THE SEDIMENT BUDGET OF THE GLACIAL STREAMS IN THE CATCHMENT AREA OF THE GEPATSCH RESERVOIR IN THE ÖTZTAL ALPS IN THE PERIOD 1965-2015 *

Dr. J. SCHÖBER
Dipl.-Ing. Dr. B. HOFER

Department for hydropower planning,
TIWAG-TIROLER WASSERKRAFT AG

AUSTRIA

1. INTRODUCTION

Sediment transport in high-altitude Alpine headwaters with characteristics typical of the area (glacierized catchment areas, steep slopes, large sediment volumes, weak vegetation cover etc.) has been the subject of scientific research for many decades [1], [2]. Given the periods of glacial advance and ablation in the Quarternary, with their highly erosive effect providing sediment material and moraines forming large deposits of bed load and suspended load, glacial streams show some 5 to 10 times the sediment yield of streams without any glaciers in their catchment area [3]. Consequently, sediment yield and glacial cover of catchment areas are typically positively correlated [1]. Transported sediment yields show large intraday and seasonal variations, which are strongly affected by hydrological processes such as volume of snow melt or glacier runoff and precipitation volumes [4], [5], with the biggest sediment yields being recorded as consequences of the erosion of subglacial sediment layers in connection with heavy rainfall [6].

The demand on appropriate sediment data has grown increasingly in the

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* *Le bilan alluvionnement des courants glaciaires dans le bassin versant du réservoir Gepatsch dans les Alpes de l'Ötztal au cours de la période 1965-2015*

last years since near-natural river engineering, adjustments for flood and debris flows and water resources management have to account for sustainable sediment dynamics. Moreover, the restoration of the longitudinal continuum of sediment transport in rivers is claimed in the national water management plan of Austria. Power station operators operating facilities in high-altitude mountainous regions have to deal with sedimentation of the facilities, which is why successful sediment management requires a good grasp of past and future sediment transport situations taking into account climate change [7]. Thus, a great number of the existing series of long-term data on sediment transport in Alpine catchment areas were collected in reservoirs or water intake struktures [8], [3]. In the Alps, average annual reservoir sedimentation is estimated at some 0.2% [9].

For more than 50 years, TIWAG-Tiroler Wasserkraft AG has operated the Kaunertal power station in the western part of the Ötztal Alps, with the Gepatsch reservoir as its core element. Straight from the beginning of planning works in the 1950s and especially since the power station took up operation in 1964, TIWAG has placed a special focus on the sediment budget in the power station's catchment area as well as in the wider region [10], [4], [1], [11], [2], [12]. In the winter of 2015/16, the Gepatsch reservoir was drained completely. The bottom of the reservoir thus exposed was thoroughly measured, allowing for sedimentation to be calculated based on the known reservoir capacity originally available before the first impounding in 1964. This paper, based on regular continuous measurements of suspended load and bed load transport in the streams of the catchment area of the Gepatsch reservoir, will reconstruct these over 50 years of sedimentation. This is an update of the 25-year sediment balance presented by [1]. It is mainly the monitoring period of more than 50 years covered in this paper which can safely be classified as sufficiently representative, with singularities in individual events and measurements no longer standing out among the derived parameters.

2. DESCRIPTION OF THE CATCHMENT AREA

The Kaunertal power station built by TIWAG in the years 1961 to 1964 is located in the South-West of Tyrol, at the confluence of the Faggenbach and the Inn. The core element of this station is the Gepatsch seasonal reservoir, which had a storage capacity of 139×10^6 m³ at the time it was built. The power conduits comprise a 13 km pressure tunnel and a 1.9 km pressure shaft leading to the power house in Prutz, where the water is discharged into the Inn river, making a gross head of 870 m. At a design discharge of 52 m^3/s, the power station has a power generating capacity of 325-392 MW, depending on the water level in the reservoir. Mean annual generating capacity was 696 GWh in the period 1965-2015. The Gepatsch reservoir receives the natural runoff from a catchment area of 107 km². Three diversion systems channel additional runoff from a further 172 km² from the upper reaches of the Pitztal, the Radurschltal and the eastern catchment area towards the end of the Kaunertal (Fig. 1). These diversion systems comprise a total of 10 stream intakes with a design capacity of between 0.8 and 12.1 m³/s. Nine of these intakes feature a Tyrolean weir, the largest intake being the one on the Taschachbach with a 12 m arch dam. The water intakes divert only suspended load, which contributes to reservoir sedimentation. Bed load is separated from runoff by the desilting chambers of the intakes.

