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The biological cost of hydropower

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The construction of dams in rivers has brought many benefits to human societies, such as electricity, irrigation, domestic water supply, transportation and flood protection. However, an environmental cost is paid for these benefits in form of disrupted ecosystems and reduced biodiversity. Most river systems are already affected by dams, and restoring the values destroyed by dams would, if possible, be very costly and take a long time. Therefore, exploitation of rivers by new dams to produce hydropower is not an ecologically sustainable means of power production.

Most river systems are affected by dams

The majority of the world's large river systems are affected by water-flow regulation and fragmentation by dams. Seventy-seven percent of the flow in the 139 largest river systems (mean annual discharge >350 m^3/s) in North America, Europe and the former Soviet Union is moderately or strongly affected by fragmentation or flow regulation (Dynesius and Nilsson 1994). Out of 13 river systems of this size in the catchment of the Baltic Sea, only one of remain unaffected by dams: The Torne-Kalix River system on the border between northern Sweden and Finland. In fact, this is the only river system of this size in Europe outside Russia that remains free-flowing.

Smaller river systems are affected by dams and flow regulation to a similar degree. In Sweden, Norway and Finland, 85% of the medium-sized river systems (mean annual discharge 40-350 m^3/s) are affected by dams (Dynesius and Nilsson 1994). Most of the major tributaries to regulated main river channels have dams as well. There are only two unaffected tributaries with a mean annual discharge >100 m^3/s in Sweden, Norway and Finland. Moreover, there are thousands of dams in small streams with discharges <1 m^3/s. Thus, any new dams in unaffected rivers in Europe will risk destroying unique environments.

Effects of hydropower on biodiversity

The effect of dams and flow regulation on biodiversity varies strongly with the spatial scale considered. Hydropower has caused relatively few species to go extinct from an entire river system in Northern Europe. However, at the scale of river reaches, river regulation has reduced species richness, altered species composition and ecosystem functioning.

Riparian zones along free-flowing rivers harbour one of the most species-rich vegetation types in temperate to arctic biomes. The riparian vegetation is generally vertically zoned due to differences in flooding tolerance among species. A typical zonation goes from a riparian forest rich in herbs at the top, followed by a shrub zone, graminoids, and amphibious and aquatic plants at the bottom. In regulated rivers, some lakes have been dammed to act as storage reservoirs, storing water from periods of high flow to periods when the demand for

