected by reduction of available water volume (Schleiss and Oehy, 2002). In turn, sediment studies in these reservoirs allow relative simple quantification of erosion rates and sediment budgets (McIntyre, 1993; Einsele and Hinderer, 1997; De Cesare et al., 2001). As a consequence of their sediment retaining capabilities, they affect the downstream particle transport so that the sediment budgets at lower elevations may be altered significantly (Vörösmarty et al., 1997, 2003; Teodoru and Wehrli, 2005; Finger et al., 2006). Furthermore, parameters such as water temperature (Preece and Jones, 2002; Meier et al., 2003), turbidity (Loizeau and Dominik, 2000; Jaun et al., 2007), nutrients (Humborg et al., 2000; Friedl et al., 2004) and resulting biological communities (Hart et al., 2002) may be altered by damming.

The study presented here focuses on the effect of the Grimsel reservoirs (Grimselsee, Oberaarsee, Räterichsbodensee) on particle transport and deposition in an alpine source-sink system (Lake Brienz catchment; Fig. 1). The three reservoirs lie at elevations between 1760 and 2300 m asl, embedded in the crystalline Aar Massif (Fig. 2; Table 1). They were built between 1929 and 1953 and flooded alpine meadows, two natural lakes, proglacial floodplains and the tongues of the Oberaar and Unteraar glaciers. The reservoirs drain through the Aare into downstream Lake Brienz, which lies at an elevation of 566 m asl in a deep glacial valley within the Helvetic Nappes of the frontal Alpine range (Jurassic and Cretaceous calcareous formations). Next to the Aare, the Lake Brienz catchment (area 1140 km^2, of which 19 % is glaciated) is drained by a second large river, the Lütschine (Fig. 1). The effect of the high-alpine reservoirs on downstream Lake Brienz is of particular interest because during 1999 Lake Brienz experienced an extremely low fish yield (Wüest et al., 2007), an event that initiated a multidisciplinary study. Several aspects of the Grimsel-Brienz source-sink system were studied. One possible scenario was that the amount and timing of suspended particles (Finger et al., 2006) and colloids (Chanudet and Filella, 2007) released to Lake Brienz changed over time with direct consequences on water clarity. All of these parameters might have furthermore affected the availability of nutrients (Müller et al., 2007a), primary production (Finger et al., 2007), the *Daphnia* population (Rellstab et al., 2007) and fish ecology (Müller et al., 2007b).

The goals of this study were to (1) quantify the amount of sediment retained in the reservoirs and subsequently not flushed into Lake Brienz; (2) calculate the erosion rate in the glaciated catchment; (3) address the change in flow regime of the Aare occurring as a result of the dam construction, and (4) evaluate related changes in the hydrologic and sedimentologic patterns of Lake Brienz.

For this purpose, recent sedimentation processes for both the reservoirs and Lake Brienz are described, quantified and interpreted. In Section 2 of this study, we first quantify the sediment budgets, resulting erosion rates and type of retained sediment loads in the reservoirs. In Section 3, we describe how flow regime and transport of suspended solid particles of the Aare changed as a result of damming. In Section 4, we evaluate how the sedimentation pattern in Lake Brienz was altered as a result of these upstream changes. Finally in section 5, all observations are put into the context of evaluating the impact of the hydropower dams on the sedimentologic regime of Lake Brienz and the potential role this may have played in the observed environmental changes in the late 1990 s.

2. Erosion and sedimentation in the glaciated Grimsel area

Characteristics of the proglacial reservoirs

All three investigated reservoirs (Table 1) are connected by a series of pipelines that are either used for

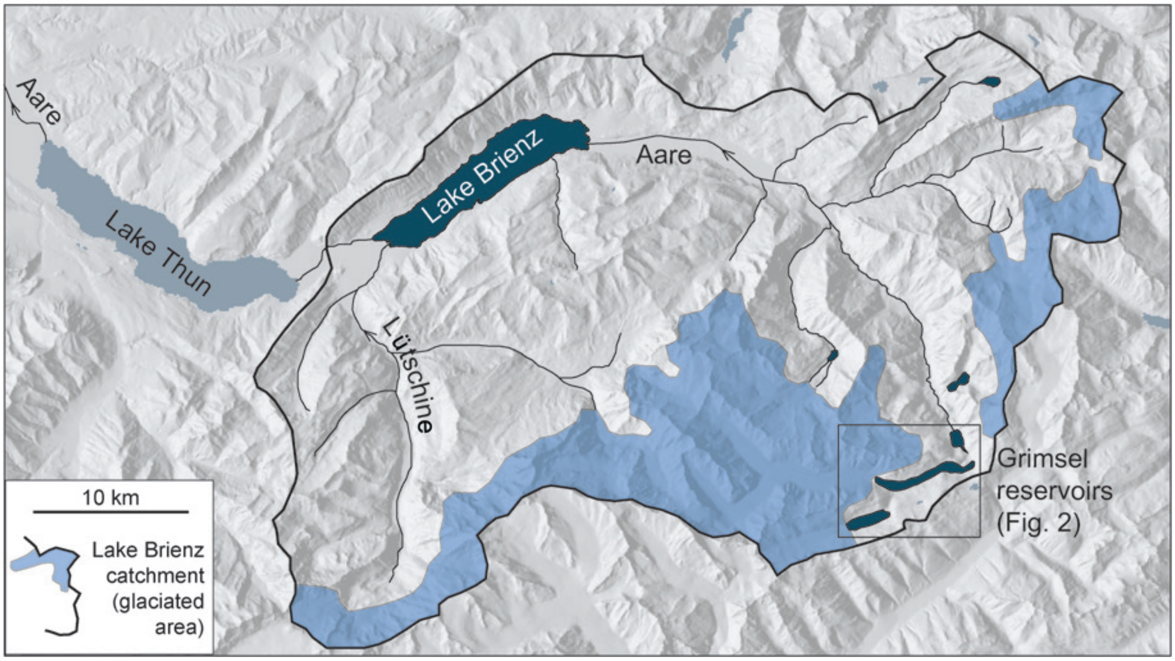

Fig. 1. Map of Lake Brienz catchment. Glaciated areas are marked with blue shading. The Eastern Aare catchment is dominated by glacial influence.

power generation or for water exchange. Since 1980, Grimselsee and Oberaarsee were also connected by a pump-storage system that is able to pump 80 m^3/s to the higher reservoir for hydro-peaking.

The catchment area of the three reservoirs (Figs. 1, 2), ranging in elevation between 1908 and 4273 m asl has a total size of 111.5 km^2, of which 44.8 km^2 are covered by glaciers (Bühler, 2003). The runoff of Oberaar Glacier drained prior to construction of the Oberaarsee dam (built in 1953) into Grimselsee. Räterichsbodensee has basically no glaciated catchment and is only fed by small creeks that provide little sediment to the reservoir. The bulk of its sediment originates from Grimselsee that is periodically drained so that its reworked sediments become redeposited in Räterichsbodensee. The combined sediments of the three reservoirs, and the fine particles leaving the system in suspension, thus reflect the total sediment budget of the catchment since the construction of the main hydropower dams in 1929.

All three reservoirs exhibit strong water level fluctuations, with generally low stands in late winter when they are totally covered with ice for several months, and high stands in summer. The three reservoirs have been emptied several times during the last 71 years for maintenance. Grimselsee was emptied twice, in winter 1976 and 2000, as was Räterichsbodensee in 1974 and 1990. Oberaarsee was emptied only once in 2004. These drainage events led to flow conduits at the lake floor that are characterized by channels cutting into the sediments. A large amount of sediment is consequently transported into the next lower basin. However, no sediment other than the finest suspension load can escape the lowest reservoir Räterichsbodensee, which forms the ultimate closure of the sediment trap.

Methods

Seismic survey methods. In summer 2001 and 2002, high-resolution reflection seismic investigations were performed with a 3.5 kHz pinger system mounted on an inflatable catamaran that was pushed by an inflatable boat. A dense grid of seismic lines with a spacing of < 100 m was digitally acquired to obtain quasi-3D images of the sedimentary infill (Figs. 2, 3). Navigation was achieved with a conventional GPS system (+/- 5 m accuracy). Processing of the acquired data consisted of an automatic gain control (window length 100 ms), band pass filter (1800/2000–6000/6500 Hz), water bottom muting and, only for Grimselsee and Räterichsbodensee data, a constant-velocity migration (with $V_p = 1430$ m/s). The used zero times reference levels are 2300 m (Oberaarsee), 1910 m (Grimselsee) and 1767 m (Räterichsbodensee).

Sediment volume calculations. The difference between the lowermost reflection and the basin floor indicates the total sediment thickness that was interpolated for all three reservoirs (Fig. 4). In the glacial-proximal parts towards the eastern ends of Grimselsee and

