The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium[1]

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Abstract: Climate warming will adversely affect Canadian water quality and water quantity. The magnitude and timing of river flows and lake levels and water renewal times will change. In many regions, wetlands will disappear and water tables will decline. Habitats for cold stenothermic organisms will be reduced in small lakes. Warmer temperatures will affect fish migrations in some regions. Climate will interact with overexploitation, dams and diversions, habitat destruction, non-native species, and pollution to destroy native freshwater fisheries. Acute water problems in the United States and other parts of the world will threaten Canadian water security. Aquatic communities will be restructured as the result of changes to competition, changing life cycles of many organisms, and the invasions of many non-native species. Decreased water renewal will increase eutrophication and enhance many biogeochemical processes. In poorly buffered lakes and streams, climate warming will exacerbate the effects of acid precipitation. Decreases in dissolved organic carbon caused by climate warming and acidification will cause increased penetration of ultraviolet radiation in freshwaters. Increasing industrial agriculture and human populations will require more sophisticated and costly water and sewage treatment. Increased research and a national water strategy offer the only hope for preventing a freshwater crisis in Canada.

Résumé : Le réchauffement climatique va avoir des effets négatifs sur la quantité et la qualité des ressources en eau du Canada. L'ampleur et le régime temporel de l'écoulement des cours d'eau vont changer, tout comme le niveau des lacs et la période de renouvellement. Dans de nombreuses régions, les milieux humides vont disparaître et le niveau des nappes phréatiques va baisser. L'habitat des organismes sténothermes d'eau froide va se réduire dans les petits lacs. Le relèvement des températures va affecter les migrations des poissons dans certaines régions. Le climat va interagir avec la surexploitation, les barrages et dérivations, la destruction de l'habitat, les espèces introduites et la pollution pour mettre en péril les pêches d'espèces indigènes en eau douce. Les problèmes aigus d'approvisionnement en eau que connaissent les États-Unis et d'autres régions du monde vont menacer la sécurité hydrique du Canada. Les communautés aquatiques seront restructurées suite aux modifications dans la compétition, aux changements dans le cycle vital de nombreux organismes et à l'invasion de nombreuses espèces exotiques. Le ralentissement du renouvellement de l'eau va accroître l'eutrophisation et stimuler de nombreux processus biogéochimiques. Dans les lacs et les cours d'eau à faible capacité tampon, le réchauffement climatique va exacerber les effets des précipitations acides. La diminution du carbone organique dissous causée par le réchauffement climatique et l'acidification va faire croître la pénétration du rayonnement ultraviolet dans les eaux douces. Le développement de l'agriculture industrielle et l'essor démographique vont exiger des techniques de traitement de l'eau et des eaux usées plus perfectionnées et plus coûteuses. L'intensification de la recherche et l'adoption d'une stratégie nationale de l'eau peuvent seules offrir l'espoir de prévenir une crise de l'eau douce au Canada.

[Traduit par la Rédaction]

...by means of water we give life to everything.
Koran 21:30

Introduction

Considering its importance to all life on earth, it is strange that freshwater has been our most mistreated and ignored natural resource. Water has been used as a conduit for diluting and transporting human and industrial waste. These activities were almost unrestricted until the mid-twentieth century and in some areas are little restricted today. Dams, impoundments, and diversions have destroyed river habitats, prevented fish migrations, and mixed the biotas of rivers that have been isolated for many thousands of years. Overexploitation has depleted fish stocks. Airborne pollutants have caused acidification of lakes and contaminated food webs to the point where in many areas, concentrations of pesticides, polychlorinated biphenyls (PCBs), mercury, and other persistent organic chemicals in fishes are high enough to require that human consumption be restricted. Human and livestock wastes have caused the eutrophication of many waters in southern Canada and contaminated them with pathogens that will greatly increase the cost of water treatment and health costs from waterborne illnesses.

Despite these well-known problems, Canadians have a rather cavalier attitude toward aquatic ecosystems, probably

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because water is so abundant. Overall, lakes cover 7.6% of the country's surface, over 755 000 km^2. Canada's rivers discharge 9% of the global flow, 14% of the land surface is covered by wetlands, and 2% is covered by snow and ice (Environment Canada 1998). There are also extensive groundwater reserves in most areas. Globally, only Oceania has such plentiful water supplies.