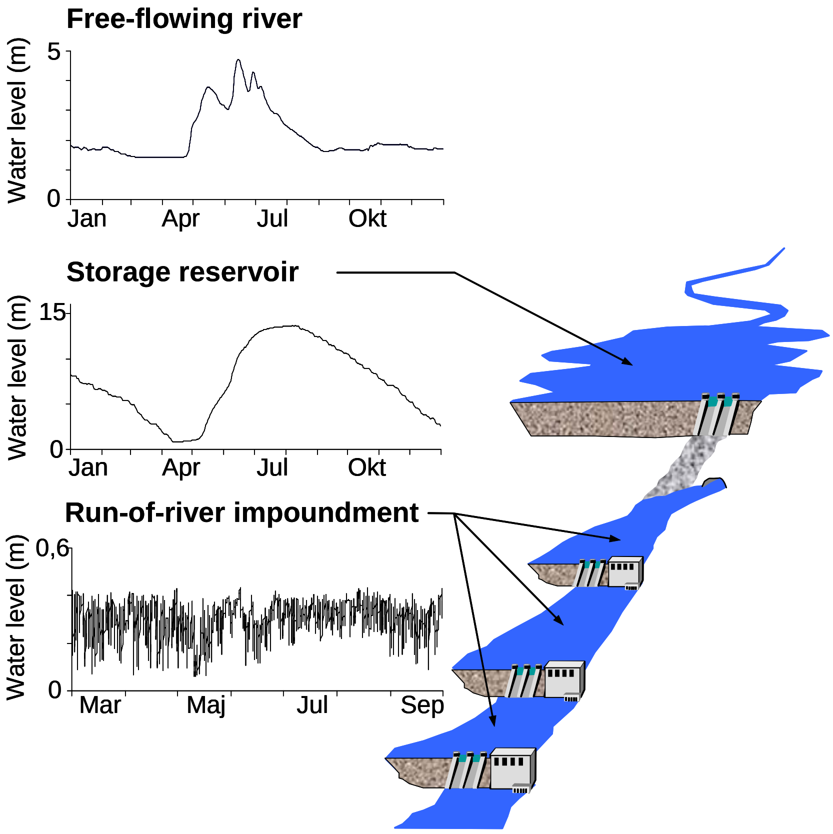

Figure 1. Schematic illustration of a regulated river and the two main types of regulated flow regimes, with free-flowing water-flow variation for comparison (top graph). In free-flowing rivers, water levels peak during spring floods, and then mostly recede until the following spring. Regulated rivers are dominated by storage reservoirs, where water is stored to be used in the following autumn and winter, and run-of-river impoundments characterised by frequent changes with small amplitude.

electricity is high (Figure 1). Water-level variations in storage reservoirs are often very large. The riparian zones are more or less devoid of vegetation, since they become successively flooded during the growing season as reservoirs are filled. Vegetation is limited to a narrow zone along the high-water level. In run-of-river impoundments, water levels vary according to the demand for water in the power station (Figure 1). Water levels fluctuate up and down daily and weekly within a range of about one meter, throughout the year. The river margins become steep and narrow, and fine material is successively eroded away. The riparian vegetation along run-of-river impoundments often forms a narrow belt without zonation close to the high water-level, and below this there are sparse occurrences of amphibious and aquatic species.

The species richness of riparian plants varies depending on the type of regulated water-level regime (Jansson et al. 2000a). In free-flowing rivers in northern Sweden, there are about 90 vascular plant species per 200-m-long stretch of river margin (Figure 2). Almost as many species are found along unimpounded reaches downstream of dams, whereas the number of species is somewhat lower along reaches that are mostly laid dry or which have reduced discharge. Along run-of-river impoundments, about one fourth of the species have disappeared, whereas one third of the species are lost from storage reservoirs, compared to free-flowing rivers (Figure 2).

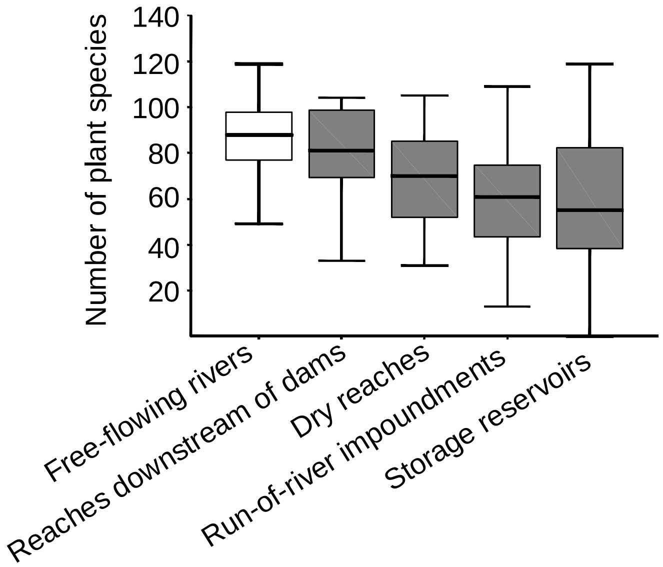

Figure 2. Box plot showing numbers of plant species per 200-m-long stretch of river margin along free-flowing rivers and water bodies with different types of regulated water-level regimes. For each type of water-level regime, 50% of the observed species-richness values are contained within the box, and 90% of the values are within the hooks. The horizontal line across the boxes mark mean values.

Flow regulation also affects macroinvertebrate faunas. The composition of bottom-living invertebrates changes and species richness decreases (Henricson and Müller 1979). In the most heavily regulated reaches (frequent short-term regulation, going down to zero discharge), both total biomass and species richness of bottom dwelling invertebrates are strongly reduced far downstream of dams. However, in less severe cases biomass may be similar to free-flowing rivers, although the faunal composition has changed. Generally, the species richness of mayflies (Ephemoptera) and stoneflies (Plecoptera) decreases, whereas species richness of caddisflies (Trichoptera) may be comparable to free-flowing rivers, although species with net-spinning larvae are disfavoured, and only a few species remain abundant. Blackfly larvae (Simuliidae), typical at lake outlets, are generally absent from regulated parts of rivers.

