Reservoir Hydroelectric Dams

Silica Depletion

Silica Shelled Diatom Phytoplankton

A Gulf of Maine Catastrophe

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November 28, 2018

INTRODUCTION

I wrote a Report The Problem is the Lack of Silica on October 15, 2018 and submitted it at a public hearing by Maine's Public Utility Commission on the proposed New England Clean Energy Connect (NECEC) by Avangrid/Central Maine Power (CMP). This Report documented how Hydro-Quebec has significantly reduced the annual budget of dissolved silica to the northwest Atlantic and Gulf of Maine and how this reduction is the major driver in the starvation of many of the fisheries in these waters.

I handed out over 30 copies of this Report at the hearing and e-mailed more copies to interested parties. Someone shared my report with a scientist who commented *"the Gulf of Maine is too big to be affected by the releases from Hydro-Quebec's reservoir hydroelectric dams."*

This Report has been written to not only respond to the above observation, but also to the claim of Maine Marine Resources that "*Climate change is driving the decline in the shrimp fishery."*

The major source of the annual budget of fresh water and dissolved silicate to the Gulf of Maine is the St. Lawrence River, whose head waters are Lake Michigan, which is the fifth largest water body in the world. The St. Lawrence is the 27th largest river in the world, and its daily water flows of 300,000 to 500,000 cubic feet (ft.^{3}) per second dwarf the flows of Maine's largest rivers (see Graphs 1 and 2 on page 4).

The proliferation (see Maps 1 & 2 on pages 3 & 5 and Tables 1-3 on pages 6 &11) of Hydro-Quebec's reservoir hydroelectric facilities on the major rivers discharging into the St. Lawrence River, James Bay, Hudson Bay and Labrador Current have significantly altered the natural hydrologic cycle and silica cycle, which has starved the silica encased diatom phytoplankton in the Gulf of Maine of dissolved silicate. Diatom phytoplankton is the essential basis of the marine food web, including Maine's shrimp.

The building of these dams would have violated section 401 of the Clean Waters Act and Maine's Natural Resources Act and never could have been built in Maine. These reservoir dams have been built not only on all of the major rivers, but also on many of the tributaries and outlets of thousands of lakes and ponds in the watersheds of these major rivers.

These rivers and water bodies are all part of the Gulf of Maine's ecosystem and for over 70 years Maine officials have stayed silent while Hydro-Quebec built dams discharging waters depleted of dissolved silicate, and thereby, polluting the waters of the Gulf of Maine by starving them of the essential nutrients that support phytoplankton growth.

In the late 1950's there was a major decline in the annual load of dissolved silicate transported to the Gulf of Maine via the St. Lawrence River. This decline was brought on, not by dams, but by a silica limitation in Lake Michigan, which is the head waters of St. Lawrence River.

A 1970's study on the eutrophication of Lake Michigan was done by Claire Schelsky and Eugene Stoermer and was summarized in *Silica Stories by Conley and DeLaRocha,* in 2017 (see Attachment 1).

I believe the cumulative impact of this annual silica limitation in Lake Michigan was the driving force behind the first red tide event in 1958 in the Gulf of Maine. Coincidence, I don't think so. See Attachment #1 and look at the graph in Case Study #1 and the huge increase in silica burial in Lake Michigan from 1930 on. Please note that this has never happened before in Lake Michigan's 14,000 year history.

"Thirty years ago paralytic shellfish poisoning (PSP) was virtually unknown in New England, yet now, significant portions of the region's intertidal shellfish resources are closed annually to harvesting because of toxicity. A further expansion of the problem occurred in 1989 when off-shore shellfish resources on George's Bank and Nantucket Shoals were shown to contain dangerous levels of toxin. (White et.al. 1993)

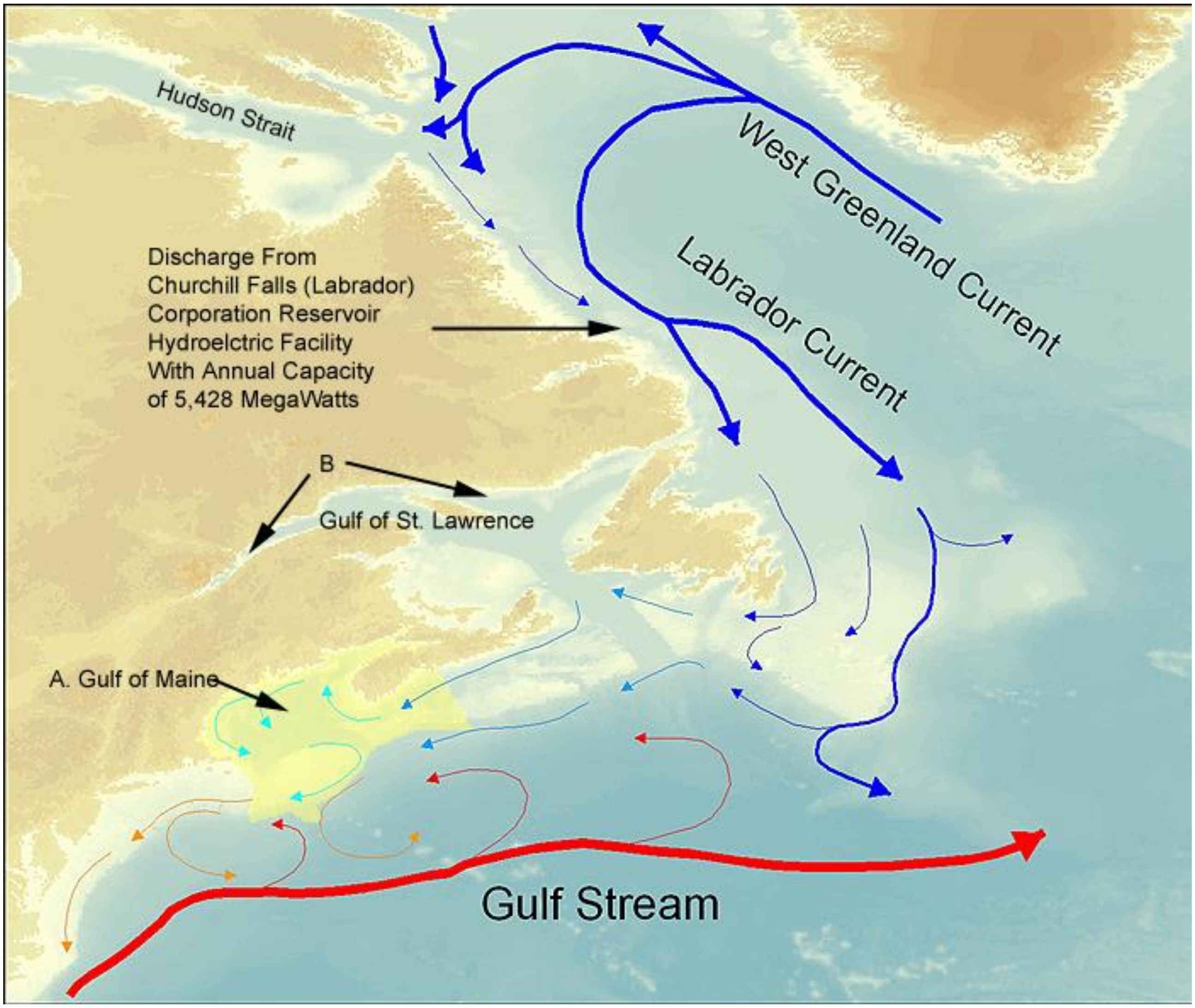
The following is the last paragraph of the Case Study #1:

"Overall, diatoms getting shut out of the latter part of the growing season in Lake Michigan while there is still plenty of nitrogen and phosphorus available for growth is a bad thing. It means a decrease in the flow of energy and materials through diatom-based food webs, which generally efficiently lead to fish, and an increase in the growth of noxious plankton species like dinodflagellates.[11] *Worse yet, what happens in Lake Michigan doesn't stay in Lake Michigan. Now stripped of their dissolved silica, the waters of Lake Michigan flow into Lake Huron and then Lake Erie, go over Niagara Falls, flow into Lake Ontario, and then via the Saint Lawrence River, arrive at the Atlantic Ocean at the Gulf of Saint Lawrence in all the full glory of their silica deficiency. You can almost hear the coastal diatoms screaming." (Silica Stories, Conley et. al. 2017.)*

On November 16, 2018, the Atlantic States Maine Fisheries Commission voted to close the Gulf of Maine winter shrimp season for three years. This agency said: *"The stock has shown very little signs of recovery. It's considered a depleted resource."*

With complete respect for these officials, the shrimp have become a depleted resource because we have allowed reservoir hydroelectric facilities to change the historic (before dams) natural silica cycle. This has depleted the essential nutrient dissolved silica from the waters of the Gulf of Maine and northwest Atlantic during the growing season of silica encased diatom phytoplankton.

Many of the major rivers now have more than one reservoir on them, which only compounds the negative impacts described above of captured dissolved silicate in the spring and the sinking and burying of biogenic silica in the reservoirs through the process of eutrophication.

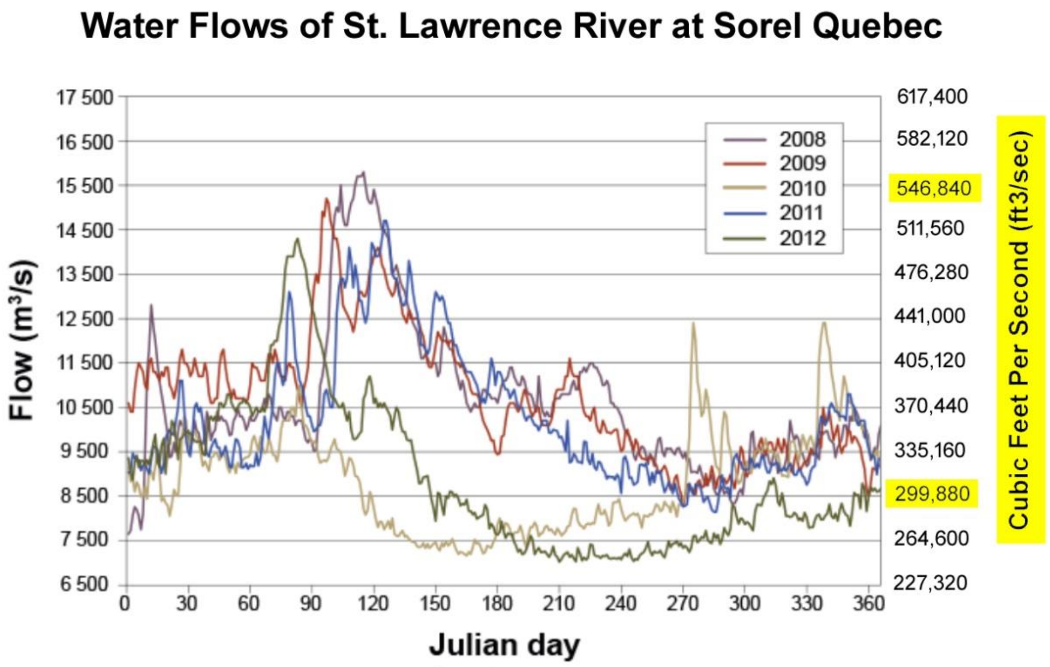


Map 1

A. Maine's six major rivers (see Graph 2 on page 4) discharge into the Gulf of Maine in the above area marked "A". The hydroelectric facilities on these rivers typically operate in a "run of river" mode and have an annual capacity of 526 MW. Maine's total capacity is only 723MW.