The abundance of water has also caused Canadians to ignore the effects of climate warming on their water supplies. Research on the effects of climate change on freshwaters is scarce and poorly funded. This is a grave mistake. As I shall show below, in addition to its direct effects, climate warming will exacerbate the effects of many other human activities. The effects of extirpation of fisheries by overexploitation, the deliberate and accidental introductions of non-native species that often displace their native counterparts, the effects of acid rain, increased exposure to ultraviolet (UV) radiation caused by stratospheric ozone depletion, water pollution, and water withdrawals are among the stresses that will be increased by climate warming. Agriculture and forestry will be limited by water shortages. Canadian water abundance, pollutant concentrations, aquatic biota, wetland and riparian areas, agriculture, forests, arctic ice packs, and navigation will be affected. Each stressor viewed by itself does not seem all that harmful (at least to some), but the overall effect will be the degradation of Canadian freshwater on a scale that was not comprehensible to the average Canadian at the end of the twentieth century.

Elsewhere, I have reviewed many of the effects of climate warming on lakes and streams at the Experimental Lakes Area (ELA) (Schindler et al. 1990, 1996*a*) and also on a more general level (Schindler 1997, 1998*a*). Here, I shall focus largely on topics not treated in the above papers, including synergistic interactions, and speculate about the role that climate warming might play in affecting freshwater quality and quantity, fisheries, and other biota in the next 100 years. This topic is enormous, and in the available space, I can give only selected examples of what will happen to make water the most important economic and environmental issue of the twenty-first century.

Effects of global change on water quantity

At present, the amount of water per capita in Canada is huge. But its distribution renders much of it unavailable, for most Canadian rivers flow northward, away from the 300-km-wide band along the U.S. border where almost all of the country's 30 million people reside. Canadians are profligate water users. The average Canadian consumes about 326 L of water per day at home, about twice the per capita water use in Europe (Environment Canada 1998), and many times that of countries in the Middle East (Postel 1998; Falkenmark 1999). This figure does not include industrial, agricultural, or hydroelectric power usages, which would greatly increase estimated water use. Population growth, industrialization, expansion of agriculture, increased demand for hydroelectric power, and other activities will greatly increase the demand for water in the years ahead, both in Canada and globally (Postel 1998).

Effects of climate on water yields from snow and ice fields

Much of the usable water in western Canada originates in the snow and ice fields of the Rocky Mountains. Water from the Rockies feeds rivers that flow to all Canadian oceans: to the Pacific via the Fraser and the Columbia rivers, to the Arctic via the Peace–Athabasca–Slave–Mackenzie River system, and to the Atlantic via the Saskatchewan–Nelson River system. Arid regions of the prairies are particularly dependent on these snow and ice fields. For example, total river flows to the Saskatchewan River system from the Rocky Mountains are 87% of the flow volume at the river's mouth (Schindler and Pacas 1996). Already, agriculture in southern Alberta and Saskatchewan depends heavily on irrigation, and water shortages are sometimes encountered. The glaciers of the Rockies are both receding and thinning. For example, the Athabasca Glacier, a popular tourist stop in the national parks of the Rockies, receded over 1.5 km in the twentieth century. Its losses of ice are over 16×10^6 m^3 greater than is replaced each year (Canadian Heritage Rivers Board 1998). Further recessions of mountain glaciers may jeopardize prairie water supplies.

Effects of increased evaporation on water availability

Most global climate models do not predict great changes in precipitation for Canada. This tends to make people believe that there will be little effect on water availability. However, evaporation increases rapidly as climate warms. Effects are larger than most expect. For example, an increase in average air temperature from 14 to 16°C at ELA caused an increase in evaporation of 30%. As a result of lower precipitation and increased evaporation, permanent first-order streams became ephemeral (Schindler et al. 1996*a*). Lower humidity and greater wind velocity also enhance evaporation, the latter at an exponential rate. Stronger winds have already been observed at the ELA (Schindler et al. 1990), possibly as the result of increased convection over clearcut and burned catchments in the region. However, increased extreme weather events have also been predicted by global climate models (Intergovernmental Panel on Climate Change 1996). Greatly increased evapotranspiration in the catchment of the Great Lakes is expected, despite predicted increases in precipitation for some parts of it (Mortsch and Quinn 1996). Large effects on navigation in the lakes are expected. In brief, only areas that have greatly increased precipitation will escape the effects of drought.

Lessons from the past

Examples from the warm, dry mid-Holocene warn us of impending water scarcity on the prairies. Current global climate models predict that warming in the twenty-first century will cause temperatures to greatly exceed those of the mid-Holocene, when temperatures were only 1–2°C warmer than in the mid-twentieth century.