Also fish faunas shift in composition in regulated rivers. In general, populations of salmonid species are reduced or destroyed, and lake-inhabiting species take over (Henricson and Müller 1979). Migration along the rivers, which is crucial in allowing fish to utilise different food resources and to reach spawning grounds, is blocked by dams. Moreover, salmonid spawning grounds are often destroyed. The reduction in fast-flowing reaches, and the increase in slow-flowing, lake-like reservoirs, leads to the replacement of salmonids by lake-inhabiting fish species, such as perch *Perca fluviatilis*, ruffe *Acerina cernua*, roach *Rutilus rutilus*, and pike *Esox lucius*, which flourish in run-of-river impoundments. Whitefish *Coregonus* spp. may be abundant in regulated rivers, but its growth is frequently impaired. Populations of grayling *Thymallus thymallus* and especially brown trout *Salmo trutta* are reduced due to competition and predation from other fishes.

Natural flow regimes create habit diversity favouring biodiversity

In a free-flowing river, different aspects of the flowing water create a mosaic of environments, providing habitats for a wide arrange of organisms (Figure 3A). The water flowing downstream carries organisms, such as seeds and aquatic insects, from upstream areas, enabling them to disperse to and colonize new areas. Organic matter and sediment are eroded from some areas, transported and deposited downstream. Fish can migrate upstream as well as downstream along the river. The river periodically floods and drains the riverbanks, due to variations in its flow. When riverbanks are flooded, they receive nutrients and sediment transported by the water, increasing the productivity of the vegetation. Some areas are cleared from litter, enhancing the development of riparian plants. The litter is redistributed into packs and piles, or end up in the river. Seeds carried by the flowing water are deposited on the riverbank. They may then germinate and establish. The floods are also a disturbance to riparian zones, eroding riparian soils, and tearing way entire plants or plant parts. This stops dominant plant species from excluding competitively inferior ones, and creates open patches for plant colonization. The result is species-rich plant communities. Organic matter from riparian zones also ends up in the river, being an important input to aquatic food webs.

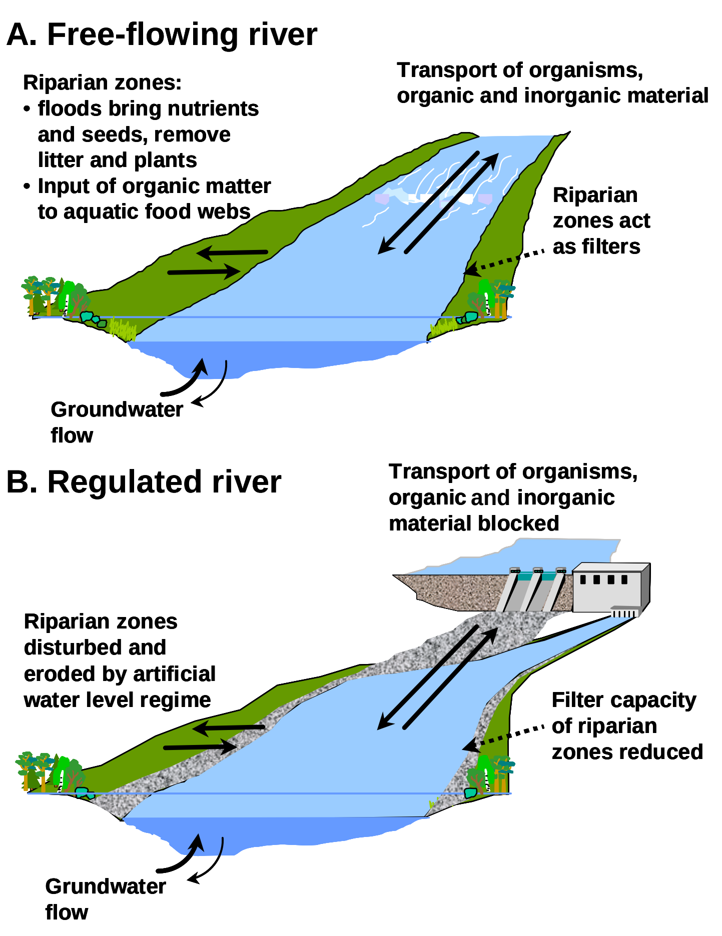

Figure 3. Examples of flows of water, matter and organisms in a free-flowing and a regulated river. Dams fundamentally change most of these flows.

