Pictured is the Eel Weir Dam powerhouse, the building thereof at the head of Sebago Lake caused a host of cascading effects. PHOTOGRAPH BY ROGER WHEELER

Unnatural Freshwater Flow Project

In this report, you will find the amalgamation of a months-long look into the harmful effects of hydropower reservoirs onto the environment. Across decades, regions, interviews, and research, you will learn about the multidisciplinary science and pioneering voices that have raised the alarm against this underserved environmental issue. The report is a translation of the website project in report form. That being the case, for links to downloadable material and cited works please visit https://friendsofsebago.org/unnatural-freshwater-flow/.

Table of Contents

A Brief History of Hydropower

Hydropower can be traced back to over two thousand years. In its simplest form, the Chinese, during their Han dynasty, used falling water powering tilt hammers to process grains, ores, and paper. The ancient Greeks created waterwheels for similar purposes around the same time.

It was not until the First Industrial Revolution that modern hydropower took shape. The year 1827 brought about invention of the turbine by French engineer, Benoit Fourneyron. In 1831, Michael Faraday created the first electric generator. The combination thereof with modifications and improvements over 50 years later, in 1882, resulted in the first hydroelectric power plant opened in Appleton, Wisconsin, powering a paper mill and two other buildings. This event, unknown to those at the time, would cause the advent of numerous environmental and social debacles. We will go over these issues in the **Geographic and Social Costs** section.

Figure 1: Fox River Dam, the first hydroelectric station built in 1882, in Wisconsin. PHOTOGRAPH FROM THE LIBRARY OF CONGRESS

Hydroelectric power plants sprung up like weeds around the turn of the 20th century and continued to experience significant construction growth throughout the mid-1900's, all over the world. By the 1970's, people began to rally against the unregulated expansions of these projects. People like Dr. Hans Neu (pronounced Noy).

Dr. Hans Neu was a German engineer and oceanographer who, ahead of his time, predicted how the storage of water in reservoirs and the eventual release back into the environment, disrupts the natural seasonal hydrological cycle. Before we delve into his work, it is important to get a picture of his background and the reasons why his voice still resonates today.

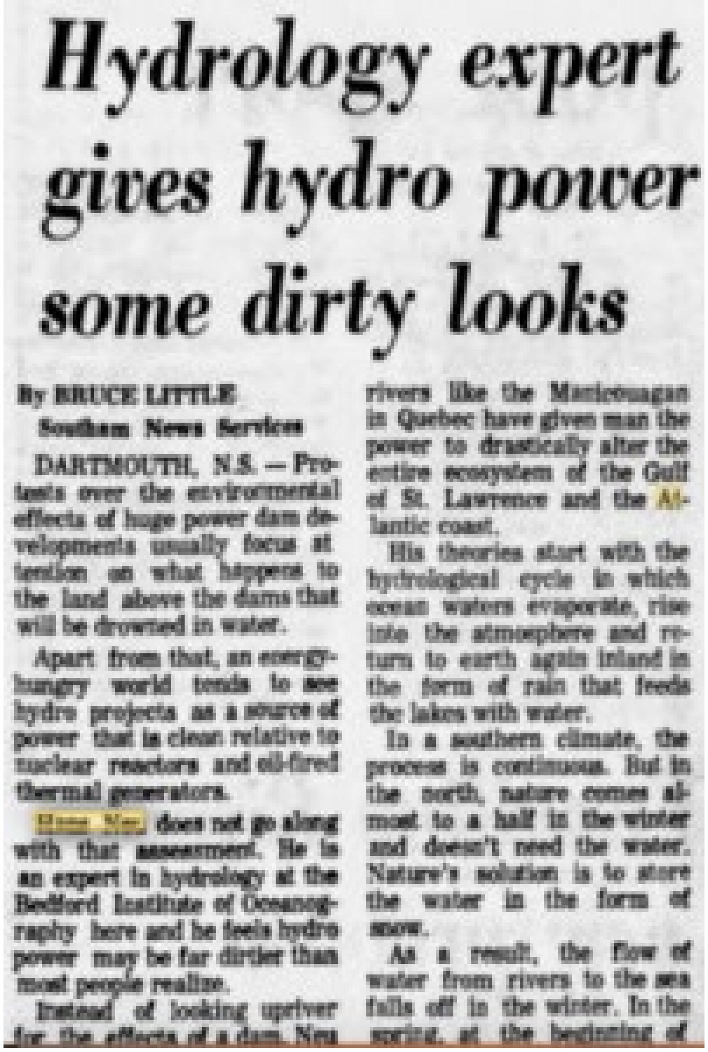
"You know, it seemed to me that what he was doing should be done. It was very exciting. It's looking at a process, and raising an alarm. We should be careful and see what the implications are because--and [for] all of these environmental issues--it's always a matter of a balance. Hans, you know, I think was bang on to raise these issues." ***Donald Gordon, Scientist Emeritus at the Bedford Institute of Oceanography, former colleague of Neu's***

Before migrating to Canada in the early 1950's, Neu worked as a mechanical engineer on small low-head rivers and the building of dams in Germany. Due to increasing political turmoil at home, he and his wife migrated to Canada where Hans soon worked for the National Research Council (NRC) in Ottawa: the scientific research wing of Canadian government. In that era of marine research in Canada, the country lacked research professionals and would often hire those from overseas, namely Europe.

