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Sediment balance of a cascade of alpine reservoirs based on multi-decadal data records

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Abstract. Reservoir sedimentation is a major concern in the operational management of dams and appurtenant structures. The increasing volume of sediments deposited in reservoirs leads to a loss of water storage, undermining the purpose itself of the dam for human use or protection. The deposition of sediments (mostly fine) in the vicinity of the dam's operational structures, such as bottom outlets and power intakes, may result in partial or total blockage of these structures. To cope with these problems, it is essential to determine the sediment balance of the reservoirs, by assessing the origin and quantity of the in- and out-fluxes of sediments. This paper presents a methodology to determine the annual sediment balance of a system of interlinked reservoirs across several decades, as well as its application to the alpine hydropower cascade formed by the Oberaar, Grimsel and Räterichsboden reservoirs located in Switzerland. At that aim, the annual sediment fluxes and the sedimentation rates of each reservoir were characterized. Also, the percentage of fine sediments ($d_m < 10$ μm) included in the total sedimentation rate was estimated. The results reveal that the annual sedimentation rate of the lowermost reservoir of the system (Räterichsboden) is highly altered by the flushing operations of the reservoir upstream (Grimsel). Also, for the uppermost reservoir of the system (Oberaar), the volume of fine sediments deposited annually can reach up to 46% of the total sedimentation rate.

1. Introduction

The volume of sediments deposited annually in water reservoirs has negative impacts on their sustainability and on the dam security [1, 2]. Also, the impoundment of sediments by dams may modify the sediment balance of the river catchment and coastal areas, which may result in negative impacts on the riverine environment. In extreme situations, sediments can reach and block the operational structures of the dam (bottom outlets and water intakes), jeopardizing the security of the dam and/or interrupting the water use. In this context, characterizing the sediment balance of water reservoirs is the first step to deal with the aforementioned issues.

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Although significant research progress has however been achieved over recent decades on several isolated domains pertaining to sediment balance [3–5], there is a clear research gap on how to make best use of these different degrees of knowledge and availability of information to compute sediment balance at an individual location and across river basins.

The aim of the present study is to establish a methodology to define the annual sediment balance of a cascade of reservoirs and implement and validate it in the so-called Grimsel hydropower cascade system. This system includes the Oberaar, Grimsel and Räterichsboden reservoirs. They are located in the Swiss Alps, in the upper part of the catchment of the Aare River, which is a tributary of the Rhine River. These reservoirs are part of a complex hydropower system operated by Kraftwerke Oberhasli AG (KWO). Figure 1 depicts an aerial view of the three reservoirs with their sub-catchments together with a sketch of the hydropower system. The area of the catchment of the three reservoirs is approximately of 115 km², of which 20% is covered by glaciers (Oberaargletscher and Unteraargletscher in Fig**.** 1). The altitude in these catchments ranges between approx. 1650 masl and 4262 masl. The hydrology is markedly seasonal, as most of the annual runoff is registered between the months of June and September.

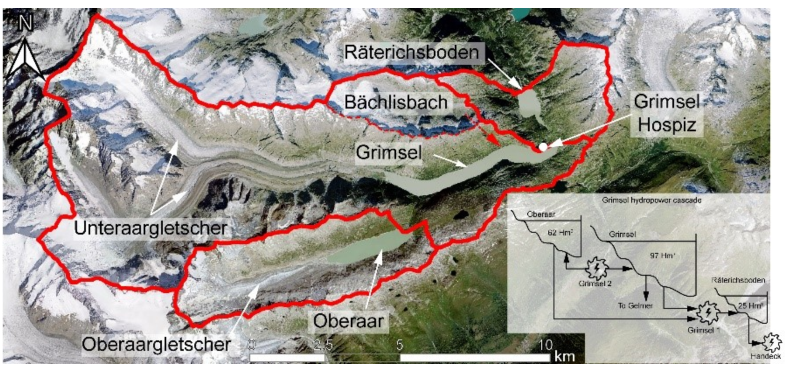

Fig. 1 Aerial view of the Grimsel cascade system with the three sub-catchments analyzed. [Background image: SwissTopo]. On the lower-right corner, sketch of the hydropower cascade.