Dams are barriers to the movement of organisms and transport of matter

In regulated rivers, water flows have been fundamentally changed (Figure 3B). Dams block the downstream transport of organisms, organic matter and sediments. Sediment accumulates in the reservoirs upstream of dams, and fish migration is impeded since most dams lack functional fish ladders. The artificial water-level fluctuations constitute a stress to the riparian vegetation, which largely becomes restricted to a band along the high-water level (Jansson et al. 2000a). In run-of-river impoundments, the riverbanks are frequently flooded and drained, whereas margins along storage reservoirs are successively flooded during the growing season, retarding plant growth. The ability of the sparse riparian vegetation to stop excess nutrients and toxins to enter the river is reduced, and less organic matter from the riparian zones end up in the river. As rapids and waterfalls disappear, so do organisms specialized to that habitat. Thus, the altered patterns of water flow in regulated rivers restrain the flows of energy, matter and species.

In floodplain rivers, flow regulation disrupts the connectivity between the main river channel and its floodplain (Ward and Stanford 1995), i.e. there is less transport of organisms energy and matter between them. The floodplain is no longer flooded by the river, reducing the productivity of both the river and floodplain habitats. Riparian and wetland communities on the floodplain are replaced by terrestrial plant communities. Dams block sediment transport, leading to channel deepening below the dams.

Natural rivers can be said to be corridors through the landscape, as organisms may move along or in them, thus reaching areas otherwise out of reach. Dams are barriers to such movements. Dams not only block the migration of fish, but also water dispersal by plants. In free-flowing rivers, large amounts of seeds are dispersed by the river during floods, whereas in regulated rivers, floating seeds have difficulties in passing the dams. Both the abundance and the species richness of floating seeds are lower in regulated rivers (Andersson et al. 2000). Moreover, adjacent impoundments separated by dams develop different riparian plant floras, despite that the environmental conditions of their riverbanks are similar (Jansson et al. 2000b). It is primarily species with short-floating seeds that are present in some impoundments, but missing from adjacent ones. Probably, short-floating seeds have difficulties in dispersing across dams, either because they sink or are washed ashore. In free-flowing rivers, there are no such discontinuities in the distribution of riparian plants along the rivers, suggesting that dispersal is not limiting.

Small-scale hydropower is not an environmentally friendly alternative

Small hydropower plants, often called small-scale hydropower, are often claimed to have less negative effects on the environment compared to large hydropower schemes. Few comprehensive studies of the biological effects of small-scale hydropower have been made, but available evidence indicates that *the damage per capita energy produced caused by small power plants is as bad or may be even more severe compared to large power plants*.

The physical prerequisites are the same for small as for large hydropower schemes (Figure 4). In both cases, a dam regulating the water level to the inlet of the power station is needed. The water-level variation in the water body impounded by the dam will be determined by the needs of the power station, usually implying frequent water-level changes. Below the dam, where rapids used to be, there is often a river reach which is dry or have reduced discharge. In