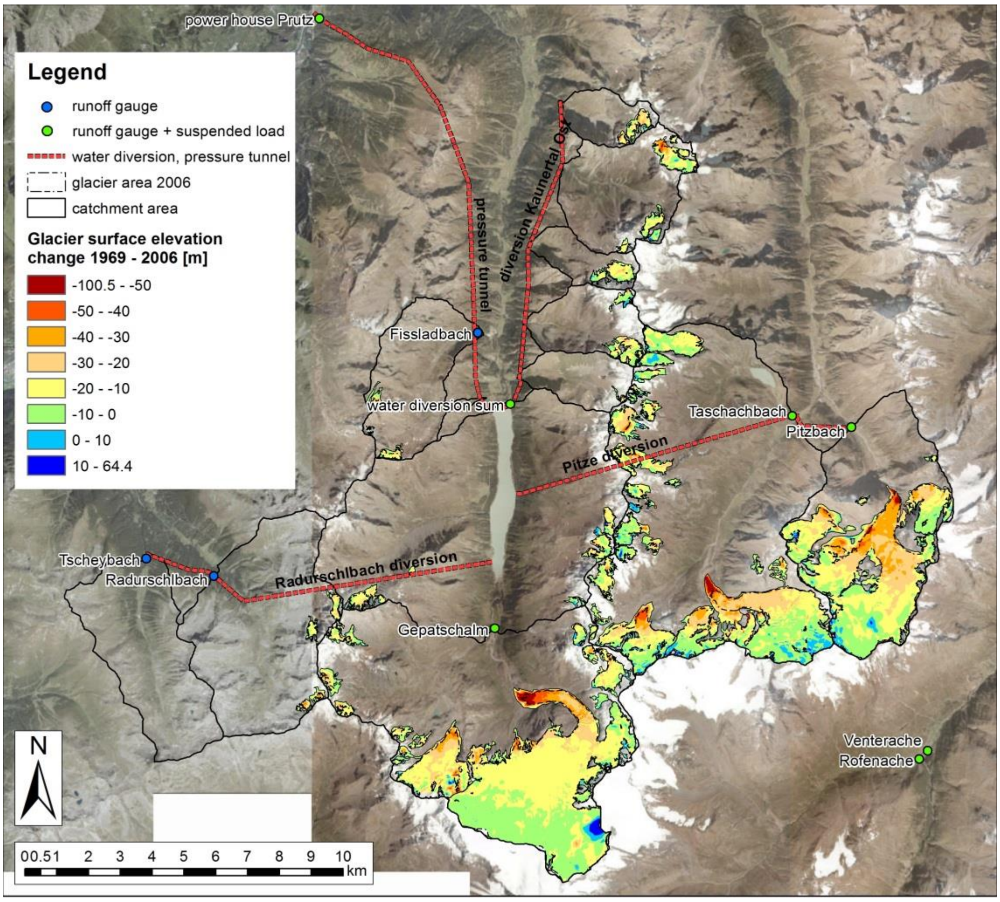

Fig. 1

Catchment area of the Gepatsch reservoir (279 km²) including its gauging stations and water intakes. Glacier areas existing in 1969 are in color and glacier areas existing in 2006 are indicated by dashed lines, color grading indicating changes in the glacier's surface elevation between 1969 and 2006.

Bassin versant du réservoir Gepatsch (279 km²)

Geologically speaking, the Faggenbach, the main draining river in the Kaunertal, and the diverted streams are located in the crystalline basement of the Ötztal massif, which is made up of gneisses and granite. The catchment area is located at an altitude of 1,770 m measured at the dam crest of the Gepatsch reservoir and extends to up to 3,770 m at the Wildspitze in the catchment area of the Taschachbach. The Alpine catchment area is characterized by extensive glacial cover. The streams used for the diversion systems mainly pass through moraine and scree zones with steep slopes except for short stretches of pasture and woodland.

3. DATA AND METHODS

3.1. GLACIOLOGY

The investigation area features data from three glacier inventories for the years 1969, 1998 and 2006 (source: University of Innsbruck). They provide both area data and digital elevation models for the individual glaciers in the investigation area [13].

3.2. RUNOFF

In total, there are eight continuous runoff measurements for the catchment area of the Gepatsch reservoir at eight gauging stations or water intakes (Fig. 1). Runoff data is available for the entire term of operation of the Kaunertal power station. All measurement sites in Fig. 1 are operated by TIWAG except for the Rofenache gauging station, which is operated by hydrographic service Tirol. Further gauging stations at the end of the Ötztal and in the Stubai Alps complete the picture of the hydrological situation in the monitored area. For comparison purposes, gauging station data from the Bernina Range (Switzerland), the Zillertal Alps and the High Tauern (Austria) are analyzed in terms of specific runoff and glacial cover. This comparative data is taken from measurement sites of TIWAG, or is obtained from Austria's Hydrographic Service (Neukaser, Matreier Tauernhaus, Obersulzbach, Obersulzbachkees, Untersulzbach; source: http://ehyd.gv.at/) or was provided by the Swiss Bundesamt für Umwelt (BAFU).

3.3. SUSPENDED LOAD

Of the eight gauging stations and water intakes in the catchment area of the Gepatsch reservoir, five measurement sites continuously measure also suspended load using turbidity meters (Fig. 1). This allows for monitoring the suspended load data collected on the Pitzbach diversion and the Kaunertal East diversion. In the orographic catchment area, the turbidity of the Faggenbach is measured at the Gepatschalm gauging station and the turbidity of the turbine water in Prutz is also recorded. Further turbidity meters are located at the gauging stations Rofenache (source: hydrographic service Tirol), Venterache (Fig. 1) and Obergurgl at the end of the Ötztal and at measurement sites in the Stubai Alps (Gries/Fischbach gauging station, Mutterbergalm/Ruetz gauging station and in the tunnel of the Melach diversion of TIWAG's Sellrain-Silz storage power station). The turbidity meters were installed in the years 2006 to 2008. The analysis described in this paper used turbidity data for the period 2008 to 2015 taken from all measurement sites.

For the purpose of calibrating the turbidity meters, a large number of samples (direct measurement of suspended load concentration by way of containers holding 1 liter, which can be aligned in the current using weights) are taken from the streams during various runoff conditions (if possible also at times of high suspended load concentrations). Based on annual rating curves, the values measured by the turbidity meters are then translated into continuous, calibrated hydrographs of suspended load concentration [mg l^{-1}]. Later on, runoff is used to calculate the suspended sediment transport rate [kg s^{-1}] and then the total suspended load [t $year^{-1}$] of the individual measurement sites. In order to ensure better comparability of the data, the annual total suspended load is divided by the basin area to thus arrive at the specific total suspended load [t km^{-2} $year^{-1}$]. The turbidity meters at the gauging stations and water intakes of these high-altitude mountain streams are removed each year in winter (November to March), because the measuring devices can be severely damaged by ice. Since the streams have very little runoff in these winter months, and the suspended load concentration is very low, the lack of measurement data for this time of year is of no major relevance for the annual yield. At the Pitzbach and Taschachbach water intakes, the turbidity meters are located in the water intake structure, meaning that the suspended load concentration of the diverted water is measured. For the purpose of calculating the total suspended load of the catchment area, it is assumed that the suspended load concentration of the inflow (intake + overflow) equals the suspended load concentration of the diverted water. For the Taschachbach water intake, which features a reservoir, three flushings per year have been taken into account [14], which increases the diverted annual total suspended load.

The suspended load transport passing through the Gepatsch reservoir (hereinafter referred to as suspended load in the turbine) is a key indicator with regard to the sedimentation of the reservoir. It consists mainly of particles, which remain suspended and are discharged into the Inn river via the turbines in Prutz. Additionally, particles can be whirled up again when the water level in the reservoir is low. [1] indicate that the total suspended load of the turbine water in Prutz for the period 1965-1990 was on average 11,000 m^3 $year^{-1}$. Based on the water level records for the reservoir, this value can largely be regarded as representative also for the period 1990-2009. Taking into account the measurements of the past years, suspended load in the turbine for the 51-year period is calculated at 12,300 m^{-3} $year^{-1}$ or 16,000 t $year^{-1}$.