2. Methodology

To characterize the annual sediment balance of the Grimsel cascade system, four components were analyzed for each sub-catchment: i) the sediment yield, which is the annual volume of sediments eroded within the catchment and conveyed to the reservoir; ii) the sedimentation rate (*SR*), which is the annual volume of sediments deposited in a reservoir. This volume includes all sediment sizes; iii) the sedimentation rate of fine sediments (*SRF*), which is the annual volume of fine sediments (d_m < 10 µm) deposited in a reservoir. This volume is part of the *SR* and is expressed as percentage of *SR*; and iv) the sediment exchanged through the power waterways (*SPW*), which is the annual volume of sediments exchanged between reservoirs by hydropower operations.

2.1. Sediment yield

For each sub-catchment, the annual sediment yield was estimated by using the formula proposed by Beyer Portner (1998)[6]. This formula reads:

$$V_A = 93 \cdot 10^{-15} \cdot H_{summer}^{0.052} \cdot SE^{0.091} \cdot SV^{8.108} \cdot \Delta L_G^{0.082} + 274 \quad (1)$$

where V_A is the annual sediment yield per unit area in $m^3 \cdot km^{-2} \cdot yr^{-1}$, H_{summer} is the precipitation in mm registered between June and September, *SE* is the percentage of surface of erodible soil (not including the glacier), *SV* is the percentage of surface without vegetation (including the glacier), and ΔL_G is the annual decrease of the glacier length in percentage with respect to the total glacier length. This formula was purposely calibrated to estimate the sediment yield for alpine catchments, as the results provided by other formulas such as those of USLE and Gavrilovic (1988) [7, 8] differed significantly from field measurements[6]. The Beyer Portner's (1998)[6] formula was validated by comparing the estimated sediment yield to that measured in 19 alpine catchments, in which H_{summer} ranged from 247 mm to 938 mm, *SE* from 26% to 92%, *SV* from 2% to 91%, and ΔL_G from 0% to 3%. In this study, H_{summer} was obtained from the precipitation data measured at the Grimsel Hospiz gauging station, which is representative for the three sub-catchments (Fig. 1). The precipitation database consists of hourly values from 01.01.1990 to 31.12.2015. H_{summer} was computed for each year by adding those values between June 1st and September 30th. The values of *SE* and *SV* were derived from the land use data obtained from the Swiss Federal Office for Topography (www.swisstopo.admin.ch). The glacier surface and the annual variation of the glacier length (ΔL_G) were obtained from the Swiss Glacier Monitoring Network (www.swiss-glaciers.glaciology.ethz.ch). This database consists of yearly measurements of the glacier length from 1990 to 2012. In the case of Räterichsboden, since there is no glacier coverage in this subcatchment, the term $\Delta L_G^{0.082}$ was considered equal to 1. The sediment inflows originated from mountain intakes were accounted for in the drainage area of each reservoir and corresponding assessment of the sediment yield. This is the case for the Bächli diversion to Grimsel reservoir (Fig. 1). However, the role of the intake works in filtering the coarser material was neglected and the transit of the fine material is fully accounted for.

2.2. Sedimentation rate

For each reservoir, the sedimentation rate (*SR*) was derived from the difference in storage curves from bathymetric surveys performed in each reservoir since their commissioning. Bathymetric surveys were conducted in 1957, 1990, and 2000 in Oberaar; in 1942, 1973, 2000, 2006, and 2016 in Grimsel; and in 1949, 1974, 2000, 2012, and 2015 in Räterichsboden. *SR* was estimated as the difference in volume between two consecutive bathymetries divided by the time elapsed between them. The pairs of consecutive bathymetries were chosen by considering those periods in which no flushing operations were conducted; i.e. 1990 and 2000 for Oberaar, 2006 and 2016 for Grimsel, and 2000 and 2012 for Räterichsboden. The values thus obtained were then compared to those reported by Anselmetti et al. (2007)[3], who quantified the volume of sediment deposits for each reservoir since their commissioning. These volumes were estimated by means of seismic surveys of the reservoirs' bottoms and their correlation with core samples and bathymetries where the acoustic signal could not identify the basin floor.