During his time at the NRC, Neu was responsible for helping design construction variations and flows through the Saint Lawrence River waterways to bypass obstructed sections. Another major project he was tasked with was recommending changes to a Fraser River tidal project for deep-sea navigation that had been switching hands between the University of British Columbia, the British Columbia Department of Public Works, and private industry. In both of these experiences, politics limited the scope of Neu's attempts to ameliorate project impacts on the environment. Lacking freedom and feeling frustrated, Neu decided to work at the Bedford Institute of Oceanography (BIO), a newly-funded research institute based in Darthmouth, Nova Scotia. Neu worked at BIO until the day he retired.

The BIO chapter of Hans Neu's career allowed him to conduct research across different branches of oceanography and allowed him to research further and wider. Some of these areas include: improving the layout of the Halifax harbor, the hydrodynamics of Chedabucto Bay, decade-long investigations into the wave action climate of the Atlantic Ocean, sedimentation in Rivière-au-Tonnerre, and even ice drift in the Arctic. **Through meticulous online queries, visits to BIO and the NRC, we have acquired much of Neu's research for your perusal on the website.**

Based on his years of dam design and construction work in Germany and his extensive research across Canada, Neu's understanding of environmental ramifications from oceanographic and riverine engineering projects grew and he became passionate about how environmental condemnation costs from these projects outweighed the benefits. Beginning in the 1960's, Neu turned to the press and wrote a number of research papers about the effects of hydropower runoff (which you can read below): Man-Made Storage of Water Resources—A Liability to the Ocean Environment? Part I & II and Runoff Regulation for Hydro-Power and its Effect on the Ocean Environment.



Hydrology expert gives hydro power some dirty looks

By BRUCE LITTLE
Southam News Services

DARTMOUTH, N.S. — Protests over the environmental effects of huge power dam developments usually focus attention on what happens to the land above the dams that will be drowned in water.

Apart from that, an energy-hungry world tends to see hydro projects as a source of power that is clean relative to nuclear reactors and oil-fired thermal generators.

Hans Neu does not go along with that assessment. He is an expert in hydrology at the Bedford Institute of Oceanography here and he feels hydro power may be far dirtier than most people realize.

Instead of looking upriver for the effects of a dam, Neu … rivers like the Manicouagan in Quebec have given man the power to drastically alter the entire ecosystem of the Gulf of St. Lawrence and the Atlantic coast.

His theories start with the hydrological cycle in which ocean waters evaporate, rise into the atmosphere and return to earth again inland in the form of rain that feeds the lakes with water.

In a southern climate, the process is continuous. But in the north, nature comes almost to a halt in the winter and doesn't need the water. Nature's solution is to store the water in the form of snow.

As a result, the flow of water from rivers to the sea falls off in the winter. In the spring, at the beginning of

Figure 2: With his reach at the Bedford Institute, Neu was able to relay his message through the press all over the country.
ARTICLE FROM THE EDMONTON JOURNAL, FEBRUARY 26, 1974

Chief amongst his concerns were the cascading effects of what seasonal discharges of reservoir water back into the environment would cause: aggravating water temperature levels, water salinity affecting boundary mixing in estuaries, sediment deposition changing spawning rates for fish, and the lack of nutrients causing wide-spread, complete trophic level disturbances.

Neu's work across oceanography and marine research has been used as primary-sourced literature for scientists and as historical records for subsequent work. He has been cited in the seminal *Silenced Rivers: The Ecology and Politics of Large Dams* by Patrick McCully. Until the end, Hans Neu was an adamant dissenter of hydropower damming, particularly large-scale projects. Neu's prescient voice foretold serious issues we face today including habitat destruction, fisheries collapse and climate change.

Geographic and Social Costs

The advent of hydropower dominating the “clean energy” space has brought about a host of social and environmental tragedies. A simple cursory search on Google illustrates this fact. The costs of large dams and their associated generation and transmission infrastructure have been, and will continue to be, at the expense of the lives of people and the natural world around them. Typically, because of resource locations, indigenous cultures generally bear the brunt of these developments, raising serious questions of environmental justice. Below, we describe simply two examples of the price of hydropower.