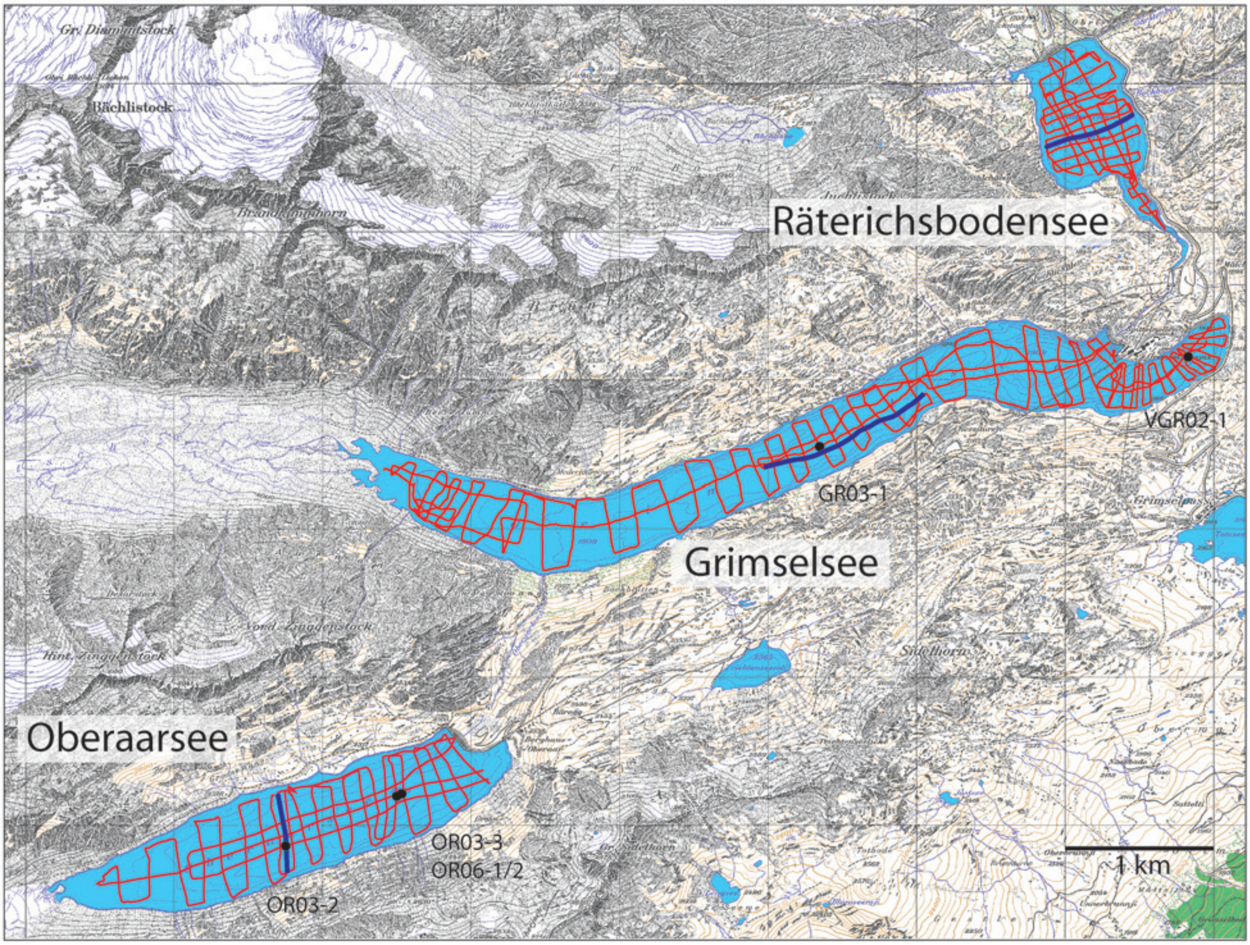

Fig. 2. Map of reservoirs. Red lines mark track lines from seismic surveys (for sediment volume calculations). Black dots indicate coring locations (with core numbers). Location of seismic lines in figure 3 are marked in blue bold lines.

Oberaarsee, the acoustic signal could not penetrate the basin floor sufficiently due to coarse sand or gravel lithologies. In these areas, sediment thickness was estimated based on a core taken in Grimselsee from the exposed basin floor in spring 2002 (Bühler, 2003), which helped to interpolate the delta area with the most proximal seismic sediment thicknesses. Sediment volumes could thus be estimated for the entire Grimselsee and, with a similar procedure, for Oberaarsee. In Räterichsbodensee, the former valley floor could be seismically detected only in a few areas. For this basin, however, a topographic map from immediately prior to dam construction was digitized and projected onto the seismic sections (Fig. 3C). Depths obtained through this procedure showed a good match to the areas where the former valley floor could be seismically recognized and, consequently, allowed basinwide calculation of sediment thickness. In addition, a second topographic map dating from the year 1974, when the reservoir was emptied for the first time, provided an additional chronostratigraphic seismic horizon to subdivide the sedimentary succession.

Sediment coring and analytical techniques. A series of sediment cores were collected from the ice (Figs. 2, 5). In Grimselsee, two ~1 m long vibracores were retrieved in 2002 at the locations of the former natural lakes. Cores from the main depocenter in Grimselsee and from Oberaarsee with a maximum core length of over 2 m were recovered using a percussion-piston corer in winter of 2003 and 2006. All cores were split, scanned petrophysically using a multisensor core logger (bulk density/porosity), photographed and described sedimentologically. Particle-size analysis of bulk sediment was performed on a Malvern Master Sizer 2000 laser diffraction instrument (range 0.02 μm to 2 mm).

Catchment erosion rates. For the calculation of the sediment yield and erosion rate for the 71 years after 1929, sediment volumes had to be corrected for porosity, which was determined to average 35 % by comparing the measured bulk densities to grain densities. Eroded rock volumes then were converted to particle mass with a bedrock density of 2.6 g/cm^3.

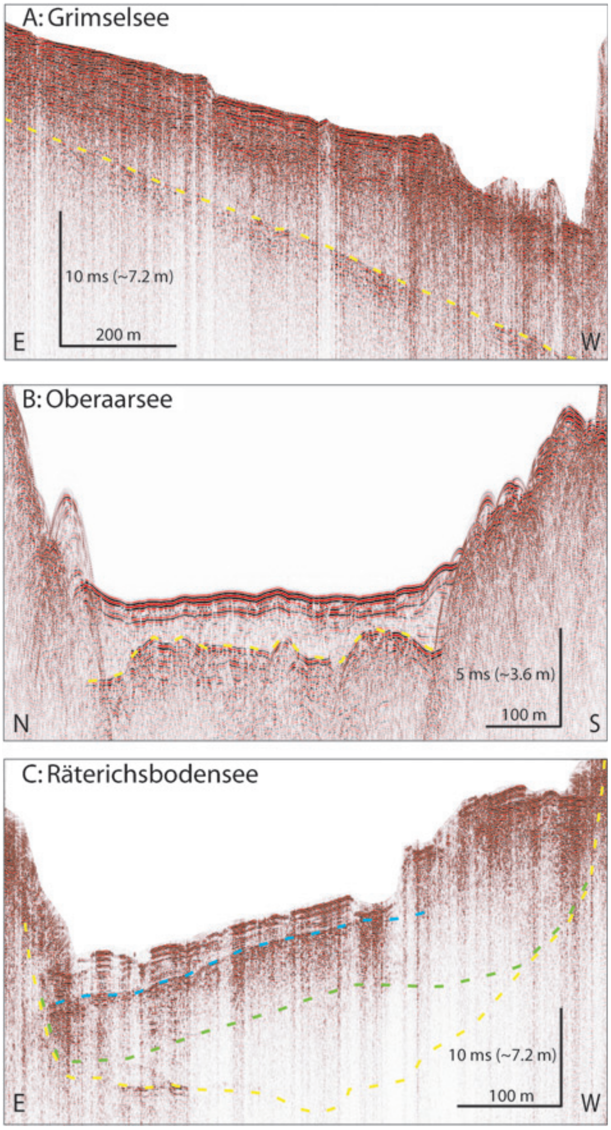

Fig. 3. A 3.5 kHz seismic sections of Grimselsee (A), Oberaarsee (B), and Räterichsbodensee (C). For line location see Figure 2. Yellow dashed line indicates former valley floor in all reservoirs. Green dashed line in C marks measured topography after full drainage in 1974. Blue dashed line in C marks an unconformity related to a flushing event in Grimselsee. Note the vertical exaggeration.

The annual amount of finest fraction, which escapes the reservoirs through suspended load, was quantified by daily sampling and using the discharge data (Finger et al., 2006) and was summed to get the full amount in eroded rock volume (Table 2).

Sediment and depositional processes in Grimselsee

Sediment distribution. The former valley floor is overlain by a thick sediment succession, that accumulates only in the basin and not on lateral slopes. A longitudinal section (Fig. 3A) shows a downvalley-thickening wedge of sediment with a maximum thickness of ~11 m directly in front of a 30 m-high basement ridge (Fig. 4A). A second depocenter with a maximum thickness of 6 m can be found in the deepest part in front of the northern dam (Fig. 4A). This pattern is caused by the slowing of proglacial turbidity currents as an effect of the first obstacle resulting from settling of the major part of the sediment input (Weirich, 1986; De Cesare et al., 2001; Bühler et al., 2005). A smaller portion of the sediment load passes through a former gorge to the deeper area, where in a similar fashion, the dam stops the turbidity currents and creates a second center of sediment accumulation. The eastern area, where two natural lakes were located, is covered by ~70 cm of proglacial sediment because this part lies ~50 m above the thalweg of the main valley and is bypassed by all coarse glacier-derived sediments. In addition, during low water levels in winter and spring, this part of the reservoir is separated from the main basin and becomes completely detached from any sediment input.

Lithology. Despite strong coring disturbance, an over 2 m long core from the deep central part of the Grimselsee (GR03–1) shows that sedimentation in this area is dominated by coarse sediment deposited by turbiditic flows (Bühler 2003; Lancini, 2004). A vibracore from the area of the natural Grimsel lakes (VGR02–1; Fig. 5 A,B) that is bypassed by the main turbidites shows the transition from gyttja sediments

Table 2. Sediment and erosion budgets of Grimsel area. Infilling times are calculated under the assumption of constant sedimentation rates.

	Sediment volumes (10^3 m^3)	Infilling times (yr)	Eroded bedrock-volumes (10^3 m^3)	Solid particle mass (kt)
Oberaarsee (49 yr)	934	2990	607	1579
Grimselsee (71 yr)	5300	1270	3445	8957
Räterichsbodensee (50 yr)	3584	350	2294	5965
All three lakes (71 yr)	9818		6346	16,501
retained in reservoirs per year (71 yr)	138		89	232
Annual suspension in Aare			15	39
Total annual input from catchment			104	271

of the former mountain lakes to grey-colored proglacial deposits in the reservoir after 1929. The succession consists of 71 varves with an average thickness of ~8 mm. The average mean grain size of these rather 'pelagic-type' sediments is 8.2 μm for the light-colored summer layers and 4.7 μm for the dark and fine winter layers (Lancini, 2004). The summer part of the varves comprise a series of stacked mm- to cm-scale graded layers. Such a complex varve formation was also documented in the nearby proglacial lake Steinsee (Blass et al., 2003). The thickness of the varves in Grimselsee (Fig. 6) can be correlated to strong rainfall events that exceed a certain threshold value (Lancini, 2004). Other than a color change related to an oxidation process of the top layers (red Fe-staining), no overall trend in varve thickness and other lithologic parameters (e.g. grain size) can be determined over the 71-year sediment record (Fig. 6). In particular, no significant change in the sedimentation pattern, varve thickness or grain size appears around the introduction of the pump storage activities in 1980.

Sediment budget. The total interpolated sediment volume of Grimselsee was calculated to be $5.3*10^6\,m^3$ (Table 2), yielding an average annual sedimentation volume of 74,650 m^3. If the infilling rate stays constant, the reservoir will be filled in 1270 years.

Sediment and depositional processes in Räterichsbodensee

Sediment distribution. The seismic stratigraphy of the Räterichsbodensee infill can be divided into three different sequences (Fig. 3C). The base of the top sequence can be traced seismically throughout the reservoir, whereas the bases of the lower two sequences are only partly imaged by seismic reflections and are also defined by projected paleomorphologic data (see Methods). The lowermost sequence overlies the former valley floor and is interpreted to have been deposited from 1950–1974 before the Räterichsbodensee was emptied for the first time. It has a partly erosive top with maximum erosion occurring approximately along the flow path of the former Aare. The overlying middle sequence is more or less equally thick. It is interpreted to correspond to the time between 1974 and 1990, after which a second complete drainage occurred. The topmost of the three sequences is seismically well-layered and contrasts to the transparent underlying sequences (Fig. 3C). The top of this sequence, the modern basin floor reflection, is marked by recent erosion processes, likely due to the total drainage of Grimselsee in 2001, which triggered intense water circulation in Räterichsbodensee.