2.3. Sedimentation rate of fine sediments (*SRF*)

Bonalumi et al. (2011)[4] propose estimating the annual volume of fine sediments (d_m < 10μm) deposited in each reservoir (*SRF*) by means of:

$$SRF = \int w_s \cdot SSC(t) \cdot A(t) \cdot dt \quad (2)$$

where w_s is the settling velocity, *SSC* (*t*) is the evolution of the suspended sediment concentration of the reservoir during a year, and *A*(*t*) is the evolution of the surface area of the lake during a year (variable according to the reservoir's filling ratio). The settling velocity was computed according to the expression proposed by van Rijn (1984)[9]:

$$w_s = \frac{\left(\rho_s/\rho_w - 1\right) \cdot g \cdot d_m^2}{18 \cdot \nu} \tag{3}$$

where ρ_s and ρ_w stand for the density of sediment and water respectively, g is the gravitational acceleration, d_m is the characteristic grain size diameter of the mixture, and v is the kinematic viscosity of water. The characteristics of the suspended sediments, as well as the evolution of the suspended sediment concentration (*SSC (t)*) for Oberaar and Grimsel were obtained from Bonalumi et al. (2011)[4], who characterized the spatial and temporal distribution of sediment concentration for these two lakes. In the case of Räterichsboden, the sediment characteristics were assumed to be the same as for the other two lakes, whereas for the *SSC(t)* the average between the values of Oberaar and Grimsel was adopted. Based on Bonalumi's et al. (2011)[4] data, the sediment characteristics are $\rho_s = 2650$ kg/m^3, d_m = 3.1 μm, and bulk density = 1700 kg/m^3, considering a porosity of 35%. By assuming that the sediment characteristics remain constant over time, the settling velocity is also constant with a value of 0.5 m/day. The evolution of the surface of the reservoir (*A(t)*) was obtained from the data provided by KWO, which consisted of: i) daily values of water level and hydropower operations for Oberaar, Grimsel, and Räterichsboden (from 1980 to 2014); and ii) inundated area curves for each reservoir.

2.4. Sediment exchanged through the power waterways (*SPW*)

The annual volume of sediments exchanged by hydropower operations (*SPW*) was estimated as follows:

$$SPW = \int C(t) \cdot Q(t) \cdot dt \tag{4}$$

where *C(t)* is the concentration of suspended sediments of the exchanged volume of water, and *Q(t)* is the discharge of the pumped-storage operations. For the water exchanges originating in Oberaar and Grimsel (those exchanged through Grimsel 1 and 2), *C(t)* was characterized by means of the turbidity measurements performed by Müller et al. (2014)[10]. These measurements were conducted from October 2010 to June 2011 in the pressure shaft of the hydropower plant Grimsel 2, which allow the transference of water between Oberaar and Grimsel. For the water flows leaving Räterichsboden *C(t)* was characterized by means of the turbidity measurements performed immediately downstream of the latter at Handeck by KWO in (2016) (not published). An average sediment concentration of 50 mg/l was selected and combined with the operational discharge time series.

3. Results

3.1. Sediment yield

For each sub-catchment, the sediment yield per unit area was characterized by the average of V_A from 1990 to 2012. These averaged values are contained in Table 1, together with the surface of the catchment, the maximum, minimum and mean altitude, the averaged values of H_{summer}, glacier surface, *SE, SV*, and ΔL_G, and the total sediment yield for each subcatchment.

Table 1 Topographic characteristics and 22-years-average values of data to compute the annual sediment yield for each subcatchment

	Oberaar	Grimsel	Räterichsboden
Surface [km²]	19.24	84.88	11.51
Min altitude [masl]	2209	1800	1650
Max altitude [masl]	3622	4262	3237
Mean altitude [masl]	2729	2669	2426
H_{summer} [mm]	535	535	535
Glacier surface [%]	29	24	0
SE [%]	60	56	94
SV [%]	88	85	94
ΔL_G [%]	0.26	0.28	
V_A [$m^3 \cdot km^{-2} \cdot yr^{-1}$]	1281	993	2186
Sediment yield [$m^3 \cdot yr^{-1}$]	24652	84247	25157