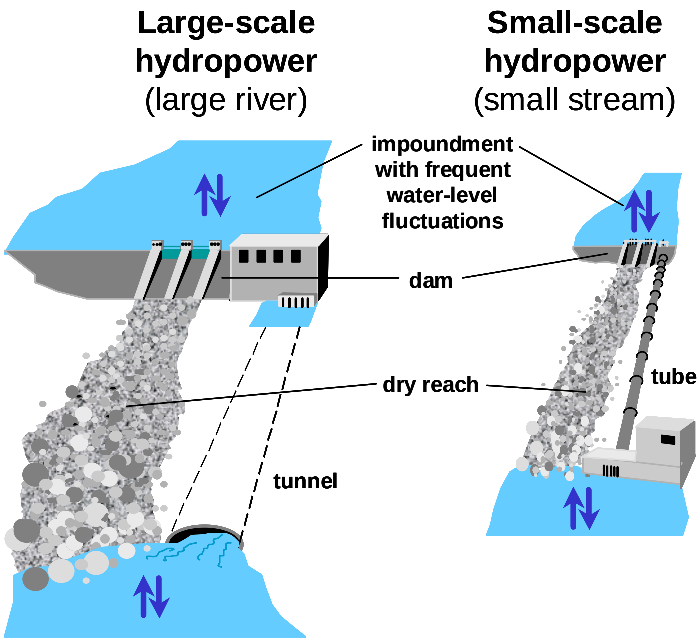

Figure 4. Comparison of large-scale and small-scale hydropower plants. Both imply similar sets of physical structures, having similar effects on river ecosystems. The main difference is the size of the affected river systems.

large rivers, water may be led by canals or tunnels from the river channel to the power station, and back again. In small rivers and streams, water is often led through tubes to power stations. In many situations, the power station is situated directly at the dam, making tunnels or tubes superfluous. The water flow in the reach below the power station is determined by operation of the power station, usually implying frequent and rapid water-level changes.

The perhaps best-documented example of the effects of small-scale hydropower on biodiversity comes from a study of the effects of changing the operation of the small, regulated stream Gunnilboån in central Sweden (Möllersten 1998). In 1996, the intensity of water-flow variation was increased, making the stream frequently vary in width from 7 to 1-2 m. In 1996 and 1997, 62 of the 198 taxa found in the stream before the new operations were commenced were missing, and the local population of stationary trout went extinct. Thus, the effects of small-scale hydropower schemes seem to be similar to large-scale ones. Small-scale hydropower schemes are small copies of large ones, applied to small rivers.

Is hydropower ecologically sustainable?

To evaluate the ecological sustainability of an energy source, it is useful to separate its environmental effects into (1) effects caused during the construction phase, (2) effects caused by the power production during the lifetime of the power plant, and (3) measures needed to restore the environment into its original or an equivalent state after power production has stopped. Hydropower by necessity means that the river and its surroundings are removed far from their original state: Lakes are dammed, land areas permanently flooded, river reaches and rapids laid dry, and canals and tunnels constructed.

Hydropower production reduces the biodiversity of river species, but is this change permanent or transient? It might be that damages to ecosystems occur primarily during the construction phase, and that ecosystems recover by time. However, the potential for recovery of riparian

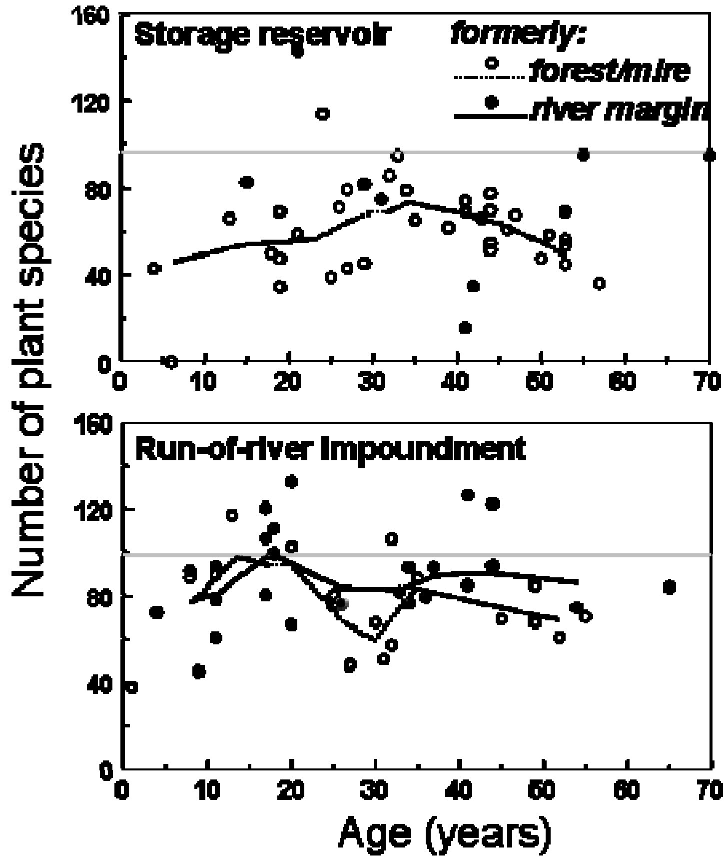

Figure 5. Numbers of plant species per 200-m-long stretch of river margin along reservoirs of different ages. Grey lines indicate mean plant species richness of comparable riparian zones in free-flowing rivers. Unfilled dots and hatched lines represent margins formed following flooding of former forests and mire, whereas filled dots and straight lines represent margins remaining in the same position as before onset of regulation.