B. In the area marked "B," Hydro-Quebec has 16 reservoir hydroelectric facilities built on 9 rivers discharging into the St. Lawrence River and /or its Gulf (see Map 2 on page 5 for more details). These facilities have annual capacity of 12,749 MW (see Table I on page 6).

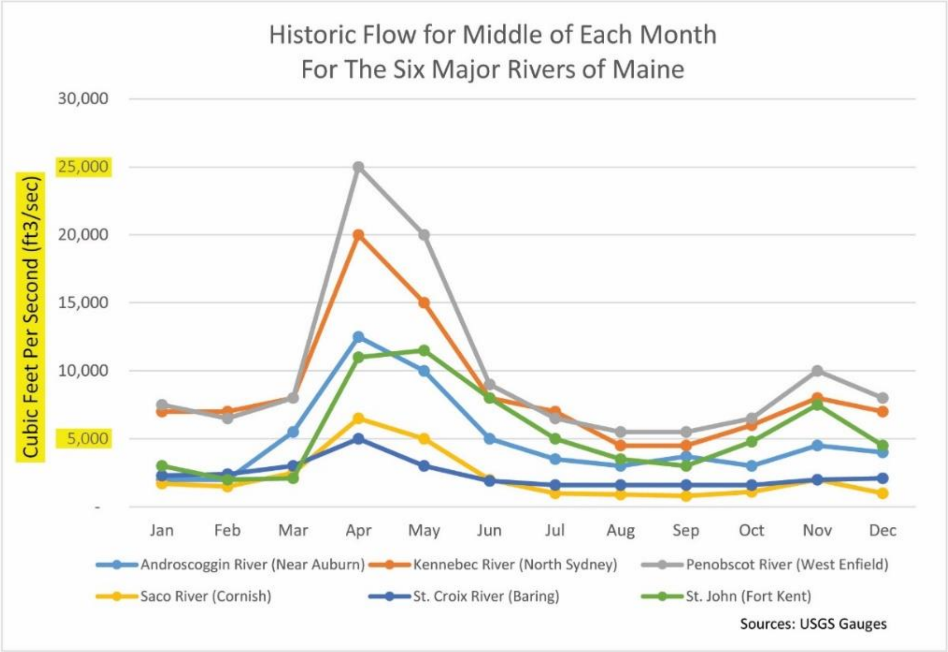
THE ST. LAWRENCE RIVER IS THE 27TH LARGEST RIVER IN THE WORLD AND HISTORICALLY TRANSPORTED WITHIN DAYS THE DISSOLVED SILICATE FROM ITS TRIBUTARIES INTO THE GULF OF MAINE.



Graph 1

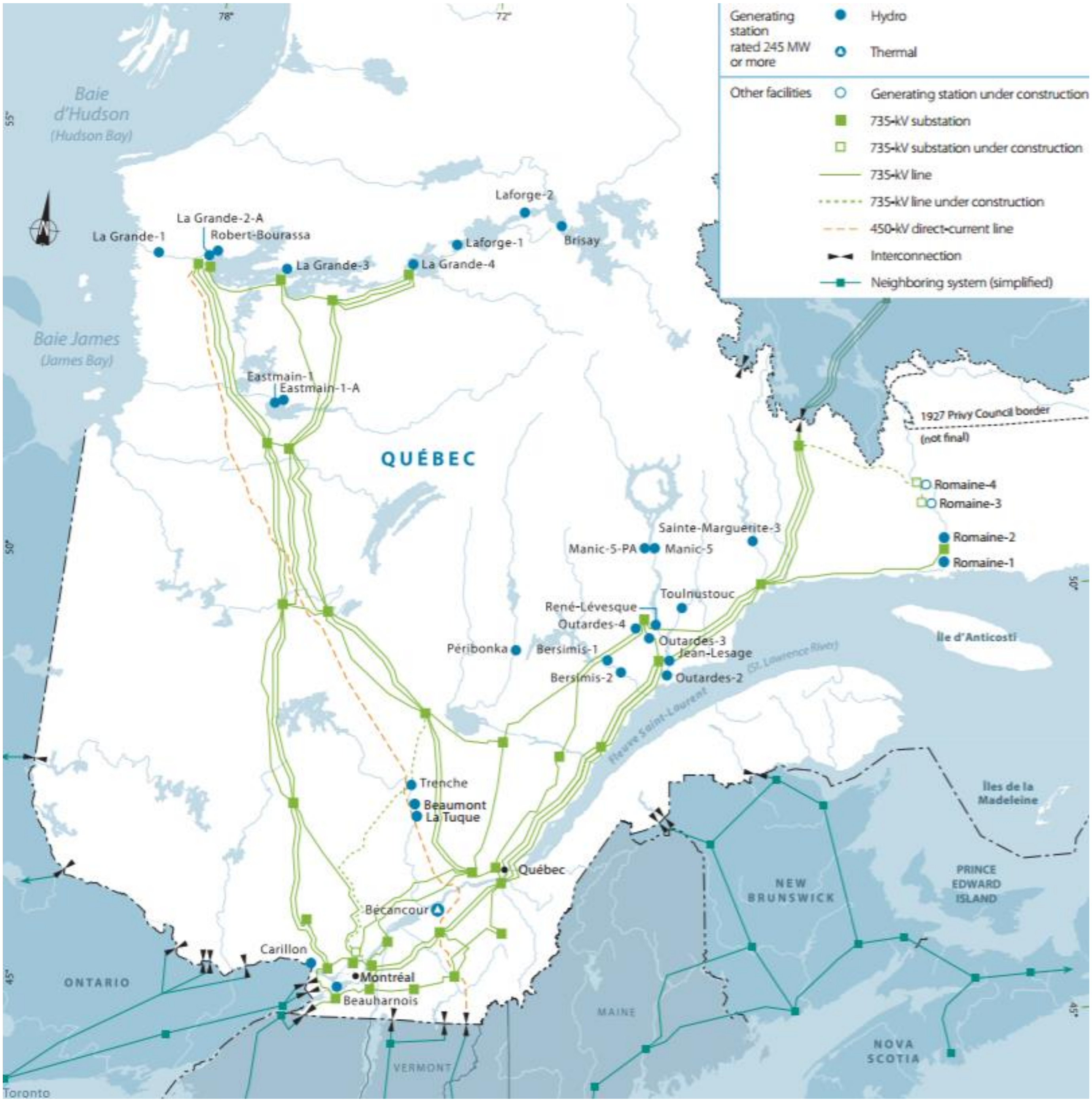
Source: St. Lawrence Action Plan 2011-2026

Water flows of St. Lawrence River dwarf the flows of Maine six major rivers



Graph 2

HYDRO-QUEBEC HAS BUILT 16 RESERVOIR FACILITIES ON 9 RIVERS IN SOUTHEAST QUEBEC THAT FLOW INTO THE ST. LAWRENCE RIVER. THESE 16 FACILITIES HAVE AN ANNUAL CAPACITY OF 12,749 MEGAWATTS (MW), COMPARED TO MAINE'S ANNUAL CAPACITY OF 753 MW.



Map 2

Table I

Reservoir Hydroelectric Generating Stations
Discharging into St. Lawrence River or Gulf

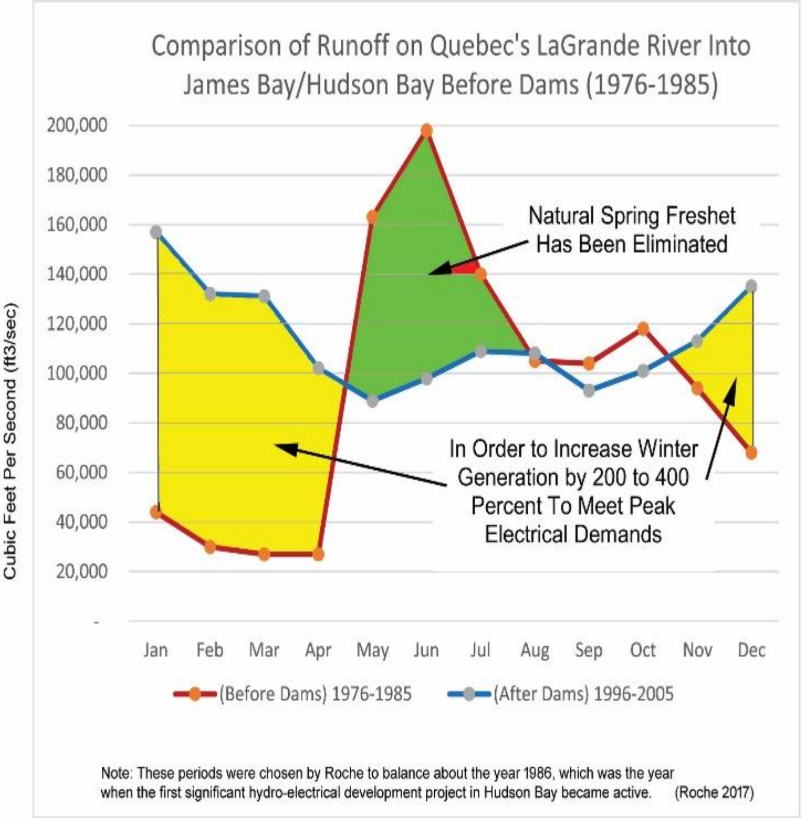
Owner	Name	Capacity In Megawatts (MW)	Commissioned	Watershed
Hydro-Quebec	Rapids Blanc	204	1934-35	St. Maurice
Hydro-Quebec	Bersimis-1	1,178	1956	Betsiamites
Hydro-Quebec	Bersimis-2	869	1959	Betsiamites
Hydro-Quebec	Jean-Lesage (Manic-2)	1,145	1965-67	Manicouagan
Hydro-Quebec	Outardes-4	785	1969	Outardes
Hydro-Quebec	Outardes-3	1,023	1969	Outardes
Hydro-Quebec	Outardes-2	523	1978	Outardes
Hydro-Quebec	Manic-5	1,596	1970	Manicouagan
Hydro-Quebec	Rene-Levesque (Manic-3)	1,244	1975-76	Manicouagan
Hydro-Quebec	Manic-5-PA	1,064	1989	Manicouagan
Hydro-Quebec	Sainte-Marguerite	882	2003	Saint-Marguerite
Hydro-Quebec	Touinstouc	526	2005	Touinstouc
Hydro-Quebec	Peribonka	405	2007-08	Peribonka
Hydro-Quebec	Romaine-2	640	2014	Romaine
Hydro-Quebec	Romaine-1	270	2015-16	Romaine
Hydro-Quebec	Romaine-3	395	2017	Romaine
		12,749		

Discharging into Labrador Current

Owner	Name	Capacity In Megawatts (MW)	Commissioned	Watershed
Churchill Falls (Labrador) Corp.	Churchill Falls	5,428	1971-74	Churchill

THESE RESERVOIR DAMS HAVE CHANGED THE HYDROLOGIC CYCLE AND SILICA CYCLE FOR THE GULF OF MAINE BY CAPTURING AND STORING THE WATERS OF THE SPRING FRESHET IN ORDER TO MEET PEAK WINTER DEMAND FOR ELECTRICITY

I have plotted on Graph No. 1 the monthly flow curve of the LaGrande River before damming (1976-1985) and the flow curve after damming (1996-2005) (Roche 2017). I converted the water flows in Roche 2007 Report from KM³/month to ft. ³/sec.