On the most extreme end of the spectrum, there is China’s infamous Three Gorges Dam. It is the largest in the world, producing 22.5 GW of energy. The construction of the dam displaced an estimated 1.2 million people, flooded countless cities and villages, decimating fisheries, and eroding hundreds of kilometers of land, to simply name a few problems. The Yangtze River, on which the dam is situated, has been irreversibly changed, killing off additional local economies for those needing it to survive.

Closer to home, there is Hydro-Québec (HQ). The origins of Hydro-Québec run parallel with the boom of damming projects during the Second Industrial Revolution during the late 19th century: the Second Industrial Revolution is a period of technological innovation demarking the standardization of production and manufacturing, allowing for accessibility and globalization. Hydro-Québec is the largest producer of electricity in Canada generating over 45,000 MW. To put that in perspective, that is only around twice as much as the Three Gorges Dam. Taking the Chinese dam’s monstrosity of the scale further, HQ provides 96% of the province’s electricity. The success of their numerous hydroelectric power plants (63 to be exact) allows the corporation to export energy into New England and New York. There are plans, as you read this, for HQ to expand into other northeastern states, like Maine (continued on next page).

Figure 3: A 2010 map of the locations of major Hydro-Québec facilities. The map does not include substations and areas of neighboring connections. PHOTOGRAPHY BY RICHARD GERVAIS ET AL.

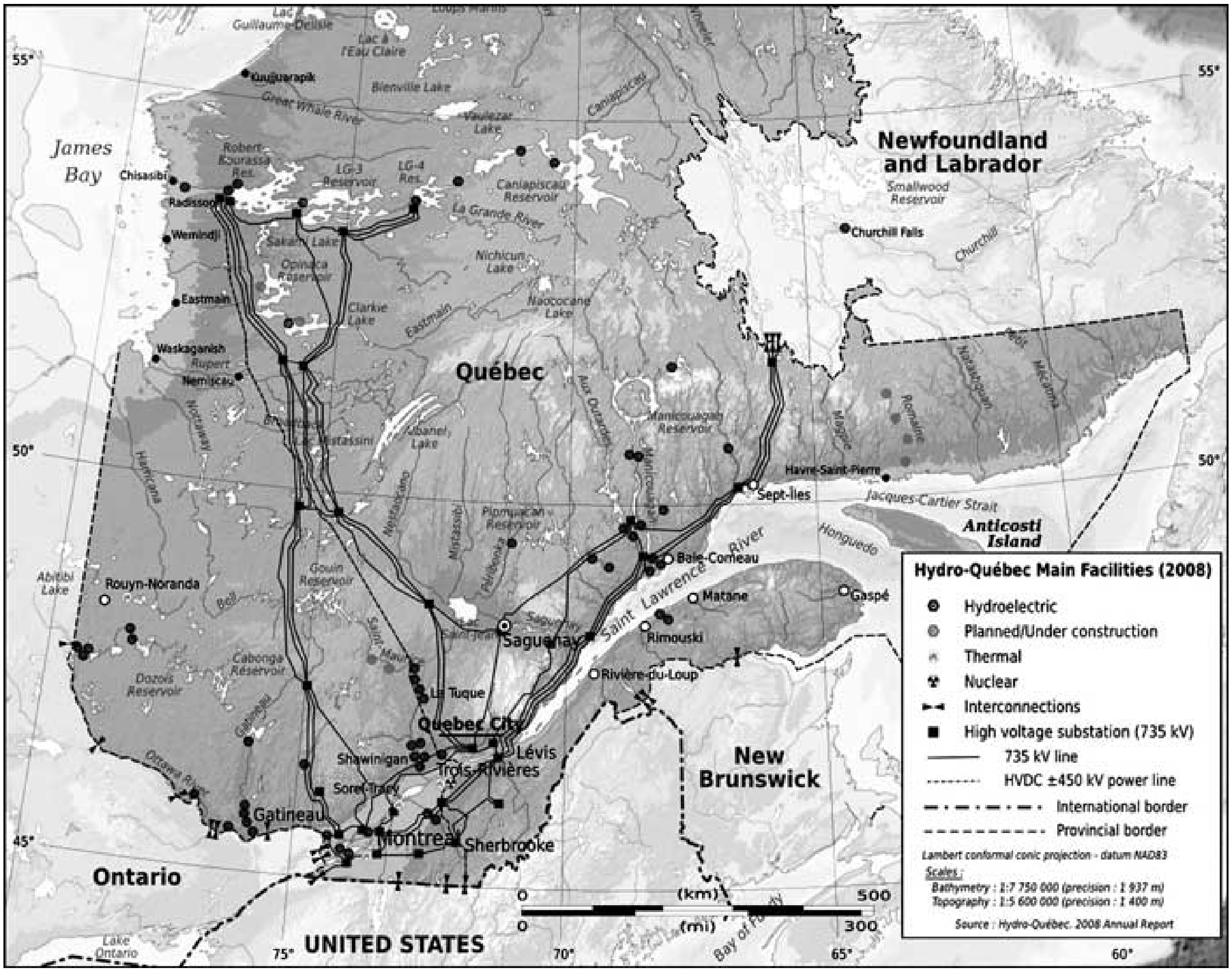


Figure 4: Hydro-Quebec map of connecting major facilities across the province.

