Particle dynamics in high-Alpine proglacial reservoirs modified by pumped-storage operation

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[1] Temperature and suspended particle distribution were surveyed and modeled in two high-Alpine reservoirs in Switzerland, connected by pumped-storage operations for ~30 years. Due to different glacier coverage of the catchments, the two reservoirs exhibit different particle concentrations and temperatures. After ice-breakup, the lower reservoir with a higher glacier cover in its catchment experiences a higher particle input becoming more turbid than the upper reservoir, which in contrast becomes warmer and thermally more stratified. The pumped-storage operations, which replace the basin volumes annually at least 6 (larger lower basin) to 10 (smaller upper basin) times, modify the physical characteristics of the two reservoirs. This is especially so in winter, when they are ice-covered, without riverine input and at low water level. Our reservoir investigations between 2007 and 2009 and the subsequent particle-balance model show that the upper and lower basins have become more and less turbid, respectively. Pumped-storage operations modify the stratification and particle distribution in both reservoirs and therefore alter the particle outflow and sedimentation. However, on the basis of particle concentrations and reservoir volumes, it is evident that the annually integrated particle release to downstream (~40% of total) and to overall sedimentation (~60%) have hardly changed. The budget model was useful in the prediction of particle distribution and sedimentation dynamics in the pumped-storage system. It implies that this approach can be useful for further employment during planning stages of power plants in order to modify and mitigate downstream particle loads in reservoir operations.

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1. Introduction

[2] Damming of rivers represents the main anthropogenic change of hydrological cycling on a catchment-scale, as it alters river flows and particle retention over different spatial and temporal scales [*Petts and Gurnell*, 2005]. In the last century, ~48,000 large dams have been built globally to meet energy and water needs. Globally, one-third of the world's countries rely on hydropower for more than half of their electricity supply, and large dams generate ~19% of the total electricity [*World Commission on Dams*, 2000]. In Switzerland, several hundred hydropower dams exist, which provide ~60% of the country's electricity demand [*Truffer et al.*, 2003].

[3] Pumped-storage (PS) schemes are currently being explored and developed throughout the European Alpine regions to meet future electricity peak-demands. The basis of PS operation is to store potential energy during low-demand periods in an upper basin and to produce electricity during peak-demand by releasing the water to the lower basin. The exchange of water between two reservoirs located at different altitudes is thought to modify the physical and geochemical properties—stratification as well as suspended particle and thermal regimes—of the two water bodies involved. PS differs markedly from standard hydropower production where water movement is unidirectional. With PS, the water level can rise and fall rapidly in both reservoirs within a few hours, whereas the difference of reservoir levels between winter and summer seasons can be attenuated compared to reservoirs used for seasonal power production only. Further, PS operations are expected to alter the thermal stratification [*Anderson*, 2010], to resuspend sediments [*U.S. Bureau of Reclamation*, 1993] and to entrain organisms [*Potter et al.*, 1982; *Hauck and Edson*, 1976] from reservoirs connected by PS operations. The subsequent modification of turbidity, water temperature, and nutrient fluxes can affect downstream fisheries [*Miracle and Gardner*, 1980; *Oliver and Hudson*, 1980; *Rosenberg et al.*, 1997]. In addition, PS operations can cause various downstream alterations, such as changes in thermal regime of the rivers [*Caissie*, 2002], aquatic biodiversity of rivers and lakes [*Bunn and Arthington*, 2002] and biogeochemical cycling by interrupting the flow of organic carbon and changing the nutrient balance [*Finger et al.*, 2007; *Müller et al.*, 2007].

[4] Until now, no specific investigations concerning changes to particle dynamics and temperature have been

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performed in a PS-operation system connecting two reservoirs. Here, we investigate the effects of PS operations on the physical characteristics of two reservoirs, which originally exhibited quite different conditions.

[5] Emphasis is specifically placed on the basin-internal particle-mass concentration (PMC) and its vertical stratification and spatial distribution as well as the particle sedimentation within the PS system. For this purpose, the seasonal development of temperature and suspended particles of the reservoir waters were measured, as these quantities are influenced in a complex manner by the combined effect of high-Alpine weather and seasonal variations in hydroelectric power production. Using a mass-budgeting approach, the effects of PS on the temporal development of the PMC and downstream particle fluxes are evaluated by quantifying the particle masses exchanged between the two reservoirs and their impact on sedimentation with and without PS operation. The longer-term goal is to assess expected modifications for downstream lakes and rivers already in the planning stage (M. Bonalumi et al., Modeling of temperature and turbidity in two water basins connected by pumped-storage operations, manuscript in preparation, 2011).

2. Study Area

[6] The most prominent example of PS operations in Switzerland is located in the Grimsel region (Figure 1). The hydropower scheme—operated by "Kraftwerke Oberhasli (KWO)"—consists of four reservoirs (Oberaarsee, Grimselsee, Gelmersee, and Räterichsbodensee, Figure 1) located in a partially glaciated catchment. The construction of these Grimsel reservoirs resulted in both considerable changes in the downstream river flow due to shifting of runoff from summer to winter [*Wüest et al.*, 2007] as well as in the retention of suspended particles in the reservoirs [*Oehy and Schleiss*, 2002]. *Anselmetti et al.* [2007] showed that 230 kt of inorganic matter were annually deposited in the Grimsel reservoirs, while only ~40 kt yr^{-1} of mostly fine-grained suspended particles leave the entire hydropower system to the downstream waters. Additionally, the downstream impacts of dam construction on Lake Brienz (Figure 1) and specifically hydropower-related changes have been investigated for the fate of inorganic colloids [*Chanudet and Filella*, 2007], the subsequent light regime [*Jaun et al.*, 2007], phytoplankton productivity [*Finger et al.*, 2006, 2007], and oligotrophication [*Müller et al.*, 2007].

[7] Two of the Grimsel reservoirs, Oberaarsee and Grimselsee (Table 1, Figure 1), have been connected since 1980 by a PS scheme including the power plant "Grimsel 2," which can either produce power (~340 MW) with a water flow around 93 m^3 s^{-1} or, alternatively, pump water (~363 MW) at a rate of up to 80 m^3 s^{-1} from the lower Grimselsee to the ~400 m higher-elevated Oberaarsee (the intake/outlet are located at 2232 m asl and 1841 m asl, respectively) through a 5 km long penstock with a diameter between 3.8 and 6.8 m (Figure 1). Since dam constructions, the waters

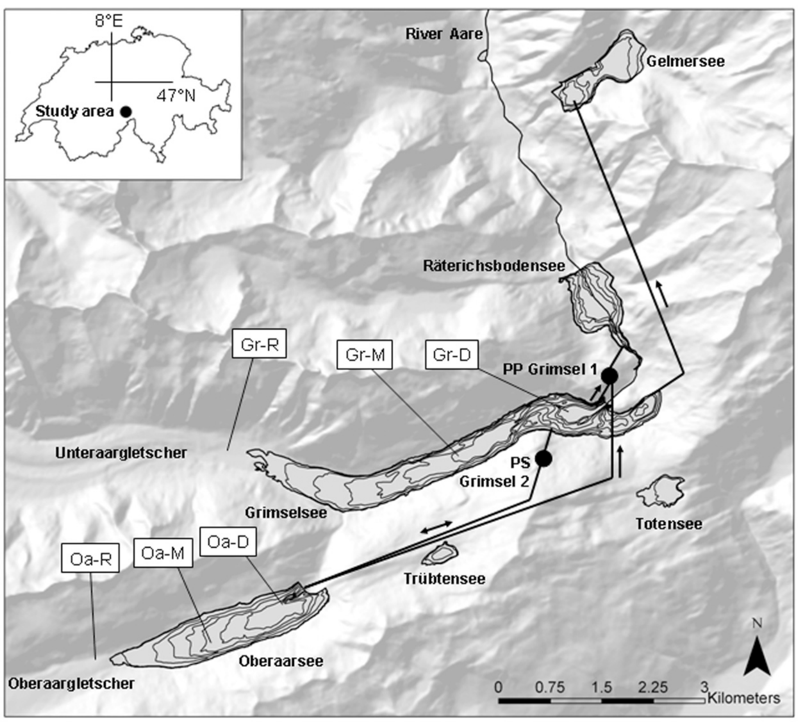

Figure 1. Map of Oberaarsee (upper basin) and Grimselsee (lower basin) with depth-contours of 10 m intervals. The reservoirs are connected by a 5 km long penstock via PS plant "Grimsel 2." "PP Grimsel 1" (PP = power production only) connects Oberaarsee and Grimselsee with Räterichsbodensee, while Gelmersee collects water from Grimselsee through a penstock. The labels in the white boxes indicate water-sampling locations in the reservoirs Oberaarsee (Oa-M and Oa-D) and Grimselsee (Gr-M and Gr-D), as well as in the two rivers Oberaarbach (Oa-R) and Unteraarbach (Gr-R); M = middle of reservoir; D = near dam or near intake/outlet. The inset shows the study location within Switzerland.