3.4. Bed load

The desilting chambers of the nine water intakes featuring a Tyrolean weir separate water and bed load (with grain sizes >= 0.5 mm). The desilting chambers of the Tyrolean weirs are equipped with automatic hydraulic flushing mechanisms, whose purpose is to avoid too large deposits of bed load in the facilities. Since the number of flushings is recorded and the bed load yield per flushing is known, this allows for the calculation of annual total bed load for each water intake. [2] show annual total bed loads for the water intakes of the Kaunertal power station for the period 1965-2013, which provides a reliable basis for the calculation of average total bed load. Given the size of the space between the rods used in the weir, the fraction of bed load with a grain size of >= 15 cm is not recorded in the flushing data. According to [4], this portion is insignificant in terms of total bed load. Neither do the records cover extreme events such as debris flow, which flow over the weirs. Records kept in the course of power station operation allowed for conclusions relating to the bed load volumes of such extreme events to be drawn (mainly based on mechanically cleared bed load volumes). This allowed for a supplementation of mean bed load data taken from desilting chamber flushings.

3.5. DRAINING OF THE LAKE IN 2015

To perform maintenance work on the water intake structures and the bottom outlet of the Gepatsch dam, the reservoir was completely drained in December 2015. The exposed bottom of the reservoir was surveyed by means of terrestrial laser scanning and photogrammetric analyses. Knowing the originally available reservoir capacity (139×10^6 m³), sedimentation of the reservoir was calculated at 4.9×10^6 m³ or 6.4×10^6 t. To translate the sediment volume into t of dry material, samples were taken in different places of the sediment deposited in the reservoir. The samples showed medium diameters of grains being classified as medium- to coarse-grained silt. A mean density of 1.308 t m^{-3} was determined. In this paper, a density of 1.3 t m^{-3} is therefore used, which is in line with information provided in other papers on this matter [3].

3.6. RECONSTRUCTION OF THE SEDIMENTATION OF THE GEPATSCH RESERVOIR

To calculate the sediment budget of the Gepatsch reservoir, mean total suspended loads of the Gepatschalm gauging station is added to the observed total load collected from the Pitzbach and Taschachbach intakes as well as the Kaunertal East diversion. Total suspended load of the remaining catchment area of the Gepatsch reservoir as well as the Fissladbach, Radurschlbach and Tscheybach intakes (Fig. 1) is estimated. Calculation method (A) uses the specific total suspended load of the Kaunertal East diversion, which largely corresponds, in terms of area, elevation and glacial cover, to these catchment areas for which there is no suspended load data. To derive a method with greater universal applicability from the available data, regression models taking into account annual specific runoff [10^6 m³ km^{-2} $year^{-1}$] and specific total suspended load [t km^{-2} $year^{-1}$] are developed. Additional correlations of total suspended load and glaciological data are used for data classification. Further methods for calculating the suspended load balance provide for either (method B) an estimate of the ungauged areas by way of a regression model or, as in method (C), an estimate of the suspended loads of all partial areas of the reservoir (irrespective of whether there are measurement data available for these areas or not) by way of regression models. To complete the reservoir's sediment balance, the long-term bed load records at the water intakes [2] are a reliable basis for estimating total bed loads of the Faggenbach and the other tributaries to the reservoir. [2] found a strong correlation between annual total bed load and relative glacial cover of the monitored catchment areas in the Ötztal Alps and Stubai Alps. Due to catchment area characteristics and parallels in suspended load transport, the specific total bed load [$m^3\ km^{-2}\ year^{-1}$] of the neighboring catchment areas of Pitzbach and Kaunertal East diversion are used for calculating total bed load contributing to the sedimentation of the reservoir. In the area of the head of the reservoir, some 350 m^3 of bed load are extracted each year, which need to be subtracted from mean annual sedimentation.

This paper places a special focus on suspended load modelling. Since there are only eight measured values of annual total suspended load per catchment area, the entire data is used to calculate the regression coefficients. The models are then checked by way of cross validation. This means that all data of one year (2008-2015) is systematically excluded and the regression coefficients and the coefficient of determination of the regression model (R^2) are calculated anew. Each of the new models is used to calculate the total suspended loads for the data of the excluded year and the mean absolute error (MAE). The overall error of the model is given as the average of all MAE values. Additionally available independent data taken from other papers [4], [5] and relating to other catchment areas not used in creating the models (Vernagtbach and Venterache in Ötztal; Kalserbach, Tauernbach and Dorferbach in the High Tauern) provide further indication as to the models' quality and transferability.

4. RESULTS

4.1. GLACIOLOGY

Table 1: Glacierized area in the investigation area (279 km²) as registered in different inventories

Glacier inventory	Area [km²]	Glacial cover [%]
1969	61.3	22.0
1997/98	53.1	19.0
2006	49.5	17.7

Since the power station took up operation in 1964, the glaciers underwent great changes. The late 1970s and early 1980s were characterized by a short period of glacial advance. At the latest by the 1990s, there was increased ablation indicating a marked trend reversal. Table 1 shows the change in glacial cover of the catchment area of the Gepatsch reservoir (279 km²) based on the three glacier inventories.

The glaciers lost on average 13.6 m in elevation in the period 1969 to 2006 (Table 2) with ice ablations of 50 to 100 m occurring in low-altitude tongues of large glaciers. In the accumulation zones, the elevation changes were lower. In some zones, calculations indicated that elevation even increased. In Fig. 1, colors denote the elevation differences in the glaciers in the investigation area between 1969 and 2006. The ice melt in the period between the 2nd and the 3rd glacier inventory (9 years) was somewhat larger than the ice melt in the period between the 1st and the 2nd glacier inventory (some 28 years). An average density of 850 kg m^{-3} [15] is used to calculate the geodetic glacier mass balance. Consequently, the average ice loss of -13.6 m in the investigation area can be translated to some 11,500 mm of water, which in turn allows for determining the water contributed by glacier melt in the catchment area.

Table 2: Average surface elevation changes of the glaciers in the investigation area (279 km²)

	1997-1969 Area as in 1969	2006-1997 Area as in 1997	2006-1969 Area as in 1969
Ice elevation change [m]	-6.8	-7.1	-13.6
Mass balance [mm water equivalent]	-5764	-6033	-11525
Total runoff [10^6 m³]	353.33	320.36	706.46
Average annual runoff [10^6 m³ year-1]	12.18	35.60	18.59

4.2. HYDROLOGY

The mean annual water loss from the glaciers determined in the above chapter can be related with the mean annual discharge observations. This paper focuses on the extensively glacierized catchment areas Gepatschalm, Pitzbach and Taschachbach. In the nine hydrological years 1997/98 to 2005/06, which corresponds approximately to the period between the 2nd and the 3rd glacier inventory, the portion of ice melt in total runoff is 23% for the Pitzbach, 14% for the Gepatschalm gauging station and 10% for the Taschachbach. Consequently, the biggest share in runoff can be attributed to seasonal and annual precipitation, approximately 25 to 35% of which is due to seasonal snow melt in the catchment areas of the Ötztal Alps, according to [16] and [17].