plant communities by time is limited. The species richness of riparian plants along storage reservoirs increases the first 30-40 years after onset of regulation, but decreases thereafter (Figure 5; Nilsson et al. 1997). Plant cover drops from on average 42% of the margin to about 2%, without any signs of recovery. The reason for the rise in species richness during the first decades is that plants successively colonise the new margins. With time, fine-grained soils erode away from the upper parts of the margins, where plants may grow, and diversity is reduced.

Along run-of-river impoundments, riparian plant species richness increases the first 10-20 years, irrespective of whether the margins have developed in flooded forest/mire areas, or remain in the same position as before onset of regulation (Figure 5). After that, no clear trend is discernible. Species richness is calculated taking the available area into account, making the run-of-river impoundments appearing almost as species rich as riverbanks along free-flowing rivers. However, they encompass smaller areas than prior to regulation. Plant cover of herbs and dwarf shrubs decreases from about 50% to 30% of the margin. To conclude, the effects of regulation on species richness of riparian plants remain about 70 years after onset of regulation, and are probably permanent.

Hydropower is usually considered clean in that it does not emit any greenhouse gases or toxins. However, in cases when areas with large amounts of accumulated organic matter, such as mires and bogs, are permanently flooded, the organic matter will eventually be released to the atmosphere in the form of methane or carbon dioxide, the two most important greenhouse gases (St. Louis et al. 2000). These emissions represent a net contribution to the atmosphere, given that few plants grow in the reservoir to accumulate the emitted carbon. The problem is considerable only in situations where the amount of organic matter dammed over is large in relation to the power produced. Organic matter often contains small amounts of mercury, which may be released as highly toxic methyl mercury when organic matter is decomposed. The mercury is accumulated in the food web, and mercury levels can be high in fish from reservoirs created by damming areas of mires and bogs (Rosenberg et al. 1995).

To restore a regulated river to something approaching the original state requires removal of the dams and restoration of the former river channel. The costs associated with doing this are huge, but despite that, there are ongoing projects to remove dams deemed to be too environmentally costly in relation to their power benefits, primarily in the USA (Bednarek, 2001). Presently, knowledge of techniques to restore rivers is insufficient to allow large-scale restoration of entire rivers. To conclude, hydropower entails strong effects on the river and its ecosystems, which will remain as long as long as power production continues, and restoration to their original states would be extremely expensive or impossible with present level of knowledge.

Conclusions – Environmental effects of river regulation

- Most river systems are already affected by dams, implying that new dams would destroy unique environments.
- The effects of dams and flow regulation on species richness vary with the spatial scale considered, and are most severe at the scale of river reaches and smaller scales.
- River regulation reduces numbers of riparian-plant species. About one third of the species per 200-m-stretch of river margin along storage reservoirs, and one fourth of the species along run-of-river impoundments are lost.
- River regulation also changes the species composition and richness of macroinvertebrates, such as aquatic insects.
- Populations of salmonid fish species are reduced or destroyed, and lake-inhabiting species such as perch and pike take over.
- Dams are barriers to the movement of organisms (e.g. fish and plants) and transport of organic matter and sediment. This impedes the formation of new habitat, which is necessary for maintaining biodiversity, and reduces ecosystem productivity.
- The damage per capita energy produced caused by small power plants is as bad or may even be more severe compared to large power plants.
- The effects of river regulation on the diversity of riverine species are not transient, but remain after 70 years and appear to be permanent.
- Although hydropower is considered not to emit any pollutants, it may under certain circumstances lead to considerable emissions of the greenhouse gases carbon dioxide and methane, and lead to accumulation of toxic methyl mercury in the food chain.
- Hydropower cannot be considered a sustainable means of power production since (1) it leads to large changes in the environment of rivers, (2) the changes remain as long as power continue to be produced, and (3) restoration would be extremely difficult and expensive.

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