

Alpine Hydroelectric Power Plants and their “Long-range Effects” on Downstream Waters

Alpine hydroelectric power plants not only affect the local waters, but also streams and lakes that lie far downstream. The transport of suspended solids, for example, is significantly reduced below reservoirs, which affects the oxygen content of lower lying lakes. Apart from suspended solids, reservoirs also retain nutrients. The collapse of landlocked salmon populations in the Canadian Columbia River, for example, appears to be caused by the construction of several dams, which reduced the nutrient concentrations in downstream lakes. Hydroelectric power generation also changes the temperature regime of downstream waters.

Hydroelectric power is of enormous importance to our economy and to society in general. With an annual production of 38 TWh, Switzerland's hydroelectric power plants provide 58% of the domestic electricity production; approximately 60% of this production is generated in the Alps. Over the last 50 years, 130 reservoirs have been built. With a total volume of 4 km³, they can retain a quarter of the annual discharge from our alpine watersheds (Rhône, Ticino, Rhine, Reuss and Aare).

Downstream Export of Ecological Deficits

Such intensive utilization cannot be without ecological impacts on streams (see box). In addition to the well-known local effects, there are impacts that can be felt in distant, lower-lying stream sections, lakes and coastal waters [1]. The worldwide criticism of hydropower [2], therefore, calls for the differentiated assessment of these frequently neglected impacts. It is the purpose

of this article to discuss some of these ecological deficits that are being exported, together with the electricity, to the lowlands (see also article by M. Fette on p. 21).

Reservoirs as Particle Traps

Since construction of the roughly 50 dams in the Rhône watershed, the annual suspended solid load carried into Lake Geneva has dropped by almost 50% to approximately 1.5 million tons [3]. Because the main demand for electricity is during the winter months, most of the water is stored in the reservoirs for more than half a year before it is sent through the turbines. During this time, most of the suspended solids settle to the bottom of the reservoirs. As an additional consequence, the frequency of flooding in the Rhône has dropped significantly. Before construction of the dams, discharge volumes exceeding 500 m³/s were observed on 23 days per year, whereas today such high discharge takes only place at an average of five days [3].

The reduced suspended solid load and flooding frequency also change the hydraulic regime of most lower lying alpine lakes. The reason is that the water density depends in part on temperature and dissolved solids, but even more on the concentration of suspended solids. When the concentration of suspended solids exceeds approximately 0.5 g/l (Tab. 1), the stream water becomes heavier than lake water and sinks to the deep regions of the lake. This effect is

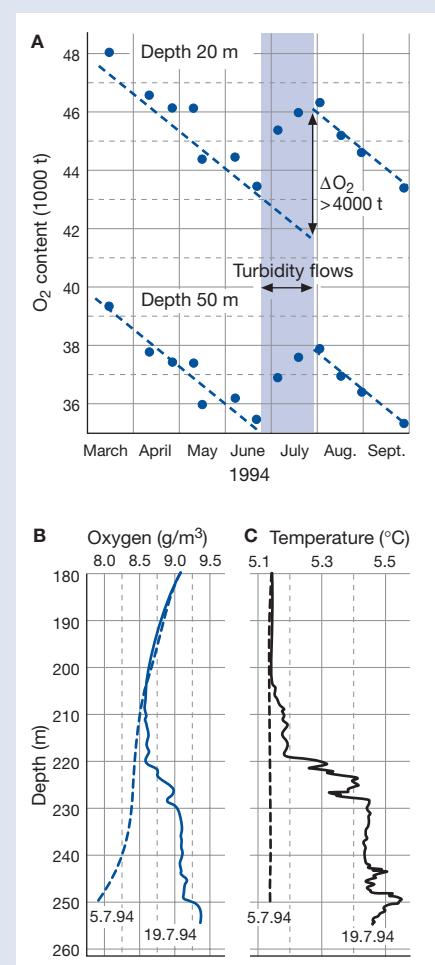


Fig. 1: Oxygen budget in deep water of Brienzensee in the summer of 1994: in July, several warm and particle-loaden flows from the Aare and the Lüttschine – induced by thunderstorms – transported approximately 4000 tons of oxygen into the deep water layers within only a few hours (A). Oxygen (B) and heat (C) input between July 5 and 19 occurred primarily in the bottom 50 m.

Lake (river/sampling location)	Annual suspended solid load ¹ (million tons/year)	Average suspended solid concentration in summer ² (g/l)
Lake Constance (Rhine, Diepoldsau)	3.6	0.91
Lake Geneva (Rhône, Porte du Scex)	1.9	0.52
Brienzersee (Lüttschine, Gsteig)	0.16	0.39
Walensee (Linth, Mollis)	0.11	0.18
Brienzersee (Aare, Brienzwiler)	0.11	0.14
Lago Maggiore (Ticino, Bellinzona)	0.47	0.12
Urnersee (Reuss, Seedorf)	0.05	0.047

Tab. 1: Input of suspended solids into prealpine Swiss lakes (data: BWG/LHG, Berne).