Precipitation in the catchment areas of the Gepatsch reservoir is measured at six automatic weather stations and numerous cumulative rain gauge stations, some of which are located in remote areas. The data shows an increase in precipitation with elevation. The automatic weather station with the highest altitude shows annual precipitation sums of 1,200 mm on average and according to the water balance (Pitzbach, Taschachbach and Gepatschalm), annual precipitation is between 1,500 and 1,650 mm on average. These values largely correspond to the findings of [18].

Table 3: Size of catchment areas, glacial cover and average share in the total inflow to the Kaunertal power station of individual partial catchment areas in the period 1980-2015.

	Size of catchment area [km^2]	Glacial cover [%]	Share in total inflow [%]	Share in total area (279km^2) [%]
Gepatschalm	55.0	39.1	26.0	19.7
Taschach	60.6	21.2	24.1	21.7
Remaining catchment area Gepatsch reservoir	52.0	1.4	14.6	18.7
Pitzbach	27.1	46.3	11.6	9.7
Sum of East conduit	31.7	7.6	8.6	11.4
Radurschlbach	24.5	1.3	7.3	8.8
Tscheybach	16.5	0.0	4.2	5.9
Fissladbach	11.3	1.7	3.6	4.1

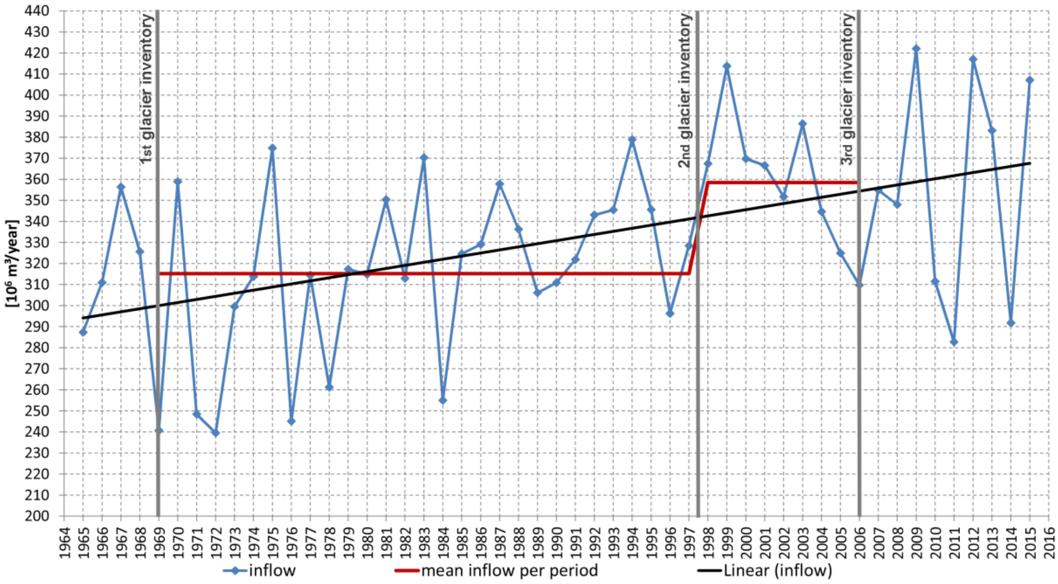

Fig. 2

Annual cumulative runoff of the Kaunertal power station [10^6 m³ year^{-1}]

Débit annuel de la centrale hydroélectrique Kaunertal [10^6 m³ year^{-1}]

The cumulative inflow to the Kaunertal power station is determined based on the discharge data of the power house in Prutz. Even though the annual inflow to the Gepatsch reservoir cannot exactly correspond to the annual discharge of the power station (storage or release of additional water), inflow and discharge values tend to converge in the long term. The discharge measurements available (Fig. 1) can be used to determine the share of the individual catchment areas in total inflow to the reservoir. Since the specific runoff is high in the extensively glacierized catchment areas, their contribution to total inflow at the Gepatsch reservoir is higher than their share in the total area (Table 3). The mean annual inflow to the Gepatsch reservoir or the Kaunertal power station in the period 1965 to 2015 is 10.5 m³/s (standard deviation = 1.4 m³/s), which corresponds to a total annual average of $331x10^6$ m³ water or 2.4 times the capacity of the Gepatsch reservoir. For the purpose of the following analyses, the catchment areas are divided into two classes: catchment areas with glacial cover >20% are classified as “extensively glacierized” and catchment areas with glacial cover <20% are classified as “slightly glacierized”. An average of 61.7% (or $204x10^6$ m³ or $1.43x10^6$ m³ km^{-2}) of the inflow comes from extensively glacierized partial catchment areas while 38.3% (or $127x10^6$ m³ or $0.93x10^6$ m³ km^{-2}) of the inflow comes from slightly glacierized partial catchment areas.

Fig. 2 shows the annual cumulative runoff (10^6 m³ year^{-1}). Despite strong interannual variability, inflow values show an upward trend. 1997 marks the availability of data from the second Austrian glacier inventory. The finding that mean glacier runoff is higher (before 1997: $12.2x10^6$ m³ year^{-1}, since 1997: $35.6x10^6$ m³ year^{-1}, Table 2) is also reflected in the higher mean inflows in the period 1998-2015 of $359x10^6$ m³ year^{-1}. This means that glacier runoff currently accounts for an average of 10% of annual inflow to the Kaunertal power station. In the period 1969 to 1997, mean annual inflow was still lower at $315x10^6$ m³ year^{-1}, the same is true for glacier runoff (4%). High annual cumulative runoff has been influenced by increased glacier runoff in the last years, with years with high sums of precipitation also showing markedly higher annual cumulative runoff values. A good example are the years 1967, 1970, 1999 and 2009, which were characterized by extraordinary volumes of snow [19].