The main sediment depocenter of Räterichsbodensee is located in the southern part of the reservoir (Fig. 4B). This sediment distribution is mainly controlled by the location of the inlet of the suspension-loaded Grimselsee waters into the narrow gorge at the southern shore. Due to the slowing of the current upon entering the larger basin, most of the sediment settles and forms an up to 28 m thick pile (Fig. 4B). This results in a surprisingly high maximum average sedimentation rate of over 50 cm/yr for the last 50 years since dam construction in 1950.

Sediment budget. Since 1950 a total sediment volume of $3.6*10^6\,m^3$ has been deposited in Räterichsbodensee, reflecting an average annual sedimentation volume of ~70,400 m^3 (Table 2). These numbers are comparable to those from the much larger Grimselsee. Assuming a constant sedimentation rate, the Räterichsbodensee will be infilled in ~350 years. Considering the small catchment and the lack of major tributaries, this high sediment budget is rather surprising and can only be explained by the occurrence of major drainages in Grimselsee causing widespread redistribution of sediment that was initially deposited in the upstream reservoir.

Sediment and depositional processes in Oberaarsee

Sediment distribution. Based on the seismic data, up to ~4.5 m of lacustrine sediment could be recognized in Oberaarsee (Figs. 3B, 4C). Maximum sediment thickness is reached in parts of the central basin that coincide with the channel of the former river and its tributary, while the adjacent steep slopes lack any detectable sediments. The main depocenter covers an area of ~400 by 400 m in the middle of the lake (Fig. 4C) located directly upstream of the now flooded Little Ice Age terminal moraine (~1890; Ammann 1976; Lancini 2004), and forms an obstacle that slows turbidity currents. A second depocenter, with a maximum sediment thickness of ~2.5 m, is located 500 m to the east of the main sediment sink (Fig. 4C) just downstream of the same moraine, where the remaining currents, after passing the moraine through the former river channel, can expand again in the basin and slow down. Furthermore, a small area with higher sedimentation rates is located in a basin in front of the dam at the Eastern end of the reservoir. All these depocenters confirm the concept of flood-induced turbiditic currents acting as main sediment distributors (Weirich, 1986; De Cesare et al., 2001). Such turbidity currents have also been observed by Bühler et al. (2005) using turbidity measurements in the outflow pipeline.

Lithology. The over 2 m long core OR03–2 from the center of the basin (Fig. 2) shows a clear change at a depth of 1.6 m from gravel-rich lithologies at the base

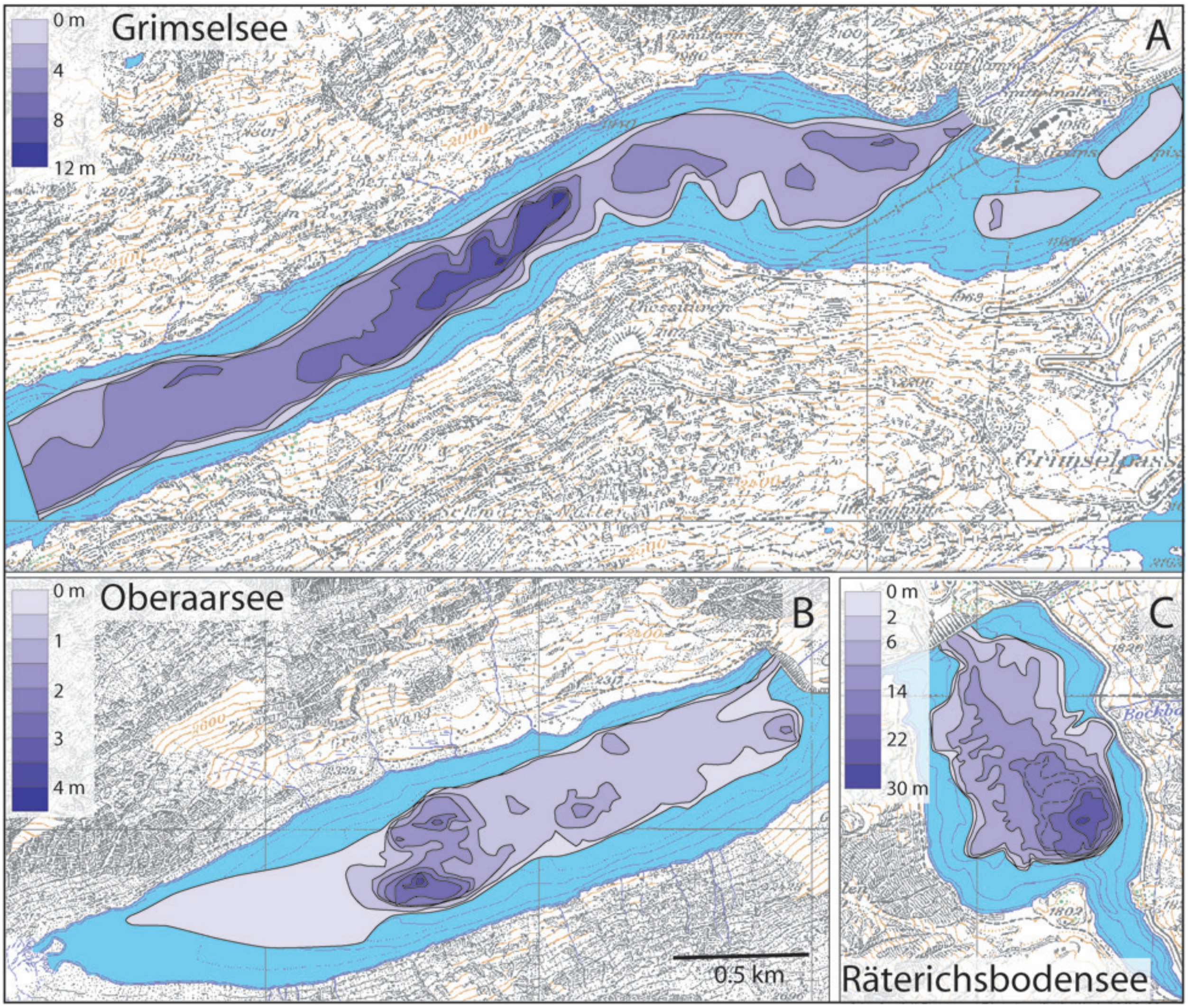

Fig. 4. Sediment isopach maps of Grimselsee (A), Oberaarsee (B) and Räterichsbodensee (C). Blue colors mark different thicknesses for each reservoir. Sediment thickness in delta proximal areas in Oberaarsee and Grimselsee were extrapolated due to limited seismic penetration depth (not shown for Grimselsee).

to relative homogenous muddy-sandy sediments at the top. This change correlates well with the total sediment thickness obtained from the seismic data and is interpreted as a transition from pre-dam fluvial sediments to lacustrine sediments. At a more distal site that is bypassed by the main turbidites, two cores (OR06–1 and -2) taken in March 2006 revealed a varved sedimentary section (Fig. 5C) that covers the entire period from 1953 to 2005 with 53 proglacial varves, similar to those from Grimselsee (e.g. dark winter layer, light-colored multi-graded summer layers that reflect strong precipitation events). Because the recovered varves show coring disturbance (Fig. 5C), an image analysis procedure was applied over 4 cm of core width to estimate varve thickness (Fig. 6A). No overall trend can be detected over the last 30 years. Around 1980 and in the mid 1990 s, varve thickness is minimal. The two highest values are caused by exceptionally-thick graded event layers.

Sediment budget. Since 1953, when the dam was built, a total sediment volume of ~934,000 m^3 has been deposited, resulting in a sedimentation rate of ~22,200 m^3/yr (Table 2). If the sedimentation rate remains stable, it will take ~3,000 years to infill this reservoir.

Total sediment budgets and implications for erosion rates

Because Oberaarsee drains into the Grimselsee, and because Räterichsbodensee only has a negligable catchment with no glacial runoff (Fig. 2), the sum of all three reservoirs represent the sediment budget of the combined catchment for the 71 year period (even