Table 1. Characteristics of Studied Pumped-Storage Reservoirs

	Oberaarsee	Grimselsee
Altitude (m asl)	2303	1908
Maximum/average surface area[a] (km^2)	1.46/1.26	2.72/1.97
Maximum[a] /average[b] volume (10^6 m^3)	65/38	101/57
Maximum/average depths (at maximum filling) (m)	90/44	100/37
Water natural inflow[b] (10^6 m^3 yr^{-1})	55	215
Water outflow (without PS)[b] (10^6 m^3 yr^{-1})	33	248
Water outflow due to PS[b] (10^6 m^3 yr^{-1})	599	576
Residence time without PS[b,c] (d)	252	96
Residence time with PS[b,c] (d)	22	26

[a]Maximum surface area and maximum volume refer to reservoirs at maximum water levels (i.e., in summer).
[b]Data from 2009.
[c]Residence time is equal to mean volume divided by total annual inflow.

from Oberaarsee (completed 1953) and Grimselsee (1932) have been used for power production by the power plant "Grimsel 1," from which the water is released downstream into Räterichsbodensee, the lowest in the chain of reservoirs (Figure 1). In addition, Grimselsee water is also partially released into another production-line via an alternative outlet (Gelmersee, Figure 1). In the last 30 years, however, the volume of pumped water (same amount as turbinated water) has increased from $\sim 100 \times 10^6$ m^3 yr^{-1} initially to ~ 600 to 700×10^6 m^3 yr^{-1}, with a particular increase in the last decade (Figure 2a). As Figure 2b documents, the seasonally pumped water volumes are larger than the reservoir volumes. This implies an extensive exchange between the two reservoirs, especially during the period January to March (Figure 2b). In this period, when the natural inflow and therefore the reservoirs level are low (Figures 2c and 2d), the exchanged volumes reach ~6 and ~7 times the volumes of Grimselsee and Oberaarsee, respectively.

[8] The catchments of the two reservoirs are part of the Aar Massif consisting primarily of crystalline rocks. The Grimselsee catchment is composed mainly of Grimsel granodiorite and Central Aare granite, whereas the Oberaarsee catchment also includes Variscan basement gneisses of granitic composition containing up to 5% (wt.) of calcite. The particles contained in the reservoirs, resulting from the erosion of the catchment, are composed of quartz, k-feldspar, plagioclase, mica (mostly biotite and phengite), and clay minerals [*Stalder*, 1964; *Oberhänsli and Schenker*, 1988; *Hosein et al.*, 2004]. Vegetation cover is absent except for pioneer plants typical of areas that only recently became ice-free, a few isolated Cembran pine trees and high-Alpine grass/moss [*Kratochwil and Schwabe*, 1994].

[9] The study area receives in average ~ 2.2 m yr^{-1} of precipitation, of which 60% is snow. The annual average temperature is $-1.0°C$ at Oberaarsee and $+1.2°C$ at Grimselsee [*Schwarb et al.*, 2001]. Both reservoirs are dimictic and ice-covered from November to June and ice-free for the other half of the year. They exhibit almost completely abiotic conditions due to low nutrient levels and poor light penetration into the water, caused by the extreme attenuation of the high inorganic suspended-particle content. This reflects the large glacier coverage in both catchments (Figure 1), which is also responsible for the low water

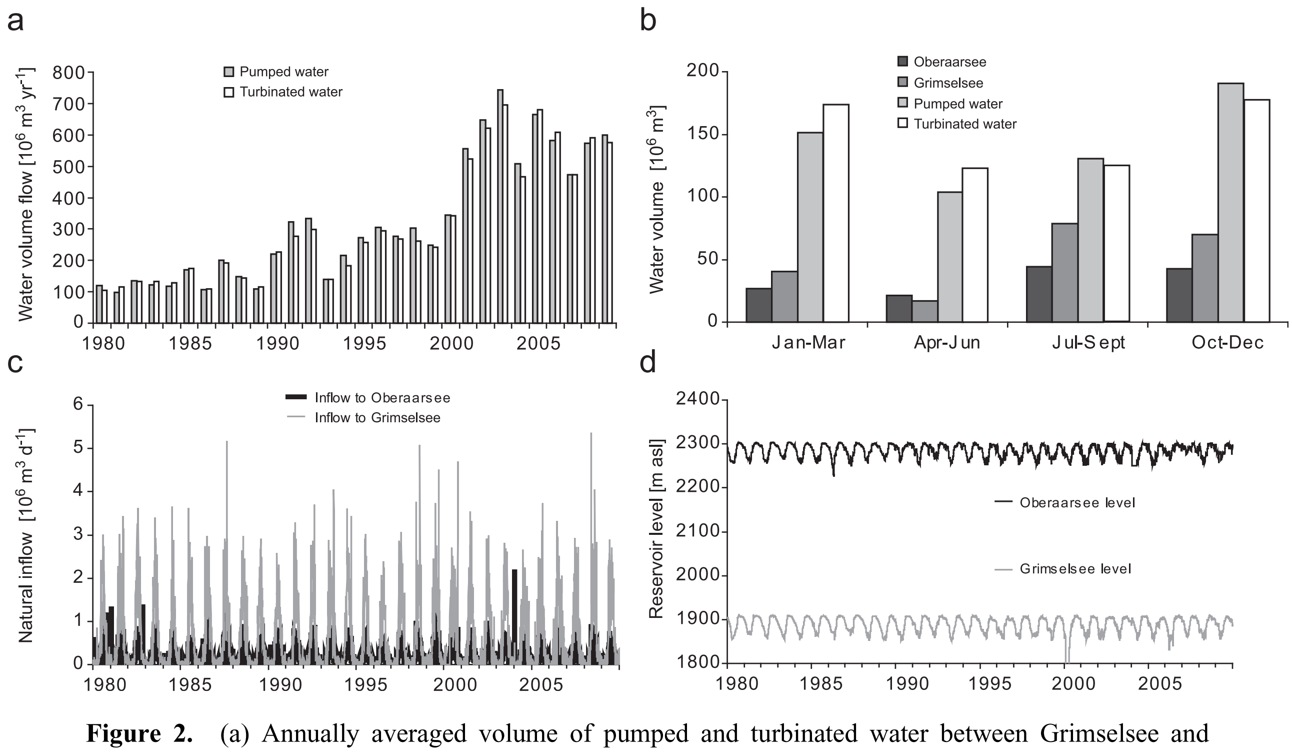

Figure 2. (a) Annually averaged volume of pumped and turbinated water between Grimselsee and Oberaarsee from 1980 to 2009. (b) Seasonally averaged volumes of Oberaarsee and Grimselsee compared with total volumes of water pumped and turbinated during the four seasons in 2009. Note that pumped water amounts to several times the volume of each reservoir. (c) Daily riverine water inflow to Oberaarsee and Grimselsee in the period 1980 to 2009. (d) Reservoir levels of Oberaarsee and Grimselsee from 1980 to 2009. Data provided by KWO.

temperature of the reservoirs. According to *Hallet et al.* [1996], the areas covered by glaciers are more subject to erosion than the ice-free regions. In the two catchments the denudation rates has been quantified at 1 to 2 mm yr^{-1} [*Bezinge*, 1987; *Anselmetti et al.*, 2007]. Erosion in the catchments depends not only on the type and lithology of the bedrock, but also on meteorological conditions. As a consequence of the high-Alpine environment, the particle input to the reservoirs is negligible during the cold and ice-covered season. Particle input, which occurs in the western part of the reservoirs downstream of the glaciers (Figure 1), happens mainly during snowmelt in late spring/early summer and during extreme runoff events in summer. This occurs to a larger degree in Grimselsee, which exhibits a higher riverine input (Figure 2d). Coarse particles settle rapidly at inflow-proximal locations and near the thalweg of the reservoirs all the way to the dam, while the fine particles remain in suspension. In fact, measurements of PMC close to the dam in both reservoirs performed by *Bühler et al.* [2005] and *Finger et al.* [2006] documented higher particle content in Grimselsee than in Oberaarsee.

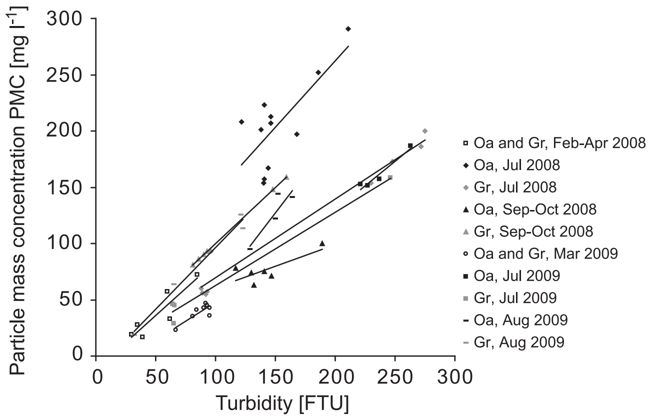

Figure 3. Particle-mass concentration (PMC) (mg l^{-1}) of water samples from both reservoirs versus turbidity (FTU) obtained by the turbidimeter HACH 2100 AN. Dots represent single measurements, while lines are fits to samples from individual dates. The turbidity/mass ratio is smaller in summer than in winter, due to the larger particles in summer (after input) compared to winter (smaller particles, which are not yet settled) [*Vangriesheim et al.*, 1992].

3. Methods

[10] Different measurement methods were employed to characterize the waters. Conductivity, temperature, depth (CTD) casts of the water column (60 M Sea and Sun Instrument, Germany) provided profiles of temperature, conductivity and turbidity in the reservoirs. Using a light beam consisting of wavelengths ranging between 400 and 600 nm (Seapoint Sensor), turbidity was measured after 90° scattering by the particles [*Clesceri et al.*, 1998]. Water samples for laboratory analyses were collected in the tributaries as well as in two depths (at the surface and ~2 m above bottom) in the reservoirs. Turbidity (Formazin turbidity units (FTU)) was again analyzed in the water samples with a turbidimeter (HACH 2100 AN, USA), which—analogous to the CTD—measures the light scattered by the suspended particles in the sample via a 90° scatter detector. Particles contained in the water samples were also analyzed for their diameters using laser diffraction (Malvern Mastersizer 2000 Particle Size Analyzer, UK). The particle-size distributions and the number concentrations were determined with a single particle counter (Klotz, Particle Measuring System Syringe, Germany) using the optical particle-counting method [*Göppert and Goldscheider*, 2008]. With this method, the light absorbance (extinction) determines diameters when the particles pass through a tube illuminated by a laser beam (655 nm). The PMC was finally derived from filtration of a known volume of water on membrane filters of 0.40 µm pore size, which were weighed before and after filtration [*Hofmann and Dominik*, 2005].