Throughout their decades of expansion, none were more affected than the James Bay Cree and Inuit. The notorious James Bay Project of the early 70's saw the flooding of over 11,000 square kilometers of land, diversions of important local rivers, forests incinerated, toxic mercury accumulation in fish, and much more. The flooding killed over 10,000 migrating caribou in what would be considered "one of the worst environmental catastrophes in Quebec history". Years-long disputes and court battles between the Cree and HQ played out with settlements, renegotiation, expansions, but with the eventual result of its development. The construction, of what would be two hydroelectric power plants, flooded and diverted land and rivers the size of Belgium. To understand what it meant for the Cree to lose the land, read this account by Jamie Pashagumskum on how the construction of the James Bay Project has affected his family and the legacy it leaves behind: **Connection to the Land**.

Figure 5: The corpses of migrating caribou along the Caniapiscau River from Hydro-Québec land flooding. PHOTOGRAPH FROM THE CANADIAN PRESS

The examples above paint a narrow picture of the staggering scale that the world has been changed by harnessing this energy resource. Can you imagine the harm done in other regions in the world? Although we graze the surface of the resulting social and geographic impacts of hydropower projects, we need to delve deeper into the science to understand their lasting effects. Read on to the **Research** section.

Research

The manifold effects of hydropower reservoir projects cross multiple fields with their fallout ranging from micro to macro. This page aims to distill these effects from the ground up, according to research discipline. Research papers and references mentioned in the subsections below can be found in the **Document Database** page on the website.

Hydrogeology and Geography

When utilities or other hydropower entities flood land to create reservoirs, porous soil absorbs water which typically moves downward and often horizontally. In natural cycling, water can fill the space between rocks or crevices, extending to over 100 meters below ground. This layer is known as the unsaturated zone. Below this layer, we have the water table, and here, the space is completely filled with water. This saturated groundwater layer is also known as an aquifer, which can be deep, shallow, homogeneous or "perched" upon an impermeable layer. Aquifers can be colloquially visualized as underground rivers, all the way to the scale of lakes or inland seas like the 175,000 square mile Oglalla aquifer in the U.S. west.

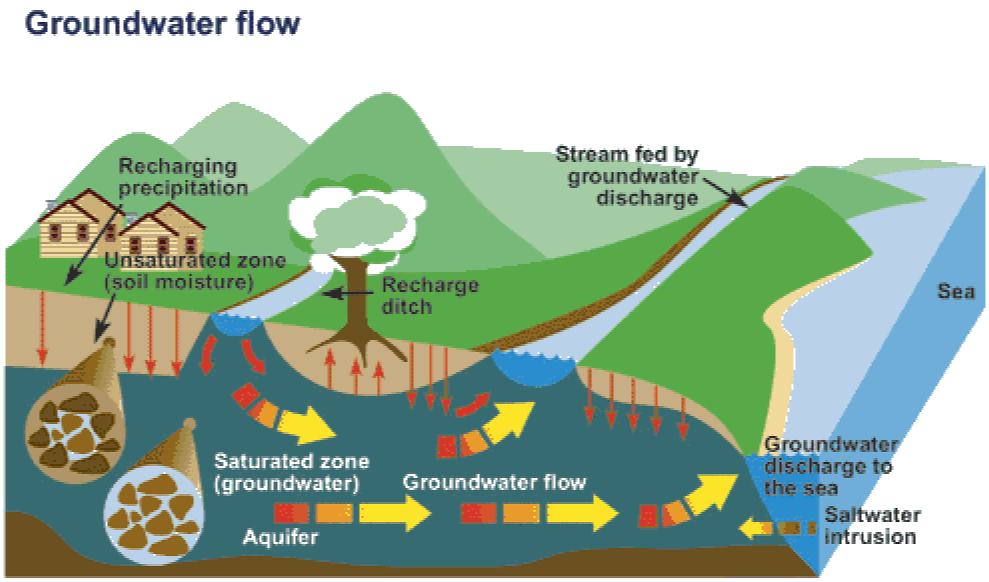


Figure 6: Visualization of how groundwater moves through the earth. ILLUSTRATION FROM THE GOVERNMENT OF CANADA.