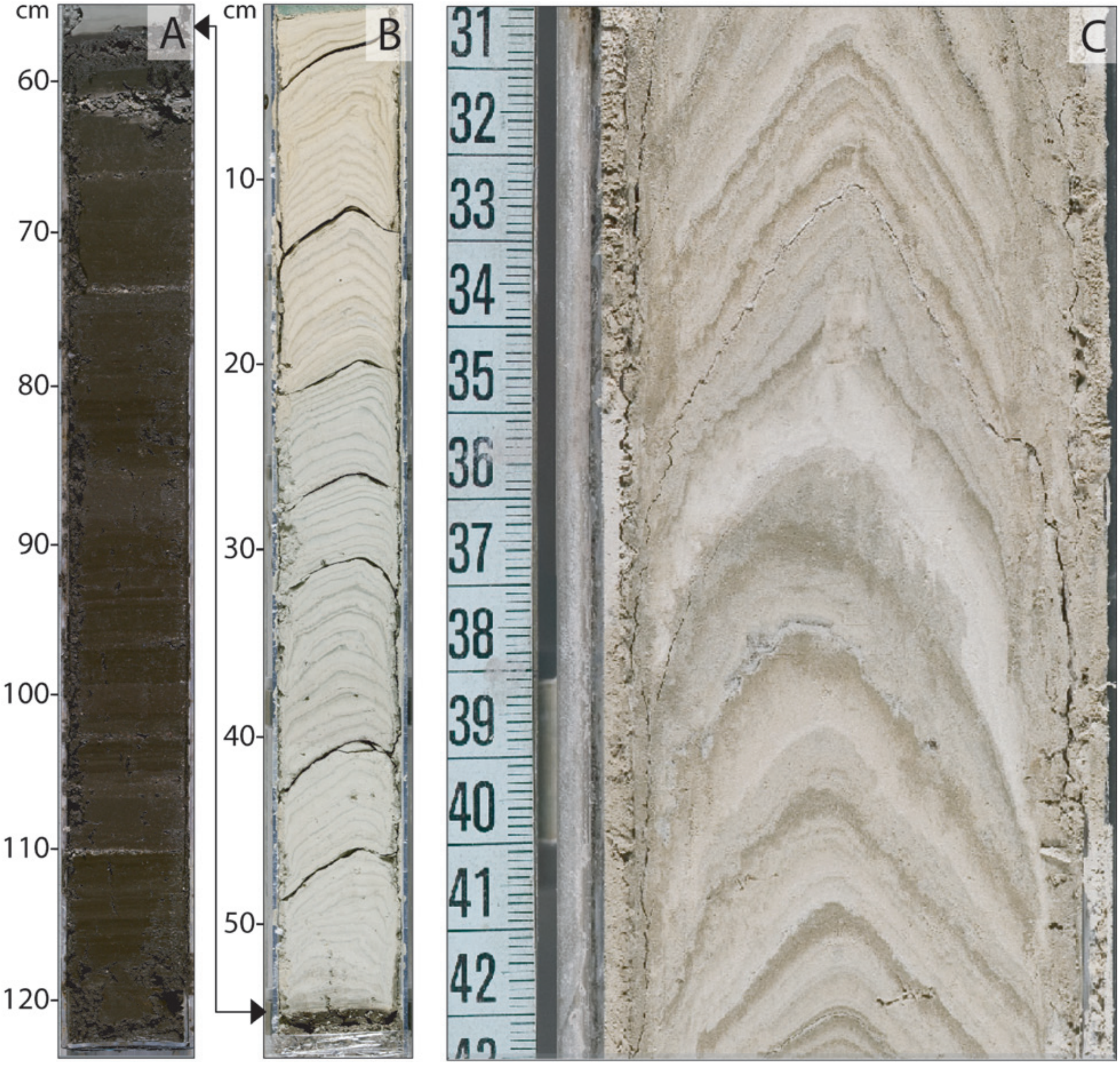

Fig. 5. Photographs of sediment cores from reservoirs: A, B: Core from Grimselsee: Sediment from former natural lakes location showing diatom-rich gyttja (dark brown, A) overlain by 71 proglacial varves (B) that were deposited after the first inundation of the Grimselsee in 1929. C: Core from Oberaarsee showing details of proglacial varves. The darker layers represent fine-grained sediments that are deposited during winter in the frozen lake.

though the Oberaarsee and Räterichsbodensee were built ~20 years after the Grimselsee). The entire sediment volume thus is considered to be the product of 71 years of erosion in the combined total catchment area, resulting in an average volume of 138,300 m^3/yr that is equivalent of a retention of 232 kt/yr of sediment (Table 2). In order to calculate catchment erosion rates, the suspended particles leaving the reservoir system must be taken into account. Measurements in the Aare in Innertkirchen indicate an annual transport of suspended particles of 39 kt (Finger et al., 2006) that must be added to the sediment mass in order to estimate the amount of eroded rock material.

The erosion rate can be calculated for two different scenarios, depending on postulated erosional processes: In a first scenario, bedrock erosion is equally distributed over the entire catchment resulting in an average erosion rate of 0.94 mm/yr. For a second scenario, erosion is only considered for the glaciated areas (40 % of catchment) through pure subglacial processes, resulting in an erosion rate of 2.33 mm/yr. Both denudation values are much higher than those usually assumed for central alpine areas (0.1 to 0.65 mm/yr; Hinderer, 2001). The 0.94 mm/year valid for the entire catchment coincides, however, with recent uplift rates for the Bernese Central Alps, that

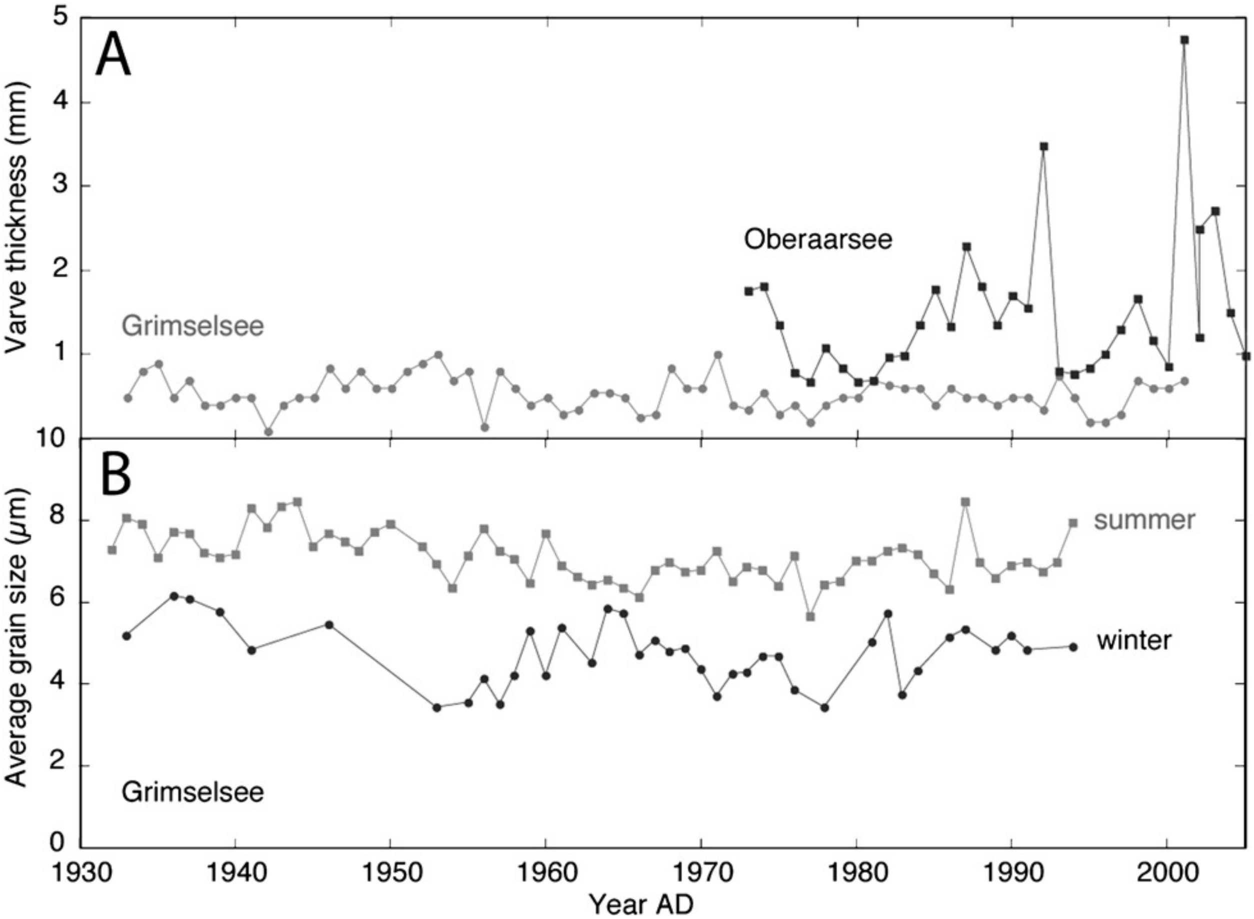

Fig. 6. A: Annual varve thickness of Oberaarsee sediment (core ORA06–1 providing record of 1973–2005) and Grimselsee sediment (at site of natural lakes, core VGR02–1, 1932–1999). Both coring locations only record the fine fraction and are by-passed by the major glacial-derived turbidites. The two thickest layers in Oberaarsee are produced by single turbidite events. B: A 71-year time series of grain size of Grimselsee sediment (grey: summer; black: winter).

have been determined as slightly below 1 mm/yr (Schlatter and Marti, 2002). The numbers can be converted to a total annual sediment yield per km^2, amounting to 2430 and 6050 t/(km^{2}yr), for erosion in the total or only glaciated areas, respectively. These values roughly coincide with values obtained in a similar study for Würmian glacial erosion in the Jura mountains (4400 ± 1700 t/(km^{2}yr); Buoncristini and Campy, 2001) but are larger than those given for general alpine and perialpine catchments (~100 to 2500 t/(km^{2}yr); Einsele and Hinderer, 1997, 1998; Hinderer, 2001, and references therein) reflecting the high degree of glaciation. As a comparison, the total sediment yield for Lake Brienz equals 324 t/(km^{2}yr) excluding sediments retained in the reservoirs (Finger et al., 2006), or to 572 t/(km^{2}yr) if they are included. The 2430 t/(km^{2}yr) for the entire Grimsel area alone clearly documents the high efficiency of subglacial erosion and mobilization.

3. Runoff and particle transport in tributaries of Lake Brienz

In order to assess the effects of hydropower operations in the headwaters of the Aare on particle dynamics in Lake Brienz, the particle yield of the major tributary must be compared to the situation before construction of the dams. The hydrologic regime of the Aare is the crucial link in determining the amount and timing of particle transport from the reservoirs to Lake Brienz. This chapter summarizes how the annual pattern in the hydrologic regime of the Aare changed as a result of dam construction and how this is affecting the particle budget of Lake Brienz.

Methods

Discharge and particle loads. Present particle loads were estimated for the years 1997 to 2004 (Finger et al., 2006), whereas particle load for a situation without any hydropower dams was reconstructed with numerical simulations. The Swiss Federal Office for the

Environment has monitored discharge Q (in 10 min intervals) and instant suspended particle concentrations C (twice a week) in the rivers Aare and Lütschine since 1964 (BWG/LHG). Based on this data, Finger et al. (2006) developed the adaptive rating curve (ARC) to estimate suspended particles loads in each river, consisting of an empirical relation between Q and C (Cohn et al., 1989; Crawford, 1991). In order to minimize the inaccuracy of this empirical relation, the ARC continuously corrects the relation to the bi-weekly measured particle concentrations. This increases the accuracy of particle load estimates, which are partially influenced by hydropower activities. As test runs indicate, the ARC reproduces annual suspended particle loads with an accuracy better than 20 % in the Lütschine and 30 % in the Aare. Nevertheless, long-term averages have uncertainties of < 3 % (Finger et al., 2006).

The loads for a hypothetical situation without hydropower dams were reconstructed with numerical simulations for the years 1997 to 2004: Sägesser and Weingartner (2006) simulated the discharge of a natural flow regime and Finger et al. (2006) reconstructed the particle dynamics in the Aare without particle retention in the dams.

Grain size. To simulate residence times of suspended particles in Lake Brienz, particles in the Aare and Lütschine, in the reservoir outlets, and in the sediments of the reservoirs were divided into coarse particles (> 4 µm) and fine matter (< 4 µm; Finger et al., 2006). While particle distribution in the inflows describes present particle input, sediment of the reservoirs represents distributions during pre-dam conditions. Sediment samples from the reservoirs were collected with a grab sampler across the Grimselsee, water samples were collected daily at the reservoir outlets and random samples were collected in the two rivers. In all samples, the particle size distribution was determined using static light scattering measured with a Beckman Coulter LS 230 instrument (range 0.04 µm to 2 mm; Zimmermann, 1996).