[11] Turbidity measured with the CTD and with the HACH turbidimeter gave different results because of differences in their optical designs [*McCluney*, 1975]. As a consequence, both the CTD turbidity and the HACH turbidity were calibrated with the PMC data (Figure 3), to convert turbidity to mass concentration [*Davies-Colley and Smith*, 2001]. The estimated PMC data range had a margin of error of ±10%. These different sampling and analytical methods allowed estimating different properties of the particles, such as the size distribution, the volume-based median diameter, the PMC and the turbidity for a high number of samples with an affordable effort.

[12] We probed the two reservoirs at multiple instances in two different areas, one located in the middle of the reservoirs (Oa-M and Gr-M, Figure 1) and one located near the dams and near the PS intake/outlet (Oa-D and Gr-D, Figure 1). Oa-M and Gr-M are located ~1.5 and ~2 km upstream of the respective dams, while locations Oa-D and Gr-D were within ~100 to ~300 m of the dams and within 200 m from the intake/outlet of the penstocks. Additionally, the two tributaries of the reservoirs, Oberaarbach and Unteraarbach (Oa-R and Gr-R), were sampled for temperature and turbidity (Figure 1). The sampling locations in the rivers were subject to variations due to frequent reservoir-level changes and were ~100 m upstream of the inflows. Sampling was conducted during a 2 year period between September 2007 and October 2009. For both years, at least four sampling campaigns were conducted in order to collect data, which represent the different seasons of a year.

[13] At the beginning of the survey (summer 2007), a larger number of locations and depths were chosen for water sampling, in order to characterize variations in PMC and temperature in the reservoirs. By the end of the survey, the number of samples for calibrating the CTD-based turbidity sensor (Figure 3) was reduced to two, one for each reservoir.

4. Results

4.1. Temperature and Particle-Mass Concentration in Both Reservoirs

[14] Temperature and PMC in Oberaarsee and Grimselsee vary significantly during the study period (Figure 4). Conductivity, on the contrary, varies only little and is always below 0.02 mS cm^{-1} in all studied locations of the reservoirs due to low ionic content (<20 mg l^{-1}). Hence

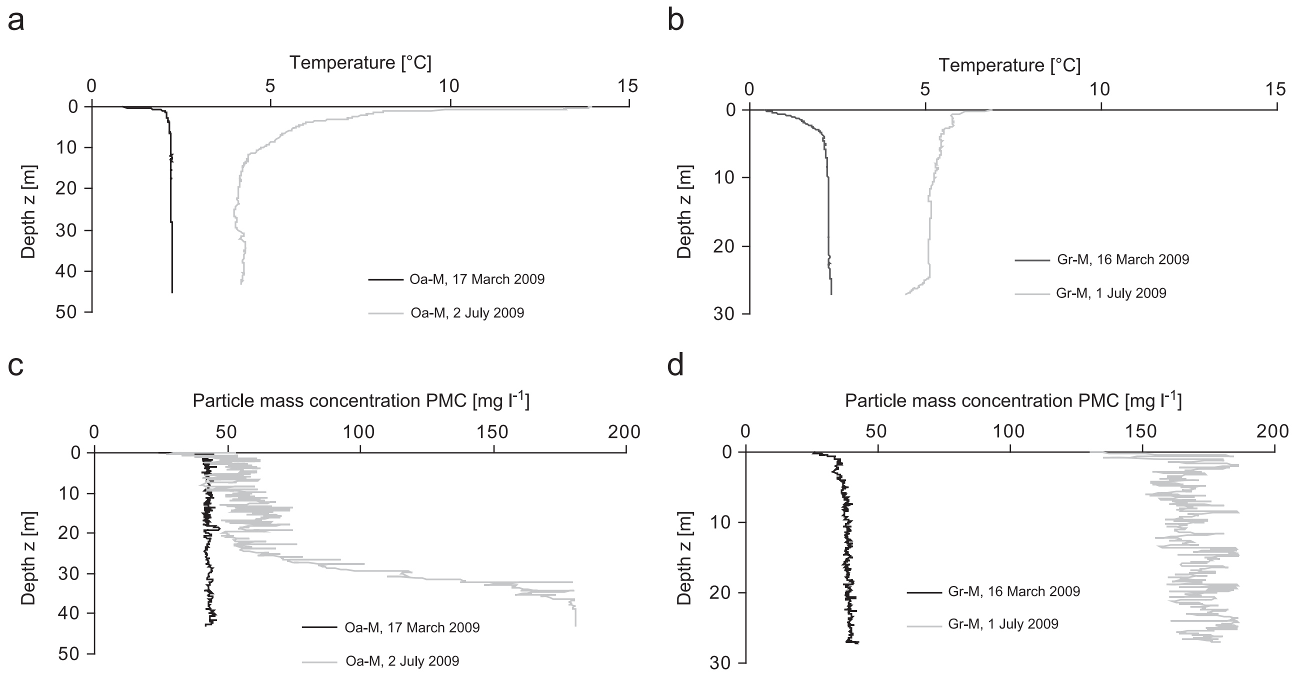

Figure 4. Temperature and PMC profiles in Oberaarsee and Grimselsee measured with a CTD in winter (16/17 March 2009; ice-covered; black lines) and in summer (1/2 July 2009; ice-free; gray lines) at the central reservoir locations Oa-M and Gr-M. (a) Oberaarsee temperature, with inverse stratification in winter and strong thermal stratification in summer. (b) Grimselsee temperature, with inverse stratification in winter and negligible stratification—compared to (Figure 4a)—in summer. (c) Oberaarsee PMC, with low surface PMC but high deep-water PMC in summer. (d) Grimselsee PMC, with also higher values in summer compared to winter and weak gradients with depth for both seasons.

salinity (conductivity, total dissolved solids) is not discussed further.

4.1.1. Temperature

[15] In winter, the reservoirs are covered by ice and are inversely stratified, i.e., temperature increases with depth. Temperature profiles collected below ice in Oberaarsee show an increase from 0°C just below the ice to a maximum of 2.5°C in the deep-water (Figure 4a, black line) with the highest values already reached at 1 to 2 m depth. Similar to Oberaarsee, also Grimselsee is inversely stratified under the ice, with temperatures increasing to 2.5°C in the top 5 m and remaining constant down to the deepest reaches of the reservoir (Figure 4b, black line).

[16] In July, both reservoirs are ice-free and thermally stratified. In Oberaarsee surface water temperature reaches 14°C to 15°C with a thermocline at ~15 m depth and deep-water temperatures of ~4°C (Figure 4a, gray line). In contrast, the surface temperature of Grimselsee is lower, reaching a maximum of ~10°C (Figure 4b, gray line). The thermocline, in only a few m depths, is less developed, and the temperature decreases to below 5°C in the deepest zone. Temperatures vary systematically between days and nights when the reservoirs are ice-free. Even if no measurements were taken during nights, temperatures show variations of up to 1°C to 2°C in the surface water between early morning (representing night temperatures) and afternoon due to the daily heating/cooling cycle.

4.1.2. Particle-Mass Concentration

[17] PMC undergoes a seasonal variation, with a maximum in early summer when the main particle input occurs and a minimum at the end of the winter when the settling of the particles exceeds the input for several months under the ice. During ice cover periods, PMC in Oberaarsee varies around 40 to 45 mg l^{-1} (Figure 4c, black line) and no major differences are observed between the surface and the deep-waters. Similar to Oberaarsee, PMC in Grimselsee drop under the ice to values of ~35 mg l^{-1} that are slightly increasing with depth reaching ~40 mg l^{-1} (Figure 4d, black line).

[18] A strong PMC contrast between the two reservoirs was observed in summer, when Oberaarsee (Figure 4c, gray line) is less turbid than Grimselsee (Figure 4d, black line), at least at the surface. In fact, Oberaarsee surface water is characterized by PMC between 40 and 60 mg l^{-1}, only slightly higher compared to those observed in winter, while in the deeper zones of Oberaarsee, PMC increases drastically up to 180 mg l^{-1}. The Grimselsee PMC profiles show in summer PMC between 130 (at surface) and 180 mg l^{-1} (deep-water).

[19] While the temperature and the calibrated PMC profiles (Figure 3) from end of March and from early July (Figure 4) represent typical conditions during the ice-cover period and after snow melt, respectively, it cannot be excluded that significant variations of PMC may be related to special events. Individual warm days in March may occur and increase the PMC through short snowmelt events increasing particle inflow to the reservoirs. Moreover but mainly in summer, snow melt or precipitation-driven turbidity currents are a frequent phenomenon [*Bühler et al.*, 2005] and may increase rapidly the PMC of the reservoirs, in particular in deeper zones. Major snow melt occurs

generally in the first half of June. In fact, as discussed in detail in section 4.2, the two reservoirs experience often different weather conditions causing snow melt to occur earlier in one reservoir with respect to the other.

4.2. Effects of Inflows

[20] The main inflows of both reservoirs directly originate from the glacier tongues, which in 2009 were located ~0.15 and ~2 km upstream of the uppermost deltas (highest water levels) in Oberaarsee and Grimselsee, respectively. This glacially scoured material ("glacial milk") explains the high PMC in the reservoirs. Particle inflow occurs mainly during snow melt in spring/early summer, while particle supply is low in fall and mostly absent during winter. The seasonal particle-relevant characteristics of these proglacial inflows can be divided into four periods: (1) no inflow from frozen catchments, (2) high particle-inflow during snow melt, (3) inflow of clear water while cooling in fall, and (4) high particle inflow during rain events.