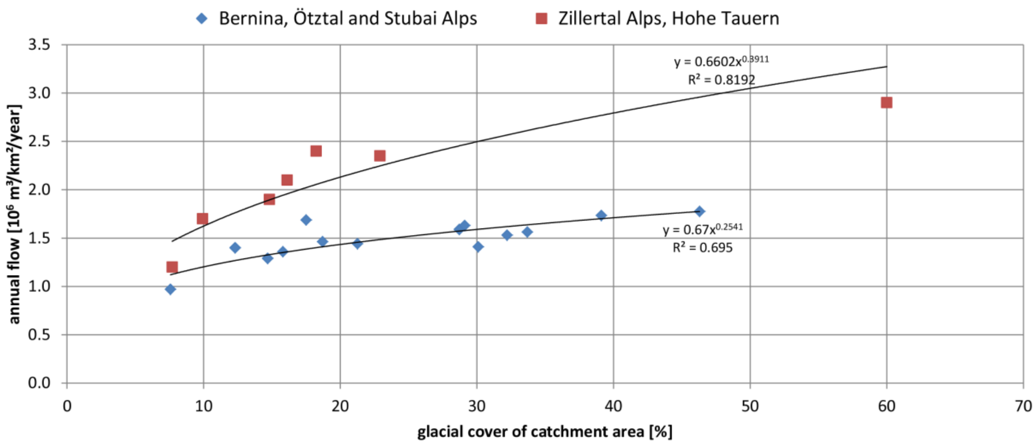

Fig. 3

Correlation of glacial cover and annual specific runoff in glacierized catchments of the Eastern Alps (source: TIWAG, ehyd.gv.at, BAFU and [7])

Corrélation de la couverture glaciaire et débit annuel dans les Alpes orientales

Fig. 3 shows the gauging station data of the Ötztal Alps and the Stubai Alps used in this paper to determine the correlation of glacial cover (as in 2006) and specific runoff (2008-2015). The data retrieved from gauging stations in glacierized catchment areas in the Zillertal Alps and the High Tauern are shown for comparative purposes. There were regional differences in annual specific runoff showing lower annual specific runoff values in the Bernina region and the Ötztal Alps and Stubai Alps than in the Zillertal Alps and the High Tauern. The equations in Fig. 3 can be used to estimate the annual specific runoff of glacierized catchment areas in the Eastern Alps without any measurements from gauging stations when glacial cover the of the catchment area is known.

4.3. SUSPENDED LOAD

Table 4 shows the annual suspended load of the nine measurement sites available. For better comparability, specific yield (divided by the size of the catchment area) is used. It is known that there is a positive correlation between suspended load and glacial cover of the catchment area. Fig. 4(a) shows the corresponding result for the catchment areas of the Ötztal Alps (values given in Table 4). Catchment areas with a glacial cover <20% show a clear, almost linear, correlation with suspended load. Catchment areas with high glacial cover, on the other hand, do not show such a clear, positive correlation with suspended load. The two high-altitude catchment areas of the Ötztal (Obergurgl and Rofenache) on average have higher specific total suspended loads than the Gepatschalm and Pitzbach catchment areas, which are more extensively glacierized compared to the above.

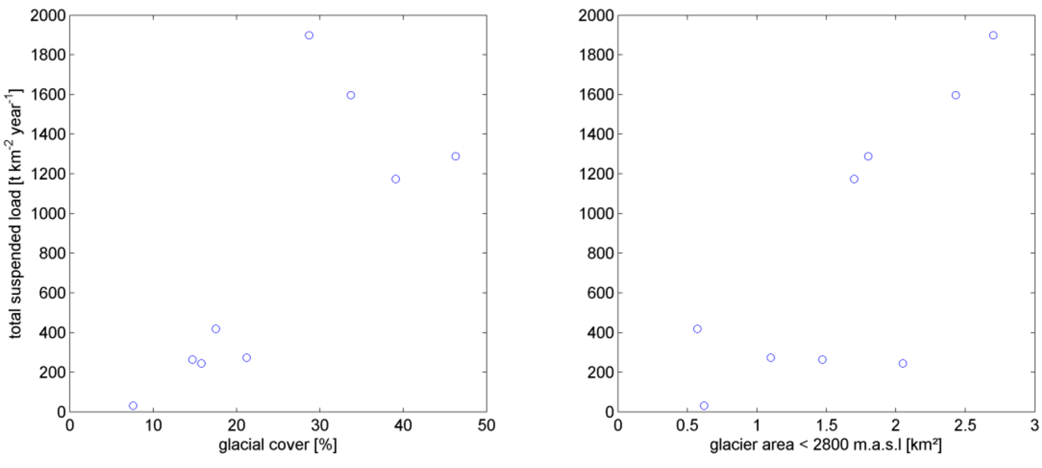

Fig. 4

Correlation between (a) glacial cover [%] and (b) glacier surface below 2800 m a.s.l. with mean specific total suspended load (t km^{-2} $year^{-1}$).

Corrélation entre mesures glaciologiques et débit solide en suspension

The catchment area of the Obergurgl gauging station (highest mean suspended load) is characterized by four large glaciers, all of which have a separate glacier tongue and feed their own glacial stream. Compared to this, the catchment area of the Pitzbach intake (highest glacial cover in %) only has one large glacier, which discharges into one single stream. Consequently, it is hypothesized that a catchment area with several glacier tongues leads to greater yields of suspended load. An explanation could be that the tongues of the large valley glaciers still show high flow rates of 10 to 40 m per year, e.g. [6], and that thus high sediment transport is to be expected in the area of the large valley glacier tongues. Additionally, mainly low-altitude glacier tongues show the highest negative changes in the longitudinal profiles of glaciers from ablation, which releases sediment from ground and lateral moraines.

Table 4: Annual specific runoff and suspended load at measurement sites in the Ötztal Alps and Stubai Alps in North Tyrol. The top line for each measurement site shows the cumulative runoff [10^6 m^3 $km^{-2}year^{-1}$] while the bottom line shows suspended load [t $km^{-2}year^{-1}$]. Column “G” shows the glacial cover in [%] and column “G<2800” shows the area of glacier tongues below 2800 m a.s.l. in [km²]. “M” shows the mean value for the years 2008-2015.