Lake Manitoba, one of the prairies' great lakes, was dry during the mid-Holocene, as shown by layers of prairie grasses embedded in lake sediments (Teller and Last 1982). Even the droughts of the mid-1930s have important messages for us to consider (Rosenzweig and Hillel 1993). Lakes that were previously exorheic became endorheic, and endorheic lakes either dried up altogether or became much more saline. Chemical composition changes greatly as concentrations increase to exceed the solubility of some salts. Typical calcium bicarbonate waters can become dominated by sodium sulfate or other cation–anion combinations, depending on local geology (Rawson and Moore 1944). Eventually, sodium chloride becomes dominant as less soluble salts precipitate. Few organisms are able to tolerate the highest levels of salinity. Unfortunately, there is no record of changes in the biota of shallow prairie lakes before the "dirty 30s." However, paleoecological studies show that in shallow prairie lakes, there were considerable changes to algae, macrophytes, and other aquatic organisms during the period of low lake levels in the 1920s and 1930s (Vinebrooke et al. 1998; Leavitt et al. 1999).

The special vulnerability of wetlands

There were few, if any, wetlands in the southern prairies in the dry mid-Holocene. Dated peat deposits show that most contemporary wetlands in the area were only formed 3000–4000 years ago (Zoltai and Vitt 1990).

Recent data also indicate that wetlands may be particularly vulnerable. Climate warming exacerbated the effects of Bennett Dam on the Peace River on the vast Peace–Athabasca Delta by contributing to thinner ice cover and weaker spring flows, greatly decreasing the incidence of ice jams that caused spring floods to rejuvenate ecosystems of the Delta (Prowse and Demuth 1996). As a result, shallow, perched lakes in the Delta that are dependent on periodic inundation have disappeared, leading to the demise of important muskrat populations and fisheries. The local economy of the region, which depended heavily on muskrat trapping and country foods, has collapsed (Green 1992; Scrimgeour et al. 1994). Poiani et al. (1996) have shown that increased drought and warm temperatures greatly change the vegetation of prairie wetlands. As expected, during periods when ephemeral wetlands are dry, waterfowl production is greatly decreased (Larson 1994) and acts synergistically with other human activities, as I shall discuss later. The decreased water levels expected in the Great Lakes will cause extensive detrimental effects to wetlands surrounding the lakes (Mortsch and Quinn 1996).

Changes to river and stream flow patterns

Most Canadian streams and rivers outside the mountains have an annual maximum flow in the spring, as the result of spring snowmelt. Typically, from 25 to 50% of total annual flow occurs as winter snowpacks melt. These spring melt pulses typically govern the form of river channels, which are generally shaped by maximum flows (Newbury and Gaboury 1993). Also, the spring floods rejuvenate riparian and floodplain areas, where many plant and animal species depend on periodic inundation (Rood and Mahoney 1990; Green 1992; Schindler 1998*b*). In areas where less precipitation falls as snow, or periodic melting decreases the size of the spring snowpack, many physical and biological features will change with a warmer climate.

Effects of international water shortages on Canadian water security

The growth of human populations, industries, and climate warming will act in concert to increase the demand for water, both in Canada and elsewhere. Water shortages elsewhere may pose further threats to Canadian water supplies, for there are sure to be demands that we share our abundant waters with water-poor regions. Barlow (1999) warned that water is rapidly becoming "blue gold." Much of the Middle East already has so little water that it is reliant on other regions for almost all of its agricultural needs (Postel 1998; Falkenmark 1999). The burgeoning populations and profligate lifestyles of the American Southwest are already causing most of their rivers and aquifers to be oversubscribed. The mighty Colorado River has been reduced to a trickle by the time it reaches the Gulf of California by demands for irrigation water and urban water supplies. The Oglala aquifer, which serves much of the west-central regions of the United States, is being exploited eightfold faster than its waters are renewed from natural sources (Barlow 1999). These conditions will become worse as climate warms, and the demand for Canadian water will increase.

Pressures to export water will come from both inside and outside of Canada. Many believe that Canadians are morally obligated to share their water with the rest of the world, regardless of how wasteful other societies have been with their water supplies or what the effects might be on Canadian water supplies, climate, and aquatic biota. Others simply wish to profit from exports of Canadian freshwater. At present, several cases are in the courts, with multinational corporations claiming that the North American Free Trade Agreement (NAFTA) gives them the right to export Canadian water: a scenario that the Mulroney government assured Canadians could never happen under NAFTA. Until the outcomes of these disputes are clear, we must regard water export as a further threat to Canadian water security.

If the proponents of water export win, water will be exported from Canada to water-poor regions by tankers, pipelines, and rerouting of rivers. Some of the proposed schemes are enormous. The Great Recycling and Northern Development (GRAND) canal scheme would dam James Bay, making it into a freshwater reservoir to store the water entering it from the 20 or so rivers that surround it. A massive series of canals, locks, power plants, and dams would divert the water to Georgian Bay, where it would be flushed through the Great Lakes to feed pipelines to the southwestern United States (Bocking 1987; Barlow 1999).

