HUMAN-MADE LAKES AND RESERVOIRS: THE IMPACT OF PHYSICAL ALTERATIONS

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Keywords: Reservoirs, lakes, dams, nutrients, fish, temperature, hydroelectric power, oxygen depletion, hydro-peaking, particle trapping.

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Summary

Up to now, humankind has created about 800 000 artificial lakes and reservoirs (covering an area of 500 000 km^2) for drinking water supply, hydropower production, irrigation and flood control. Some 40 000 of those are so-called large dams, exceeding a height of 15 m. Beside the new aquatic ecosystems, which are often an asset in several respects, such as welcomed recreation opportunities, fishing as well as transportation, the slowdown and blocking of rivers show many ecological deficiencies such as oxygen depletion, greenhouse gas emissions, remobilization of metals, changes in natural variation of water discharge and temperature, changes in the nutrient balance, sediment trapping, blocking of upstream anadromous fish movement, and increased mortality of

downstream anadromous movements and fragmentation of the ecosystem. Sustainable management of natural resources should include environmentally sound dam operations with regard to the downstream as well as a quasi-natural management of the reservoir itself. This chapter concentrates solely on negative environmental concerns, knowing that this is only part of the picture.

1. Introduction

Damming of rivers and preexisting lakes has a significant impact on our natural water resources. Almost 800 000 artificial lakes and reservoirs (covering an area of about 500,000 km^2; ≈ 3% of the land surface) have been created by humankind in order to provide services such as drinking water supply, hydropower production, irrigation and flood control (often combined to multipurpose utilities). More than 40 000 of those impoundments are so-called large dams, raising the water in the reservoir at least 15 m above the river level. On a global scale, river damming increased the average residence time of the free flowing river waters on the continents by a factor of 2 from about two weeks to a month. Authors like Vörösmarty calculated that at a given moment in 1997, the amount of water stored behind dams is seven times the natural river water. In certain regions such as Southeast Asia man-made lakes and reservoirs comprise by far the greatest area of stratified inland waters.

Two aquatic ecosystems are the main subjects of concern: the downstream river stretches and the reservoirs themselves. On the one hand, impoundments turn the “rivers” into “lakes”, affecting not only the hydrology but also the physical, chemical as well as biological characteristics, including increased residence time, stratification, reduction in turbulence, decrease in turbidity, and increase of autochthonous primary production. On the other hand, residual flow, hydro-peaking and seasonal changes of hydrological regime will affect the reservoir itself, but mainly downstream rivers and lakes.

In addition, some impoundments can show greatly increased evaporative losses and thereby reduce the basin runoff. Although on a global scale only a small fraction of water is lost by evaporation, such losses can be important on a regional scale, especially in arid and semiarid climates, such as for the Nasser Reservoir in Egypt, where annually about 10 % of the stored water is lost . Similarly losses occur in many semiarid regions for example Lake Kariba (Zambesi River) and Tiga Reservoir in Nigeria.

This chapter gives an overview of the effects of man-made lakes on the “life supporting system” of natural lakes and rivers. By storing water for different anthropogenic purposes, humankind changes primarily the physical parameters of surface water. This in turn influences the chemical conditions and thus influences the biota within the downstream rivers as far as to the coastal seas. In the following the relevant processes are exemplified based on cases chosen from different regions in the world.

2. Turning Rivers into Lakes

2.1. Particle Trapping versus Particle Washout

A key aspect of human-made lakes and reservoirs is the slowdown of the flow velocity and the related settling of particles. The particle sinking velocity v_p [m s^{-1}] can be estimated by Stokes' relation

$$v_\mathrm{p} = \frac{\Delta\rho}{\rho}\frac{g}{18\nu}D_\mathrm{p}^2, \qquad (1)$$

where $\Delta\rho$ [kg m^{-3}] is the density difference between particles and water, ρ is the density of water [≈1000 kg m^{-3}], g = 9.81 m s^{-2} is the gravitational acceleration, ν [≈ 1-1.5·10^{-6} m^2 s^{-1}] is the viscosity of water and D_p is the particle diameter. River water, intruding into a reservoir with the discharge Q [m^3 s^{-1}] causes the water layers above the intrusion level to lift up with the velocity

$$w(z) = Q(z)/A(z), \qquad (2)$$

with $A(z)$ being the area at a certain depth above the intrusion level. If the settling velocity v_p is larger than the upwelling velocity (i.e. $v_\mathrm{p} > w(z)$) the particle will settle out, while the water flows through the reservoir.