Groundwater is a reliable source of freshwater. The quality of uncontaminated freshwater from groundwater is a result of how it moves through rocks and sediment formations, imbuing essential mineral content. The world relies on groundwater for potability and agriculture, with 30% of the world's freshwater coming from groundwater (vs surface waters).

Groundwater is an important component of the global water cycle. On a seasonal scale, when spring thaw arrives, the increase in water availability from melt contributes to recharging the groundwater table, along with precipitation. Subsequently, summer evaporation depletes groundwater. Groundwater, especially in coastal systems, feeds rivers and lakes, maintaining regular flow. As hydropower damming controls local water resources through altering river and runoff flows back into the environment, natural groundwater processes are impeded. Hydropower, utility, and other entities control when and how much water is released back into the environment. An important note, impoundments can be created for different purposes including drinking water, flood and erosion control, navigation, agriculture and recreation—not just hydropower. All of these may still schedule releases and impede groundwater flow. Hans Neu in his seminal paper, "Man-Made Storage of Water Resources—A Liability to the Ocean Environment", discusses these phenomena:

"*...reducing the flow of fresh water during the biologically active season of the year, or even reversing the cyclic flow altogether, represents a fundamental modification of a natural system. Such a modification must have far reaching consequences on the life and reproduction cycle in the marine environment of the region affected"*

Excess withholding of water upstream can diminish downstream river or water body connectivity to underground replenishment, as found in Zeng and Cai (2014). Additionally, compounding effects include land subsidence, water quality deterioration, and surrounding habitat loss.

Another geological issue resulting from reservoirs is the retention of sediment. Under the natural order, for instance, sediment materials are picked up by currents and in suspension transported towards the coast. Sediment is important for maintaining site morphology, spawning sites, habitat renewal, or nutrient delivery. Ezcurra et al. (2019) investigated and tested the effects of how sediment trapped by Mexican reservoirs change coasts and estuaries. Results unequivocally show a decline in shore stability and coastal erosion in two of their sites on rivers where dams were present and clear accretion in one (as seen below) without dams.

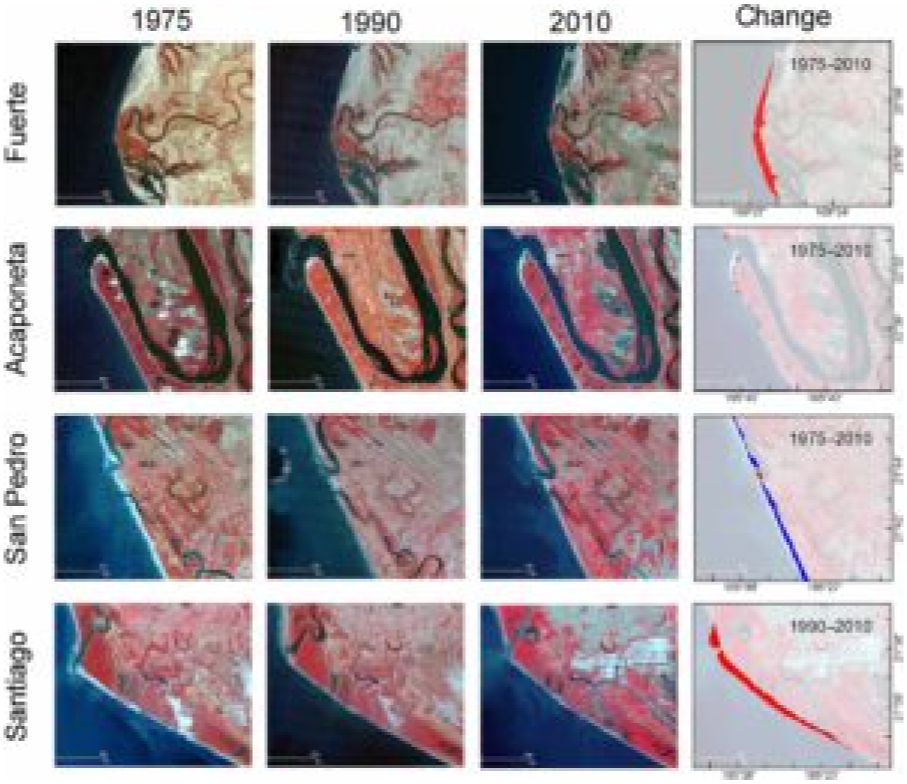


Figure 7: Changing coast line measured over decades in Ezcurra et al. (2019). Blue represents accretion and red represents erosion. FIGURE FROM EZCURRA ET AL. (2019)

These changes, if left unattended, will alter landmass geography for many years to come. In a landmark case, the removal of the Elwha and Glines Canyon Dams from the Elwha River in Washington, USA, resulted in the renaturalization of the river (Warrick et al. 2019). The process of dam removal over three years, from 2011 to 2014, subsequently restored the river morphodynamics. In Maine, the removals of Edwards dam on the Kennebec River and Ft. Halifax dam on the Sebasticook River are two excellent examples of riparian restoration and species recolonization once flows were again unimpeded.