4.2.1. No Inflow (Winter) Period

[21] During winter, both reservoirs are ice-covered. The freezing of the reservoir's surface lasts for half of the year from end of November (±2 weeks) to end of May (±2 weeks). As precipitation in winter occurs as snow, the inflows are marginal and the reservoirs experience minimal particle supply. At the end of winter, the first warm days causing snow melt and particle inflow occur in April and May. Even if there are no data from the rivers during this period, Oberaarsee PMC measured in the deepest waters (location Oa-M) on 27 February and 25 April 2008, show an increase from 22 to 57 mg l^{-1}, which indicates first particle inflows into the reservoirs below the ice cover.

4.2.2. High Particle-Inflow During Snow Melting

[22] During the observed periods, high particle inflow occurs in both reservoir catchments simultaneously to the ice melting of the reservoir surface. Within annual variations of 1 or 2 weeks, the period of high particle-inflow takes place in late spring in both reservoirs right after the onset of snow melting in the catchment. Representative for this period is the PMC measured on a sample from Unteraarbach (Gr-R) from 2 July 2009, which shows turbidity above 500 FTU (up to 700–800 mg l^{-1}). In fact, PMC at the location Oa-M and especially Gr-M show an increase from April to July 2008 and also from March to July 2009 (Figures 4c and 4d), which reflects the particle input from the suspension-rich tributaries Unteraarbach and Oberaarbach.

4.2.3. Inflow of Clear Water

[23] This period starts after the high particle inflow when snow melting ends and runoff drops. It is characterized by low particle-inflow, with tributaries less turbid than the reservoirs that cause dilution of the reservoir waters. Figures 5a and 5c show two-dimensional CTD-based PMC profiles of the reservoirs in September and October 2008, when the inflows are clearer and cooler than the reservoirs. In contrast to the snow-melting period, PMC is lower in the reservoirs close to the inflows (left sides of Figures 5a and 5c), where the inflowing waters usually form underflows due to higher density caused by low temperature (Figures 5b and 5d). The PMC of the tributaries tends to decrease during the course of summer, as shown in the data collected in 2007 and to some degree also in 2008. In fact, turbidity measurements in the tributaries rarely show values higher than 80 FTU in September/October, while in July they can increase up to 150 FTU. Following the decrease of PMC in the river, also Oberaarsee and Grimselsee (locations Oa-M and Gr-M) experience a decrease during the period July to October 2008 (Oberaarsee shows only a slight decrease) and in the same way during the period July to October 2009.

4.2.4. Peak Particle-Inflow During Rain Events

[24] High particle inflows into the reservoirs take place during a few events during summer and fall, at times, when usually the tributaries are less turbid than the reservoirs. In August 2009, for example, turbidity of Oberaarbach (Oa-R) amounts to 268 FTU and that of Unteraarbach to 460 FTU (CTD-based PMC of 668 and 851 mg l^{-1}, respectively).

[25] As shown in the two-dimensional transect in Grimselsee based on data collected in August 2009 (Figure 5e), these cool and suspension-loaded river waters are denser than the reservoir waters and cause underflows. Even if this particular density-current reached only a distance of 500 m from the river inlet, where it starts to fade and mix horizontally with the reservoir waters, *Oehy and Schleiss* [2002] document that such underflows can continue all the way to the dam. Furthermore, a water sample collected on 25 June 2009, in the penstocks of the power plant "Grimsel 2" during power operations, showed turbidity as high as 644 FTU, indicating a likely contribution from a turbidity current reaching the water intake near the dam of Oberaarsee. This value may be comparable with ~700 mg l^{-1} measured in a turbidity current in summer 2001 as reported by *Bühler et al.* [2005]. Even though these events increase rapidly the PMC of the reservoirs, the summer-long decreasing trend is not affected by these episodic high-concentration particle pulses.

4.3. Particle-Mass Concentration of Oberaarsee and Grimselsee

4.3.1. Reservoir-Internal Particle Concentration Structure

[26] A comparison between the CTD-based PMC profiles taken in the middle of the reservoirs (Oa-M and Gr-M) and those taken close to the penstocks intake/outlet (Oa-D and Gr-D) show important differences. The strongest variations in PMC can be observed in the surface waters while in the deep-waters PMC do not vary significantly between the different locations. Considering the similar catchment and observation with the light microscope, the mineralogy of particles of the two reservoirs does however not differ noticeably. Moreover, their diameter size distributions, determined with the Malvern Lasersizer (Figure 6), look similar and follow lognormal forms.

[27] Two Grimselsee profiles collected below the ice cover on 28 February 2008 (Figures 7a and 7b) illustrate that the water in the middle of the lake is characterized by a 5 m thick low PMC surface layer, while this layer is only ~2 m thick closer to the dam. Measurements of turbidity, particle diameter, particle number (diameter between 1 and 32 μm), and PMC of water samples taken at these locations resulted in a similar pattern (Table 2). At the location close to the power plant intake/outlet (Gr-D), turbidity and PMC are 1.5 times higher (Figure 7a) and the particle median diameters and the amount of particles are both more than twice as high as at the center of the reservoirs (Gr-M). The same trends resulted from analyses of Oberaarsee water samples collected in April also below ice cover. All

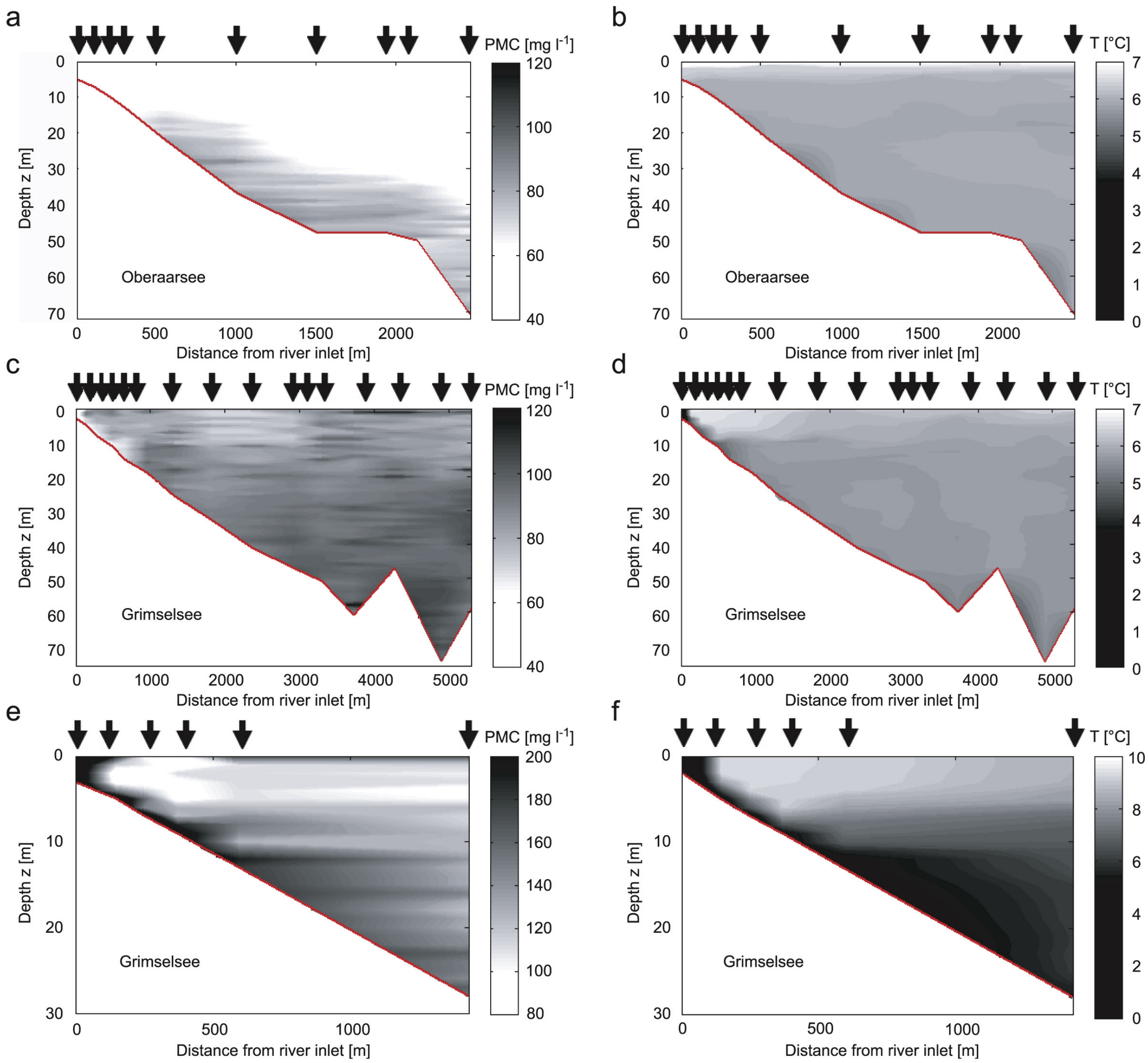

Figure 5. (a) Two-dimensional interpolation of autumn turbidity-based PMC profiles and (b) temperature profiles obtained with a CTD at 10 locations (indicated by black arrows) in Oberaarsee on 1 October 2008. Note that during fall, (1) the water from the inflow is clearer than reservoir water and (2) that the reservoir deep-water is more turbid than surface water. (c) Two-dimensional interpolation of autumn turbidity-based PMC profiles and (d) temperature profiles obtained with a CTD at 16 locations (indicated by black arrows) in Grimselsee on 19 September 2008. Similar to Oberaarsee (Figure 5a), the Grimselsee inflow is less turbid than the reservoir in fall. Note the underflow of cold and dense inflowing waters. (e) Two-dimensional interpolation of turbidity-based PMC profiles and (f) temperature profiles in summer obtained at six locations (black arrows) close to River Unteraarbach inlet in Grimselsee on 25 August 2009. The measurements were taken during a rain event after a temperate week (daily precipitation up to $\sim$8 mm d^{-1}; mean temperature of $\sim$14°C before measurements; data by Swiss Meteo). Note the turbid river inflow to the reservoirs. Similar patterns occur upon snow melt.

parameters, including PMC, are at least 1.2 times higher in the surface waters close to the intake/outlet (Oa-D) than in the middle of the reservoir (Oa-M, Table 2). Moreover, temperature measured close to the intake/outlet was found to be slightly warmer than in the center (Figure 7b).