¹ Annual average between 1979 and 1993 [LHG Berne]. (Biweekly measurement of suspended solids).
² Averaged solid concentrations in summer (June to August).

Impacts of reservoirs on downstream rivers and lakes in a global context [2]

Impacts marked in *cursive* are relevant in an alpine environment.

Hydrology:

Seasonal shift in the discharge pattern, fewer flood events, hydro peaking, in-stream flow, changes in groundwater levels, changes in the internal hydraulic processes of downstream lakes, water loss.

River morphology and suspended solids:

Retention of suspended solids, temporal shift in turbidity and particle/nutrient transport, clogging, stagnant river morphology, erosion, delta and shore recession.

Geochemical cycles:

Primary productivity, modification of water quality, self-purification and nutrient retention in reservoirs, anoxic reservoir runoff, release of reduced compounds and metals, methane production.

River and floodplain ecology:

Shift in composition of biotic communities, disruption of connectivity, loss of flooded wetlands, flood plains, and stream-land transitional zones, new wetlands in root dam zones.

Fish ecology:

Interference with migration and fragmentation of populations, shift from stream species to lake species, flooding of spawning grounds, changes in thermal regime, reduction of habitat quality in sections with low residual flow or hydro peaking, gas bubble disease, anoxic reservoir runoff.

particularly pronounced in the case of high water events that are caused by thunderstorms, since they tend to carry high loads of suspended solids. The result is an increase in the oxygen content of the deep water.

This increase in oxygen concentrations is directly caused by the sinking stream water transporting large amounts of oxygen to the bottom of the lake. An EAWAG report [4] documented that in July of 1994 several of such flows of dense stream water carried approximately 4000 tons of oxygen into the deep water of Brienzensee (Fig. 1A). This caused a dramatic increase in oxygen concentrations (Fig. 1B) especially in the deepest layers. By comparison, artificial aeration of lakes on the Swiss plateau introduces less than 500 tons of oxygen per year.

There is also an indirect mechanism for introducing oxygen. The stream water is not only denser but also warmer than the deep lake water, so each episode of stream water intrusion causes a slight warming of the deep water (Fig. 1C). Over a period of years, the temperature of deep water gradually increases – as, for example, in Lake Geneva where the temperature has increased by 1.5 °C [5]. As a result, the density gradient in the deep parts of the lake becomes smaller, which prepares the lake for efficient, deep mixing. Such a complete turnover event occurs sporadically, approximately every 5–10 years, and also brings a lot of oxygen-rich water to the deepest parts of the lake.

Flash-floodings that carry high suspended solid loads, therefore, have an important ecological function in the large prealpine lakes (Tab. 1). The direct and indirect supply of oxygen has in the past contributed substantially to the fact that these lakes (with the exception of Lake Lugano) had relatively favourable oxygen conditions, even in times of high nutrient loading. The less frequently such sinking stream surges occur, the more the oxygen conditions near the lake bottom will deteriorate. From the viewpoint of lake ecology, any further reduction in particle-rich flood events is highly undesirable.

Reservoirs as Nutrient Traps

Along with suspended solids, reservoirs also retain nutrients. While this is a positive side effect in our over-fertilized Swiss watersheds, it can lead to detrimental changes in the fauna and flora of nutrient-poor regions. We became painfully aware of this fact in the late 1980s, when the populations of a unique landlocked salmon, the “Kokanee”, in Lake Kootenay and in the Arrow Lakes of British Columbia (Canada) collapsed in a disturbing way (Fig. 2). These lakes are on the Kootenay and Columbia Rivers, both of which have seen the construction of two major dams. Since their construction, the annual phosphorus input to the downstream lakes has dropped by approximately 50 tons [6].

For the lack of other convincing arguments, nutrient retention by the upstream dams/

reservoirs was identified as the most likely cause for the “Kokanee crisis”. In response, the lakes (Kootenay Lake since 1992 and the Arrow Lakes since 1999) are being fertilized with 50 tons of phosphorus and 200 tons of nitrogen annually (see photo on p. 20). Whether this highly controversial emergency measure was effective – it was feared that these salmon populations were going to be lost entirely – cannot be concluded with any certainty at this point; however, the number of spawners appears to have stabilized to that of previous levels (Fig. 2) [6]. EAWAG asked the question about whether other factors might not have contributed to the decline in Kokanee populations [7]. These studies revealed that the additional damming of the Arrow Lakes themselves, and the depth of the outlet in particular, had a critical effect on the flushing of biomass from the lake system.