Ecology

Surrounding wildlife and flora are susceptible victims of hydropower. Effects on native fish populations are good examples and a 2014 study from Catalonia, Spain provides some excellent and typical illustrations. The study found clear evidence of poor refuge and habitat quality for fish, decreasing species diversity and fish size from water-diverted rivers. Underwater refugia contributions come from macrophytes and other marine plants similarly sensitive to changing flows and water levels. Without this flora, there is reduced photosynthesis (in areas of light penetration) causing water quality reductions from lower dissolved oxygen and loss of filtration. Without adequate flora there is a reduction in environmental cooling along with inadequate sanctuary habitat offering predator protection. These changes create stressors for local fauna. As ecosystems become more homogeneous, genetic diversity of resident species is reduced and adaptive advantages are lost to future generations (Hughes et al. 2008).

Casas-Mullet et al. (2016) extends further effects from hydropower on fish in Norway. Although known that there is an increase in mortality, from reservoir barriers to spawning habit routes and otherwise, Atlantic salmon show decrease egg hatching. Collapsing fisheries have always been a concern to anti-hydropower advocates. Although implementations of weirs and fish ladders mitigate some of the fallout, there is yet to be full measures in place to account for all life-stages of migratory fish.

Figure 8: In Vietnam, the release of water from the Hoa Binh hydropower reservoir back in the Da River killed fish breeding stocks, costing one fisherman up to $30,500. PHOTOGRAPH BY TRUNG KIEN

Casas-Mullet et al. (2016) describe further effects from hydropower on fish in Norway. Besides an increase in upstream and downstream mortality from reservoir barriers to spawning habit routes and otherwise, Atlantic salmon also showed a decrease in egg survival. . Collapsing fisheries have always been a concern to anti-hydropower advocates. Although implementations of weirs and fish ladders mitigate some of the fallout, there are yet to be full measures in place facilitating all life-stages of migratory fish.

Landscape fragmentation occurs in riparian zones: the interface between land and water bodies . As dams are barriers to fish migration, so too do they similarly affect plants. In natural rivers, vascular plant diaspores (botanical term for spores) flow along a valley and colonize sections, but impoundments prevent this (Jansson et al. 2000). There is a lower count of diaspores flowing through reservoirs, and the ones that do pass, represent a fraction of the species upstream. Diaspores that cannot make the trek end up sinking or being swept ashore. Downstream populations of aquatic plants (often invasives species), unimpeded by normal levels of competition from upstream, flourish. In Portugal (Aguiar et al. 2016), comparisons of riparian environments over decades show dwindling complexity in aquatic plants. Plants here influenced by altered flows, encroach further into the stream, losing river dimensionality. As the current situation stands, there are no procedures or measures in place to account for resilience in plant species affected by reservoirs. Moreover, clear-cutting of forests for reservoir building require an essential, absolutely important oversight that is presently lacking.

Biogeochemistry and Oceanography

With the previously mentioned run-off from reservoirs making its way back into the environment, into oceans, natural physical oceanographic processes exhibit dynamic fluxes. Storage time in reservoirs inevitably alter the properties of water. Once in an ocean, or in deep, measurably stratified water bodies, the effects of reservoir water become apparent.

This topic has been the subject of a considerable number of papers, like Ye et al. (2003) and Prinsenberg (1991 Common to these papers and others is how circulation and vertical mixing change over time. Run-off commonly exhibits a stronger salinity profile which increases water density. This addition causes an increase in stratification whereby freshwater will sit above the dense, salty water. When this situation arises, water column mixing necessary for example to circulate nutrients, is reduced, because now greater than normal energy is required by tidal waves or upwelling to dissolve the stratification. With lower mixing comes higher temperature levels and in regions around the world with even insignificant wind forcing, marine life suffers. The Hudson Bay, known for collecting some of the highest levels of run-off in the world, exhibits this very stratification phenomenon from hydropower projects.

Within deep impoundments temperature also plays a critical role. In summer, cooler water sinks to the bottom sometimes creating a thermocline below which conditions may be anoxic creating “dead zones.” In the winter, surface waters, responding to air temperature become colder than the lower denser layers. Because hydro developers typically lower impoundment levels in winter to make room for snow melt and spring runoff, they are releasing relatively warm waters including nutrients, into generally cooler receiving bodies (the ocean) at a time when adverse effects may result. These include the inhibition of sea ice formation and a nutrient flush at a time when biological organisms are unavailable to use them.