[28] These patterns were not observed as strongly during summer and fall. However, some variations similar to those observed in winter were measured in the surface waters of Grimselsee during ice-free periods as well (Figure 5c).

4.3.2. Comparison of Particle Concentrations at Oa-M and Gr-M

[29] The CTD-based PMC values, measured for the different sampling campaigns at Oa-M and Gr-M (Figure 8a), are highest in summer (June to August 2008 and 2009). In

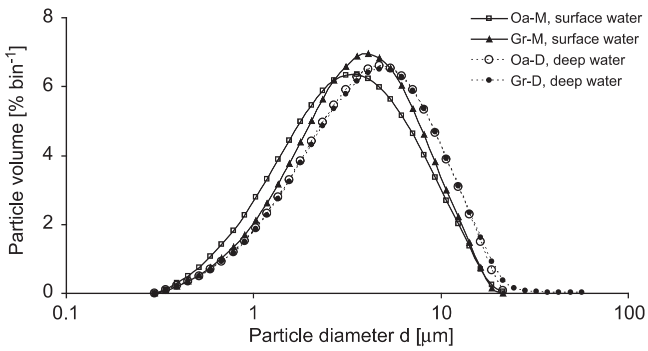

Figure 6. Particle size distribution measured with the Malvern Laser Sizer of water samples collected in Oberaarsee (15 July 2008) and in Grimselsee (16 July 2008). The corresponding median particle diameters are 3.20 μm (Oa-M, surface water), 3.63 μm (Gr-M, surface water), 4.17 μm (Oa-D, deep water) and 4.09 μm (Gr-D, deep water).

winter, in contrast, when no rivers enter the reservoirs and PMC is at its lowest, Oberaarsee shows particle sizes slightly higher than in Grimselsee (Figure 8b), however not supported by differences in PMC, which are similar in both reservoirs (February to April 2008 and March 2009). In summer and fall (July to October 2008 and 2009), PMC shows a decreasing trend with time, in particular in Grimselsee. Moreover, during this period, PMC (and also particle sizes) at the surface of Grimselsee are much higher with respect to the values measured in Oberaarsee (Figure 8a). Unlike the surface waters, the deep-waters appear to have approximately the same characteristics both in Oberaarsee and Grimselsee (Figures 8c and 8d).

4.3.3. Comparison of Particle-Mass Concentration at Oa-D and Gr-D

[30] Similar to the middle of the reservoirs, PMC as well as particle sizes close to the dams are in summer higher in Grimselsee than in Oberaarsee, while during winter, the reservoirs have similar properties (Figures 8e and 8f). Furthermore, at the dam of Oberaarsee the surface water shows only a small seasonal PMC variation compared to Grimselsee.

[31] As mentioned above and as shown in Figure 4, PMC are generally increasing with depth in both reservoirs so that the highest PMC are found in the deepest part. In fact, as shown in Figure 8g, the highest values measured (up to 200 mg l^{-1}) are found in the deep-waters of Grimselsee during summer (June to August for both 2008 and 2009). Similar to Oa-M and Gr-M (Figure 8a), PMC of the deep-waters increase in spring and decrease in late summer. PMC measured in the deep-water of Grimselsee close to the intake/outlet (Figure 8g) is in most cases higher than in Oberaarsee. This pattern can also be observed in the particle-size analyses, which, with the exception of a single measurement on a sample collected in June 2008, results for all seasons in higher particle diameters in Grimselsee compared to Oberaarsee (Figure 8h).

5. Discussion

5.1. Effects of Hydropower Operations on Reservoir Particle Content

5.1.1. Variations Caused by Water Exchanged Between Reservoirs

[32] The turbidity and CTD-based PMC distribution in the reservoirs follows a combined effect of various factors, including natural parameters (such as weather and glacial melting) and man-made activities (such as electricity production and PS operations).

[33] Snow melt—determined by weather—causes intense particle input to the reservoirs in late spring. This occurs approximately during the same period for both reservoirs, even though Oberaarsee is located 400 m higher than Grimselsee (Table 1). The catchments of the reservoirs exhibit different characteristics: the one of Grimselsee is larger and has a higher glaciated percentage glaciated compared to Oberaarsee [*Anselmetti et al.*, 2007]. As the glacial abrasion is the most effective erosion process, this different glacier coverage explains the higher particle content in the Grimselsee tributary, the higher particle inflow to Grimselsee and higher PMC in Grimselsee consistently observed after snow melt (Figures 5a and 5c).

[34] The most important difference between the reservoirs is visible in the ice-free surface layers. Grimselsee surface water is colder and thermally less stratified (Figures 4b and 5d) than that of Oberaarsee (Figures 4a and 5b). As PMC is lower in Oberaarsee, more sunlight can penetrate into the water body and thereby warm and stratify the

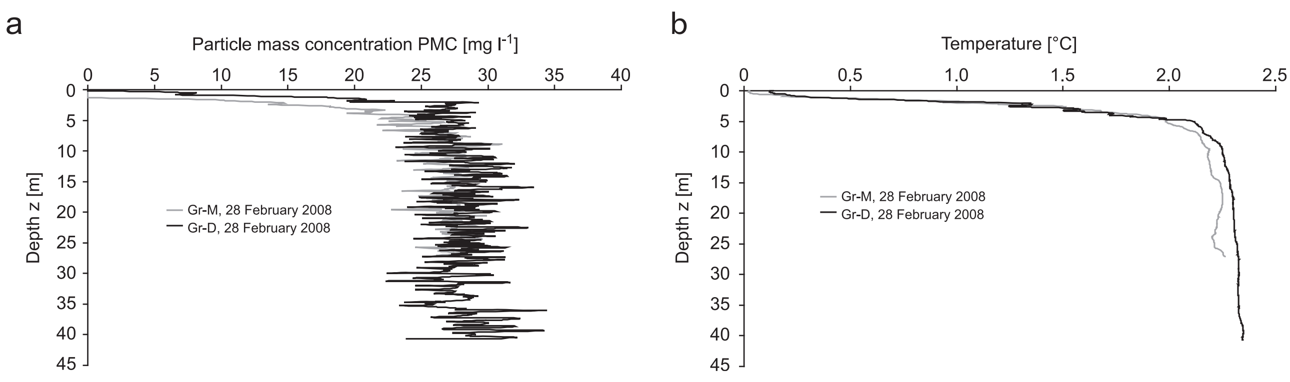

Figure 7. (a) CTD-based PMC profiles and (b) temperature profiles obtained in Grimselsee on 28 February 2008 below ice cover. Close to the intake/outlet (Gr-D; black line) the water is more turbid in the top 2 m and warmer than the water collected in the center (Gr-M; gray line).

Table 2. Turbidity, Particle Diameter, Particle Number and PMC of Surface Water Collected Close to the Power Plant Intake/Outlet of Oberaarsee and Grimselsee and in the Middle of the Two Reservoirs[a]

	Gr-D (28 Feb 2008)	Oa-D (25 Apr 2008)	Gr-M (28 Feb 2008)	Oa-M (25 Apr 2008)
Turbidity (FTU)	47	62	30	35
Median particle diameter (μm)	2.6	2.6	1.0	2.0
Particle (1–32 μm) number (μl^{-1})	880	1435	306	996
PMC ($mg\ l^{-1}$)	19	33	-	26

[a]Surface water is at 2 m depth. Measurements for Oberaarsee is Oa-D and for Grimselsee is Gr-D and the middle of the two reservoirs are Oa-M, Gr-M.

surface layer (Figure 4b). This slight density stratification protects the surface from particle entrainment (mixing) from below and supports a pronounced particle stratification, which causes a positive feedback on sunlight, temperature and density stratification.

[35] Deep convective mixing of the reservoirs, occurring in early winter before freezing [*Geyer*, 1993], causes homogenous PMC from the surface to the deep-water in both reservoirs (Figures 4c and 4d). Moreover, PS operations exert a main impact on the PMC, especially in winter without riverine inflow but with water exchanged up to several times the reservoir volumes (Figure 2b). PS operations bring more turbid water into Oberaarsee and, in contrast, power-producing releases clearer water into Grimselsee. In fact, measurements have shown different turbidity and PMC between pumped and turbinated water. Measurements performed on a time scale of a few hours on 23 and April 2009 show strongly varying turbidity after changing of operation mode, ranging between 130 and 135 FTU during pumping and 175 and 190 FTU during power production. In winter, when the particle input by rivers is low, a uniform PMC pattern with equal profiles both in Oberaarsee and Grimselsee is established, at least close to the penstocks. This pattern is caused by (1) the intense and continuous water exchange between the reservoirs and (2) the fact that particles of Grimselsee settle faster than in Oberaarsee due to their larger particle diameters. These under-ice processes are maintained throughout the winter until snow melt reactivates particle input (see above).

[36] PS operations may have an impact on the ice-free reservoirs also during summer months. However, as the penstocks intake/outlets are located in the deep-water, and the water column of the reservoirs is thermally stratified, this exchange occurs mainly in both deep-water compartments, where consequently PMC characteristics of both reservoirs become similar.