Figure 2a shows the values of H_{summer} from 1990 to 2015 and the average during this period, which is 535 mm (dashed line in Fig. 2a). Figure 2b shows the accumulated value of ΔL_G from 1990 to 2012 for Oberaargletscher and Unteraargletscher. Figure 2c illustrates the percentage of glacier surface, erodible soil (*SE*), and vegetated surface (*100-SV*) for each sub-catchment. Figure 2d illustrates, for each sub-catchment, the evolution of the annual sediment yield per unit area (V_A) from 1990 to 2012. In absolute terms, the annual sediment yield estimated for Grimsel (84247 $m^3 \cdot yr^{-1}$) was the highest compared to those estimated for Oberaar and Räterichsboden (24652 and 25157 $m^3 \cdot yr^{-1}$ respectively). However, in relative terms, the sediment yield per unit area (V_A) estimated for Räterichsboden is significantly higher than those obtained for Oberaar and Grimsel. Thus, the value of V_A estimated for Räterichsboden is between 1.7 and 2.2 times higher than the values estimated for Oberaar and Grimsel respectively. These differences can be attributed to the fact that the percentage of erodible soil of Räterichsboden is significantly higher than those of Oberaar and Grimsel (*SE* in Fig. 2c). For Oberaar and Grimsel, V_A increases from 1990 to 2012 owing to the glacier retreat registered during this period (Fig. 2b). This retreat led to an increase of the erodible surface and consequently to a higher sediment yield.

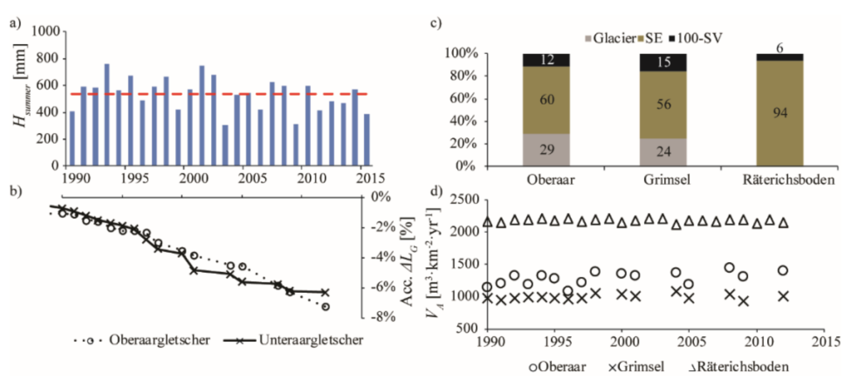

Fig. 2 a) Evolution of H_{summer} from 1990 to 2015 and the average value during this period (dashed line). b) Accumulated value of ΔL_G from 1990 to 2012 for Oberaargletscher (Oberaar) and Unteraargletscher (Grimsel). c) Percentage of the glacier surface, erodible soil (*SE*), and vegetated surface (*SV*) for the three sub-catchments. d) Evolution of the sediment yield per unit surface from 1990 to 2012 for the three sub-catchments.

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3.2. Sedimentation rate

Figure 3 illustrates the evolution of the capacity of the reservoirs at their respective maximum supply level since their commissioning. Also, Figure 3 shows the sedimentation rates estimated for the three reservoirs in 2001 by Anselmetti et al. (2007)[3]. In the case of Oberaar and Grimsel, the sedimentation rates derived from bathymetries, show a very good agreement with those reported by Anselmetti et al. (2007)[3] (Fig. 3a-b). In contrast, in the case of Räterichsboden, the sedimentation rate by Anselmetti et al. (2007)[3] differs significantly from that derived from bathymetries (Fig. 3c). This discrepancy may be attributed to the fact that in 2000, Grimsel was emptied completely and a big amount of sediments was delivered into Räterichsboden. This volume of sediments may have altered the measurements performed in Räterichsboden in 2001 by Anselmetti et al. (2007)[3]. Hence, the sedimentation rate of Räterichsboden was calculated from the bathymetries performed in 2000 (conducted after the Grimsel emptying in 2000) and 2012. In summary, the annual sedimentation rates considered in this study correspond to those reported by Anselmetti et al. (2007)[3] for Oberaar and Grimsel (22200 m^3/yr and 74650 m^3/yr respectively), and that obtained from bathymetries for Räterichsboden (25139 m^3/yr).