The North American Water and Power Alliance (NAWAPA) project would be still larger. The Yukon, Liard, and Peace rivers would be diverted to the Rocky Mountain Trench, creating an 800-km-long reservoir that would transport water from the Yukon to Washington State, where it would be supplied to 35 states. The total discharge volume would approximately equal that of the St. Lawrence River (Barlow 1999). Huge fleets of supertankers would operate around the clock to move Canadian freshwater around the world, hauling trillions of litres each year. All of this activity would require the increased burning of fossil fuel, further exacerbating greenhouse warming.

Effects of global change on water quality

As flows decline, the capacity of freshwaters to tolerate pollutant loads is reduced. It is well known that water inputs are as important in determining the concentrations and fates of pollutants in lakes and rivers as the "loading" of pollutants (Vollenweider 1969; Dillon and Rigler 1974; Schindler et al. 1978). For biologically conservative chemicals, incoming effluents are simply diluted less. For biologically reactive pollutants, the higher concentrations of inputs and slower water renewal rates will exacerbate eutrophication.

Declining water flows will cause declining inputs of chemicals to lakes from their catchments. For example, in the dry 1970s and 1980s, Lake 239 had declining inputs of all chemicals (Schindler et al. 1996*a*). But lower water flows also cause declines in chemical outputs from lakes, i.e., longer residence times. As a result, for biologically conservative chemicals that enter lakes directly from the atmosphere, sediments, or effluent pipes, the increased water residence times of lakes cause concentrations to increase. For example, sediments are an important source of calcium to ELA lakes (Schiff and Anderson 1987). During periods of drought, calcium increases as a direct function of water renewal time (Schindler et al. 1996*a*). In contrast, biologically active chemicals can decrease because increased residence times allow more time for biological action. Examples include nutrients, as mentioned above, and sulfate, where removal by sulfate reduction is a function of contact time between water and sediments (Baker et al. 1986; Kelly et al. 1987). As the result of increasing calcium inputs from sediments and increased reduction of sulfate followed by sedimentation, alkalinity of Canadian Shield lakes appears to increase as water flows decline (Schindler et al. 1996*a*). The situation is more complicated for seepage lakes, as discussed below (Webster et al. 1996). In summary, few, if any, ions are unaffected by changes in inputs, outputs, or soil processes, causing significant changes to lake chemistry (Schindler et al. 1996*a*). The direction, magnitude, and speed of change in the chemistry of lakes will therefore depend on basin size, morphometry, and water regime, as well as the extent of wetlands in the basin, groundwater flows, and many other features.

Changes in dissolved organic carbon (DOC) are perhaps one of the most important effects of climate warming. Allochthonous DOC is the most important determinant of thermocline depth in small boreal lakes (Perez-Fuentetaja et al. 1999). In small lakes where colored allochthonous DOC inputs are decreased as the result of decreased stream flows, drier soils, and lower water tables in wetlands, waters become clearer, and the increased penetration of solar radiation causes thermoclines to deepen. The effect will be amplified by increased bacterial action and chemical precipitation, as expected with longer water residence times, as well as higher solar radiation due to decreased cloud cover (Schindler et al. 1996*a*; Donahue et al. 1998; Myneni et al. 1999).

However, other studies have documented the formation of shallower thermoclines in warm years, due to rapid onset of spring stratification (Robertson and Ragotzkie 1990; Snucins and Gunn 2000). Climate models indicate that spring will be the period of most intense warming, so that such effects are to be expected. However, the deepening thermoclines at ELA occurred during a period when rapid spring warming was recorded, suggesting that where both factors are present, decreases in colored DOC may be the overriding factor.

Deeper thermoclines and euphotic zones and greater visibility for sight-dependent predators will probably result from the above changes. Thermal capacity also increases, as the result of deeper thermoclines, warmer waters, and generally longer ice-free seasons.

Effects on the quality of drinking water

As flows decline and human populations increase, the quality of water for drinking will deteriorate. Rapidly expanding industrial agriculture will greatly exacerbate the problem, for many industrial farms now put out amounts of nutrients and pathogens that would equal those of a moderate to large city. In many areas, lax municipal or provincial regulations permit effluents from livestock operations with tens of thousands of animals to be released to the environment with little or no treatment. Soil erosion, destruction of riparian areas and wetlands, and overuse of fertilizers are also common in agricultural areas. For example, in central and southern Alberta, most streams, dugouts, and irrigation canals in agricultural areas are out of compliance with provincial guidelines for nutrients and coliform bacteria (Canada–Alberta Environmentally Sustainable Agriculture Water Quality Committee 1998).