5.1.2. Variations in Particle Stratification Caused by Turbulence

[37] Differences in measured particle stratification during winter are most probably generated by different turbulence intensity within each reservoir. PMC and temperature are higher (Figures 7a and 7b), the latter also due to heat dissipation by the hydraulic machines. These increased values occur especially at the surface close to the intake/outlet of the power plant penstocks which experience higher turbulence due to the water flow, while the middle areas of the reservoirs are less disturbed (Figure 7a). Turbulence-induced mixing cause diffusive-type upward fluxes of particles in the water column decreasing the deep-water particle content and thus reducing sedimentation rates in the reservoirs [*Wolanski et al.*, 1992].

[38] This increase in surface PMC close to the dam is mainly observed in Grimselsee, while in Oberaarsee the center of the reservoir shows slightly higher PMC than at the equivalent location in Grimselsee (Figure 7a). We explain this by Oa-M being closer to the intake/outlet of the penstocks and, moreover, because Grimselsee is divided by a natural bedrock barrier in two morphologic basins, thus separating Gr-M water more from Gr-D water. This suppression of lateral mixing in Grimselsee is in particular effective at low water levels (winter and spring), when this barrier leaves only a narrow passage between the basins.

5.2. Reservoir Sedimentation

[39] Before PS operations started in 1980, no connection existed between the two reservoirs, except for a minor natural river. As a consequence, Oberaarsee became more turbid, whereas Grimselsee became clearer since PS operations started to exchange water between the reservoirs. This is especially valid for the winter season, when the reservoir volumes are exchanged several times but also for the summer, when the reservoirs exchange less water compared to their volume (Figure 2b) but of distinctly different and higher PMC. These variations in PMC should be reflected also in the sedimentation, which should have been modified since 1980 similar to PMC. In this study, we consider only sedimentation of the suspended fine particles from the water column, which are distributed laterally over the entire reservoir. The dominantly sand-sized particles, entering laterally by turbidity currents in the thalweg of the reservoirs and providing the bulk of the retained sediment mass, are not subject of this study, as this fast-settling coarse material is not affected by PS operations.

[40] Variations in PMC and sedimentation rates in the reservoirs imply a change of PMC characteristics in the downstream waters. However, the outflow of the reservoirs, which enters into Räterichsbodensee (power plant “Grimsel 1”) or into Gelmersee (Figure 1) before being released to the downstream River Aare, is irregular, making it difficult to determine any consistent trends. Furthermore, no direct pre-PS turbidity or PMC measurements were performed so that no data is available for direct comparison. However, an approximated estimation of the sedimentation in the water column can be made using the CTD-based PMC measurements in the reservoirs. The volume-integrated particle mass PM in a reservoir (Table 3a) is obtained from the $PMC(z)$ and the bathymetry-dependent area $A(z)$, which are both a function of depth z, by (in grams)

$$\mathrm{PM} = \int_{z_{\max}}^{z_{\mathrm{surf}}} PMC(z)\,A(z)\,dz.$$

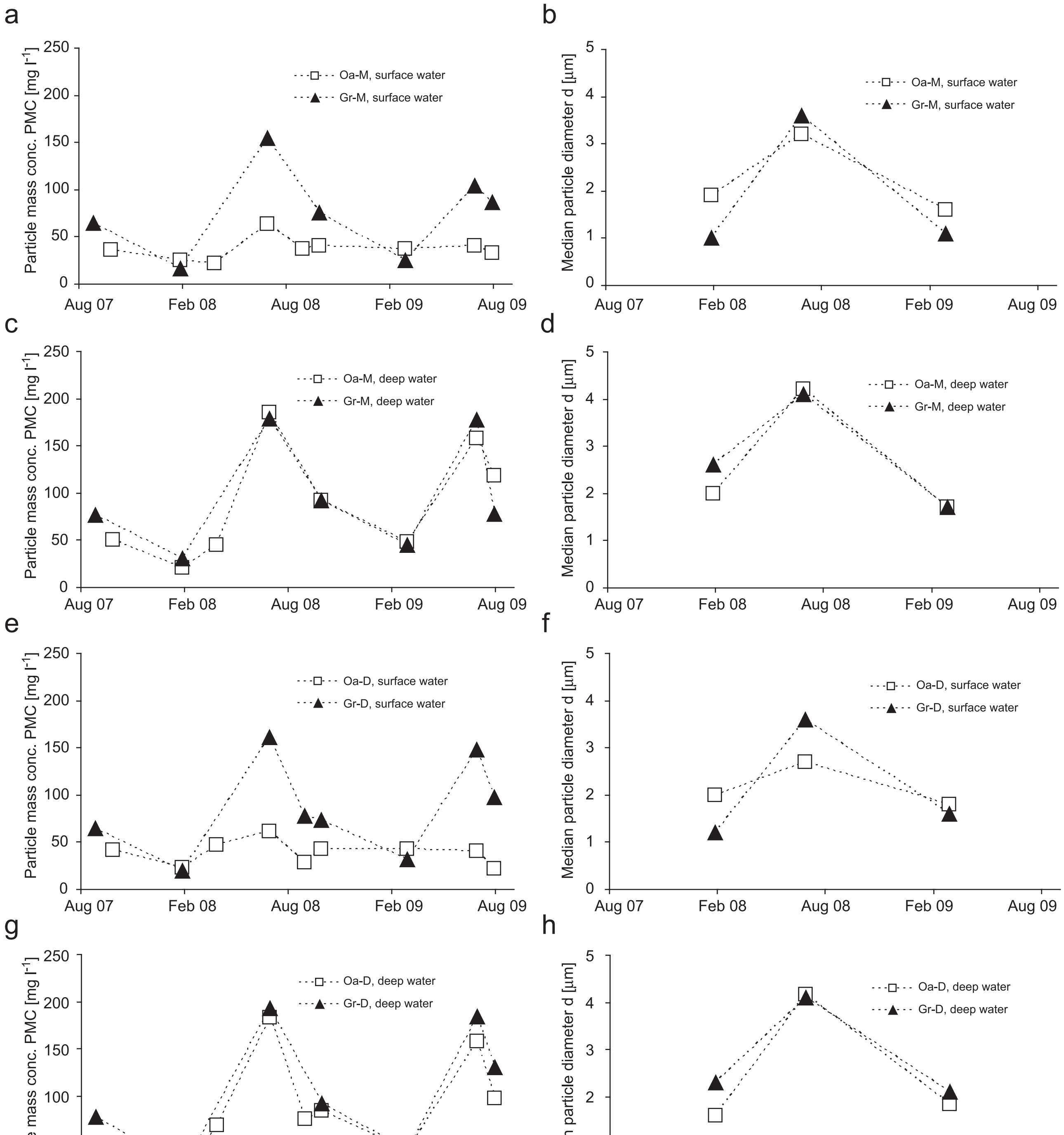

Figure 8. PMC and median particle diameters measured in surface and deep water samples collected in the middle of Oberaarsee and Grimselsee ((Figures 8a–8d); Oa-M, Gr-M) and close to the intake/outlet of "Grimsel 2" ((Figures 8e–8h); Oa-D, Gr-D). (a) In summer PMC values at Gr-M are higher than those at Oa-M; but in winter PMC in the surface water in the middle is similar in both reservoirs. (b) Median particle diameter of deep-water is slightly higher in Oa-M in late winter and higher in Gr-M in summer. (c and d) The deep-waters show similar PMC and median particle diameters in both reservoirs. (e) In summer, PMC is higher in Grimselsee. Surface water from close to intakes/outlets shows similar PMC in winter in both reservoirs. (f) Particle diameters in the surface water close to the intakes/outlets are higher in Grimselsee in summer and slightly higher in Oberaarsee in winter. (g) PMC of deep-water close to intakes/outlets is similar in both reservoirs. Only in summer, Gr-D shows slightly higher values than Oa-D. (h) Median particle diameters of deep-water are similar in both reservoirs in winter and in summer season.

Table 3a. Particle Budget of the Reservoirs With and Without PS

	Water Flow (10^6 m^3 yr^{-1})	Particle Budget With PS (kt yr^{-1})		Particle Budget Without PS (kt yr^{-1})	
		Input			
Oberaarbach	46.5	6.8	(70% in summer)	6.8	(70% in summer)
Unteraarbach	223.5	51.2	(70% in summer)	51.2	(70% in summer)
Total input	270	58		58	
		Outflow			
From Oberaarsee (upper basin)	46.5	3.9	(avg. PMC = 83.7 mg l^{-1})	2.6	(avg. PMC = 55.3 mg l^{-1})
From Grimselsee (lower basin)	223.5	20.8	(avg. PMC = 93.0 mg l^{-1})	22.3	(avg. PMC = 99.7 mg l^{-1})
Total outflow	270	24.7		24.9	
		Pumped-Storage Fluxes			
Oberaarsee -> Grimselsee	600	50.2	(avg. PMC = 83.7 mg l^{-1})		
Grimselsee -> Oberaarsee	600	55.8	(avg. PMC = 93.0 mg l^{-1})		
		Sedimentation[a]			
Oberaarsee (upper basin)		8.5	(avg. PMC = 62.9 mg l^{-1})	4.2	(avg. PMC = 42.9 mg l^{-1})
Grimselsee (lower basin)		24.8	(avg. PMC = 82.4 mg l^{-1})	28.9	(avg. PMC = 88.3 mg l^{-1})
Total sedimentation		33.3		33.1	

[a]Surface water is at 2 m depth. Measurements for Oberaarsee is Oa-D and for Grimselsee is Gr-D and the middle of the two reservoirs are Oa-M, Gr-M.