Dissolved nutrients may also be retained selectively, depending on the conditions of individual reservoirs. If the retention time is long enough, diatoms can effectively remove silicic acid [8]. For example, rivers in

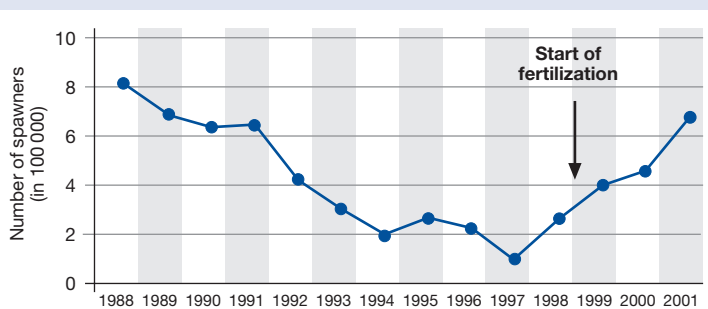


Fig. 2: Collapse and recovery of the population of the landlocked salmon Kokanee in the Arrow Lakes [6].



K. Ashley, Canada

Barge with nutrient tanks on Kootenay Lake, which has received 50 tons of phosphorus fertilizer annually since 1992 [6].

the mountains of northern Sweden that are dammed, carry up to 60% less silicic acid to the Baltic Sea than rivers from watersheds that are not dammed [9]. There are concerns that the diatoms in the Baltic Sea will gradually be replaced by other species, which could lead to changes in the composition of both zooplankton and fish communities. A similar downstream effect is currently being investigated in an EAWAG project concerning the “Iron Gate” dam on the system of the Danube and the Black Sea.

Reservoirs as Modulators of River Temperature

The utilization of hydropower affects not only particle and nutrient transport, but also the temperature regime of downstream lakes and streams. When water drives turbines in a power plant, potential energy is converted to electricity. Under natural discharge conditions, this energy is dissipated via friction into heat, thus warming the stream water. Operation of a turbine, therefore, causes cooling of the stream. For the Swiss Alps as a whole, the average temperature drop is 1.1 °C, and this in streams that

are normally rather cool. The effect is most significant on the Rhone where the temperature drop is 1.6 °C.

When taking annual and diurnal cycles into account, however, this estimate paints a rather incomplete picture since several indirect effects need to be considered as well. An enormous amount of heat energy is absorbed through the surface of the reservoirs during the summer months (ca. 14 km² in the case of the Rhone watershed) and partially carried over to the winter. Water sent through the turbines is taken from the bottom of the three large reservoirs (Mauvoisin, Grand Dixence and Cleuson) and has an even temperature of 4–5 °C over the entire year. In winter, when the discharge of the Rhone is low, the return water typically warms the river by 0.5 °C. During summer, water retention in the reservoirs reduces flow downstream, which leads to an increase in water temperatures. When turbine water is returned to the river, the cooler water abruptly lowers the temperature of the river. These temperature changes can amount to several °C (Fig. 3A and B).

Studies that are currently being conducted in the context of the revitalization project “Rhone/Thur” (see article by M. Fette on p. 21) are intended to investigate the effects of hydroelectric power generation on the thermal regime of the Rhone and to describe consequences for its inhabitants.

Current Swiss Problems

Since the 1980s, the fishermen on Brienzensee have warned about potential ecological changes caused by the hydroelectric power generation in the Grimsel area. As a result, EAWAG has conducted several studies investigating the potential effect on turbidity, which shows a different seasonal pattern due to the reservoirs [4]. After a massive collapse of fish yields and *Daphnia* populations in Brienzensee in 1999, the Canton of Bern decided to investigate the

ecological mechanisms in Brienzensee and their potential changes in more detail. Nine hypotheses were formulated; they will be tested in a number of research projects over the coming years. EAWAG will participate both indirectly in a consulting function, and directly by conducting research projects (fish, biological production, stratification, suspended solids, etc.). It is a rather complex and far-reaching task to document which of the large number of factors are the key “long-range effects” impacting Brienzensee.



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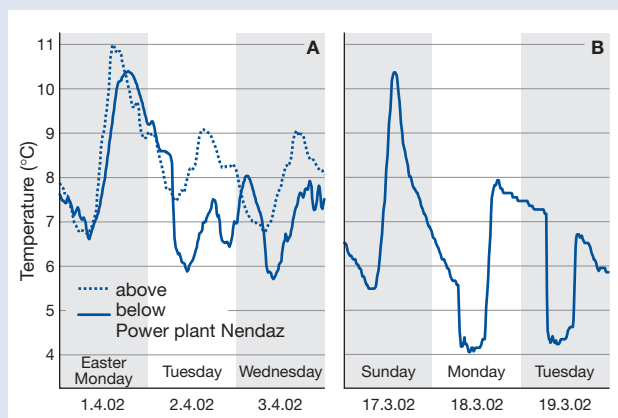


Fig. 3: (A) Temperature as a function of time in the Rhone above (dotted line) and below (solid line) the power plant outlet of Nendaz April 1–3, 2002. While on Easter Sunday (plant not operating) the temperature rose to over 10 °C at noon, the cold water of the Grande Dixence cooled the Rhone to below 6 °C on work days. (B) Temperature as a function of time in the Lonzonza (tributary of the Rhone) below the power plant outlet of Lötschen on March 17–19, 2002. For the same reasons as discussed above, the temperature varies by more than 6 °C between Sunday and Monday.