In part, the problem seems to be one of increasing virulence of pathogens that have been in water for years. For example, the recently appearing virulent strain 0157 of the common intestinal bacterium *Escherichia coli* is now a widespread contaminant in meat, water, and vegetables in areas where livestock are abundant. The recent tragedy at Walkerton, Ontario, where several deaths have been caused by *E. coli* contamination, demonstrates the potentially great health costs of inadequate protection of watercourses from contamination.

Many citizens believe that the use of more chlorination will solve the problem of providing good drinking water. But there is emerging evidence that the byproducts of disinfection with chlorine can cause a variety of adverse health effects, including bladder cancer (Mills et al. 1998) and developmental abnormalities (Reif et al. 1996; Magnus et al. 1999). *Cryptosporidium parvum*, which has caused gastrointestinal problems worldwide, is resistant to chlorination. Other toxic algae, such as *Microcystis*, can produce microcystin, a potent hepatotoxin (Lambert et al. 1994). At best, the cost of potable drinking water will increase rapidly. At worst, there will be increasing health problems associated with pathogenic bacteria and toxic algal blooms. Only comprehensive approaches to the conservation and management of the catchments that supply drinking water can prevent major water problems.

Effects on fisheries

Warming has direct effects on fisheries as well as amplifying the effects of other human and natural stresses to freshwater ecosystems. Among direct effects, waters of many large, unstratified northern lakes that currently support coldwater fisheries may warm to above the optimum temperatures for species like lake trout (*Salvelinus namaycush*), lowering the production of desirable species. Even at sublethal temperatures, warming would cause severalfold increases in the energy requirements of young-of-the-year lake trout (McDonald et al. 1996).

Wind velocities have also increased at ELA (Schindler et al. 1990), and coupled with forest fires and clearcut logging in the area, small lakes are more exposed to wind. This has caused a decrease in the incidence of transient thermoclines in the epilimnions of lakes (M.A. Xenopoulos and D.W. Schindler, unpublished data), as well as contributing to the increasing thermocline depth discussed above (Schindler et al. 1990). The net result of increased thermocline depth is to decrease the subthermocline habitats available as summer refugia for cold-water species. Other studies support the possibility that increases in warmwater species may affect cold-water species like lake trout more than direct thermal stress (Shuter and Meisner 1992).

One study also suggests that some cold stenotherms may adapt to warm temperatures. In three of four lakes investigated at ELA, lake trout showed the usual preference to spend most of their time in hypolimnions less than 15°C. However, one population, in Roddy Lake, remained throughout the summer in the epilimnion at temperatures of 20–21°C (Sellers et al. 1998). This fishery is also more productive than others of the area (K. Mills, Freshwater Institute, Winnipeg, MB R3T 2N6, Canada, personal communication). The frequency of occurrence of such adapted populations is not known, and the above studies need to be backed up with genetic information before the possibility that they are adapted to warmer temperatures can be accepted. In another case, lake trout exhibited behavioral adaptation, spending much of their time near cold springs, with occasional feeding forays into lakes that have temperatures which would normally exceed thermal tolerances (Snucins and Gunn 1995).

Some fish species are expected to simply change their distribution as temperatures warm. In particular, their migrations to colder parts of lakes and streams will be more difficult as water temperatures exceed temperature tolerances or become ephemeral. Streams appear to be particularly vulnerable. For example, Meisner (1990) predicted that increasing temperatures will eliminate habitat for brook trout (*Salvelinus fontinalis)* at the southern end of their range. Similarly, in mountainous regions, the warming of montane regions is predicted to render a high proportion of streams too warm for native fish species, which will retreat to increasingly isolated high-altitude headwaters (Rahel et al. 1996). Eaton and Scheller (1996) studied the temperature tolerances of 57 freshwater species in the United States. They predicted that climate warming caused by a doubling of CO_2 would reduce habitat for cold- and cool-water species by 57%.

Based on modeling studies, Magnuson et al. (1990) suggested that in large lakes, thermal stratification may become stronger and that shallower thermoclines may increase the deep cold-water habitat for fishes. So far, the models have not been verified by data in great lakes, although the predictions are consistent with the results in smaller lakes, as discussed above.

Effects on other biota

Many effects of climate on lower trophic levels have been noticed. Temperature is well known to affect the geographical distribution of various diatom species (Reynolds 1984) as well as affecting the growth rates and competition for nutrients of algal species (Rhee and Gotham 1981). Differential temperature tolerances can affect the outcome of competition between species (Tilman 1982). There is a considerable literature on the temperature ranges preferred by various algal species, but it is too large to review here. Warmer waters also increase the outbreaks of toxic algal blooms and their toxicity to other organisms (Hallegraeff 1993; Gilbert 1996).