For a typical example, such as the Upper Arrow Reservoir (British Columbia, Canada, see map below) the discharge of the Columbia River (average $Q \approx 1020$ m^3 s^{-1}) and the reservoir surface area ($A \approx 330$ km^2) leads to a vertical velocity of $w \approx 0.3$ m per day at the surface. It means, that all particles larger than

$$D_\mathrm{p} > \left(\frac{\rho}{\Delta\rho}\frac{18\nu}{g}\frac{Q}{A}\right)^{1/2} \qquad (3)$$

will sink to the bottom of the reservoir. For inorganic particles, where $\Delta\rho$ (≈1700 kg m^{-3}) is large, the limiting particle diameter is ≈1.8 microns (μm), whereas for organic particles ($\Delta\rho \approx 50$ kg m^{-3} is small) the limit would be as large as ≈13 microns (μm). Among the inorganic particles, mainly the colloidal fraction remains suspended in the water. In contrast, from the organic particles even the large ones can remain in the water body and can subsequently get washed out, especially if the reservoir outlet is at the base of the dam.

This settling versus discharge relationship is exemplified in Figure 1, where the clarity (expressed by the Secchi-depth) of Brienzersee water (a lake in Switzerland) is plotted for two consecutive years. The turbidity of this lake water is mainly of natural origin and is due to glacial flour originating from the mountainous watershed.

Although the seasonal hydrological regime is substantially affected by the hydro-power production within the catchment area, the annual discharge and particle input remained the same. During low discharge periods, such as during autumn 1995, upwelling w drops drastically and subsequently the particle concentration and the size of the suspended particles decrease. If the particle sizes fall below the range of visible light (≈0.3 μm) the water turns very clear and the Secchi-depth increases drastically, as shown in Figure 1.

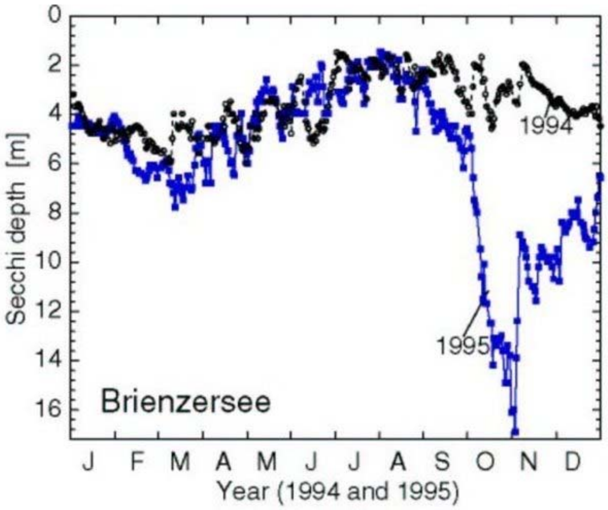

Figure 1: Secchi-depth as a function of time during two years in Brienzersee (a natural lake in Central Switzerland). The clarity of the water increased dramatically in autumn 1995 (compared to 1994), during dry-weather–related low river discharge.
Source: Sturm, M., C. Siegenthaler, H. P. Suter and A. Wüest.. (1996). Das Verhalten von Schwebstoffen im Brienzersee (Untersuchungsergebnisse der Jahre 1994-1995).

In reservoirs with low nutrient supply (typical for mountainous regions), algae are rather small in size and therefore their sinking velocity will be small (see Eq. (1)). As a result, the washout of biota can be substantial in strongly flushed reservoirs. While capturing the nutrients in the river system is a desired effect of a “classical” river dam in eutrophicated systems, it might be disadvantageous if the reservoir is a dammed (preexisting) lake. The potential effect of particle trapping will be discussed in Section 3.1 below.

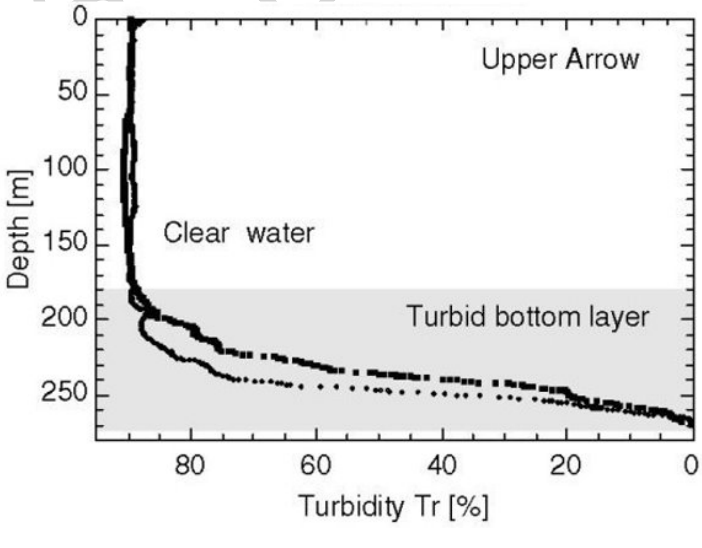

Figure 2: Transmissivity *Tr* [%] of light, measured at 0.68 μm over 25 cm path length, plotted as a function of depth in the Upper Arrow Reservoir (British Columbia, Canada, Figure 4) on 7. April, 1999, reveals *a* ≈ 80 m thick turbid near-bottom layer over a vast area of the reservoir.