Note: These periods were chosen by Roche to balance about the year 1986, which was the year when the first significant hydro-electrical development project in Hudson Bay became active. (Roche 2017)

Graph 3

Most of the hydroelectric facilities on Maine's rivers are operated in a "run of river" mode and have not eliminated the spring freshet. "Run of river" facilities have very little storage capability. Storage is typically measured in hours unlike large reservoir facilities which can store water for six months or more.

A HEALTHY FISHERY IN THE GULF OF MAINE AND NORTHWEST ATLANTIC IS BASED ON "THREE NUTRIENT-ENRICHMENT PROCESSES: COASTAL UPWELLING, TIDAL MIXING AND LAND-BASED RUNOFF, INCLUDING MAJOR RIVER OUTFLOW" (CADDY AND BAKUN, 1994).

The delivery of nutrients to coastal waters via upwelling is a hypothesis, and *"there is a caveat to this mechanism: nutrients in the up welled waters must be continually replenished in order for this transient upwelling to sustain phytoplankton growth over the long term,"* and "*this supply is only effective as long as there is a mechanism by which nutrients are replenished in the upper thermo cline."* (Williams and Fallows, 2011.) This mechanism was the historic (before dams) silica cycle.

***"EIGHTY PERCENT OF THE ANNUAL INPUT OF DISSOLVED SILICATE TO THE OCEAN IS TRANSPORTED VIA OUR RIVERS AND STREAMS."*(PAUL TREGUER ET. AL. 1995).** In the Gulf of Maine, the majority of this annual budget was historically delivered by the roaring rivers of the spring freshet, which Hydro-Quebec has now eliminated.

> *"Reservoirs built in those cool, temperate zones that play host to much of Europe, Asia, and North America and therefore a large percent of the world's industrialized nations are the worst, retaining nearly half of this region's seaward sediment flux. Nearly half! This enormous retention of sediment occurs because there are a lot of dams in these regions and is made worse by cool, temperate zone rivers tending to be turbid (full of particles.).*
>
> *Less obvious to the naked eye is the deprivation of downstream areas of dissolved silica. This deprivation occurs because a portion of the suspended material normally transported by a river dissolves en route, releasing dissolved silica into the river system to be delivered to the sea. But once particles are buried in a reservoir sealed in their sedimentary tomb, there is little chance of this happening. This is one way that dams starve downstream areas of dissolved silica that would normally have been used to fuel the growth of diatoms, reeds and grasses, and other silica-producing organisms.*
>
> *But there is a second process at work behind dams that is even more insidiously silica-stealing: diatom blooms**.** When the moving water of the river hits a reservoir and slows down and all those particles that were in suspension sink out, the water becomes a lot more clear. This means light can penetrate into the water more than the couple of feet or inches it could before and that means photosynthetic plankton living in the water can suddenly make a good living. Phytoplankton can finally fix carbon into organic matter faster they respire it away. They can begin to grow.*
>
> *But a dam means not only light, but also the time to put it to good use. Water that would have shot through that stretch of river in hours to days will now spend weeks to months to years in the extra reservoir volume. That's ample opportunity for phytoplankton like diatoms to build up biomass into thick blooms and to remove almost all the dissolved silica in the water. And because these stretches of quiet water with an enormously tall concrete wall at the downstream end are great places to build up sediments, the biogenic silica that has been produced stands a very good chance of sinking down and getting buried. The buck stops here, as they say, and as a result of downstream areas are starved of silica."* (Silica Stories Conley et. al. 2017).

HYDRO QUEBEC AND THE ADVOCATES OF HYDROELECTRICITY CLAIM IT IS A POWER SOURCE THAT IS CLEAN AND RENEWABLE BECAUSE IT USES THE EARTH'S ANNUAL WATER CYCLE TO GENERATE ELECTRICITY. THERE IS SOME TRUTH TO THIS CLAIM, AS IT PERTAINS TO "RUN OF RIVER" HYDROELECTRIC DAMS, BUT IS A FALSEHOOD WHEN IT COMES TO LARGE RESERVOIR DAMS BECAUSE THEY HAVE ALTERED THE "HYDROLOGIC CYCLE," WHICH IS DEFINED AS FOLLOWS BY BRITANNICA:

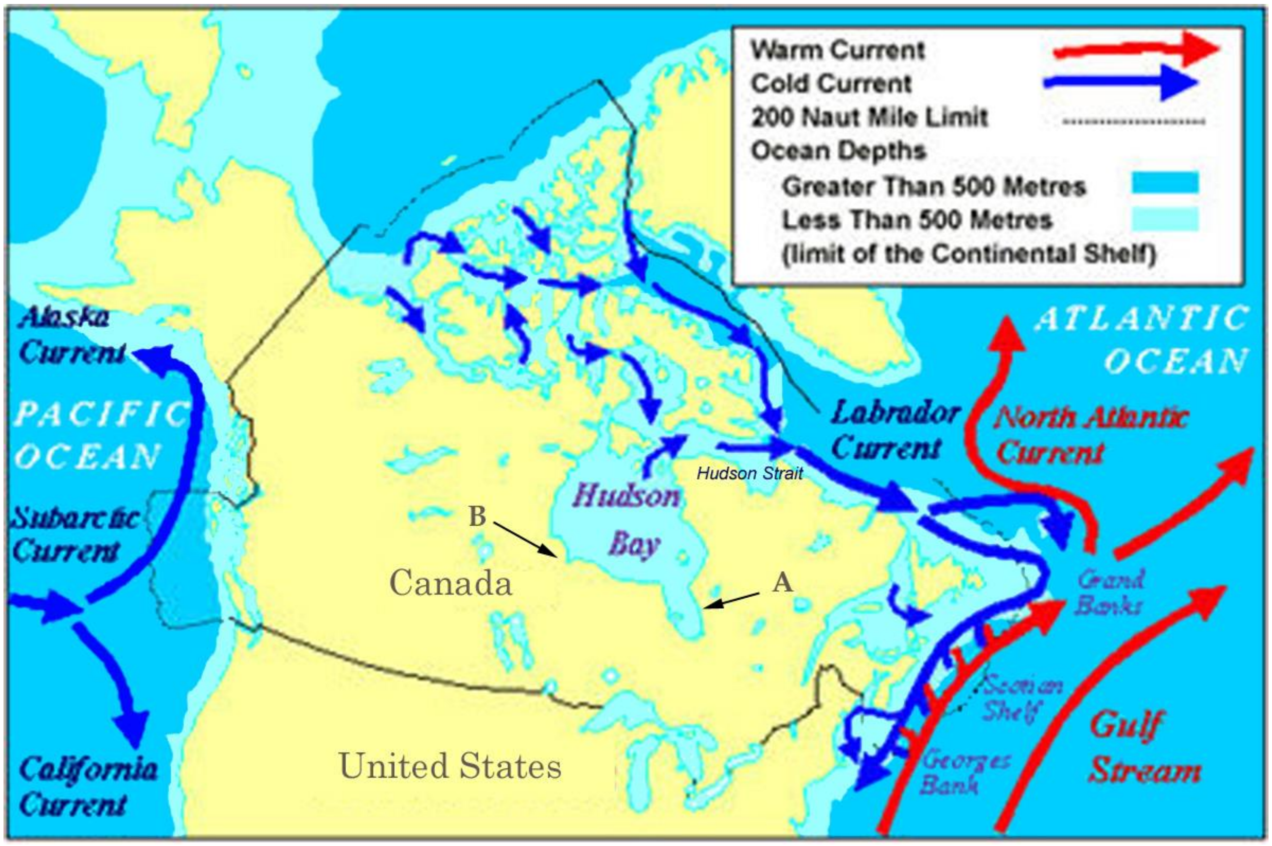
"Water on earth exists in all three of its phases-solid, liquid and gaseous. The liquid phase predominates. By Volume, 97.957 percent of the water on earth exists as oceanic water and associated sea ice. The gaseous phase and droplet water in the atmosphere constitutes 0.001 percent. Fresh water in lakes and streams makes up 0.036 percent, while groundwater is 10 times more abundant at 0.365 percent.

Each of the above is considered to be a reservoir of water. Water continuously circulates between these reservoirs in what is called the "hydrologic cycle," which is driven by energy from the sun, evaporation, precipitation, movement of the atmosphere, and the downhill flow of river water, glaciers, and groundwater keep water in motion between the reservoirs and maintains the hydrologic cycle."

The construction and management of reservoir dams by Hydro Quebec not only has significantly altered the hydrologic cycle, but also negatively impacted the silica cycle.

> *"Today, rivers and the release of groundwater through submarine springs deliver 85% of the reactive silica that enters the oceans.*
>
> *Up at the top of the ocean, dissolved silica taken up by silica biomineralizers like diatoms becomes incorporated into biogenic silica, most of which dissolved before it manages to sink all the way to the seafloor.*
>
> *Once added to the ocean, dissolved silica is available for use by silica biomineralizers such as diatoms. Furthermore, because our friends the diatoms are impressively numerous, fast-growing, and notably siliceous, it is a safe bet that most of the 240 teramoles (240 x 10^{12} mol aka 1.4 x 10 ^{1º} metric tons) of biogenic silica produced in the upper ocean each year is being produced by diatoms. Thus the production of biogenic silica in the oceans is depicted in the upper part of the ocean on the silica cycle.*
>
> *The fate of almost all of this biogenic silica that is made each year is to rapidly dissolve. The modern day ocean is after all extremely undersaturated with respect to noncrystalline silica. So strong is the power of this undersaturation, slightly more than half of the biogenic silica produced each year dissolved even before it has had time to sink only 100 to 200 meters. In the end only 2-3% of the biogenic silica produced in the oceans each year becomes permanently buried in ocean sediments.*
>
> *But permanent export of 2-3% of each year's crop of biogenic silica is enough to (more or less) equal the amount of reactive silica coming in to the ocean via rivers, submarine groundwater springs, and mid-ocean ridge hydrothermal fluids. And because the gross amount of biogenic silica production is so high, a removal efficiency of 2-3% is enough to keep ocean waters all but entirely depleted of dissolved silica."* (Silica Stories, Conley et.al. 2017).

IN A RECENT CANADIAN STUDY OF TRENDS IN RIVER DISCHARGE FROM 1964-2014, THE AUTHORS FOUND: ***THAT THERE HAS BEEN A THREE-FOLD INCREASE IN RIVER DISCHARGE DURING WINTER, WHEN ELECTRIC DEMAND PEAKS, INTO THE ESTUARIES OF LABRADOR SEA AND EASTERN HUDSON BAY FOR THE 2006-2013 PERIOD COMPARED TO 1964-1971 AND A FORTY PERCENT REDUCTION IN DISCHARGE DURING THE SUMMER.”*** (Recent Trends and Variability in River Discharges Across Northern Canada, Dery et. al. 2016).