We briefly touched on nutrients in the previous paragraph, and reservoirs have a profound effect on nutrient cycling in the marine world. Carbon, nitrogen, phosphorus, and importantly, silica cycling are the backbone of a healthy marine ecosystem. Hydropower plays a role in disrupting all these cycles. To begin, silica, is essential for the growth of diatoms and in so doing, supports critical primary production in aquatic ecosystems. Not only that, but silica from diatom shells contributes to healthy sediment, a sorely understudied research area. At a global scale, the dissolved form of silica (DSi) is retained in reservoirs at levels reaching 163 gigamoles per year.

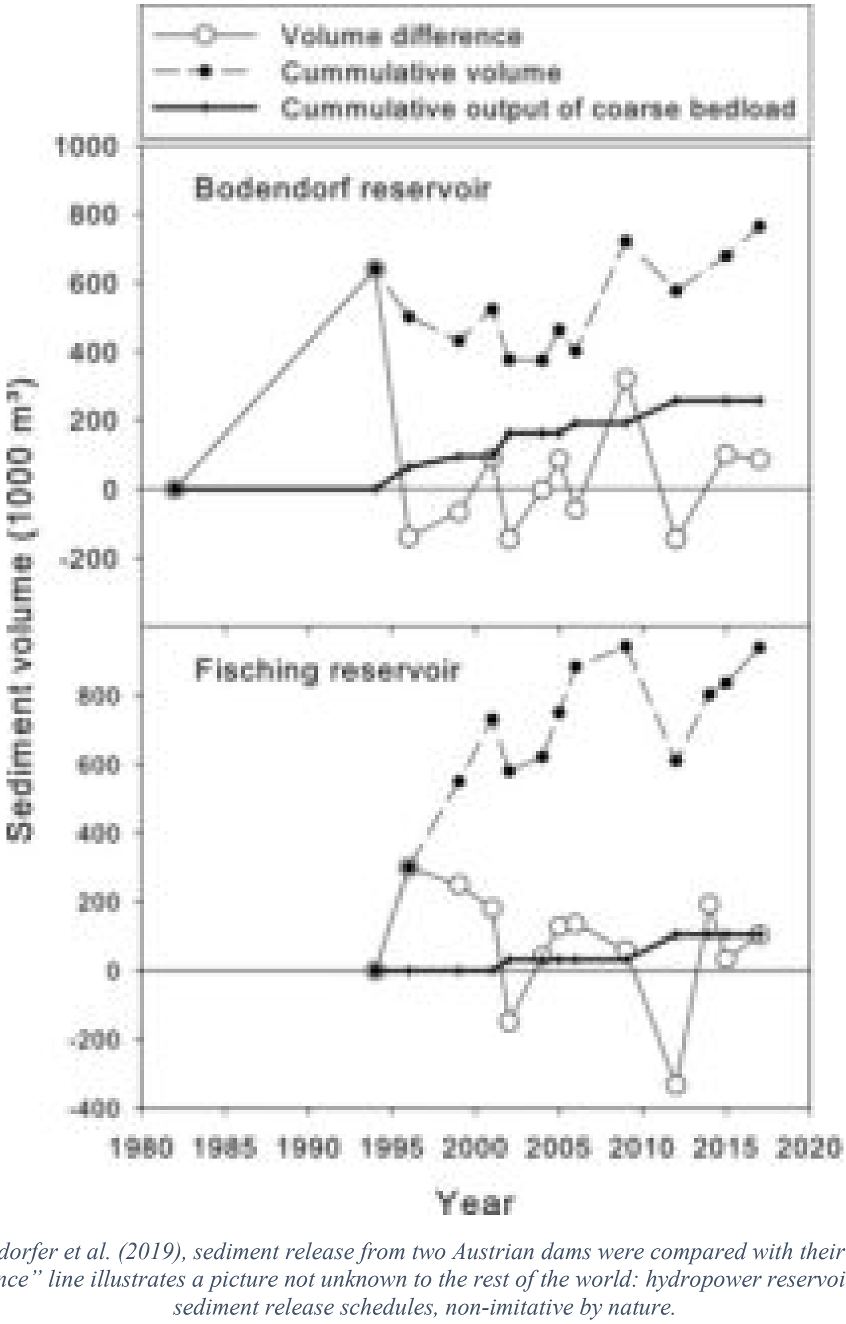


Figure 9: In Reckendorfer et al. (2019), sediment release from two Austrian dams were compared with their effects on graylings. The "volume difference" line illustrates a picture not unknown to the rest of the world: hydropower reservoirs are inconsistent in sediment release schedules, non-imitative by nature.