2.2. Reservoir Sedimentation

Typical reservoirs consist of basins, which are widening towards the dam. Therefore, the horizontal current of the water masses slows down while approaching the dam and, as a result, particles in suspension become continuously smaller. Therefore the reservoir sediment has a graded structure, from gravel to sand to silt to clay, with the largest particles (and the largest sedimentation rate) at the river mouth and the smallest particles at the dam. Consequently, the released waters carry fewer particles, have higher clarity and are usually also cleaner.

According to the management of reservoirs and human-made lakes water levels are often subject to drawdown, to comply with power production, irrigation or flood control. The newly exposed sediments in the littoral zone release water as the water level drops and pressure on the sediment relaxes. As a result, air bubbles escape from supersaturated porewater and the sediment can become spontaneously unstable. Destabilized sediments can cause slumps, which have the potential to cover the benthic organisms (such as insect larvae, shrimps, worms, etc.), fish eggs and other biota over large areas of the reservoir. The larger the drawdown and the stepper the reservoir side walls the more frequent slumps will occur. Siegenthaler and Sturm described in their publication in 1991 in *Verh. Internat. Verein Limnol* 24 slump-produced turbidities (almost homogenized sediment layers) of up to more than 1 m thickness in the sediments of Urnersee (a lake in Switzerland). The material originated from unstably deposited river delta and the slumps were in this case probably triggered by earthquakes. As a result, the net sedimentation rate can be significantly larger in the flat deepest range of the basin – a phenomenon often referred to as sediment focusing.

Sediment slumps turn the water above the traveling slurry into a turbid layer. A typical signature of a slumping event is shown in Figure 2. The two turbidity profiles have been collected in the Upper Arrow Reservoir in April 1999 after the reservoir had been drawn down by ≈12 m during the previous winter. The profiles reveal that *a* ≈ 80m thick turbid (nepheloid) near-bottom layer covers a vast area of the reservoir. Such slumps have comparable effects to extreme flood events, efficiently covering and destroying the benthic organisms.

During flood events, the sedimentation rate behind dams can be gigantic, whereas there would be almost no deposition under natural riverine conditions. For example the disastrous monsoon in July 1993 swept ≈ 4 m of sediment into the Kulekhani Reservoir (Nepal) and reduced the storage capacity by ≈10% within a day .

2.3. Oxygen Depletion in Reservoirs

With the slowdown of the flow and the subsequent particle settling, turbidity decreases and light transmissivity increases, enhancing the in-situ primary production in the dammed river stretch. Thus, from the headwater of the reservoir to the dam the river changes from an allochthonous dominated system to a lacustrine system, where autochthonous production of organic matter dominates. The upper part of the reservoir receives organic matter of riverine origin, which is deposited on the sediment and mineralized. In the deeper part of the reservoir also in-situ produced particles (e.g.

algae) sink to the sediment, where they undergo decomposition. Either way, the decomposition of organic matter uses oxygen: $CH_2O + O_2 \Rightarrow CO_2 + H_2O$, where CH_2O stands for organic matter. The oxygen consumption depends on the allochthonous input of organic matter and on primary production. Oxygen concentration in the bottom water decreases if the delivery of oxygen is smaller than the demand. During thermal stratification the exchange between deep water and the atmosphere, and thus the oxygen supply, is cut short during stratification. The decomposition of organic matter consumes the deep water oxygen, subsequently leading to anoxic conditions. Depletion of oxygen evokes the reduction of nitrate, manganese (hydr)oxides, iron hydroxides and sulfate. Those are reduced to products such as Mn^{2+}, Fe^{2+} and H_2S, which will accumulate in the deep water. Under such conditions, microbial methanogenesis leads to the production and possible emission of the greenhouse gas methane (CH_4).

In some countries, discharged waters from hydropower reservoirs have to meet certain water quality standards set by the local authorities. For example many US Federal Energy Regulatory Commission licenses now include minimum dissolved oxygen levels of typically ≈ 5 to 6 g m^{-3} in the released water. If reservoirs are used for drinking water supply, the quality requires higher standards and as a result, oxygen depletion and subsequent dissolved metal and sulfur compounds make the water unsuitable for domestic uses. As a consequence, oxygen is frequently added either to the release of water or to the hypolimnion of the reservoir. The latter is often chosen to prevent costly treatment of the water but also to improve the reservoir as fish habitat and to improve the overall geochemical situation of the reservoir.