Map 3

A. In this area marked “A,” Hydro Quebec has 9 reservoir hydroelectric facilities in the watershed of the LaGrande River and 2 on the Eastmain River. The annual capacity of these 11 facilities is 17,383 MW (see Map 2 on page 5 and Tables 2and 3 on page 11 for more detail).
B. In the area marked “B,” Manitoba Hydro has 4 reservoir hydroelectric facilities in the watershed of the Nelson River with an annual capacity of 3,837 MW (see Tables 2 and 3 for more details).
C. The proliferation of these reservoir hydroelectric facilities in the Gulf of Maine’s ecosystem over the past 70 years is summarized in the next two Tables. I did not include facilities with an annual capacity of less than 200 MW. There are thousands of them also altering the silica cycle.

Table 2

Reservoir Hydroelectric Generating Stations Discharging Into James Bay and Hudson Bay

Owner	Name	Capacity in Megawatts MW	Commissioned	Watershed
Manitoba hydro	Kelsey	287	1957	Nelson
Manitoba Hydro	Kettle	1,220	1970	Nelson
Manitoba-Hydro	Lang-Spruce	980	1977	Nelson
Hydro Quebec	Robert-Bourassa	5,616	1979-81	LaGrande
Hydro Quebec	LaGrande-3	2,417	1982-84	LaGrande
Hydro Quebec	LaGrande-4	2,779	1984-86	LaGrande
Manitoba-Hydro	Limestone	1,350	1990	Nelson
Hydro-Quebec	Brisay	469	1993	Caniapiscau
Hydro Quebec	LaGrande-2-A	2,106	1991-92	LaGrande
Hydro Quebec	Laforge-1	878	1993-94	Laforge
Hydro Quebec	LaGrande-1	1,463	1994-95	LaGrande
Hydro Quebec	Laforge-2	319	1996	Laforge
Hydro Quebec	Eastmain-1	507	2006	Eastmain
Hydro Quebec	Eastmain-1-A	829	2011-12	Eastmain
		21,220		

Table 3

Summary of Tables 1 & 2

Annual Capacity in Mega Watts (MW) of Reservoir Hydroelectric Generating Stations Discharging Into

	James Bay and Hudson Bay	St. Lawrence River	Labrador Current	Total
1930-39				
1940-49		204		204
1950-59	2,334	2,047		2,334
1960-69		2,953		2,953
1970-79	2,200	3,363	5,428	10,991
1980-89	10,812	1,064		11,876
1990-99	6,116	469		6,585
2000-2009	507	1,813		2,320
2010-2018	829	1,305		2,134
	21,220	12,749	5,428	39,397

ACCORDING TO A 2007 REPORT BY STRANEO AND SOUCIER: *"OUR RESULTS SUGGEST THAT APPROXIMATELY 15% OF THE VOLUME AND 50% THE FRESHWATER CARRIED BY THE LABRADOR CURRENT IS DUE TO HUDSON STRAIT OUTFLOW."*

The St. Lawrence River is the largest river in Quebec, and the second largest is the LaGrande, which flows into James Bay/Hudson Bay. Hudson Bay flows into Hudson Strait and continues south into the Labrador Current.

The Labrador Current is 6 to 12 miles wide and transports approximately 6 million cubic meters of fresh water each second southward, which is approximately 10% of the volume of the Labrador Current. This fresh water is carrying dissolved silica and other essential nutrients which stimulate biological productivity in the coastal waters of Labrador, which becomes progressively more productive from north to south.

Further south an inshore branch of the Labrador Current continues around the southern shore of Newfoundland and enters the Gulf of St. Lawrence (see Map 3 on page 10). The outflow of the St. Lawrence tends to follow the south shore and mixes with the Labrador Current. The circulation on the Scotia Shelf is dominated by a southwestward coastal current flowing from the Gulf of St. Lawrence to the Gulf of Maine.

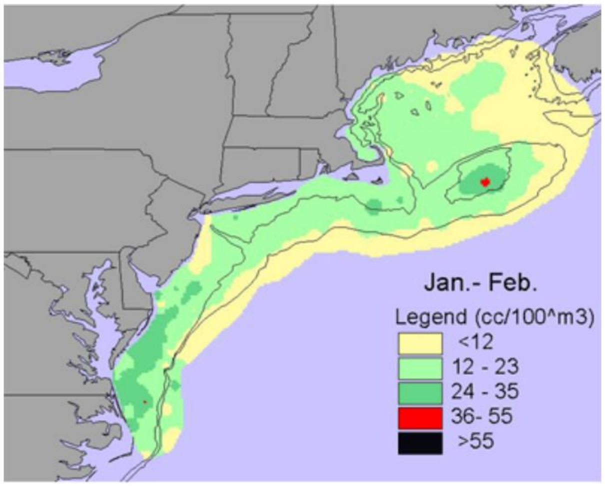
Silica-encased phytoplankton is the foundation of the aquatic food web, the primary producers, feeding everything from microscopic animal-like zooplankton to multi-ton whales. Small fish and invertebrates also graze on the plant-like organisms, and then those smaller animals are eaten by bigger ones. Phytoplankton is responsible for most of the transfer of carbon dioxide from the atmosphere to the ocean.

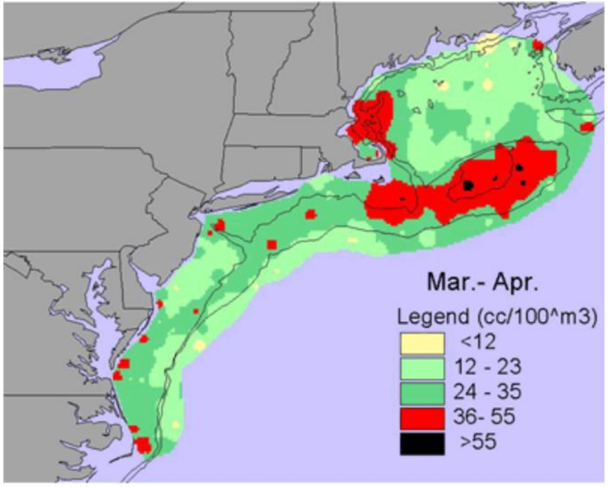
On the next page are satellite images showing how the pastures of zooplankton start blooming during the March through June period, in conjunction with the March/June period of the spring freshet of Maine's rivers discharging into the Gulf of Maine (see Map 1 on page 3 and Graph No.2 on page 4).

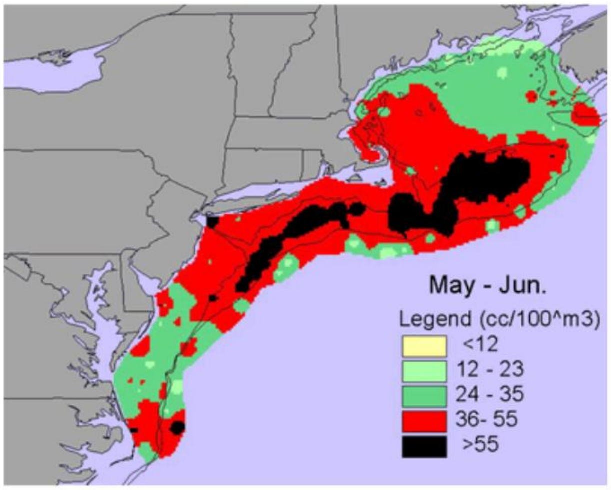
BEFORE RESERVOIR DAMS THE GULF OF MAINE WAS THE BENEFICIARY OF A PROLONGED SPRING FRESHET FROM ITS RIVERS, THE ST. LAWRENCE RIVER AND ITS TRIBUTARIES, AND THEN THE RIVERS OF NL, NORTHWEST QUEBEC AND MANITOBA VIA THE LABRADOR CURRENT.

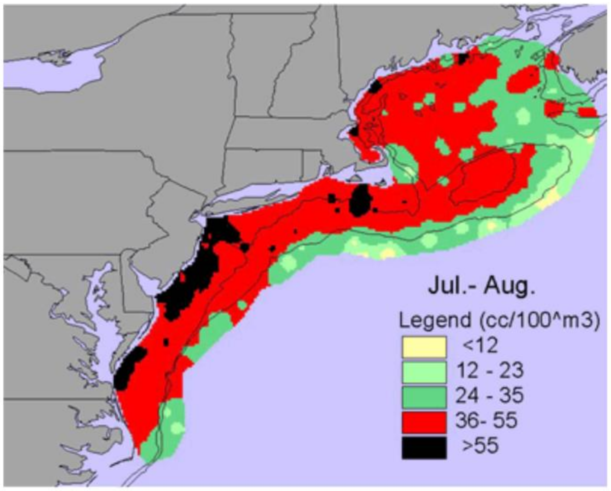
Hydro-Quebec has eliminated the historical (before reservoir dams) spring freshet from the major rivers into the St. Lawrence River. This freshet occurred during the April/June period, and the dissolved silicate in this freshet was quickly transported to the Gulf of Maine via the high river flows of the St. Lawrence River as measured at Sorel, Quebec in Graph No. 1 on page 3.

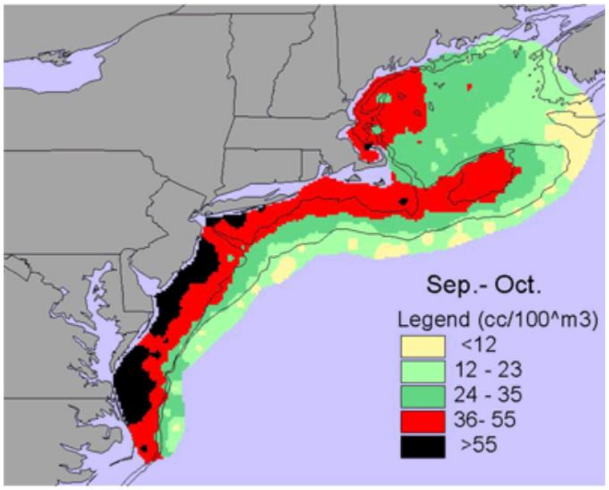
Biovolume of Zooplankton
Northeast U.S. Continental Shelf Large Marine Ecosystem

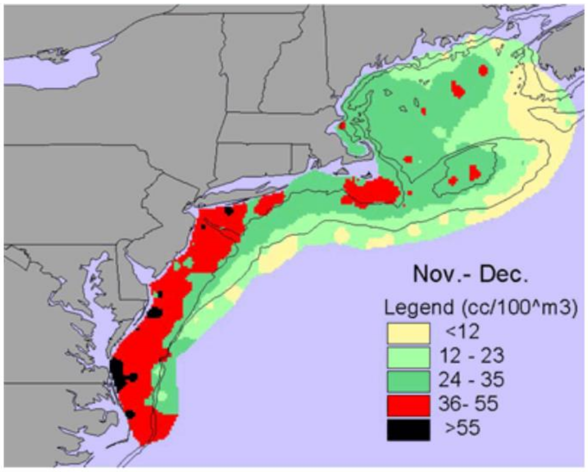








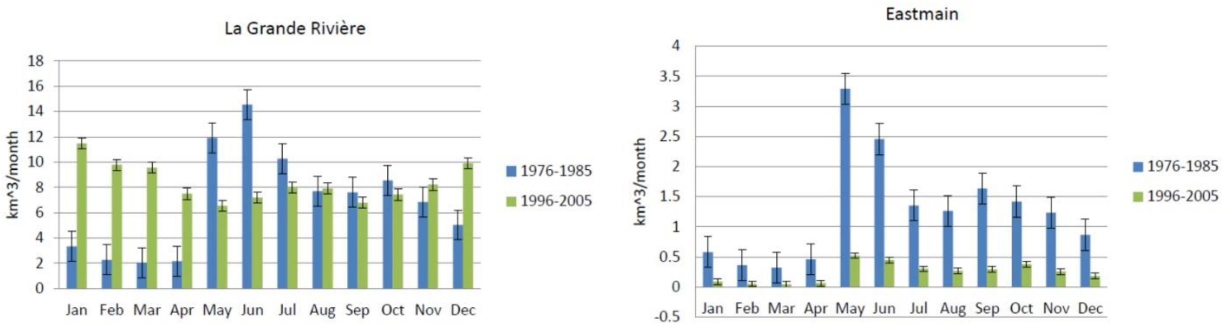




Source: NOAA – Northeast Fisheries Science Center

Roche wrote the following in his 2007 Report:

“In 1980, 80% of the flow from the Eastmain River was diverted in the LaGrande River, and seasonal runoff was impounded so that it could be released to produce electricity in the winter; consequently, the natural spring freshet into James Bay does not occur at either river. The plume from the Eastmain River is now much smaller and the size and shape of the summer plume from the LaGrande River are essentially unchanged; however, the area of the under-ice plume from the LaGrande River has trebled (Figure 3.1) and can now extend 100 km (62 miles) northward under the land fast ice of James Bay.”