Gauge/stream or intake	**A [km²]**	**G [%]**	**G<2800 [km²]**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**M**
Pitzbach (water intake)	27.1	46.3	1.80	*1.82*	*1.86*	*1.62*	*1.79*	*2.00*	*1.65*	*1.61*	*1.96*	*1.79*
				971	1171	1346	1731	1934	1033	669	1455	1289
Gepatschalm/ Fagge	55.0	39.1	1.70	*1.76*	*1.79*	*1.59*	*1.73*	*1.93*	*1.65*	*1.55*	*1.80*	*1.72*
				900	1066	945	1466	1772	709	1013	1525	1174
Vent/ Rofenache	98.1	33.7	2.43	*1.52*	*1.75*	*1.52*	*1.51*	*2.16*	*1.52*	*1.48*	*1.21*	*1.58*
				1449	1626	2051	1719	2308	818	1124	1681	1597
Obergurgl/ Gurglerache	72.5	28.7	2.70	*1.60*	*1.52*	*1.56*	*1.54*	*1.61*	*1.67*	*1.62*	*1.61*	*1.59*
				1703	786	2481	1578	1855	1208	1573	4005	1899
Taschachbach (water intake)	60.6	21.2	1.10	*1.59*	*1.48*	*1.36*	*1.36*	*1.55*	*1.44*	*1.37*	*1.53*	*1.46*
				273	209	130	254	398	290	208	419	273
Mutterbergalm/ Ruetz	28.0	17.5	0.57	*2.11*	*1.36*	*1.48*	*1.60*	*1.81*	*1.69*	*1.62*	*1.71*	*1.67*
				391	381	333	568	622	398	202	457	419
Melach diversion	77.1	15.8	2.05	*1.44*	*1.35*	*1.30*	*1.29*	*1.50*	*1.39*	*1.31*	*1.33*	*1.36*
				300	290	289	135	275	190	157	321	245
Gries/ Fischbach	71.1	14.7	1.47	*1.41*	*1.21*	*1.26*	*1.18*	*1.42*	*1.42*	*1.27*	*1.33*	*1.31*
				250	172	423	201	379	180	241	266	264
Kaunertal East	31.7	7.6	0.62	*1.01*	*0.93*	*1.00*	*0.85*	*1.01*	*1.04*	*0.95*	*0.98*	*0.97*
				33	27	23	25	41	29	26	55	32

The great influence that glacier tongues have on total suspended load is further shown in Fig. 4(b). Summing up the glacier areas below 2800 m above sea level of the individual catchment areas to compare them with specific suspended load, there is an almost linear correlation for the most extensively glacierized catchment areas, which show no clear correlation in Fig. 4(a). For instance, the Obergurgl catchment area has the largest glacier surface below 2800 m a.s.l. and also the highest mean specific total suspended load. A linear regression calculation for the five catchment areas Obergurgl, Rofenache, Pitzbach, Gepatschalm and Taschachbach using the parameters glacier surface below 2800 m a.s.l. versus suspended load results in $R^2 = 0.93$. This linear correlation could even be shown for the catchment of the Kaunertal East diversion, which shows the lowest glacial cover. The catchment areas Mutterbergalm, Gries and Melach diversion, which are located in the Stubai Alps, do not fit the picture. The glaciers in this area are different from the glaciers of the Ötztal Alps in terms of elevation. The glaciers in the Stubai Alps are generally located at a lower altitude, which is why their tongues are currently less pronounced.

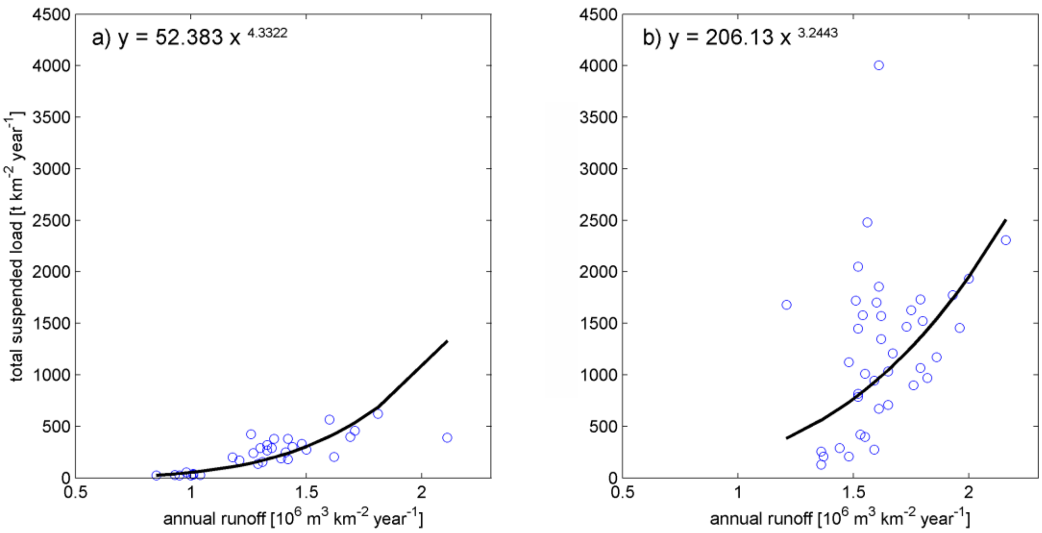

Fig. 5

Correlation between annual specific runoff and total suspended load in the catchments of the Ötztal and Stubai Alps with glacial cover of (a) <20% and (b) >20%.

Corrélation entre débit annuel et débit solide en suspension

Fig. 5 shows correlations between specific runoff of the catchment areas [10^6 m^3 km^{-2} $year^{-1}$] and the corresponding suspended loads [t km^{-2} $year^{-1}$] (data from Table 4). The data is pre-sorted based on glacial cover to account for the two data clusters given in Fig. 4 (influence of glacial cover or glacier surface <2800 m). The catchment areas with glacial cover <20% show a satisfying model having $R^2=0.76$. The calculated R^2 values for the data sets reduced by one year are each between 0.74 to 0.8, with the best result being achieved when the data for the year 2010 is excluded. Cross validation results in a mean absolute error MAE = 80 t km^{-2} $year^{-1}$ for the model of catchments with glacial cover <20%. For the catchments with glacial cover >20%, the calculated $R^2 = 0.22$, meaning that regression accounts for only a comparably small part of the variability of the measurements. In some years, mainly the Obergurgl and Rofenache catchment areas show significantly higher total suspended loads with only average cumulative runoffs. R^2 improves to 0.36 when the data for 2015 (outlier data in Obergurgl) is excluded. The worst R^2 (0.17) is calculated using data excluding the year 2012. In total, cross validation results in a MAE = 529 t km^{-2} $year^{-1}$ for the model of catchments with glacial cover >20%.