Among the zooplankton, feeding, assimilation, growth, and reproduction roughly double for a 10° increase in temperature (Schindler 1968). Maturation is at younger age, and broods are produced more frequently (Orcutt and Porter 1984). Species richness will probably increase (Stemberger et al. 1996). Other community characteristics, such as vertical distribution and competition, will also change, but the topic is too large to discuss here.

Many invertebrate species will complete their life cycles more quickly. For example, Wilhelm (1999) found that *Gammarus lacustris* required 3 years to complete its life cycle in alpine lakes in cold years, but in warmer summers, this could be decreased to 2 years. The same species at lower elevations completes its life cycle in a single year.

In summary, some of the above studies are based on scenarios from global climate models, and predictions remain to be verified. But it seems clear that warming will modify aquatic communities to affect interspecific interactions between predators and prey and warmwater and cold-water species of competitors.

Effects of climate warming on groundwaters

Groundwaters and groundwater-fed lakes are also affected by climate warming. For lakes, the importance of position in the landscape has been documented (Kratz et al. 1997). Lakes high in the landscape tend to have groundwater inputs diminished by drier conditions. In particular, declining inputs of alkalinity via groundwater make the lakes increasingly dominated by acidic inputs from precipitation. The effect can be great enough to delay or prevent the recovery of acidified lakes, even when sulfate inputs are greatly reduced (Webster and Brezonik 1995; Webster et al. 1996). If the precipitation is quite acid, acidification of the lakes can be greatly accelerated (Webster et al. 1990).

In contrast, lakes downstream in the aquifers have increasing inputs of chemicals from groundwater because drought causes increased contact time of groundwaters with substrates (Webster et al. 1990). The direction and magnitude of the effect on water chemistry are predictable from lake order, substrate chemistry, and flow paths, and models of key processes are quite advanced (Riera et al. 2000).

We probably know enough about the factors affecting water chemistry and sediment water interactions that it should be possible to construct models which will accurately predict the rate and magnitude of changes in water quality under various climate change scenarios in lakes with surface inputs, but so far this has not been done.

Synergistic effects of climate change and other stressors

The overall effects of climate and other human stressors are generically referred to as “global change” (e.g., Mungall and McLaren 1990). Oddly, despite the recognition over a decade ago that such "cumulative effects" of human activity were occurring, little research has been devoted to such issues. Below, I give some examples of cumulative interactions with climate that may be of significance to Canadian freshwater.

Climate warming and ecological invasions

The invasion of Canadian freshwaters by non-native species is perhaps the greatest threat to the integrity of lakes and rivers. Several general reviews have summarized North American data. Approximately 700 species of fishes occupy temperate North America. Of these, 103 species and subspecies are endangered, 114 are threatened, and 147 deserve special protection (Allan and Flecker 1993). Between 1900 and 1999, 123 freshwater species became extinct in North America (Ricciardi and Rasmussen 1999). Freshwater mussels are even more threatened than fishes. Of 297 species, 13 are already extinct, 40 are endangered, 2 are threatened, and 74 more are candidates for protection in the United States (Ricciardi et al. 1998).

Lodge (1993) speculated that climate warming may help to accelerate the rate of spread of non-native aquatic organisms and the extinction of native species. This certainly appears to be the case for recent invaders to the St. Lawrence – Great Lakes.

The original biotic communities of the Great Lakes are gone forever. The opening of the Welland Canal in 1829 heralded the beginning of the problem with non-native species. The first well-known accidental introduction was the sea lamprey in the 1920s, which devastated lake trout stocks. Following the demise of the lake trout, several non-native salmonids were introduced into the lakes. Today, the Great Lakes are a "fish zoo."

Waves of accidental invertebrate introductions have resulted from discharge of ballast water from Eurasian ports. Among the most notorious invaders were the zebra mussel, *Dreissena polymorpha*, and the large predatory cladoceran *Bythotrephes cederstroemi*. The zebra mussel has all but obliterated native mollusks from many areas of the lakes. It causes millions of dollars in damage from clogged water pipes. Its high filtration rates and great abundance (MacIsaac et al. 1992; MacIsaac 1996) have greatly cleared the waters of the lower Great Lakes, once clouded by algal blooms caused by excessive phosphorus inputs from detergents, sewage, and bad land use practices, reaching the point where some have advocated the return of some of the now partially controlled phosphorus sources to attempt to maintain a food source for native fauna.