Comparison of runoff from two of the major rivers most affected by damming or diversion for the pre-1986 and post-1986 periods.

Source: Ray Roche (2017)

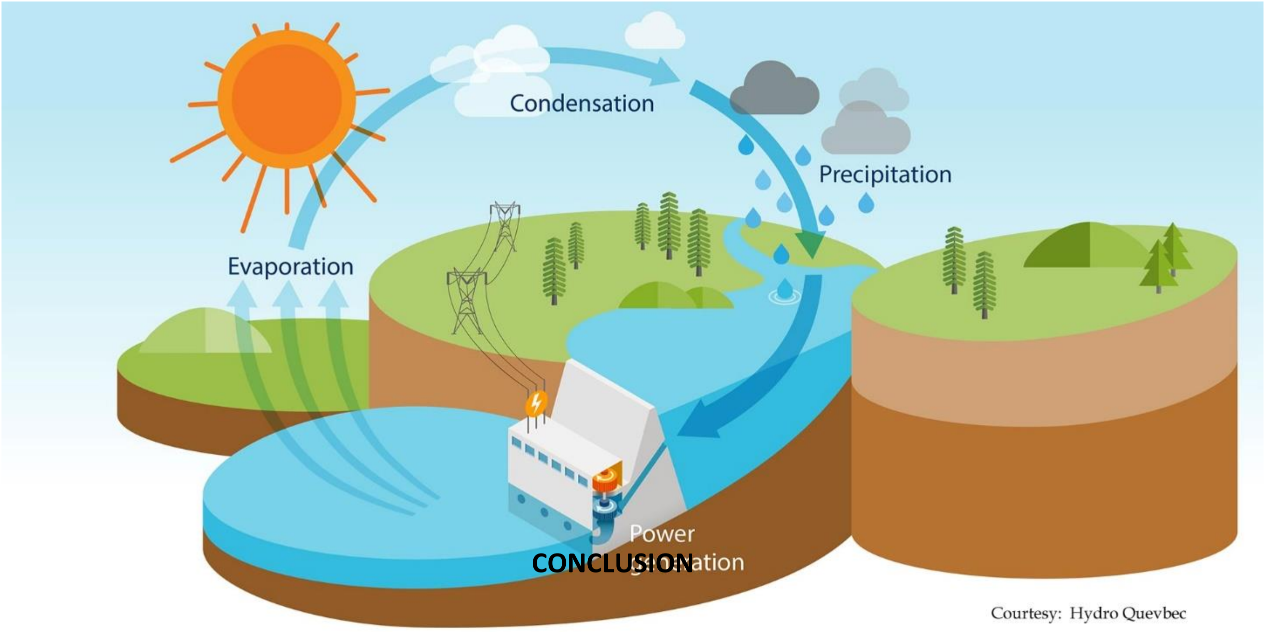
The high influx of dissolved silicate from LaGrande and Eastmain Rivers during the spring freshet is no longer available to be transported via the Labrador Current to the Gulf of Maine.

WHO DO YOU BELIEVE, THE AUTHORS OF SILICA STORIES OR HYDRO-QUEBEC?

> *"Dams in particular have had huge effects on the biogeochemistry, ecology and silica cycling of watersheds, creating lakes where there were not lakes before, trapping particles that would have otherwise been transported downstream, and obliterating seasonal flooding in favor of regulated year-round flow. Altogether this means most rivers of any note have multiple dams upon them and clogging up their spider vein watersheds. This has had a massive effect on the silica cycle, taking a lot of silica entirely out of the game before it can be transported downstream to coastal waterways.*
>
> *Worse yet, in our humble opinion as silica fans, nitrogen and phosphorus eutrophication frees up diatoms in lakes, ponds, and reservoirs to grow-grow-grow and in so doing strip out incredible amounts of dissolved silica from the water. This is a major double whammy. This silica, now bound up in the beautiful frustules of biogenic silica that diatoms produce, ends up being buried in the sediments accumulating in lakes, ponds, and reservoirs instead of supporting diatom growth in estuaries and the ocean. That represents a serious break in the silica cycle that carried silica, weathered from silicate rocks, out to the ocean to support silica biomineralizers in the sea and the profundity of food webs based upon them."* (Silica Stories by Conley et.al. 2017).

Hydropower is renewed through the natural water cycle

Hydropower starts with energy from the sun. The sun's heat causes water to evaporate and rise into the atmosphere, where it condenses and turns into clouds that are blown about by the wind. When the droplets and ice crystals that form clouds become too heavy, they fall back onto the ground as rain or snow. The water then flows through the rivers, and generating stations harness this cycle to produce electricity.



Courtesy: Hydro Quevbec

CONCLUSION

CONCLUSION

Quebec Hydro paints a benign picture of hydropower as renewable but fails to mention how it wrecks the silica cycle and the natural flow of water and nutrients especially dissolved silica which is critical for healthy fisheries and mediation of climate change.

The coastal diatoms of the Gulf of Maine have never stopped screaming for more dissolved silicate. The depletion of the shrimp, cod and other fisheries in the Gulf are the canaries in the coal mine who have been telling us for decades that there is a silica limitation in the Gulf of Maine.

This limitation has been caused by the proliferation of reservoir hydroelectric dams over the past 50 years on the major Canadian rivers, which for millennia have supplied nutrients to the Gulf.

For the Gulf of Maine's fisheries and mediating climate change nothing could be more important than restoring the natural timing, duration and quantity of fresh water flows transporting the annual load of dissolved silicate to the Gulf.

> *"But a lot of the excessive biogenic silica that freshwater diatoms are now able to produce gets buried in reservoirs and lakes, preventing its delivery downstream to the sea.*
>
> *Scientifically speaking, it took us some time to notice that dissolved silica was disappearing and yet some more time to grasp why. Of course, in retrospect, it's totally obvious. Of course this is what happened when we overloaded waterways with nitrogen and phosphorus. But in the beginning, we were probably too shocked by the eutrophication-fueled overgrowth of phytoplankton in general and all of the clogging and fouling of waterways and all of the fish-killing it was doing. Plus who would expect excessive nutrient addition to result in nutrient loss?*
>
> *And hardly anyone had the cleverness to foresee that dams would sequester silica.*
>
> *It took study of three different systems over an embarrassingly large number of decades for us to figure out what has been going on." (*Silica Stories by Conley & DeLaRocha 2017)

In Attachment 1 of this Report are these three case studies (referred to above) from Silica Stories by Conley and DeLaRocha 2017.

ATTACHMENT 1

EXCERPTS FROM <u>SILICA STORIES,</u> by DANIEL J. CONLEY
and CHRISTINE DE LAROCHA 2017

But natural is not the state of many rivers on Earth at this point. Never mind everything else we've done to them, for the last hundred or more years we've been continuously adding mind-boggling amounts nitrogen and phosphorus to rivers, groundwater, and lakes. The main culprits are fertilizers and animal waste flowing out of farms and off of fields, and poorly treated sewage (containing human waste and phosphate-containing detergents) from our houses, villages, towns, cities, and other settlements. As there is no equivalent addition of silica to balance things, the ratios of nitrogen to silica and of phosphate to silica in inland waterways have dramatically shifted against silica.

Thanks to our messiness, for the last few decades, diatoms in eutrophic systems *have not* been limited by nitrogen or phosphorus. They have been able to bloom until they have removed nearly all of the dissolved silica from the lake or river or pond or reservoir they are growing in. Some of this silica has recycled back into the water because some biogenic silica inevitably dissolves after the death of the diatom that made it. But a lot of the excessive biogenic silica that freshwater diatoms are now able to produce gets buried in reservoirs and lakes, preventing its delivery downstream to the sea.

Scientifically speaking, it took us some time to notice that dissolved silica was disappearing and yet some more time to grasp why. Of course, in retrospect, it's totally obvious. Of course this is what happened when we overloaded waterways with nitrogen and phosphorus. But in the beginning, we were probably too shocked by the eutrophication-fueled overgrowth of phytoplankton in general and all of the clogging and fouling of waterways and all of the fish-killing it was doing. Plus who would expect excessive nutrient addition to result in nutrient loss?

And hardly anyone had the cleverness to foresee that dams would sequester silica.

It took study of three different systems over an embarrassingly large number of decades for us to figure out what has been going on.

8.5 Case Study #1: The Laurentian Great Lakes

The first case that came to light of how we're screwing up the silica cycle has nothing to do with a dam, but strictly with eutrophication. It was also our first inkling that freshwater ecosystems were being shifted into silica limitation as a side effect of all the phosphorus and/or nitrogen we were spilling into waterways.

The time was the 1970s. Two to-be-giants in the field of limnology[7], Claire Schelske and Eugene Stoermer[8], both of the University of Michigan, had been studying the Laurentian Great Lakes that lie along the US-Canadian border. Before they started this work, a series of measurements on the intake waters of filtration plants serving the city of Chicago had shown that dissolved silica concentrations in Lake Michigan were decreasing. Claire and Eugene quickly discovered that the situation had escalated to the point where diatoms in Lake Michigan were running out of dissolved silica before the end of summer. This caused the growth of diatoms to screech to a halt several months before the end of their natural growing season, which had previously extended into autumn. Because diatoms serve as the base of key food webs, the knock on effect of premature stoppage in their growth was food shortage for fish and invertebrates in autumn in Lake Michigan.

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[7] Limnology is the study of inland waters, including rivers, ponds, lakes, reservoirs, wetlands, estuaries, and groundwater, with focus on the interactions between organisms and their environment.

[8] Incidentally, Eugene Stoermer was also the co-namer of the Anthropocene.