PMC(z) is linearly interpolated between measurements, while the volume of the reservoirs changes due to fluctuating water levels z_{surf}. Settling velocity w (Figure 9) is calculated using Stokes' law (in meters per second):

$$w = \frac{2(\rho_p - \rho_w)gr^2}{9\mu},$$

where ρ_p is the density of the particles (2650 kg m^{-3} [*Anselmetti et al.*, 2007]), and ρ_w is the density of water, r is the particle radius, and μ is the dynamic viscosity of water ($\sim$1.5 10^{-3} Pa s). For the particle radius we use the measured median radius—and its relation to PMC (Figure 10)—as a proxy and introduce a correction factor to match the observed sedimentation rates in the reservoirs [*Anselmetti et al.*, 2007]. Based on the particle-size distribution (Figure 6), the median particle radius is 2.5 times smaller than the distribution-based equivalent Stokes particle radius. Based on our particle budget, the correction factor is accidentally 1.0 and therefore the median radius approximates the sedimentation very well. Given the nonspherical form of the majority of the particles, the lower than Stokes settling rate is not a surprise.

[41] This allows approximating the sedimentation rate (SR) in the two reservoirs considering the time-dependent surface area $A(t)$ of the reservoir, the near-bottom *PMC(t)* and the settling velocity $w(t)$ (in grams per second)

$$\text{SR} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} w(t)PMC(t)A(t)dt.$$

The results for SR are summarized for both reservoirs in Figure 11, which shows the temporal dynamics of sedimentation over the two years of study. SR of the suspended particles increases with increasing settling velocity $w(t)$, increasing reservoir surface area $A(t)$ and *PMC*(t) and SR reaches its maximum in summer. In winter, however, SR decrease and is similar in both reservoirs (Figure 11). As a consequence, we postulate that suspended-particle sedimentation has changed since the initiation of PS operations in 1980, given that Grimselsee waters increases PMC in Oberaarsee and that less-turbid Oberaarsee waters lowers

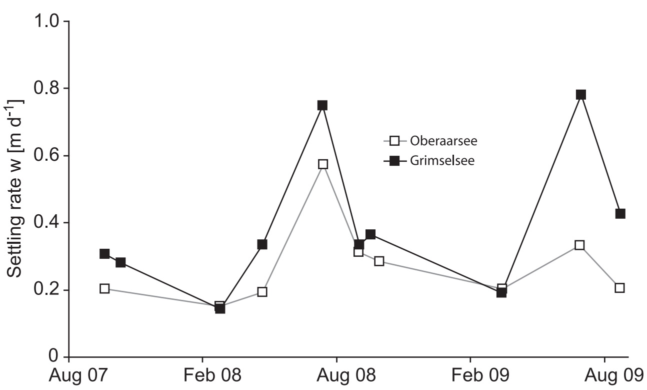

Figure 9. Settling rate of suspended particles (calculated by using Stokes' law) in Oberaarsee and Grimselsee during the 2 years of sampling. Symbols indicate sampling campaign dates (lines to guide the eyes).

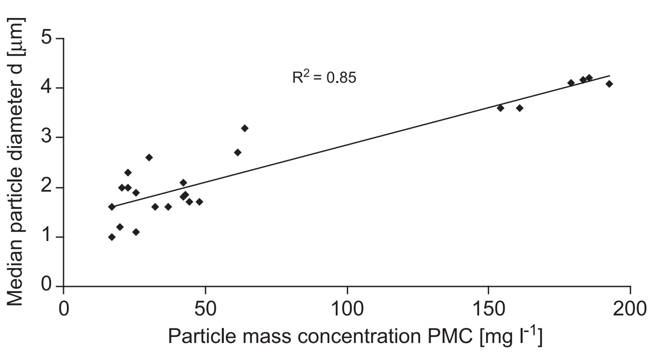

Figure 10. Relation between PMC and median particle diameter with indication of linear fit. This relation is used for calculating settling velocities of the suspended particles for the periods between sampling campaigns.

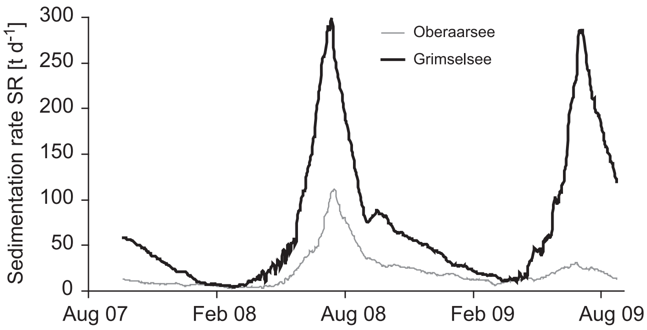

Figure 11. Simulated sedimentation rate from the water column in the two reservoirs during the 2 years of sampling. For settling velocity, see text.

PMC in Grimselsee. Unlike the mean reservoir surface (Table 1), which is not drastically different compared to pre-PS operation, PMC has been changed significantly in winter, when the volume of exchanged water is several times the reservoir volume (Figure 2b). In summer, the main change occurred in the deep zones, where waters with contrasting PMC are exchanged.

5.3. Simulation of the Reservoirs Particle Budgets

[42] In order to quantify the differences between today's condition and those during pre-PS operations, we used a mass balance model for a year-long simulation of the particle fluxes in the two reservoirs. Model assumptions are based on the observations from the 2 year measurements (Table 3a, Figure 12). The linear model allows us to simulate particle fluxes in the investigated system including particle inputs, outputs, PS-operations exchange and sedimentation. The reservoir volumes and the water flows are realistic and based on the last years' operations provided by KWO. The particle input (only suspended particles), was estimated with the goal to obtain the average observed PMC (63 mg l^{-1} and 82 mg l^{-1} for Oberaarsee and Grimselsee, respectively) similar to the average PMC from the interpolated CTD-derived PMC measurements (56 mg l^{-1} and 81 mg l^{-1} for the two reservoirs, respectively). The particle input of the reservoirs was adjusted for obtaining the observed average PMC and the seasonal fluctuations as close as possible to the measurements. Sediment resuspension is not considered in the model, as (1) the proglacial sediments are mainly composed of very fine grained inorganic particles, which are highly cohesive, making resuspension unlikely and as (2) resuspension has not been observed.

[43] For the linear model we make the following assumptions: (1) PMC in the reservoirs remain constant over the course of 1 complete year (no long-term tends); (2) the particle input is 5 times higher from June to September (after ice-breakup; snow/ice melting) than during the other 8 months; (3) the median particle diameter is related to PMC by the relation provided in Figure 10 and the corresponding settling velocity is estimated according section 5.2; (4) the PS and power production are constant throughout the year.

[44] The integrated particle-mass content, PM, is then calculated in time-steps of 1 day (*t*-1 to *t*) for both reservoirs by (in grams)

$$\begin{aligned} \mathrm{PM}(t) = \mathrm{PM}(t-1) &+ \Delta \mathrm{PM}_{\mathrm{natural\_in}}(t-1) \\ &+ \Delta PM_{power\_operation\_in}(t-1) \\ &- \Delta \mathrm{PM}_{\mathrm{power\_operation\_out}}(t-1) \\ &- \Delta \mathrm{PM}_{\mathrm{Sed}}(t-1), \end{aligned}$$

according to the natural particle inflow, the input by PS/power operation as well as the output by outflow (PS/power operation) and sedimentation. The PMC at the outflow and the PMC exchanged between the reservoirs (PS) are higher than the volume-averaged PMC in the reservoirs because

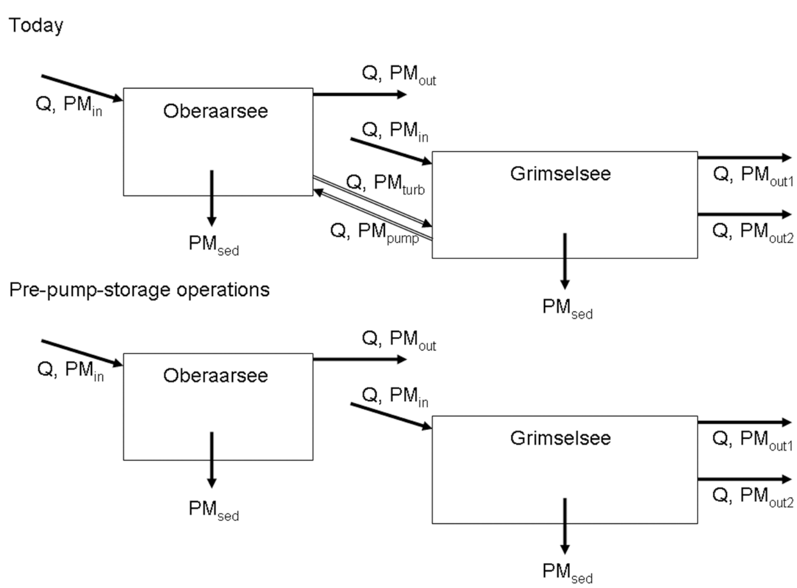

Figure 12. Diagram showing Oberaarsee and Grimselsee water and particle fluxes today (with PS operations) and without PS operations (Q: water flow, P: particle load; in: inflows, out: outflows (Grimselsee has two outflows), turb: turbine operation flow, pump: pumped (PS) flow, sed: sedimentation).

the penstocks exchange deep-waters, which are richer in particles. On the basis of the measured PMC, this factor (PMC deep-water/reservoir-averaged PMC) was fixed to 1.59 and 1.17 for Oberaarsee and Grimselsee, respectively, for the months of June to September and to 1.20 and 1.10, respectively, for the other 8 months, when the reservoirs are less stratified. The model can be used not only to simulate the current reservoir characteristics for the investigated period, but furthermore allows for any other scenario, for instance one that considers the variability of most of the parameters such as the effect of PS operations or fluctuating hydrology causing variable particle input from runoff.