Phosphorus (P) is a limiting factor for primary productivity (for example, underwater plants) in freshwater systems. Suspended sediment absorb phosphorus and when reservoirs retain sediment for extended periods of time and release the material back into the environment, eutrophication can occur. Eutrophication is the overabundance of nutrients (especially phosphorus) that cause harmful algal blooms, diminishing other elements, like dissolved oxygen. Conversely, in British Columbia, two dams built at the head of Kootenay Lake showed a decline in phosphorus downstream. There is a delicate, natural balance of nutrients where even insufficient levels alter the marine ecology of a system. Here, fisheries indeed declined along with phytoplankton levels.

Organic carbon, like silica and phosphorus, finds its way into sediment through mineralization. By 2030, 4.3 Tmol per year will be found in reservoirs, this is 4 times more than in 1970. The increase comes with new dam projects being built throughout the world.

Lastly, we have nitrogen which makes up 78% of the gases in the atmosphere. Nitrogen is an element in relation to hydropower that is understudied, like silica, but still effects persist (Akbarzadeh et al. 2019). The difficulty in understanding nitrogen effects arise from insufficient deep reservoir measurements, at regional and global scales. Scientists supplant this issue through simulations from integrated models. Dissolved nitrogen, due to its persistence in water cycling, stays in marine systems longer, considering its energetically costly reaction requirements. Dissolved or reactive nitrogen, in the form of nitrate or nitrite, need to undergo denitrification from mixing with sediment and hypoxic or anoxic reservoir water. Denitrification is the process of reducing (gaining electrons) nitrate or nitrite into nitrogen gas or nitrous oxide. Microbacteria in the sediment are responsible for carrying out the reaction. These microbacteria only thrive in low-oxygen environments, elsewise, nitrate and nitrite accumulate in water.

Greenhouse Gases

The atmospheric exchange of molecules and chemicals is nothing new in the realm of the hydrologic cycle; however, with climate change aggravating access to water resources, greenhouse gases play a significant role. Hydropower reservoirs flood vast areas of organic matter and as this material decomposes over years, impoundments emit methane, carbon dioxide, and other greenhouse gases, longstanding contributors to accelerating rapid climate change. A veritable paradox of hydro's oft-labeled "green energy" misnomer.

Two ways in which greenhouse gases accumulate in reservoirs are by organic carbon mineralization and or by standing water producing carbon dioxide. Emissions diffuse into the atmosphere at different rates depending on temperature and by latitude. Cold waters in northern reservoirs do not produce as high multi-fold levels of greenhouse gases as do tropical reservoirs. Tropical reservoirs are notorious emitters of greenhouse gases, as is most reported in the case of Brazilian dams. Large-scale, deep dams pose additional greenhouse gas threats. Volume aside, without adequate replenishment and or mixing, oxygen is depleted often causing anoxic conditions at depth. When this occurs, methanotrophic bacteria convert methane to carbon dioxide for further diffusion into the atmosphere. Now, the worst contribution of greenhouse gases from reservoirs is when bottom water is released back into the environment. Consider this movement a self-realizing ticking time bomb as 50-90% of total methane emissions originate from environmental release.

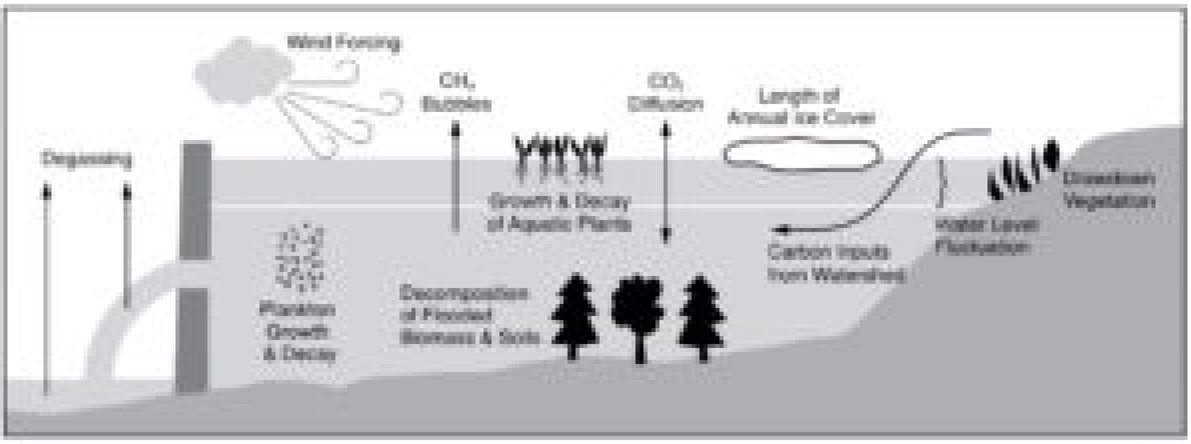


Figure 10: Illustration of factors influencing greenhouse gas emissions in reservoirs. FIGURE FROM INTERNATIONAL RIVERS