One of the first things Claire and Eugene wondered was whether the mid-summer silica depletion was something new or if it had merely previously escaped notice. The two of them sleuthed through what old, patchy datasets they could dig up from various water quality agencies. The resulting data, plotted in Fig. 8.2, revealed that the mid-summer exhaustion of dissolved silica was new. It had first showed up in Lake Michigan and settled itself fully in sometime between 1955 and 1969.

Now all they had to do was figure out why it was happening.

At first it must have been a head-scratcher. The decades leading up to and including the one that they were in had seen an explosive growth of algae beginning

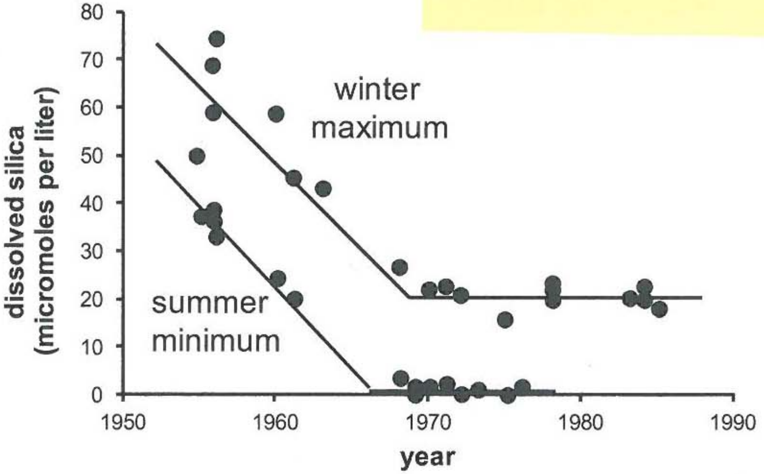

Fig. 8.2 The typical maximal concentrations of dissolved silica in winter and the typical minimum concentrations in summer in the surface waters of Lake Michigan significantly decreased during the 1950s and 1960s. This was due to excess production of biogenic silica fueled by phosphorus eutrophication. This figure has been redrawn from Internationale Revue der gesamten Hydrobiolie und Hydrologie 73, Schelske CL, Historic trends in Lake Michigan silica concentrations, 559–591, (1988), copyright © 1988 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, with permission from Wiley

to choke freshwaters across the globe. Diatom populations hitting the wall due to silica scarcity flew against the grain of this trend. It was out of step with everything turning most rather unexpectedly, unprecedentedly green.

But, when Claire and Eugene sat down and thought about it, the answer became obvious. There was a growing understanding, all over the world, that lakes, ponds, rivers, and estuaries were clogging up with excess algal growth because their concentrations of nitrogenous and phosphatic nutrients (that all phytoplankton, including diatoms, need in order to grow) were going off the charts. One reason, very well accepted at that point, was agricultural runoff that was full of biologically utilizable nitrogen and phosphorus from all the manure produced by livestock and from fertilizers applied to fields. The other widely acknowledged cause for eutrophication was human-generated sewage. But neither of these things, though, was adding much in the way of dissolved silica.

What Claire and Eugene also quickly came to realize was that, in the Great Lakes' case, the problem wasn't so much one of agricultural runoff nor was it one of too many people generating too much sewage. The problem was detergents that contained a lot of phosphate.

Detergents are crafty chemicals. One side of them is good at binding oils and fats (which, on their own, are insoluble in water) and another side of them is good at being dissolved in water. When detergents bind an oil or a fat, they thus drag it into solution. That is their cleaning power.

But detergents are not as effective in hard water, which is water that has a lot of calcium and magnesium dissolved in it. The doubly charged cations of Ca^{2+} and Mg^{2+} bind to detergents, precipitating them. Instead of foaming and doing a spanking great job of cleaning, in hard water, detergents form stubborn scum.

Most store-bought detergents have a water softener included in them to chemically preoccupy Ca^{2+} and Mg^{2+} so the detergent can do what a detergent's gotta do. Starting from about the 1950s and still in many cheaper detergents sold today, that water softener has been a phosphate such as trisodium phosphate or sodium hexametaphosphate (pronounced hexa-meta-phosphate).[9] Washing such phosphate-containing detergent down the drain, especially in areas lacking effective sewage treatment facilities, drains that phosphate straight into the nearest lake, river, or ocean, where it can feed the algae.

Take yourself back to the middle years of the twentieth century, when the human population was just beginning to embark upon the steep, wild, and crazy part of its exponential increase. At the same time modernization was marching along, introducing the washing machine and the dishwasher and then boosting their use. So not

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[9] These days we are tending towards using zeolites instead because they don't add massive amounts of a major nutrient to the water, although by even this very late date, there are few *national* laws against the use of phosphate in detergents.

only were there vastly more people than ever before living along the shores of the Great Lakes, flushing toilets and generating agricultural runoff, they were also enthusiastically doing laundry and washing dishes and the detergents they were using consisted of up to *50%* phosphate.

There is only so much even a Great Lake can take, even if it is the fifth largest lake in the world. For Lake Michigan, this was the waste water from millions of loads of laundry and dishes done each week by the people of Chicago, Milwaukee, Green Bay, and other sites on the shore on top of all the other sewage and agricultural runoff. Algae began growing like gangbusters.

As we've said before, Claire Schelske and Eugene Stoermer realized that this phosphorus eutrophication was the key to the disappearance of the silica from Lake Michigan. With the phosphorus brakes released on their growth, diatoms in Lake Michigan could grow until they had converted basically all of the dissolved silica in the lake's sunlit surface waters into diatom frustules that ended up in the sediments.

In other words, dissolved silica was disappearing from Lake Michigan because it was being turned into particulate silica by diatoms growing in the surface waters of the lake and exported, via sinking, to the bottom of the lake.

Ecologically speaking, this was dire news, but intellectually it was kind of cool. Phosphorus eutrophication was leading to silica oligotrophication, a paradox that made perfect sense. And, as ideas go, it was one that Claire and Eugene could test.

Even long-lived lakes are only temporary features of the landscape; they're busy filling up with layer upon layer of sediment. You can take advantage of this if you want to learn about the history of a lake, ecologically and climatically speaking. All you need to do is carefully take a sediment core, slice it lengthwise in half, and, moving downwards from the top of the core, begin your journey back through time.

The core that Claire Schelske, Eugene Stoermer, and their collaborators took in the middle of the deepest part of Lake Michigan (which is found within Grand Transverse Bay) was 40 centimeters long (about 16 inches) and, based on radiometric dating[10], covered the last century and a half. The milligrams of biogenic silica to be found per gram of core versus depth within the sediment core are shown in Fig. 8.3 and that's all that is needed to show the story.

Before 1920 or 1930, only 10 milligrams of every gram of sediment that was accumulating on the lakebed was biogenic silica, a content that can also be expressed as 10 parts per thousand, or 1% biogenic silica. As biogenic silica accumulation rates go, that's pathetic. Those pre-postmodern Lake Michigan diatoms should hang their heads in shame at the poor job they were doing of exporting silica to the sediments. Or maybe they should be proud, because this is the level of export of silica that the lake could maintain, given the amount that was being delivered to it each year in runoff.

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[10] Using the isotope lead-210 (^{210}Pb), which has a half-life of 22 years and is a particulate material which is continually falling out of the atmosphere following its production by the decay of radioactive radon gas.

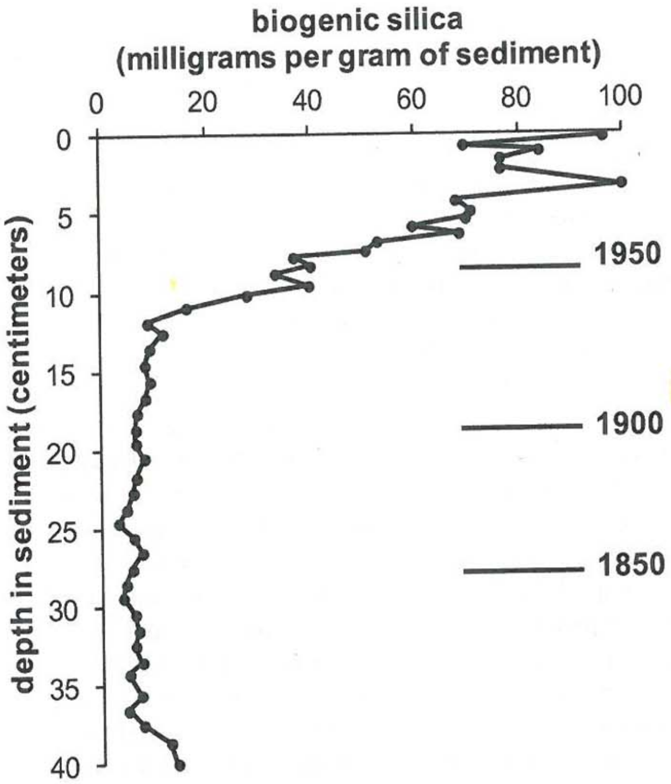

Fig. 8.3 Biogenic silica concentration versus depth in a core from Grand Traverse Bay, Lake Michigan records the transfer of Lake Michigan's silica into the sediments during the twentieth century's explosion in the use of phosphate detergents and fertilizers. This figure has been redrawn from Hydrobiologica 143, Schelske CL, Conley DJ, Stoermer EF, Newberry TL, Campbell CD, Biogenic silica and phosphorus accumulation in sediments as indices of eutrophication in the Laurentian Great Lakes, 79–86, (1986), copyright © Dr W. Junk Publishers, Dordrecht, with permission from Springer

As you move forward in time in the sediment core from 1930 it is like running up a ramp. The biogenic silica content of the sediments steadily climbs, reaching a peak of 100 milligrams of biogenic silica per gram of sediment (or 10% biogenic silica) by 1970. This you can see clearly in Fig. 8.3. What Fig. 8.3 does not show is what you would see if you made this measurement on lake sediments stretching back to the birth of Lake Michigan. The biogenic silica content of the older sediments (not shown here) reveal that such an astonishing change in silica burial had never happened before, not once in Lake Michigan's 14,000 year history.

Thus Claire and Eugene had managed to show that the disappearance of dissolved silica was due to excessive production of biogenic silica and that this excessive production of biogenic silica had never happened before people moved in by the tens of millions and started doing a lot of laundry in cities and towns along the shore of Lake Michigan.

There is another big detail of the shift that is revealed by the sedimentary record —the shift in the composition of the diatom population with the eutrophication of Lake Michigan. Diatom frustules are, after all, quite distinctive, and can be used to tell one diatom species from another.

Sediments older than the expansion of European settlements around Lake Michigan in the 1800s had a lot of different diatom species in them, representing a wide range of ecological niches (high light, low light, high silica, low silica, benthic, planktonic, spring growing, summer growing, autumn growing, etc.). But as phosphorus eutrophication (and silica depletion) increased, the variety of diatoms in the sediments narrowed to only those species that grow in late winter/early spring. This is the very start of each year's growing season, when dissolved silica concentrations are still high from winter mixing. Diatoms that would have grown later in the year were missing because by the time it was their turn to grow, there was no dissolved silica left for them to use. Benthic diatom species, meaning those that grow on the bottom of the lake (in shallow waters), also disappeared, most likely because the overgrowth of plankton due to eutrophication made it too dark down there for them to grow.