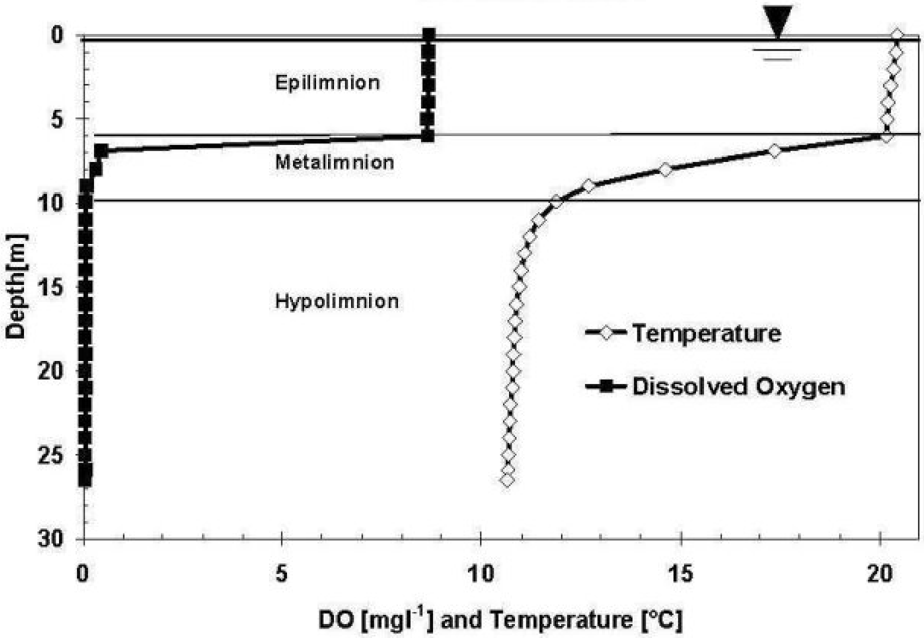

Figure 3: Dissolved oxygen (left) and temperature (right) profiles in an "East Bay reservoir" (California, USA) in September 1996. The high oxygen demand during the thermal density stratification depletes oxygen by ≈ 1 g m^{-3} per month, completely depleting oxygen by September (Source: M.H. Mobley, Technical Specialist, Engineering Laboratory, TVA, Norris, TN37828).

Figure 3 shows the situation in one of the “East Bay reservoirs" (California, USA) used for drinking water supply, where the deep water layers loose their oxygen during the summer months. By September 1996 the entire hypolimnion became anoxic giving rise to taste and odor problems. These unwanted effects were associated with blooms of small-celled colonial blue-green algae, stimulated by intense phosphorous loading. To control taste and odor problems and also to reduce the internal loading of phosphorous, hypolimnetic oxygenation systems are often installed (and planned in this case). Such technical mitigation measures have a side effect as they simultaneously improve conditions for higher organisms in the reservoir. From Figure 3 it becomes quite obvious that increased surface temperature combined with anoxic conditions in the entire hypolimnion and also close to the thermocline might limit the living space suitable for cold water fishes such as trouts. In such situations artificial oxygenation might be used to ensure the survival of certain fish species.

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Biographical Sketches

G. Friedl obtained her degree in geology at the University of Berne in 1988. After her masters degree she worked in a private company as geological and geotechnical consultant. She joined the Swiss Federal Institute for Environmental Science and Technology in 1991 and presented her dissertation based on the study of manganese cycling in Lake Sempach, Switzerland in 1995. As a postdoc she participated in the European Project EROS 2000, which was focused on nutrient cycling in the Northwestern Black Sea. During 1997 and 1998 she worked at the University of British Columbia (Canada) in field of oceanography, studying silver as a paleo indicator for productivity. Since two years, she is a senior scientist at the Limnological Research Center in Kastanienbaum (EAWAG), Switzerland, heading the group of sediment chemistry within the Department of Surface Waters. She has many years of experience in the analysis of aquatic systems and nutrient cycling. She is teaching environmental chemistry at ETH-Zürich. Since January 2000 she is member of the group for Applied Aquatic Ecology focusing her research on the environmental effects of river damming.

A. Wüest obtained his degree in particle physics at the University of Zürich in 1982. He worked on deep water mixing in natural waters (Prof. D. M. Imboden) and received his Ph.D. in 1987 from ETH Zürich including an award (Otto Jaag-Gewässerschutzpreis). Supported by a Swiss National Science Research and Travel Fellowship he worked during 1988 at the Applied Physics Laboratory (UW, Seattle, Prof. M.C. Gregg) on oceanic and estuary microstructure/turbulence. He has 16 years of experience in aquatic physics, especially in turbulence (small-scale turbulence, benthic boundary mixing, internal wave analysis and lake ecology and bio-geochemical cycling). Since 1989 he is head of the "Aquatic Physics" group and since 2000, head of the department of "Applied Aquatic Ecology". Dr. Wüst has more than 50 publications (including several book articles and consulting reports) and is teaching at ETH Zürich.