Restrictions on ballast water were imposed to counter the continued inputs of foreign biota to the Great Lakes. Tankers from foreign freshwater ports are now required to change their ballast water at sea. Unfortunately, these restrictions have not been successful. When ballast water is changed, about 5% of the original water is retained in the ballast tanks, containing millions of organisms. In addition, there is only about 90% compliance with the requirement for flushing, indicating lax enforcement. The overall result has been that species tolerant of brackish water are now favored, largely from the Ponto-Caspian area that includes the Black, Caspian, and Aral seas. This area accounts for about 75% of recent invaders to the Great Lakes. Ponto-Caspian invaders include fishes and crustaceans, as well as mollusks (Ricciardi and MacIsaac 2000). Non-native species now dominate the Great Lakes, with enormous ecological and economic consequences. The invasions continue, and the lakes have entered a phase that Ricciardi and MacIsaac (2000) termed "ecological meltdown."

What does all of this have to do with climate warming? Firstly, many of the economic advantages once believed to have been conferred by the Welland Canal may be undone if the predicted effects of warming occur. Shipping and navigation in the Great Lakes will be severely curtailed if the predicted decreases in water level occur. Secondly, most of the Ponto-Caspian species originate in warmer waters, which should amplify their competitive advantage over the cold-water species of the Great Lakes as the temperature of waters increases. The replacement of native species with non-native species may also change the biomagnification of contaminants. For example, Mazak et al. (1997) showed that zebra mussels have become an important vector transferring organochlorine contaminants to waterfowl.

Climate warming and human impacts on fisheries

Inland fisheries are also in jeopardy from a variety of factors, of which climate warming is but one. Increased access caused by logging roads, seismic lines, and other "linear disturbances" plus enormous improvements in snowmobiles and all-terrain vehicles make it possible for fishers to ride to remote lakes and streams that were inaccessible by motor vehicle only a decade or two ago. Once at the lake, powerful outboard motors take fishers rapidly to prime fishing spots, where fish are easily located with sonar. The increased ease of exploitation is causing the rapid decline of large carnivorous species. For example, the catch per unit effort of many sport fishes in Alberta has declined precipitously in the past 10 years (Ryerson and Sullivan 1998). Overexploitation by commercial fisheries has already caused the collapse of the fisheries of many large lakes in the province (Mitchell and Prepas 1990). Changes in angling regulations over the past two decades and anecdotal evidence also suggest that depleted freshwater fisheries are already very common in southern Canada.

The poor ability of lake trout to recover following population declines is of particular concern. The lake trout of Lesser Slave Lake did not recover following overexploitation by commercial fisheries in the early twentieth century and have not been seen in this enormous (1160 km^2) lake since the 1940s (Mitchell and Prepas 1990). The population of Lake 223, which was reduced by experimental acidification in the 1970s and 1980s, has not recovered fully, although the lake has returned to normal pH values (Mills et al. 2000).

Destruction of habitats may contribute to the decline in fisheries. Roads and railways often dissect riparian areas and stream channels, cutting off spawning or rearing habitats and migration routes (Mayhood 1992). Erosion causes turbidity and sediment accumulation. When humans dwell along lakes and rivers, they usually remove sunken trees, weeds, and other objects that serve as cover for fishes to make boating and swimming more convenient. The reduction in physical habitat relates directly to changes in fish production (Christensen et al. 1996), as shown by experimental habitat manipulation at the ELA (K.H. Mills, Freshwater Institute, Winnipeg, MB R3T 2N6, Canada, personal communication).

Climate warming and the resulting changes in pollutant concentrations, communities, and water exports would all cause further depletion of freshwater fisheries that have already been savaged by overharvesting, destruction of habitat, dams, diversions, introductions of diseases, parasites, non-native fishes, and pollutant loads.

We can expect the freshwater fishery to collapse much in the manner that cod and salmon fisheries already have. The west coast salmon fishery is already in trouble, despite hundreds of millions of dollars of research and mitigation. The dams on the Columbia River in the United States have totally destroyed the anadromous fishery in the upper reaches of the river, including those in southern British Columbia. The Atlantic salmon has been nearly extirpated from many rivers where the species was once plentiful.

Climate warming and contaminants

Climate warming may affect contaminant distributions in several ways. As surface waters become warmer, the ratio of mercury methylation to demethylation should increase (Ramlal et al. 1993), causing greater contamination of aquatic fauna (Bodaly et al. 1993).

The declines in DOC due to climate warming would allow deeper penetration of UV radiation, as discussed above. This would presumably allow greater conversion of methyl mercury to elemental mercury, the form susceptible to loss to the atmosphere (Sellers et al. 1996). Once in the atmosphere, mercury is susceptible to long-range transport and biomagnification in distant food chains (Schindler 1999).