Runoff

The Aare watershed is about 1.5 times larger (554 km^2) than the Lütschine (379 km^2). Accordingly, the average discharge of the Aare (34.9 m^3/s) is about 1.88 times that of the Lütschine (18.6 m^3/s). The effects of the hydropower operations on the flow regime of the Aare can be evaluated by scaling the Lütschine runoff to that of the Aare and by comparing the annual patterns throughout the last century, distinguishing four epochs with increasing hydropower activity (Fig. 7): 1) Before 1932, without any dams, both rivers Aare and Lütschine revealed a typical peri-alpine regime with high discharge in summer (due to precipitation and snow/glacier melting) and low discharge during winter (due to temperatures below freezing); 2) Between 1933 and 1955, the construction of hydropower dams in the headwaters of the Aare provoked a temporal shift of discharge from summer to winter; 3) After construction of the Oberaarsee dam in 1953, the increased storage volume led to continuously increasing winter discharge rates; 4) In 1980, the pump storage operation was introduced, which did not result in a further increase in winter discharge, as water is transported back and forth between Grimselsee and Oberaarsee (Fig. 8).

Besides the evident effects on discharge patterns, the new hydrologic regime also affected the particle transport in the Aare and subsequently in Lake Brienz. Before construction of the dams, about 10 % of the Aare discharge occurred during winter (November to March), whereas today this discharge has doubled to 21 %. The subsequent effects on particle loads are discussed in the following section.

Particle loads

Based on the ARC method, the mean annual particle load between 1997 and 2004 in the Aare and Lütschine was estimated at 128 kt/yr and 174 kt/yr, respectively (Figure 8; Finger et al., 2006). The Lütschine transports 36 % more material, although its discharge is only ~53 % of the Aare. This is a direct consequence of the particle retention in the reservoirs as documented by the load coming from the reservoir outlets (39 kt/yr), representing only 15 % of the total sediment load in the headwater above the reservoirs (272 kt/yr). The hypothetical particle load for a situation without reservoirs results from the actual particle loads in the Aare (128 kt/yr) and particle retention in the reservoirs (232 kt/yr), as shown in Section 2, amounting to 360 kt/yr. The simulations of the hypothetical situation without reservoirs for the years 1997 to 2004 reveal that the water storage in the reservoir leads to a temporal shift of particle loads from summer (April – October) to winter (November – March; Table 3). Today, particles transported in winter are 14 kt, of which at least 7 kt can be directly attributed to the reservoir outlets. About 4 kt are probably resuspended material due to intense hydroelectric production, so that only ~3 kt would be transported under natural conditions (Table 3).

Based on the sporadic measurements of particle size distributions in the Aare and Lütschine, about 27 mass-% of the suspended load entering Lake Brienz is composed of particles < 4 µm in diameter (fine fraction; Finger et al., 2006). For the particle distribution in the lake, particle size is of major importance, as only colloids (< 1 µm) and small particles remain

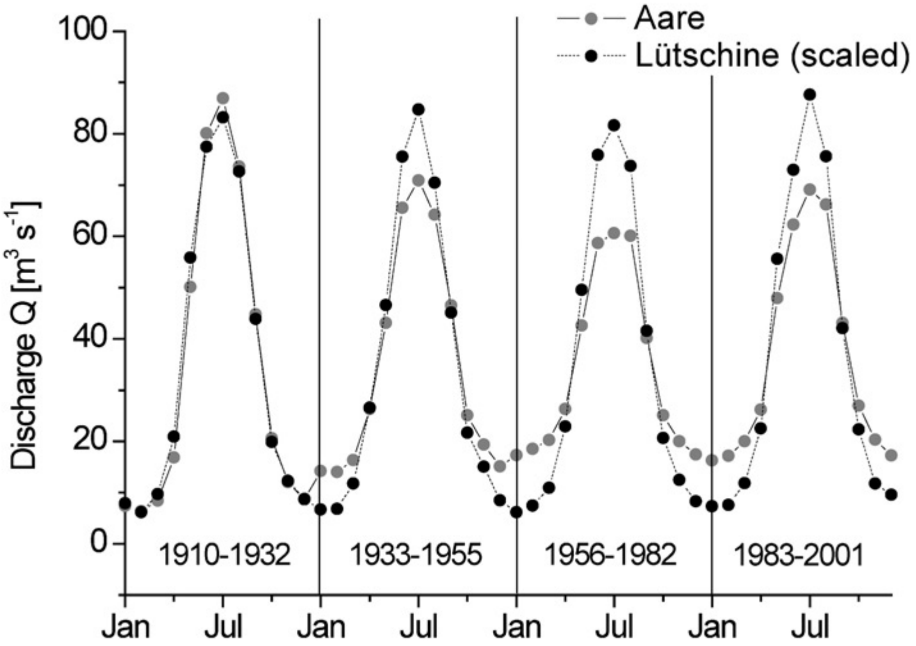

Fig. 7. Average monthly runoff rates of the Aare and scaled runoff rates of the Lütschine. Data recorded by LHG/BWG (http://www.hydrodaten.admin.ch/d/)

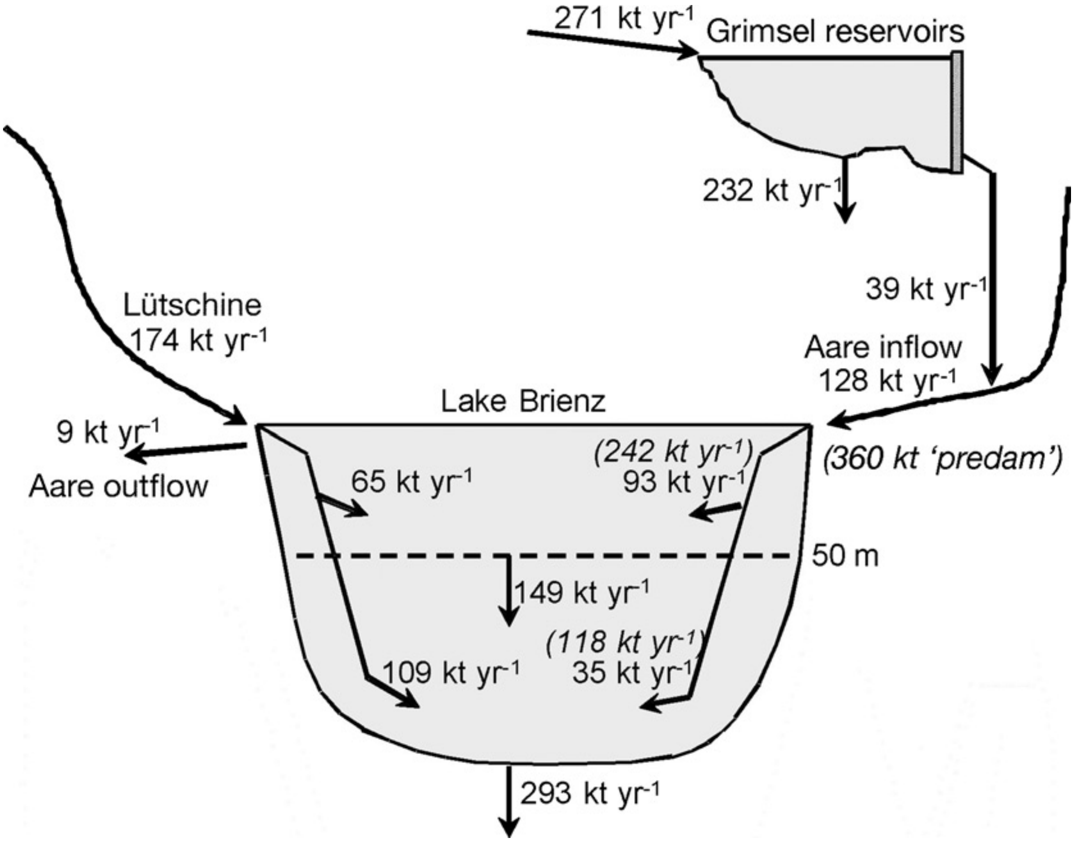

Fig. 8. Schematic plot of annual sediment fluxes in Lake Brienz and its catchments. Fluxes in parentheses and cursive are estimates for a hypothetical situation without dams (prior to 1928).

Table 3. Suspended particle loads in the Aare (with and without dam), Lütschine, and in the reservoir outlets during summer and winter. Modified from Finger et al. (2006).

	Reservoir outlets (kt)	Aare (with dam) (kt)	Lütschine (kt)	Aare prior 1928 (without dams) (kt)
Winter (November – March)	6	14	3	3
Summer (April – October)	33	115	171	357

suspended long enough to spread across the lake. At the reservoir outlets, significantly higher fractions of fine particles were measured (Finger et al., 2006): ~56 % of the load in summer and up to 82 % in winter are composed of particles < 4 µm. These numbers coincide with the size distribution of the sediment in the reservoirs: only ~3 % of the retained sediment is composed of particles < 4 µm. Large particles, which settle out fast, are retained in the reservoirs, while the small particles remain suspended and are discharged into the Aare. Fine particle load was estimated to be ~43 kt/yr and ~47 kt/yr for the Aare and Lütschine, respectively. For a hypothetical situation without reservoirs, the fine fraction load in the Aare would be only slightly higher (~50 kt/yr).

4. Recent sedimentation in Lake Brienz

Sedimentation in Lake Brienz (Fig. 9A; Table 1) is mainly controlled by the inflowing particles from the Aare and Lütschine, which build two large deltas at both ends of the lake (Sturm, 1976; Adams et al., 2001). Between 1866 and 1875, the Aare was channelized in the upstream alluvial plain and routed from its natural mouth to the south, where it presently inflows (Fig. 9A). From the time it was rerouted, the Aare built a new delta with channels that have cut into parts of the former delta structure. A surficial sediment study showed that the sediment load of lateral torrents have, compared to the two large deltas, very little influence on total lake sedimentation (Sturm, 1976).

Lake Brienz is a holomictic and oligotrophic lake (Nydegger, 1967) with almost exclusively allochthonous clastic input. Its sediment distribution is mainly controlled by the varying stratification of river inflows (over-, inter- and underflows; Sturm, 1976). Lake Brienz is subdivided into different sedimentation sectors: the proximal delta areas where mainly gravel and coarse sand deposit, the slopes where finely-laminated sediment forms clastic varves, and the deep basin where fine sediment (hemi-pelagic deposit) intercalates with small and large turbidites (non-graded and normally graded sand layers; Sturm and Matter, 1978). Small turbidites (1 mm to 10 cm thick) enter as underflows from the two large river deltas that both have distinct mineralogical signatures and colors due to their geologically contrasting catchments (Sturm and Matter, 1978). Particle residence times in Lake Brienz are < 20 and < 4.5 days for fine (< 4 µm) and coarse (> 4 µm) particles, respectively (Finger et al., 2006).