To validate the model for the catchment areas with glacial cover >20%, there was further data from the Ötztal Alps available from Rofenache gauging station (2006 and 2007), Venterache gauging station (2009-2015, glacial cover = 32.2%), Vernagtbach gauging station (2000 and 2001, glacial cover = 70%, [5]) and the Pitzbach (1981, [4]). What is noteworthy are the good results for the Pitzbach and the Vernagtbach with errors of 190 and 430 t km^{-2} $year^{-1}$. For the Venterache and the remaining data of the Rofenache, the model errors are higher than for the calibration data (MAE = 756 t km^{-2} $year^{-1}$ and 667 t km^{-2} $year^{-1}$). Two further gauging stations in the Tauern in East Tyrol with glacial cover >20%, however, show the limits of the statistical model. At the Tauernbach (Matreier Tauernhaus gauging station, glacial cover = 23%, period 2009-2014), total suspended load (600-1300 t km^{-2} $year^{-1}$) is within the range of data collected in the Ötztal Alps (Fig. 5b), runoff, however, is markedly higher than in the Ötztal Alps (see Fig. 3). Given the high specific runoff, estimates of total suspended load for this gauging station are clearly too high. By contrast, specific total suspended loads at the Dorferbach (glacial cover = 30.4%) are very low at 120-350 t km^{-2} $year^{-1}$ in the period 2008-2015, meaning that in this case estimates of total suspended load would be too high. The only data source for validating the model with glacial cover <20% is also located in the Tauern in East Tyrol. The data from the Kalserbach (Staniska gauging station, glacial cover = 7.7%, period 2014-2016), however, show a particularly low error (MAE=27 t km^{-2} $year^{-1}$). Calculations for all validation data (both models) result in a MAE = 500 t/km²/year.

4.4. BED LOAD

The fraction of bed load in the total sediment volume of the Gepatsch reservoir only consists of bed load from the orographic catchment area in the Kaunertal. As no bed load measurements are available in the orographic catchment area of the reservoir, this paper shows in Table 5 the average annual total bed load as found by the analysis in [2] for the water intakes of the Kaunertal power station in the period 1965-2013. In the table, bed load volumes in the desilting chambers are stated either as pore-free volumes (corresponding to [2]) or deposited volumes with a porosity of 30% ([10] and also mean value of current, unpublished measurements). This paper will refer only to deposited volumes in the following analyses.

Table 5: Average annual bed load yield at the water intakes of the Kaunertal power station in the years 1965-2013 (amended based on [2]). Bed load not recorded at the water intakes relate to bed load clearances near the respective water intake (0 m³/a means that almost all bed load is recorded in the intake).

Water intake	Catchment area [km²]	Pore-free bed load volume in the desilting chamber [m³ year^{-1}]	Deposited bed load volume in the desilting chamber; Density: 1.85 t/m³ [m³ year^{-1}]	Bed load not recorded in the water intake [m³ year^{-1}]	Mean annual bed load yield [m³ year^{-1}]	Specific bed load yield [m³ year^{-1} km^{-2}]
Gsallbach	3.9	51	73	0	73	19
Verpeilbach	12.3	50	71	694	765	62
Madatschbach	4.0	48	69	77	146	36
Wazebach	6.7	58	83	917	1000	149
Rostizbach	4.8	28	40	0	40	8
Radurschlbach	24.5	152	217	10	227	9
Tscheybach	16.5	246	351	0	351	21
Fissladbach	11.3	34	49	0	49	4
Pitzbach	27.1	2791	3987	1650	5637	210
all Kaunertal Tyrolean Weirs	110.8	3458.0	4940.0	3348.0	8288	75

Additionally, the annual load values are adjusted for extreme events based on operational records of mechanical clearances of the stream bed. The biggest change compared to [2] concern the Pitzbach: as a consequence of floods in 1987, 102,000 m² were mechanically cleared. A further 60,000 m³ were cleared in the period 1964–1980 and on average 30,000 m³ each in the years 1994, 1998, 2012 and 2014. These bed load clearances took place downstream of the intake, which is why the respective flushing volumes were subtracted. There are further major changes with regard to the flushing volumes at the Verpeilbach (some 2,000 m³ are cleared from a retention basin every 5 years) and at the Watzebach (1,000 m³ are cleared every year). At the other water intakes of the Kaunertal power station, there were either no or only very minor changes with regard to the bed load volumes flushed. The data of mechanical clearances is translated into an average annual fraction and added to the total bed load flushing volumes in Table 5 (total load, not recorded in water intake).

4.5. SEDIMENTATION OF THE GEPATSCH RESERVOIR IN THE PERIOD 1965-2015

Using the specific total bed load of the Pitzbach, average total bed loads of 11,500 m³ per year transported to the Gepatsch reservoir can be calculated for the catchment area of the Gepatschalm gauging station. A further 3,330 m³ of bed load per year is transported from the slightly glacierized remaining catchment area to the reservoir (data of the Kaunertal East diversion). Some 15,000 m³ of bed load is discharged into the reservoir every year, corresponding to a total of some 765,000 m³ in the 51-year period 1965-2015. It thus becomes evident that the biggest part of sedimentation measured in the Gepatsch reservoir (4.9×10^6 m³) has to be attributed to suspended load. Various methods are used to calculate the suspended load balance (Table 6).

Table 6: Sediment balance of the Gepatsch reservoir in the period 1965-2015

	Method A	**Method B**	**Method C**	
Mean annual suspended load yield	112600	118500	106200	[t year^{-1}]
Mean annual suspended load in the turbine	-16000			[t year^{-1}]
Mean annual suspended load deposits	96600	102500	90200	[t year^{-1}]
Density	1.3			[t m^{-3}]
Mean annual suspended load deposits	**74308**	**78846**	**69385**	**[m³ year^{-1}]**
Mean annual bed load yield of Gepatschalm gauging station (55 km²)	11500			[m³ year^{-1}]
Mean annual bed load yield of remaining catchment area of the reservoir (52 km²)	3328			[m³ year^{-1}]
Mean annual bed load deposit	**14828**			**[m³ year^{-1}]**
Average sedimentation balance suspended load + bed load	89136	93674	84213	[m³ year^{-1}]
Mean annual mechanical clearances at head of reservoir	-350			[m³ year^{-1}]
Sedimentation (51 years) 1965-2015	**4.53**	**4.76**	**4.28**	**[10^6 m³]**

For Method A, the mean values of the suspended load measurements (Table 4) are extrapolated for the period 1965-2016 and total suspended load of the ungauged tributaries (ungauged regarding suspended load, Chapter 3.4) are calculated using the specific suspended load values of the Kaunertal East diversion. This means that, on average, a yield of 112,600 t of suspended load per year are discharged into the reservoir. Taking into account the mean annual suspended load in the turbine, suspended load deposits are in the order of 74,300 m³ year^{-1} for Method A. Together with deposited bed load, this calculation results in average sedimentation of 89,100 m³ year^{-1}. This method results in total sedimentation of 4.53×10^6 m³ in the period 1965-2015, which corresponds to a deviation of 7.6% from actual sedimentation measured at 4.9×10^6 m³.