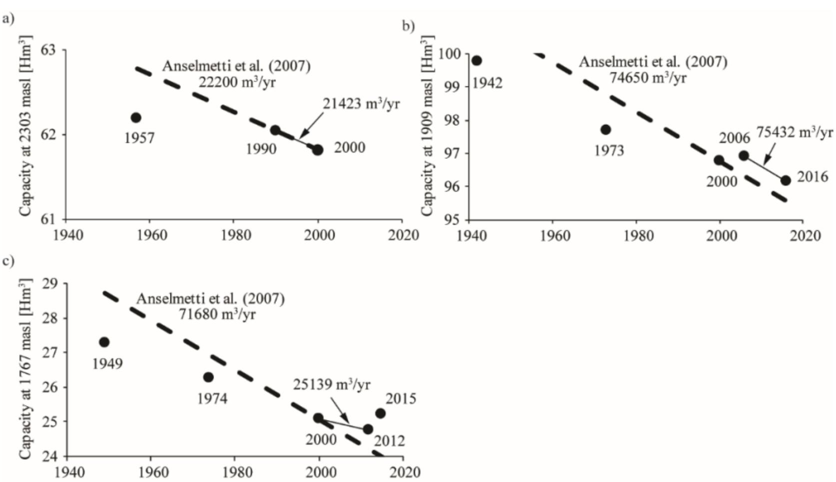

Fig. 3 Sedimentation rates estimated by means of bathymetric surveys (black dots) and those reported by Anselmetti et al. (2007)[3] (dashed lines) for: a) Oberaar, b) Grimsel, and c) Räterichsboden

3.3. Sedimentation rate of fine sediments

The annual evolution of the reservoir's water surface and the annual evolution of the concentration of suspended sediment are shown in Figure 4a for each reservoir. For all reservoirs, the water surface reaches a minimum between April and May and a maximum between August and September. Also, for all reservoirs, the concentration of suspended sediments increases from early spring to summer, and then it decreases during summer, autumn, and winter. The increase of concentration coincides with the period of glacier and snow melting and hence, it can be associated with the inflow of high concentrated glacier "milk". The decrease of concentration from summer to winter can be related to the absence of sediment laden inflows and to the sediment settling in the reservoirs. This decrease is attenuated by eventual runoffs originated by rainstorms in autumn [3, 4, 10]. In all reservoirs, *SRF* presents a similar evolution during the year, i.e. it increases from early spring to summer, reaching a maximum in July, and it decreases until the next spring reaching a minimum in March. In absolute terms, Grimsel has the highest *SRF* among the three reservoirs (19220 m^3/yr), whereas for Oberaar and Räterichsboden *SRF* is 10139 m^3/yr and 4996 m^3/yr respectively (Fig. 4b-d). In relative terms, the ratio between *SRF* and the annual sedimentation rate (Fig. 3) is 46% for Oberaar, 25% for Grimsel, and 20% for Räterichsboden.

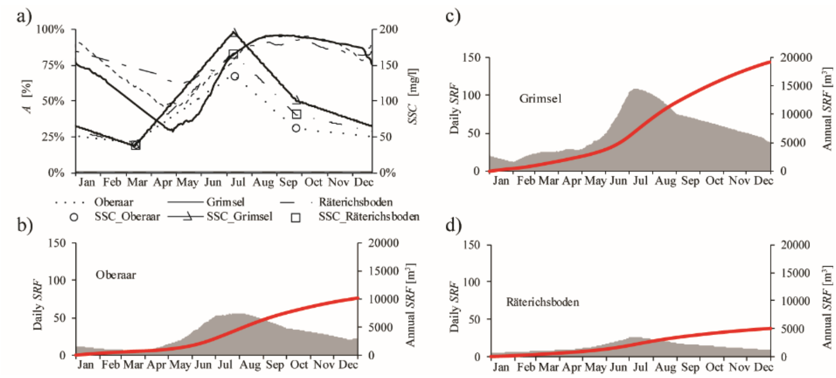

Fig. 4 a) Daily values of the surface (*A*) and of the suspended sediment concentration (*SSC*) of each reservoir during an average year. *A* is expressed as percentage with respect to the lake surface at the maximum supply level. Daily values of *SRF* (shaded area) and accumulated value of *SRF* (continuous line) during an average year for: b) Oberaar; c) Grimsel; and d) Räterichsboden