Large turbidites (0.2 to 1.3 m-thick 'megaturbidites') are rare sedimentological events. They originate from the Aare delta area and remobilize large amounts of sediment. As these sediment flows travel down to the deep basin, they even erode parts of the underlying hemi-pelagic deposits and incorporate them in their moving mass (Girardclos et al., in press). The last megaturbidite occurred in April 1996, redeposited a total volume of $2.7 * 10^6$ m^3 equivalent to a dry mass of $2.6 * 10^6$ t (~9-times the lake's annual input) and covered the entire flat lake bottom (Girardclos et al., in press). It was caused by a non-catastrophic event most likely due to overloading from normal sediment accumulation. The clay-sized sediment mobilized during this event took 6 months to completely settle (Zeh, 1997) and forms a distinct white layer, which can be followed throughout the entire deep lake basin (Fig. 9B).

Methods

Sediment coring and analytical techniques. Sediment samples were collected with a gravity corer (1–2 m length) and with a modified Kullenberg coring system (5–10 m length) from 1998–2005. After opening, sediment cores were photographed, described macroscopically and sampled. Particle-size analysis of bulk sediment was performed on a Malvern Master Sizer 2000 laser diffraction instrument (range 0.02 µm to 2 mm). Core-to-core correlation was achieved by comparing both visual characteristics and lithological properties.

Sedimentation rate and radioisotope dating. In the deep basin the recent mean sedimentation rates for 1996–2005 (black dots; Fig. 9A) were estimated with the white clay top layer of the 1996 megaturbidite used as a lower reference horizon and the top of the core (sampling year) as an upper reference (Fig. 9B). For sedimentation rates of core sections situated between

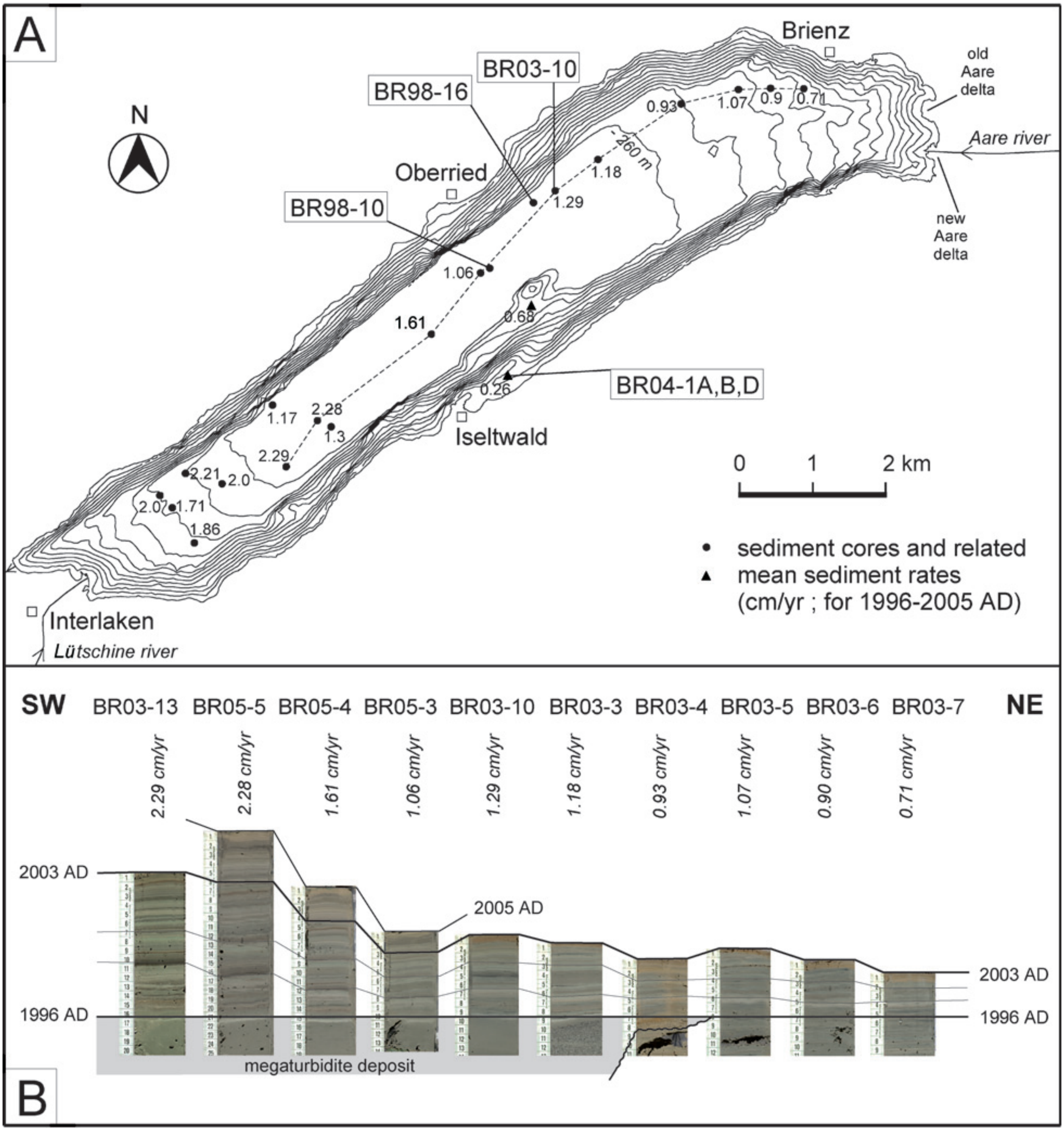

Fig. 9. (A) Bathymetric map of Lake Brienz (isolines 20 m) with core locations (black dots and triangles). Values indicate the mean sedimentation rate (cm/yr) based on lithological correlation (for 1996–2005, black dots) and varve counts (for 1996–2003, black triangles). Dashed line indicates longitudinal core-to-core profile. **(B)** Longitudinal core-to-core correlation of sediment units deposited after the 1996 megaturbidite (top of megaturbidite is shaded in grey) with calculated sedimentation rates post-1996.

the 1996 and the next older megaturbidite deposits, two Lake Brienz sediment cores retrieved in 1998 (Schmidt, 1998) from the deep lake basin were sampled every cm and ^{137}Cs activity was measured (Fig. 10, location Fig. 9A). Ages are calculated with linear interpolation and extrapolation using the two reference ^{137}Cs peaks (Fig. 10; 1963 for atmospheric nuclear tests and 1986 for Tchernobyl accident) resulting in a 1942 age for the lower megaturbidite. These interpolated and extrapolated ages are indicated by asterisks (Figs. 11 and 12). Precise lithologic core-to-core correlation allows the estimation of an error for the interpolated and extrapolated ages. To validate the annual character of laminaes in slope sediments, ^{137}Cs activity was measured on a core retrieved in 2004 near Iseltwald (Fig. 10, location Fig. 9A).

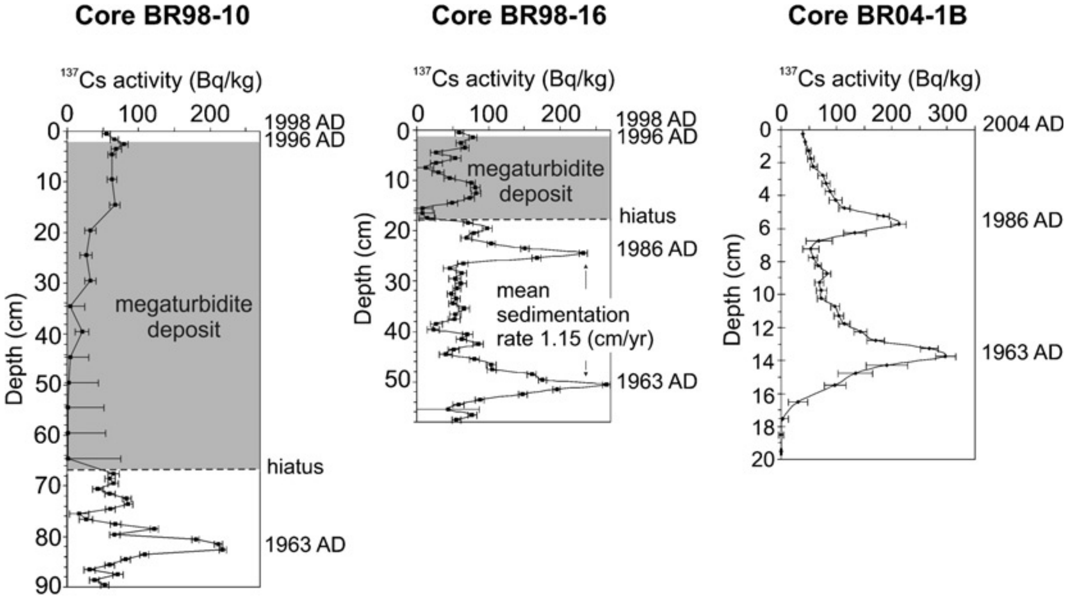

Fig. 10. ^{137}Cs activity (with errors bars) measured with depth on BR98–10, BR98–16 (from Schmidt, 1998) and BR04–1B sediment cores. The peaks from the nuclear bomb fallouts (1963) and the Tchernobyl nuclear accident (1986) are indicated. For core locations, refer to Figure 9A.

The recent mean sedimentation rates on the lake slope for 1996–2003 (black triangles; Fig. 9A) and for 1946–2004 (Fig. 13) were calculated from varve counting and varve thickness measurements averaged from two core datasets (BR04–1A and 1D). The inferred varve age model, originally established for the historical quantification of the *Daphnia* population by counting diapausing eggs at different depths of the sediment (Rellstab et al., 2007; core name synonyms: 'BR04–1A' = 'BRZ1' and 'BR04–1D' = 'BRZ2') was validated by ^{137}Cs activity peaks (1963 and 1986, Fig. 10) measured on a third core (BR04–1B) and correlated with lithology. The three cores used for these analyses come from the same location and show only small varve-depth variations.

Distribution of sedimentation rates

A longitudinal sediment profile, with core-to-core lithologic correlation, shows how sedimentation rate varies throughout the lake basin (Fig. 9B). For the 1996–2005 period, the deep central basin sedimentation rate ranges from 1.2 to 2.3 cm/yr with an increasing gradient toward the SW (Fig. 9A). In the SW part of the lake basin, i.e. near the Lütschine delta, the mean sedimentation rate varies from 1.7 to 2.2 cm/yr, and in the NE (near the Aare delta), it decreases to 1.1 to 0.7 cm/yr (Fig. 10A). Near Iseltwald, on the lake slope, sedimentation rates are much lower (0.26 to 0.68 cm/yr; Fig. 9A).