Overall, diatoms getting shut out of the latter part of the growing season in Lake Michigan while there is still plenty of nitrogen and phosphorus available for growth is a bad thing. It means a decrease in the flow of energy and materials through diatom-based food webs, which generally efficiently lead to fish, and an increase in the growth of noxious plankton species like dinoflagellates.[11] Worse yet, what happens in Lake Michigan doesn't stay in Lake Michigan. Now stripped of their dissolved silica, the waters of Lake Michigan flow into Lake Huron and then Lake Erie, go over Niagara Falls, flow into Lake Ontario, and then via the Saint Lawrence River, arrive at the Atlantic Ocean at the Gulf of Saint Lawrence in all the full glory of their silica deficiency. You can almost hear the coastal diatoms screaming.

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[11] The addendum here is that the water quality (and dissolved silica content) began improving in the first decades of the twenty-first century due to improvements in sewage treatment and to the phasing out of phosphate detergents. Then the quagga mussel invaded, via larval stages that most likely arrived in water released from the ballast tanks of transoceanic shipping vessels. The quagga and its relatives are voracious filter feeders and they've colonized enough of Lake Michigan to keep the waters clear of algal blooms, regardless of the lake's nutrient status. Unfortunately, this means that phytoplankton still aren't making it into the food chains that lead to fish, causing a collapse in the lake's fisheries. Poor Lake Michigan can't catch a break from the trouble caused by human beings.

8.6 Case Study #2: The Baltic Sea

Once the research on Lake Michigan became known, people started to have a look at other large inland bodies of water to see if the same things were happening to their local silica cycles. One of the more recent and most intensively investigated places has been the Baltic Sea.

Lake Michigan is big, but the Baltic Sea is massive. It is that large inland sea that sits in the midst of northern Europe. You could think that the Baltic Sea is too big to be notably affected by the activities of humankind. But once you start paying attention, you quickly come to pity the Baltic Sea. All but entirely encircled by Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Poland, Germany, and Denmark and additionally containing portions of Belarus, Ukraine, Norway, Slovakia, and the Czech Republic in its watershed, the Baltic Sea is subject to continual insult by the agriculture and sewage of 90 million people. This insult, which comes partly in the form of four to eight times more nitrogen and phosphorus than it tended to receive a century ago, is delivered in 16,000 metric tons of freshwater *per second* flowing off the land. Consequently, concentrations of nitrate and phosphate in the Baltic Sea have increased over the last century.

But concentrations of dissolved silica have declined. This decline has been severe. For example, concentrations of dissolved silica in subsurface waters in a central area of the Baltic Sea have decreased by one-third to two-thirds since the late 1960s, the time when monitoring began at that location.

So far so Great Lakes? It seems pretty similar. Just add eutrophication and watch those diatoms go (until they run out of dissolved silica).

Maybe. But maybe not.

There is a certain key difference in the situation of Lake Michigan and the Baltic Sea. Excess phosphorus is mainly delivered to Lake Michigan directly, from sources that originate along the shore. But the Baltic Sea is receiving waters high in phosphorus and nitrogen via rivers that travel great distances to get to the Baltic Sea and generally encounter multiple lakes and dams along the way. This gives silica plenty of opportunity to be removed and trapped in sediments long before it arrives into the Baltic Sea itself. So maybe excess production of biogenic silica within the Baltic Sea itself is stripping dissolved silica out of its waters. But maybe that silica is being removed upstream and because the Baltic Sea is being thus deprived of dissolved silica, its poor diatoms aren't growing (or producing biogenic silica) much at all. If we want to help solve the problem (in part because we'd like to get the Baltic back to supporting food webs that produce something besides enormous swarms of jellyfish) we need to know which one is going on. Plus we're just plain old curious.

The first question to tackle: do outputs of silica from exceed inputs of silica to the Baltic Sea? If so, at least some of the problem is due to eutrophication-fueled diatom growth within the Baltic itself. The straightforward way to answer the question is to put together a silica budget with inputs on one side and outputs on the other.

For a small reservoir or lake, this should be easy. You need to measure three things. One is the amount of dissolved silica flowing in with water flowing in from rivers and streams. Another is the amount of biogenic silica accumulating on the lake bed. The third is the amount of dissolved silica flowing out in the stream that serves as the lake's outflow.

But the Baltic Sea is no little lake. Nearly 100 rivers of note flow into the Baltic Sea and you'd have to monitor each one for several years. There is at least only one outflow of water from the Baltic Sea (aside from evaporation): water leaves via the Denmark Straits to the Atlantic Ocean. But sometimes, because of storms, winds, currents, and tides, the water flows in instead, bringing dissolved (and biogenic) silica with it. As far as measuring how much biogenic silica is getting buried in Baltic Sea sediments, the complication here is that the Baltic Sea is made up of numerous basins, such as Bothnian Bay, the Bothnian Sea, the Gulf of Finland, the Baltic Proper, the Gulf of Riga, the Denmark Straits, and the Kattegat, and they all behave differently (and exchange water with each other). Figuring out how much biogenic silica is accumulating in the sediments requires careful study of sediment accumulation rates (and correction for sediment winnowing and focusing due to currents) in all of these regions.

Despite the near impossibility of the task of determining whether more silica is leaving the Baltic Sea than is coming in, there have been several attempts to put together silica budgets for the Baltic Sea. (Scientists do love them a challenge.)

In their quest, two different groups of researchers have fed monthly measurements of dissolved silica from the major rivers flowing into the Baltic and measurements of wintertime dissolved silica concentrations at various locations within the Baltic Sea into a computer model of Baltic Sea circulation in order to calculate how much dissolved silica is disappearing from Baltic Sea water as it flows out to the North Atlantic. Both groups came up with much the same result, that recently roughly 1,300,000 tons of silica has been accumulating in the sediments of the Baltic Sea each year. As both modeling efforts produced a Baltic Sea whose dissolved silica concentrations decreased from year to year during the model runs, an export of 1,300,000 tons of biogenic silica to the sediments must be enough for the total export of silica from the Baltic Sea to be exceeding silica's input.

So the Baltic Sea is probably at least a little bit like Lake Michigan. Eutrophication is causing it to overproduce biogenic silica. But when you actually look at the data that were fed into the models, you realize that something else pretty major is going on.

Many of the major rivers flowing into the Baltic Sea have concentrations of dissolved silica that are, frankly, shocking.

The Neva River, which is the greatest of the rivers flowing into the Baltic Sea, contains *8* micromoles of dissolved silica per liter when it reaches the Baltic Sea. Can you hear the diatoms weeping? No self-respecting river should contain such a measly amount of dissolved silica. An *average* (as in mediocre, hum-drum, run-of-the-mill) river has 160 micromoles of dissolved silica per liter and an overachiever has 1000 micromoles of dissolved silica per liter. A number like *8* is almost unfathomable. To yield up only 8 micromoles per liter dissolved silica, the Neva River's catchment is only producing a net 63 kilograms of silica per square kilometer of catchment area per year, another number to make a diatom cry.

The Vistula, the Baltic Sea's number two river in terms of the delivery of water, is better, but at 119 micromoles of dissolved silica per liter and 580 kilograms of silica produced per square kilometer, still below average. The number three river, the Daugava, averages around 60 micromoles of dissolved silica per liter, a yield of 411 kilograms of silica per square kilometer, more dismal numbers.

But if you look at the rivers draining into the Baltic Sea from the emptier, more northern areas of the catchment, you'll find that they are not like this. The Närpiönjoki in Finland has an average dissolved silica content of 267 micromoles of dissolved silica per liter, representing a catchment yield of 2285 kilograms of silica per square kilometer. The numbers for the Isojoki, also in Finland, are similar: 195 micromoles of dissolved silica per liter and 2105 kilograms of silica per square kilometer.

What's the difference between the respectably silica-containing rivers and the failures? The silica-poor rivers draining into the Baltic Sea are found in more heavily populated areas while the silica-rich rivers are running wild. The silica-poor rivers are suffering from notably greater eutrophication and they contain much greater (natural and manmade) reservoir volume.

Take that astonishingly low-silica river, the Neva River, for example. Just upstream of St Petersburg (not so far from the Baltic shore), it runs through Lake Ladoga, one of the largest lakes in Europe. Lake Ladoga has been heavily eutrophicated since the 1960s. You can all but walk on the phytoplankton blooms, they grow so thick. This is where a lot of the Baltic Sea's silica is ending up. Buried in Lake Ladoga's sediments.

Similar, although less severe losses of silica must be occurring in lakes and reservoirs along other eutrophicated rivers that feed into the Baltic Sea.

Once you have data (on silica concentrations, water flows, surface area of river catchments, and so on), you can cross-examine them to tease out the combined effects of eutrophication and damming on the silica content of rivers draining into the Baltic Sea. You could, for example, plot the concentration of dissolved silica in a river (or, if you'd prefer, its yield of dissolved silica per catchment area) versus the amount of time water spends in the river's catchment area. Dams and natural lakes both increase the residence time of the water within the catchment. Thus a long residence time indicates the water spends a lot of time in places favorable to diatom blooms and export of silica to sediments.

In practice, residence time of water in a river catchment is not an easy thing to measure. So you can try to use a proxy, some other more easily or accurately measurable factor that is relatable enough to residence time that it can serve as a stand in. You might try hydraulic load, the amount of water, expressed as meters of height, that passes over a point in the river system each year. High hydraulic loads are associated with short residence times (fast flowing water) while low hydraulic loads indicate long ones (fairly slow, stagnant flow).

The result? The lower the hydraulic load (and the longer the residence time of water in the river system), the lower the catchment's dissolved silica yield per area and the lower the concentration of dissolved silica in the river. This is true for all types of river feeding into the Baltic Sea, meaning that reservoir volume (be it natural lakes or manmade due to damming) is giving diatoms a chance to bloom and remove silica before the silica reaches the Baltic Sea. That the problem is worse in eutrophicated river systems is also clear because concentrations of dissolved silica are lower in these rivers regardless of their hydraulic load.

This is all illustrated nicely in Fig. 8.4. The yields of dissolved silica per catchment area from a subset of the Baltic Sea catchments that are not eutrophicated and whose flows are not interrupted by dams (represented on the plot by the black triangles) range from 800 to almost 1300 kilograms of silica per square kilometer. These highest silica yields belong to fairly pristine catchments where water doesn't spend too much time hanging around. There is neither the time nor the added nitrogen and phosphorus for diatoms to bloom and remove dissolved silica. These rivers hit the Baltic Sea with a healthy load of dissolved silica and this most likely represents the natural state of the system.

The subset of the Baltic Sea catchments that are not eutrophicated but are subjected to damming (represented by the black circles on Fig. 8.4) give yields of 280 to 1100 kilograms of silica per square kilometer and the yields clearly decrease as the residence time of water in the watershed increases because waters are detained in lakes and reservoirs on their way to the Baltic Sea. There is just enough naturally occurring nitrate and phosphate for diatoms to bloom and remove some dissolved silica from the river system, thus preventing it from reaching the Baltic Sea.

The subset of the Baltic Sea catchments investigated that are both eutrophicated and dammed (the gray circles on Fig. 8.4) have yields of 60 to 600 kilograms of silica per square kilometer. There are two things going on here. Eutrophication in general is keeping the yields low because diatoms are growing and removing silica. But the lowest of the low yields are occurring in catchments where the residence time of the water is the greatest and this is because of lakes and by reservoirs produced by damming.