3.4. Sediment fluxes through the power waterways (*SPW*)

Annually, through Grimsel 1, 6000 m^3 of fine sediments are transferred from Oberaar (2000 m^3) and Grimsel (4000 m^3) to Räterichsboden (Fig. 5a). Through Grimsel 2, the annual balance of fine sediments exchanged between Oberaar and Grimsel is zero (Fig. 5b); because the volumes turbined from Oberaar to Grimsel, mostly during the first half of the year, are equivalent to those pumped from Grimsel to Oberaar during the second half of the year (Fig. 5b). Through the connection Grimsel-Gelmer, 5300 m^3 of fine sediments are transferred annually (Fig. 5c). From Räterichsboden, approximately 8000 m^3 of fine sediments per year are transferred to Handeck (Fig. 5d).

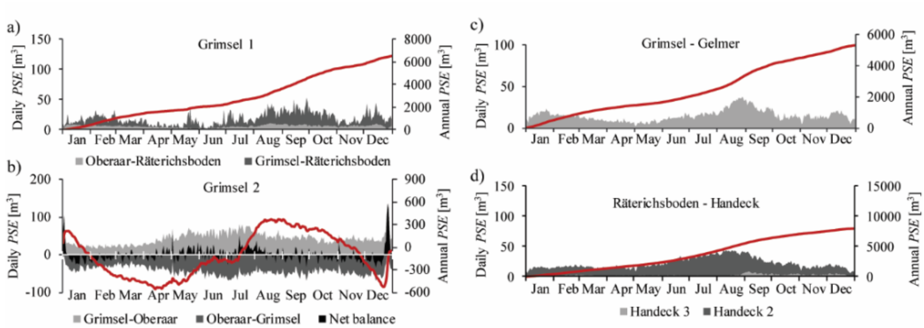

Fig. 5 Daily values of *SPW* and accumulated values of *SPW* during an average year for: a) Grimsel 1, b) Grimsel 2, c) Grimsel to Gelmer, and d) Handeck

3.5. Sediment balance of the Grimsel cascade system

The annual sediment balance of the Grimsel cascade system is illustrated in Figure 6. The balance is precise for Oberaar and Grimsel, whereas for Räterichsboden an imbalance of $2{\cdot}10^3$ m^3 is observed. This imbalance is approximately 8% of both the annual sediment yield and the annual sedimentation rate. Therefore, it can be attributed to the accuracy of the method.

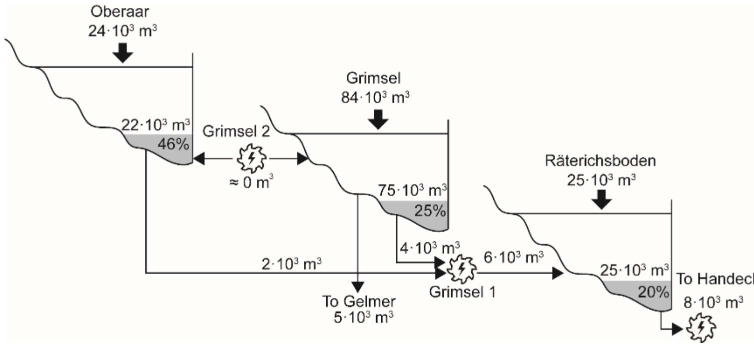

Fig. 6 Overview of the sediment balance of the Grimsel cascade system

4. Conclusions

This paper presents the sediment balance of a system of three reservoirs in cascade, based on data series recorded during several decades. The results show that the annual volume of fine sediments (below 10 µm) can reach up to 46% of the total annual sedimentation rate. Also, flushing operations performed in the upper reservoirs can influence significantly the sedimentation rate of the lowermost reservoir.

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