These sedimentation rates confirm those of the Aare and Lütschine particle load estimations (Section 3), as the total sediment flux from Lütschine (174 kt/yr) is 1.36 times larger than the one from the Aare (128 kt/yr, Fig. 8). Moreover, sedimentation rates from opposite lake ends but at a similar lake depth (Fig. 9A) point to an even higher Lütschine sediment input, reaching 1.9–2.4 times the input of the Aare. This pattern can be explained by the contrasted intrusion depth from both rivers. The Lütschine, intruding often as an underflow, brings on a regular basis coarse sediment to a distal position (i.e. below 200 m depth) and thus increases its sediment input to the deep lake basin. The Aare, in contrast, flowing less frequently as underflow, leaves coarse particles closer to its delta area, which proportionally lowers its sediment input to the deep basin. Such a physical and sedimentological behavior is confirmed by the rivers intrusion depth, both observed in-situ and simulated over a period of 8 years (1997–2004). Finger et al. (2006) showed that high discharge events that plunge to depths below 50 m occur 2.3 times more frequently in the non-dammed Lütschine than in the present Aare. On the lake slopes, only fine particles traveling as inter- or overflow are deposited. This explains the low sedimentation rates in comparison with those of the deep basin.

Distal Aare delta sediment record (1942–2003)

In order to observe the possible influence of the reservoirs on Lake Brienz sediments and to avoid the main pathway of megaturbidites (core BR03–10, Fig. 9A), we chose a core location situated in the distal Aare delta and close to the lake slope. In core BR98–16, the ^{137}Cs activity peaks from 1963 and from

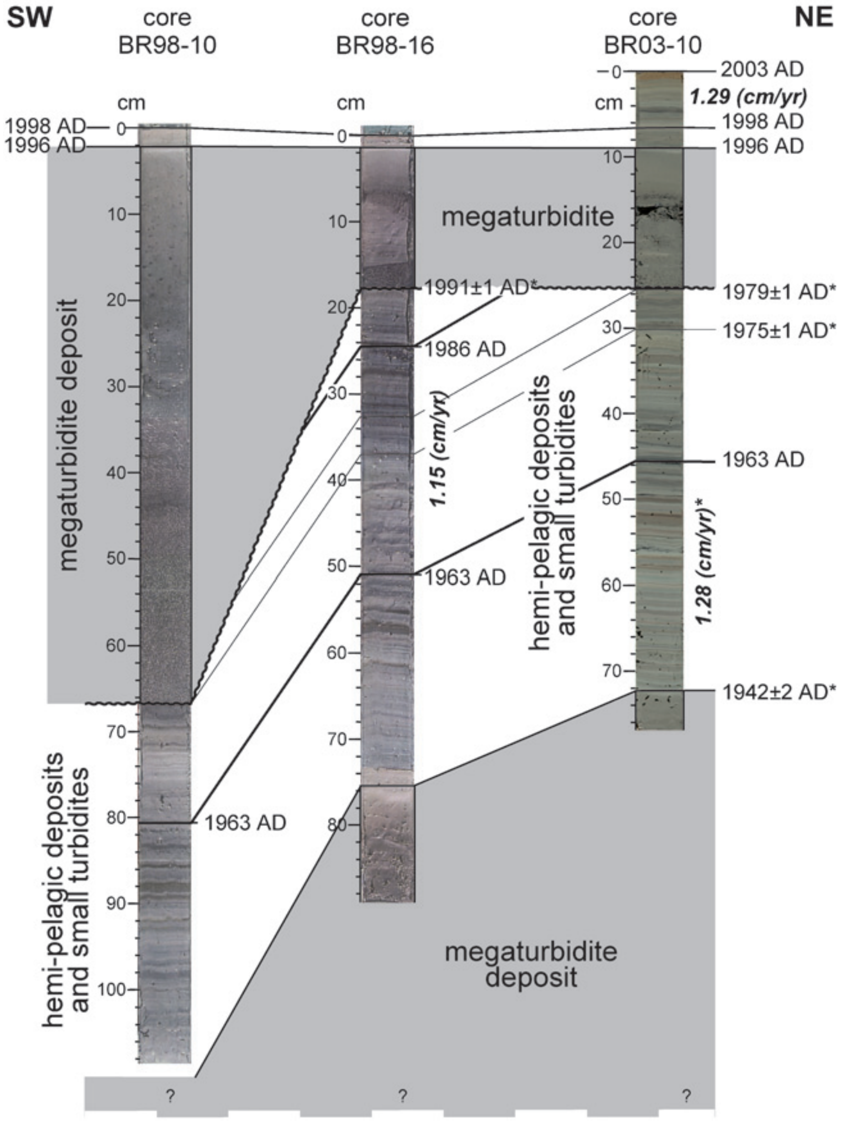

Fig. 11. Core-to-core lithology correlation from distal Aare delta sediment with ^{137}Cs dates. Extrapolated and interpolated ages from known ^{137}Cs activity peaks (Fig. 10) are indicated by an asterisk. For core locations, refer to figure 9A.

1986 are recorded at 50.5 and 24.5 cm, respectively, giving a mean sedimentation rate of 1.2 cm/yr for this time range. In core BR98–10, due to sediment erosion by the overlying megaturbidite deposit (Girardclos et al., in press), only the 1963 ^{137}Cs activity peak remains (Fig. 10).

Precise lithologic core-to-core comparison, age markers from ^{137}Cs activity, as well as interpolation and extrapolation from the calculated mean sedimentation rate (Fig. 10), allow an estimation of sediment hiatuses and the reconstruction of an age model for the three sediment cores (Fig. 11). Linearly extrapolated ages, which assume constant sedimentation rates before 1963 and after 1986, indicate that the lowest megaturbidite was deposited in 1942±2 and that core BR98–16 has a sediment hiatus of 4–6 years below the 1996 megaturbidite. This age model implies that 10–12 years (in core BR98–10) and 16–18 years (in core BR03–10) of sediment layers were eroded by the 1996 megaturbidite. In core BR03–10, the sediment interval situated above the 1996 megaturbidite, as well as the sediment intercalated between the two megaturbidite events, have the same sedimentation rate of 1.3 cm/yr, indicating a constant mean sedimentation rate for hemi-pelagic deposits during this period.

The distal Aare delta sediment record indicates that 0.2–2 cm-thick sand layers (turbidites) occurred in three phases since the 1942±2 megaturbidite: shortly after the 1942±2 megaturbidite, before 1963, and before 1975±1 (Fig. 12). The granulometric data shows that the megaturbidite deposits have a very high sand content (maximum 74 %) compared with 0.5 to

9.7 % in the remainder of the core. The sand content displays a constant general trend along the core depth and, as expected, the peaks in sand content correlate with periods of small turbidite occurrence.

The occurrence of small turbidites in the distal Aare delta can be interpreted in different ways: (1) sudden increase in sand supply from the Aare catchment (increased erosion, leached subaerial mass-movement, etc.), (2) higher frequency of deep Aare intrusions leading to enhanced sediment transport to the deep basin, or (3) sand remobilization due to internal lacustrine mass movement (slide, slump, etc.). Currently, we cannot decipher the exact cause of the small turbidites, but for the pre-1963 turbidite period (depth 46–58 cm, Fig. 12), the reddish sediment color, which accompanies the increase in sand, points to a contemporary increase in terrestrial matter (i.e. soil remains) in the sediment and, therefore, to a likely increase of erosion in the catchment. This lithology could potentially be linked to the KWO constructions in the Gadmertal, which occurred between 1958 and 1967.

Varved lateral slope sediment record (1946–2003)

Lateral slope sediments result from fine-grained sediment input deposited as clastic varves (Sturm and Matter, 1978). The mean sedimentation rate for 1946–2004, averaged from two age-depth profiles (Fig. 13A), shows that lake slope sedimentation varied from 0.13 to 0.4 cm/yr with an exceptional peak in 1995 (0.72 cm/yr; Fig. 13B). The sedimentation rate trend is subdivided into three phases: (A) a decreasing trend from 1946–1955, (B) an increasing trend from 1955–1963/64, and (C) a plateau from 1963/64–2003.

The sedimentation rates inferred from varves reflect changes in the lacustrine deposition of fine-grained sediment, and thus variations in the total fine sediment input from the Aare and Lütschine through time. As presented in Sections 2 and 3, the Grimsel dams had a relatively small influence on the retention of fine-particles, as the fine (< 4 μm in diameter) sediment fraction load in the Aare was only slightly reduced (Section 3). The 59-year time series of the fine sediment from Lake Brienz (Fig. 13A and B), which represents only a 'post-dam' sequence, doesn't allow us to validate the results of Section 3. Similarly to the reservoir record, the Lake Brienz varve record shows that the onset of the pump-storage activities around 1980 did not change significantly the fine-grained sediment input to Lake Brienz, as the average sedimentation rate variations from 1946 to 1963/64 are much higher than those after 1980. Comparison of varve- and climate-derived sedimentation rates with annual mean temperatures (Begert et al., 2005), as well as with annual precipitation (Meteo Swiss data for Interlaken and Meiringen) showed no correlation. Furthermore, none of the known reservoir maintenance events (Section 2) seem to have influenced the varve record (no sedimentation peaks). However, the increase in varve thickness from 1955 to 1963/64 might be related to the increase of fine turbidites in the distal Aare delta before 1963. The punctual high sedimentation rate (0.72 cm/yr) in 1995, being a unique high value, probably reveals a local sedimentological event.

The difficulty in interpreting the varve sedimentation rate is possibly due to the superposition of different sedimentological 'signals'. The main sources (Lütschine and Aare) for fine-grained sediment have contrasting hydrologic regimes and intrusion behaviors, and react independently. Variations in lake currents occur and, as shown in Lake Geneva (Girardclos et al., 2003; Ulmann et al., 2003), they might also induce shifts in the distribution pattern of fine sediment particles and hence cause varying sediment budgets in different lake areas over time. Also, the correlation with precipitation data from high-altitude stations might be more relevant than with those from Interlaken and Meiringen. Moreover, a time offset between climate data and sedimentation rates might exist and be hidden by the annual averaging. A longer time series, reflecting the pre-dam situation, and more detailed varve analysis (color, etc.) might contribute new insights into control on varve thickness.