[45] Our simulations indicate that, as a result of PS, Grimselsee loses particles of 5.6 kt yr^{-1} to Oberaarsee (Table 3a). Before the onset of PS, PMC and the total particle mass have been higher in Grimselsee and lower in Oberaarsee (Figures 13a and 13b). Oberaarsee, which has a lower volume and is thus more sensitive to PS operations, shows an increase in annual average PMC of ~45% (from 43 to 63 mg l^{-1}), while Grimselsee is affected by a decrease of only ~5 to 10% (from 88 to 82 mg l^{-1}). These changes are reflected in the sedimentation, which has increased from 4.2 to 8.5 kt yr^{-1} (+100%) in Oberaarsee and decreased from 28.9 to 24.2 kt yr^{-1} (−15%) in Grimselsee. Furthermore, the overall sedimentation has only slightly increased, mainly due to the fact that the settling velocity is only slightly nonlinearly related to PMC.

[46] The model was used to test for other PS scenarios considering inter-annual variability in particle input, loss of reservoir capacity, increase of PS operations and different reservoir volumes. Doubling of PS-operation activities would mix the two reservoirs further and therefore increase the PMC of Oberaarsee (~3%) and decrease slightly (1%) that of Grimselsee (Table 3b). Infilling and therefore loss of capacity of the reservoirs (simulated with 90% of the actual volume) will cause an increase of the PMC in both reservoirs by ~ 4%. On the contrary, increasing the volume and the area of Oberaarsee (reaching the volume and area of Grimselsee) would dilute the reservoirs and therefore reduce the PMC of both reservoirs (~ –30% and ~ −13%, respectively; Table 3b). Finally, a doubling of the particle input in Oberaarsee and a 50% decrease of input to Grimselsee would imply a decrease of PMC in both reservoirs and would cause an equalization of the concentrations (Table 3b). The riverine particle input to the reservoirs depends mainly on the hydrology, i.e., the rainfall amounts. In our simulation (performed with and without PS scenarios) the modification of the natural particle input (±20% and ±50%, Table 3b) causes drastic changes in PMC in the reservoirs. Reducing the input will percentage-wise enhance the effect of PS operations, while increasing the particle input will partially contrast this effect. In fact, considering the 50% decrease of particle input, PMC in Oberaarsee and Grimselsee will increase by 56% and decrease by 8% with PS operations, respectively (Table 3b). Lowering the input will instead cause a PMC difference of +42% and −7% in the reservoirs (Table 3b). In summary, various tests can be performed and concerns from downstream stakeholders—as experienced in this particular case [*Wüest et al.*, 2007]—can be addressed before upstream changes are implemented.

6. Summary and Conclusions

[47] The effects of pumped-storage (PS) operations on the temporal and spatial distribution of particles and temperature were investigated in two connected high-Alpine proglacial reservoirs (Oberaarsee and Grimselsee, Switzerland), both of which are characterized by high particle loads due to upstream glacial abrasion. Although the two reservoirs have distinctly different particle regimes, the extensive PS-related water exchange between the two reservoirs substantially equalize their concentrations. Especially in winter, the particle-mass concentrations (PMC) converge due to much higher water and particle exchange relative to the external inflow. Based on a linear coupled model, the annual average PMC has increased in the less-turbid reservoir (Oberaarsee) by ~45% and decreased in the more turbid reservoir (Grimselsee) by ~5 to 10%. Correspondingly, the annual sedimentation in the two reservoirs has increased by ~100% and decreased by ~15%, respectively, and the seasonal regimes have changed as a

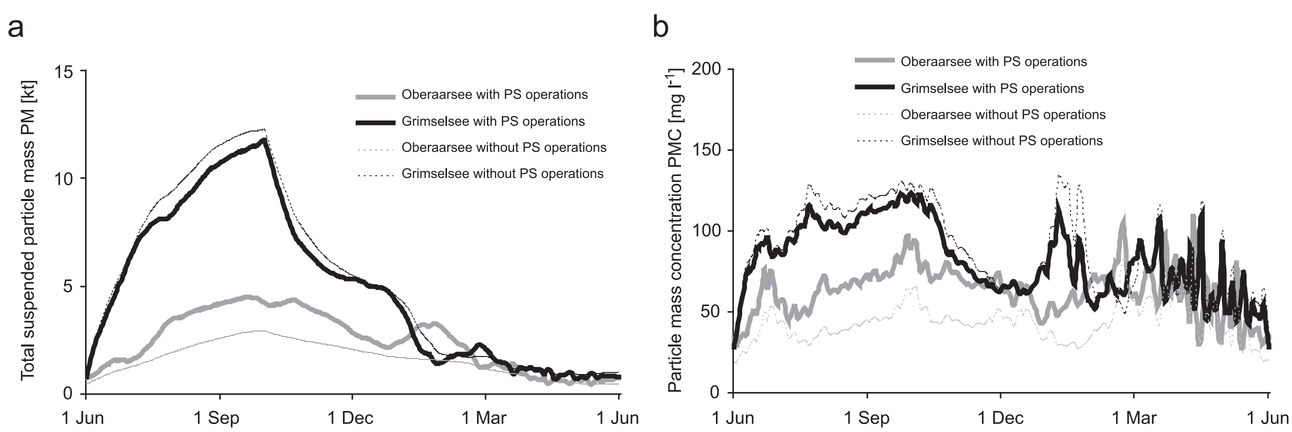

Figure 13. (a) One year simulation of volume-integrated suspended particle mass in Oberaarsee and Grimselsee, with and without PS operations. (b) One year simulation of PMC in Oberaarsee and Grimselsee, with and without PS operations. The variations in PMC in spring are due to the low water volume of the reservoirs and the corresponding large relative effect of particle input.

Table 3b. Comparison of PMC of the Reservoirs After Modification of Different Physical and Technical Parameters

	Oberaarsee Average PMC (mg l^{-1})	Grimselsee Average PMC (mg l^{-1})
Without PS operations	42.9	88.3
Without PS, increasing the riverine particle input by 20% in both reservoirs	48.6	98.8
Without PS, increasing the riverine particle input by 50% in both reservoirs	56.1	112.8
Without PS, decreasing the riverine particle input by 20% in both reservoirs	36.7	76.5
Without PS, decreasing the riverine particle input by 50% in both reservoirs	25.7	55.3
With PS operations	62.9	82.4
Increasing of PS operations from 600 to 1200 $\times$ 10^6 m^3 yr^{-1}	65.2	81.7
Increasing of PS operations from 600 to 2400 $\times$ 10^6 m^3 yr^{-1}	66.5	81.2
With PS, reducing the volume and the area of the reservoirs (both −10%) due to sediment infilling	63.9	84.3
With PS, volume and surface of Oberaarsee equalized to that of Grimselsee	43.9	71.4
With PS, doubling of riverine particle input into Oberaarsee and halving that of Grimselsee	55.6	61.0
With PS, increasing the riverine particle input by 20% in both reservoirs	70.1	92.5
With PS, increasing the riverine particle input by 50% in both reservoirs	79.5	105.8
With PS, decreasing the riverine particle input by 20% in both reservoirs	54.8	71.2
With PS, decreasing the riverine particle input by 50% in both reservoirs	40.0	51.2

result of the PS activity, although the total annual sedimentation (~60% of input) has increased by only ~1%.

[48] The modified particle distribution affects the density stratification in the reservoirs. During snow melt, the reservoir with the larger and more glaciated catchment (Grimselsee) becomes much more turbid, which prevents sunlight penetration through the turbid water and subsequently impairs considerably the development of thermally induced density stratification. This contrasts to the clearer Oberaarsee, which forms a warm surface layer. As a result, PS water-exchange during summer homogenizes the deep-water particle concentrations of the two reservoirs but minimally affects the more transparent and warmer surface layers, which become partly decoupled from the turbid deep-water.

[49] In conclusion, although the details of the findings in this case study are site specific, there are several aspects, that are relevant to any planned PS operation in the Alps and/or other mountain region lakes or rivers with considerable PMC (such as glaciated catchments).

[50] 1. The case study is representative of the Alpine region as the reservoirs investigated are typical for the central Alps. The approach allows for quantification of modifications in particle fluxes of planned (or operated) PS schemes. Although the absolute particle contents can be reconstructed with an uncertainty of ~10%, the differences between scenarios are more accurate.

[51] 2. For our specific system, in which the two reservoirs had similar average depths and hydraulic residence times, the annual downstream release of particles has changed only little. However, if the reservoir connected by PS has shallow depth and long residence time, upstream particle sedimentation would drastically increase and the annual downstream particle load would be reduced as more particles are retained.

[52] 3. The change in PMC affects light attenuation and therefore the surface temperature and the thermal density stratification. Low particle contents increase the transparency of the reservoir waters, the temperature of the downstream flow, and the stability of the water columns, thereby modifying the vertical concentration profiles. Depending on the elevation of the reservoir outlet, the temporal regime of the downstream particle load can actively be modified or even controlled.

[53] 4. Natural particle input is the primary factor causing variation in PMC between two coupled reservoirs. Enhancing PS activities increases PMC of the formerly clearer reservoir and decreases that of the more turbid reservoir.

[54] 5. The model approach used in this study can be applied in the planning phase to alter or mitigate the temporal particle load or the thermal regime. If the goal is to reduce the particles in the already affected downstream river, the PS water exchange should be confined to the deep (stratified) reservoir waters and the outflow can be skimmed from the clearer (low-particle) and warmer surface water. The design of the reservoirs and the PS scheme allows thus to reduce undesired modifications of the downstream flow regime.

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