Method B, too, uses measured total suspended load values. For estimating total suspended load in the, in terms of sediment data, ungauged catchment areas, however, the model for catchment areas with glacial cover <20% (Fig. 5) is used. For this purpose, the measurements of annual specific runoff in these catchment areas in the years 2008-2015 are used. In this calculation, total suspended load increases to 118,500 t year^{-1} and a total volume of 4.76×10^6 m³ of sediment is calculated for the period 1965-2015. This method shows the lowest deviation, at only 2.9%.

Method C, which is more universally applicable, uses the two suspended load models based on cumulative runoff in Fig. 5. The input variables for the suspended load models are annual total inflow into the reservoir (Fig. 2) as a percentage rate based on glacial cover of the partial catchment areas and their share in total inflow (Table 3). This calculation results in a time series of annual total suspended load for the period 1965-2015. According to this method, 106,200 t $year^{-1}$ of suspended sediment are discharged into the Gepatsch reservoir on average, the totals for individual years vary between 35,000 and 220,000 t. 94% of total suspended load come from the part of the catchment areas with glacial cover >20%. In total, this method arrives at a deposit in the Gepatsch reservoir of $4,28x10^6$ m^3, which corresponds to a deviation from actual values of 12.7%.

5. DISCUSSIONS AND CONCLUSIONS

Depending on the method used for calculating the suspended load discharged into the reservoir, the proportion of mean annual suspended load deposit to mean annual bed load deposit is between 4.7 and 5.3 for the Gepatsch reservoir (i.e. 82.4% to 84.2% of the sediments are suspended load). These values are relatively high and are owed to the fact that the Tyrolean Weirs only let suspended load pass while extracting bed load. Measurements and earlier studies carried out at the Pitzbach were used to compare these values. Data of the years 2008-2013 show a mean fraction of suspended load of 80% in total transported sediment. However, one has to consider that the proportion is very variable, fluctuating between 2.5 and 8.7 for individual years. These results match the results of earlier studies, which found a fraction of suspended load of 75-81%, depending on the monitored period [4], [10], [11]. In receiving waters and large rivers downstream, the fraction of suspended load transport continues to rise and is 10 to 15 times higher than the fraction of transported bed load [3].

The calculated mean absolute errors of the suspended load models correspond to relative deviations from the mean measurement values in the order of 30-40%. The results of the relatively simple suspended load models based on cumulative runoff are thus comparable to the findings of [20], whose model, however, requires more input parameters. In comparison, the results for total sedimentation of the Gepatsch reservoir are markedly better with decreases relative deviations between 3% and 13% (depending on the method). Suspended load estimates based on runoff have fewer errors in long series, since the deviations in minimum and maximum total loads can even out over time [21]. With regard to the underestimated sedimentation sums, it has to be considered that sedimentation in the first months of operation of the reservoir in 1964 is not taken into account, since the above methods only work with values for whole years.

The validation of the suspended load models using data from additional locations and data taken from scientific literature showed that the suspended load models based on runoff are applicable to the area of the Ötztal Alps and the Stubai Alps. Specific runoff as in Fig. 3 suggests that the developed models may be applicable to Eastern Alpine catchments from the Swiss Bernina Range to the Silvretta and to the slightly glacierized catchment areas of the High Tauern. In the eastern part of Austria's Central Alps, specific runoff is higher due to higher precipitation rates [18], which is where the statistical models reach their limits. Special geomorphological conditions may also restrict model applicability. The Dorferbach features shallow stretches and little lakes upstream of the measurement sites, which allow for sedimentation. A similar behavior was periodically found in one further area of the High Tauern [7].

The results of this paper can therefore be used for estimating sediment yields. If, in a glacierized mountain stream in the described areas in the Eastern Alps, runoff volume but not suspended load was measured, the equations given in Fig. 5 can be used to calculate total suspended loads if the glacial cover of the catchment area is known. Glacial cover as a parameter can be relatively easily determined based on maps. If there is no runoff data available, glacial cover and the equations in Fig. 3 can be used to estimate average runoff and consequently average suspended load. One can expect that, in an extensively glacierized catchment, the fraction of suspended load will be about 4 times the fraction of bed load. Taking into account this relation and the information provided in papers [3] and [10], it is easy to estimate also the fraction of bed load.

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SUMMARY

In 2015, the Gepatsch reservoir was drained and deposited sediment with a volume of 4.9×10^6 m³ was measured. This corresponds to 3.5% of the entire reservoir capacity (139×10^6 m³) and an annual sedimentation rate of 0.07%. Different methods (time-based extrapolation of existing sediment yields versus regression models based on runoff) were used to calculate total suspended load values for the 51-year period 1965-2015. Total bed load was derived from the long-term records on sediment flushings from the Tyrolean weirs of the Kaunertal power station. If the measured total sedimentation is separated corresponding to the results, an average of some 81,600 m³ of suspended load and 14,500 m³ of bed load are transported to the reservoir per year. Depending on the method, the overall sedimentation of the Gepatsch reservoir can be modelled with deviations of -3% to -13%. The developed methods allow for an estimate of the sediment budgets in glacierized catchments of the Eastern Alps.

RÉSUMÉ

En 2015, le réservoir de Gepatsch a été vidangé et sédiments déposés avec un volume de 4.9x106 m³ a été mesurée. Cela correspond à 3,5 % de la capacité de réservoir entier (139x106 m³) et un taux de sédimentation annuel de 0,07%. Différentes méthodes ont été utilisées pour calculer les valeurs de débit solide en suspension totale pour la période de 51 ans 1965-2015. Total des débit solide de charriage a été dérivé des enregistrements à long terme sur les sédiments rinçages de déversoirs tyrolien de la centrale du Kaunertal. Si l'alluvionnement totale mesurée est séparée correspondant aux résultats, une moyenne d’environ 81600 m³ de débit solide en suspension et 14500 m³ de débit solide de charriage sont transportés vers le réservoir par an. Selon la méthode, l'alluvionnement du réservoir Gepatsch peut être modélisée avec des déviations de -3% à -13%. Les résultats permettent une estimation des budgets sédiments dans les bassins versants englacés des Alpes orientales.