5. Summary and conclusions

Implications for retention of erosional particles in the reservoirs

The investigation of the sediment fill of the reservoirs indicates that for the last 71 years, ~232 kt/yr of sediment were retained on average in the reservoirs and, as a consequence, not fed into the Aare. This sediment is mostly brought into the reservoirs by turbiditic flows related to increased runoff events from the glacier, e.g. during strong rainfalls in summer. Sediment distribution in the reservoirs is controlled by morphobathymetric features (Fig. 4) that determine flow tracks and velocity and thus the local sediment settling rate. In addition, flushing activities can cause large quantities of sediment to be remobilized and redeposited. The quantified annual sediment load averaged from 1930 to 2001 results in a denudation rate and sediment yield of 0.94 mm/yr and 2430 t/(km^2yr) or 2.33 mm/yr and 6050 t/(km^2yr) assuming erosion in the entire catchment of the reservoirs or only in the glaciated area, respectively.

The bulk of the retained sediment consists mostly of silt and sand-size particles. The average grain size of the thinner hemipelagic-type sediment, as cored in the

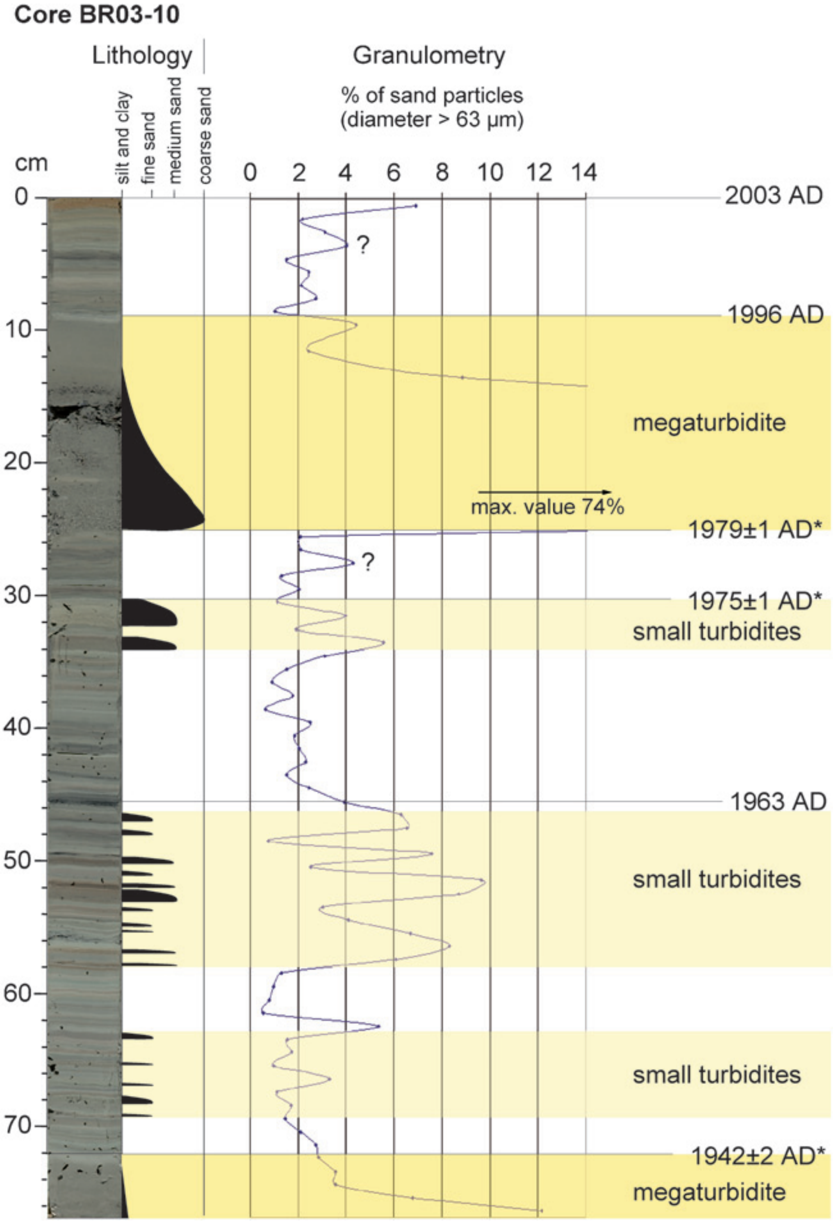

Fig. 12. Distal Aare delta sediment record (core BR03–10) from 1942–2003, with lithology and sand content (%). Three phases of small turbidites occur between 1942 and 1975.

bathymetrically elevated natural Grimsel lakes area, amounts to 4.7 and 8.2 µm, for summer and winter, respectively. A total of 39 kt/yr of fine sediment particles (mostly < 4 µm) leave the reservoirs with the outflowing Aare. Damming is thus mostly efficient in retaining the coarse fraction of the sediment. The 71-year annual time series of the fine fraction from Grimselsee, as well as the 32-year record from the Oberaarsee (Fig. 6), indicate that the onset of the pump-storage activity around 1980 neither significantly changed the sedimentation rate, nor the grain size distribution of the retained sediment. There are periods of higher and lower sedimentation rates in both reservoirs, which are, however, controlled by climatic boundary conditions such as the numbers of strong summer rainfall pulses (Bühler, 2003; Lancini, 2004).

Implications for sedimentation in Lake Brienz

Whereas damming barely altered the fine (< 4 µm) sediment fraction in the Aare (50 to 43 kt/yr; Section 3), it significantly changed the coarse sediment input. For the period 1996–2003, the distribution of sedimentation rates throughout the lake basin correlates well with independent calculations and simulations of the river intrusion depths and sediment fluxes, and

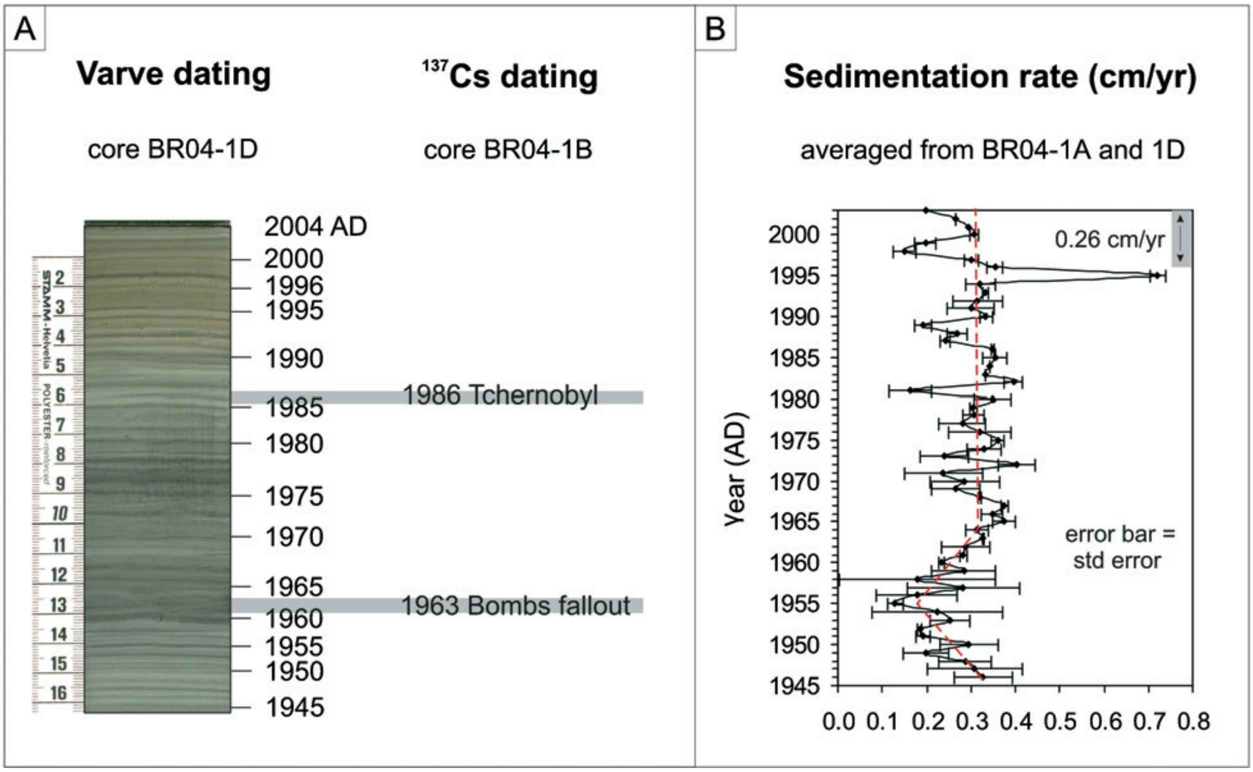

Fig. 13. **(A)** Lake slope sediment record with clastic annual varves from 1946–2004 AD (core BR04–1D). Varve dating was validated by ^{137}Cs activity peaks. **(B)** Averaged sedimentation rate (cm/yr) of two cores (BR04–1A and BR04–1D) shows three trend phases (red dashed line; see text). The high sedimentation rate (0.72 cm/yr) in 1995 reveals a local sedimentological event. For core locations, refer to Figure 9A.

confirms the dominance of the present Lütschine input over the Aare input to the deep lake basin, as well as the intrusion depth regimes of those rivers. The high sedimentation rate of Lake Brienz and the thick megaturbidite deposits prevented the coring of distal Aare delta sediments older than 1929 (i.e. before the reservoirs were built). As a consequence, the expected strong changes in Aare sediment particle-size and quantity could not be analyzed. But the 1942–2003 sediment record of the distal Aare delta shows a general constant trend in sedimentation rate and in sand content variation, and the occurrence of three periods of frequent small turbidites, one of which could be related to KWO constructions in the Gadmertal between 1958 and 1967.

In summary, two major phases of hydropower operations affected the downstream Lake Brienz sedimentation pattern. First, the closure of the two dams of Grimselsee in 1929 separated the Aare from the direct proglacial influence of the two large Oberaar and Unteraar glaciers, and coarse particles were retained in the reservoirs. Assuming that all this coarse sediment would have reached Lake Brienz within a few years (e.g. after a series of strong rainfall events), input of silt and sand-sized particles at the Aare delta was significantly lowered. Although the total amount of fine grained sediment was barely affected, the establishment of reservoirs in the headwaters did, however, affect the seasonal distribution of turbidity, as more water with fine grained suspension entered after 1929 Lake Brienz during winter and less in summer. The second major impact occurring in the context of the hydropower operations, the pump-storage activities that started around 1980, had no significant influence on the distribution, quantities, and grain size of the deposited fine fraction in the reservoirs nor in Lake Brienz, as could be shown through analysis of the varved records in Oberaarsee, Grimselsee and Lake Brienz. It is thus highly unlikely that the low fishing yield in Lake Brienz observed in 1999 had its cause in a change in the solid particle budgets. At that time, changes in the boundary conditions of hydropower activities and particle transport were insignificant, especially when compared with the major changes in the 1930 but also with the minimal changes in 1980.

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