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# Effects of upstream hydropower operation on riverine particle transport and turbidity in downstream lakes

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[1] Retention in upstream storage dams results in modified riverine water and particle discharge patterns. Particularly, suspended solids input and intrusion dynamics in downstream lakes are affected by dam operations. In a case study, size-dependent particle budgets for peri-alpine Lake Brienz (Switzerland), downstream of major hydropower installations, were determined for a recent 8-year period (1997–2004) and compared to hypothetical no-dam scenarios based on numerical simulations. For this purpose, current tributary particle loads, as well as lake-internal sedimentation and turbidity dynamics, were assessed with in situ measurements. The analysis shows that hydropower damming drastically diminishes particle fluxes and minimizes (short-term) peak discharges. Reductions of high-flow events substantially cut the number of deep intrusions increasing particle supply to the lake surface layer. Furthermore, these hydropower operations shift particle inputs from summer to winter. As a consequence, such peri-alpine lakes become more turbid during winter and less turbid during summer, influencing the seasonal light regime and subsequently the dynamics of phytoplankton growth.

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## 1. Introduction

[2] Growing demands for freshwater, irrigation, and hydropower in the recent decades have called for increasing water storage in dams, reservoirs, and artificial lakes throughout the world [*McCully*, 1996; *Vörösmarty et al.*, 1997]. The downstream ecological and social impacts are subject to ongoing investigations [*Rosenberg et al.*, 1995, 1997; *World Commission on Dams*, 2000]. Important biological implications range from interference with fish migration and biodiversity [*Hart and Poff*, 2002], to changes in downstream vegetation [*Nilsson et al.*, 1997], and damaging river ecosystems [*Ward and Stanford*, 1995; *Hart et al.*, 2002]. Some consequences of altered discharge in rivers are subtle and interfere with the biogeochemical cycle and hence only become evident at long timescales [*Friedl and Wüest*, 2002]. Notably, damming might interfere physicobiogeochemically by causing (1) water temperature changes resulting from hydropower operations [*Preece and Jones*, 2002; *Meier et al.*, 2003; *Bartholow et al.*, 2005], (2) nutrient retention [*Humborg et al.*, 2000; *Friedl et al.*, 2004], and (3) hydrological pattern changes and reductions in suspended particle loads [*Vörösmarty et al.*, 2003; *Teodoru and Wehrli*, 2005; *McGinnis et al.*, 2006].

[3] Ablation rates in the European Alps range from 0.1 to 0.65 mm $yr^{-1}$ [*Hinderer*, 2001], leading to a total particle transport of about 50 Mt $yr^{-1}$ [*Veit*, 2002]. Especially large loads are observed in rivers with glacial catchments (e.g., Massa, $\sim$265 kt $yr^{-1}$ (500 $m^3$ $yr^{-1}$ $km^{-2}$); Dixence, $\sim$177 kt $yr^{-1}$ (650 $m^3$ $yr^{-1}$ $km^{-2}$); Drance, $\sim$1,555 kt $yr^{-1}$ (850 $m^3$ $yr^{-1}$ $km^{-2}$) [*Bezinge*, 1987]). Accordingly, particle retention in large alpine reservoirs is tremendous and can locally lead to siltation problems [*Fan and Morris*, 1992; *Schleiss and Oehy*, 2002]. As a direct consequence, the suspended particle load downstream of hydropower dams is significantly reduced and its daily and seasonal dynamics are governed by hydropower operations [*Loizeau and Dominik*, 2000]. Typically, alpine rivers in Europe flow into peri-alpine lakes, which act as deposition tanks for upstream sediment erosion.

[4] Both the particulate matter inputs and the river intrusion dynamics into such lakes can be strongly modified. The intrusion depth is mainly determined by river water density, which is a function of temperature (T), salinity (S), and suspended particle concentrations (CR; in the following, suspended particle concentrations are denoted as CR for river water and CL for lake water; Table 1). Hence, if CR exceeds a certain value, river water plunges within the lake, resulting in CR-driven turbidity currents. Such phenomena were observed for the first time by *Forel* [1885] in Lake Geneva and have been reinvestigated recently [*Lambert and Giovanoli*, 1988; *Loizeau and Dominik*, 2000]. These riverine deep water renewal processes are of major importance for oxygen supply to many hypolimnia [*Lambert et al.*, 1976, 1984; *Wüest et al.*, 1988]. Recent studies indicate that intense hydropower operations can reduce the frequency of such CR-driven turbidity currents and consequently lower the oxygen supply to the deep water layers of downstream lakes [*Loizeau and Dominik*, 2000].

[5] Furthermore, changes in the intrusion dynamics affect the vertical distribution of suspended matter and therefore the light regime in downstream lakes. Frequent

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