These are, you might say, damning results for both eutrophication and damming.

Worse, we're starting to suspect that there is another process contributing to the problem. Rates of silicate weathering within damned catchment areas are probably lower than in non-dammed catchments. When you build a dam, a lot of what used to be the soils of grasslands and forests becomes the bottom of a reservoir. Weathering reactions tend to be vigorous in the soils of grasslands and forests and the dissolved silica the weathering produces is efficiently flushed into rivers when it rains. But not much silicate weathering is going to be going on at the bottom of a reservoir. As a result, not only is the reservoir sequestering silica that used to flow onwards to the ocean, it is also preventing some silica from being added to the river in the first place.

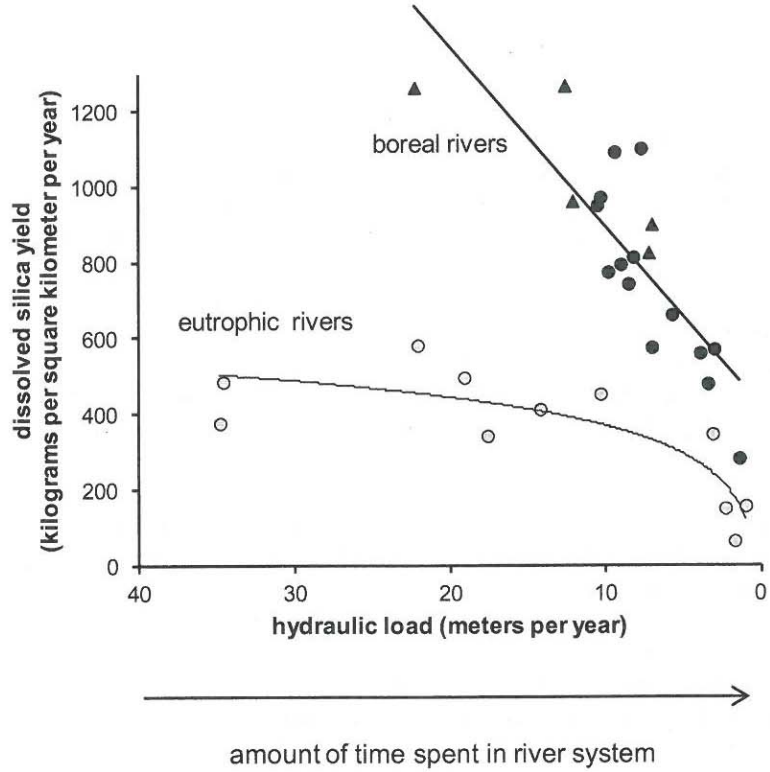

Fig. 8.4 Yield of dissolved silica compared to hydraulic load for pristine boreal rivers (*black triangles*), eutrophicated but undammed boreal rivers (*black circles*), and heavily eutrophicated and dammed rivers (*gray circles*) draining into the Baltic Sea. Hydraulic load serves as a proxy for residence time, with residence time increasing to the *right* of the figure. This figure has been redrawn from Journal of Marine Systems 73, Humborg C, Smedberg E, Medina MA, Mörth C-M, Changes in dissolved silicate loads to the Baltic Sea—the effects of lakes and reservoirs, 223–235, (2008), copyright © 2007 Elsevier B.V., with permission from Elsevier

The patterns revealed by the set of river catchments of Fig. 8.4 can be used to estimate that the combination of eutrophication and damming has decreased the amount of dissolved silica delivered into the Baltic Sea by 30–40% during the last century.

That is the sort of number that you should not announce to a silica enthusiast unless you've taken the precaution of sitting them down in a chair.

In other words, right now is a really lousy time to be a Baltic Sea diatom. All those dams we've built within the Baltic Sea catchment area and all the nitrogen and phosphorus we're pouring into it too… We're denying Baltic Sea diatoms the silica they need to survive.

8.7 Case Study #3: The Black Sea

The same sort of thing has been going on in the Black Sea. But it took us some time to understand the problem here because we got hung up on the idea that the Black Sea's silica problems stemmed from one single spot on the Danube River. It was at the time a compelling story, though, and it got a lot of people interested in the problem of silica and dams.

The Danube River, the second longest river in Europe, arises in the Black Forest, meanders through or along Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Bulgaria, Moldova, Ukraine, and Romania, collecting water from an even greater portion of Europe, and then pours into the Black Sea. Like the also enormous catchments of the two other major rivers that flow into the Black Sea (the Don and the Dieper), the Danube River catchment was dammed to the hilt between the 1960s and the present day and eutrophication is a serious problem.

At this point, you will probably nod knowingly when we tell you that for decades phytoplankton overgrowth in the Black Sea has been common and concentrations of dissolved silica have declined and that all of this has occurred alongside shifts in the composition of photosynthetic populations away from diatoms. Populations of benthic macrophytes such as seagrasses and macroalgae have also taken a serious hit and anoxia has become more widespread. This is bad, not only for Turkey's Black Sea anchovy fishery, but also for entire Black Sea beach resort industry that is important to the economies and vacations of Turkey, Bulgaria, Romania, Ukraine, Russia, and Georgia.

By 1997, which was long after Claire Schelske's and Eugene Stoermer's groundbreaking discovery that eutrophication resulted in silica removal within the Laurentian Great Lakes but a few years before the work on the Baltic Sea described in the previous section, it became clear that the Black Sea was missing a lot of dissolved silica. Monitoring that had begun in 1960 had revealed that dissolved silica concentrations had briefly shot up and then steadily dived in the Black Sea, dropping from an average of about 60 micromoles of silica per liter in the mid-1970s down to below 10 by about 1995. It was as if some single abrupt change in the system kicked off a dramatic disappearance of silica.

Enter the Iron Gate dam.

Iron Gate I runs across the Danube along a stretch that serves as the Romanian–Serbian border and is a hydroelectric generation plant. It's also the largest dam on the Danube River. It was so very most suspiciously completed in 1972, right before dissolved silica went into its dive. The obvious explanation was that the dissolved silica that was now missing from the Black Sea was accumulating as 1.3 million kilograms of biogenic silica accumulating in the sediments trapped by Iron Gate I every year. It had to be the case! The circumstantial evidence was screaming.

Simple stories are seductive. Impound a single dam on a major tributary of a fair-sized sea and send the downstream coastal areas into silica freefall. Even scientists can get enthusiastic over ideas that are too good to be true.

Of course the story turned out to be wrong, but it also turned out to be the story that got researchers interested in the effect of dams on silica. Although the problem of dams resulting in downstream waters depleted of dissolved silica had first come to light in a well-researched and well-written 1980 publication in a top-notch scientific journal by top-notch scientific researchers[12], somehow the news hadn't sunk in.

The dam's name probably helped too. With a name like that (Iron Gate) the dam had to be: Huge! Solid! Fearsome! Authoritarian! And rather like the Iron Curtain. Nothing, not even silica, could get through. Even silica scientists (initially) felt swayed. Damn that dam for stealing all the Black Sea's silica.

However, the name was merely an accident of history. Iron Gate I and its younger sibling, Iron Gate II, were not named for their formidability. They were named for their locality.

The Iron Gates are a picturesque series of gorges that the Danube runs through. That narrowed stretch of river is over a hundred miles long and its name may have originated from a number of pestilential bedrocks shoals, now long since removed, that could rip apart the hulls of ships that failed to steer around them. Perhaps hundreds of years ago, a person with poetry in their heart likened them to the spikes on an iron gate. In an alternate universe, one with a shortage of poets, there may be two Damned Shoals dams instead and nobody who thinks that particulate silica is piling up behind them.

In this universe, at least, biogeochemists eventually decided to put the hypothesis to the test.

One of the first things they noted was that, yes, the reservoir upstream of Iron Gate I is nothing to sneeze at. It is 120 kilometers (75 miles) long and holds 2.4 billion cubic meters of water. But this has more to do with the river than the dam. The Danube River carries so much water by the time it reaches the Iron Gates, the Iron Gate I dam needs 1100 meters of length in order to span the river. That's 3600 feet. So it doesn't take much diminishment in flow (or increase in water residence time) to create a large reservoir volume at this location.

Indeed, the Iron Gate dams do not significantly increase the residence time of water along this stretch of the Danube. Iron Gate I, like Iron Gate II, is a hydroelectric power generating station. Water flows FAST through the dam. It has to turn turbines.

When you measure how long the water spends in this reservoir (plus in the much smaller one downstream of it now that they've built Iron Gate II), you find that it's six and a half days, which is hardly any time at all. If we were a diatom bloom, we'd file a complaint. It's not enough time to get our work done.

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[12] Larry Mayer and Steven Gloss, two widely known and respected biogeochemists, had first noted the effect on dams on dissolved silica in 1980 in a published paper on the Colorado River in Arizona before and after the construction of Edward Abbey's favorite of favorites, the Glen Canyon Dam.

Silica budgets constructed for Iron Gate I, its reservoir, and its sediments have confirmed this. The Iron Gate dams are not a big trap for silica. It looks like about 850,000 tons of silica flows into the reservoir as dissolved silica each year and 810,000 tons flows out. The 40,000 tons of silica trapped is not nothing but it is well short of the postulated 600,000 tons.

Now that the research on silica losses in the Baltic Sea catchment area has been done, it's clear that the disappearance of silica from the Black Sea isn't the work of one fearsome dam. It's due to the tens of thousands of dams that have been built along the often eutrophicated rivers that head ultimately to the Black Sea. And of course, the eutrophication-fueled overgrowth of diatoms within the Black Sea itself has probably contributed to the decades-long decline in dissolved silica concentrations that has occurred within the Black Sea. This isn't as superficially exciting a story as one single dam having an impact so severe it was changing the ecology and biogeochemistry of the entire Black Sea, but it is profound.

8.8 The Global View

The Larentian Great Lakes, the Baltic Sea, and the Black Sea are all major bodies of water, but they are still just a drop in a bucket compared to all the fresh and salt water on Earth. But they represent a crisis that is unfolding across the Earth.

Those 850,000 dams we currently have, about 60,000 of them large, disrupt flow *on more than half* of all river systems. Various different modeling studies have calculated that altogether these dams decrease the total global flux of dissolved silica to the ocean by 5%.

Does that seem small?

It isn't. Five percent represents a deficit that adds up year after year into enough of an enormous lack of dissolved silica that diatoms in estuaries and the coastal ocean, where they are most needed to support fisheries, could be operating at a disadvantage.

Natural but now eutrophicated lakes are even worse than reservoirs, in that they seem to be better at retaining silica in their sediments. Including them in the global estimate would bring the total amount of silica flux diminished to nearly *30%*, a truly apocalyptic number.

The next time you're down at the beach, you may want to hug a diatom. They could certainly use the moral support. But they'd like it even more if you pushed your legislatures for laws requiring that detergents to be sold phosphate-free. This needs to include dishwasher detergents (which, in many places, are exempt from restrictions). Our diatom friends could also use more and better sewage treatment plants, incentives and support for farmers to do something about the millions of tons of phosphate and nitrogen fertilizers and animal waste flowing off of their lands, the removal of dams no longer needed, and some serious, sober second thoughts about building any more.