Many organic contaminants, including PCBs, dioxins, pesticides, and other toxic compounds, are semivolatile, readily reemitted to the atmosphere from contaminated surfaces at higher environmental temperatures, and redeposited at cooler sites. Warmer climate should cause reemission to increase. In contrast, until permanent snowpacks and ice deposits melt, high-latitude and high-altitude catchments, snowpacks, and glaciers would remain as important "sinks" for semivolatile pollutants (Simonich and Hites 1994; Blais et al. 1998). Particularly at high-latitude sites, contaminant levels are already unacceptably high in predators, including indigenous people (Arctic Monitoring and Assessment Programme 1998). It should be noted that mercury has many characteristics in common with organic substances: long-range transport, semivolatility, and lipophilicity. It is not therefore surprising that concentrations of mercury are also high in northern predators and aboriginals (Arctic Monitoring and Assessment Programme 1998; Schindler 1999).

Synergistic effects of climate warming and acid precipitation

In eastern Canada, acidification of rivers has already jeopardized Atlantic salmon. As others and we have shown, climate warming causes further acidification of rivers and some lakes, as sulfur deposits in wetlands and littoral areas of lakes are reoxidized (Bayley et al. 1992; Schindler et al. 1996*a*; Yan et al. 1996). This can be coupled with decreased inputs of base cations as the result of declining stream flows or groundwater inputs, as discussed above, increasing the acidifying effect. On the other hand, in lakes, increased sulfate reduction as water renewal decreases causes increased alkalinity (Schindler et al. 1996*a*).

Climate warming, acid precipitation, and stratospheric ozone depletion: a triple whammy

Above, I have discussed the increased transparency of lakes as the result of decreased DOC inputs and increased removal by precipitation and bleaching. The effect is most pronounced in acidified lakes, where the effects of increasing incident UV-B are amplified manyfold by greater penetration of solar radiation (Schindler et al. 1996*b*; Yan et al. 1996; Donahue et al. 1998). Indeed, increased penetration of shortwave solar radiation may cause increased conversion of methyl mercury to elemental mercury, which is then released to the atmosphere (Sellers et al. 1996). The effects of UV on other chemical cycles have scarcely been studied.

Canadian research on freshwater problems: from best in the world to down the drain?

In the mid-1960s, many aquatic scientists, myself included, immigrated to Canada because of new and exciting approaches to water research. Large freshwater laboratories were formed by the federal government, including the Freshwater Institute in Winnipeg, Manitoba, the Canada Centre for Inland Waters in Burlington, Ontario, and the National Hydrology Research Institute in Saskatoon, Saskatchewan. The Freshwater Institute had numerous field stations throughout the north to perform research on fisheries and water quality problems caused by hydroelectric reservoirs, overexploitation, and other human activities. The Canada Centre for Inland Waters began thorough investigations of the St. Lawrence – Great Lakes. The ELA was formed, becoming one of the few sites in the world where whole-ecosystem experiments could be done to investigate and solve pollutant and fisheries problems. This foresight caused great excitement in the global water science community: Canadian federal freshwater programs were envied throughout the world. Later, the Saqvaqjuac Program on the western shore of Hudson Bay began whole-lake experiments devoted to arctic freshwater problems.

Many Canadian university and provincial programs also became strong. The Ontario Ministry of Environment's Dorset Field Station alone had a staff of research scientists that compared with the most eminent laboratories in the world. The International Biological Program Char Lake Program, headed by the late Frank Rigler, was the first to investigate high-latitude lakes with the same thoroughness as the best temperate-zone programs.

Best of all, there was excellent interaction between federal, provincial, and university scientists, who worked together with contagious enthusiasm to develop the most powerful freshwater research teams anywhere in the world. This enthusiasm also developed excitement south of the border. Scientists from the Lamont–Doherty Earth Observatory, headed by Dr. W.S. Broecker, worked at the ELA for many years, providing a synthetic view of freshwater and marine and physical, chemical, and biological problems. Scientists from the universities of Kansas, Arizona, and Minnesota also had long-term programs at ELA. As a result of this spirit and competence, Canadian research and Canadian-trained scientists helped to solve water and fisheries problems in many areas of the world.

Unfortunately, these programs have been slowly strangled by a shortage of funds, poor salaries, and lack of replacement of departing staff. Politicians have stated the need to balance federal and provincial budgets as an excuse to reduce spending for environmental research and to decrease the size of the civil service.

Who is minding the store?

As any Canadian knows, a tiresome, juvenile turf war consumes much of the time of both federal and provincial politicians. Most of us do not care what level of government protects our resources, as long as there are not expensive overlaps, and no critical gaps are left. In aquatic science, gaps are a concern as we enter the new millennium.

Both federal and many provincial governments have simultaneously cut research budgets for freshwater research very severely in the 1990s. Environmental departments have been particularly hard hit because the effects are not as visible as in health care or education. As a result, there are huge gaps in research, monitoring, and synthesis of scientific information. In Ontario, federal laboratories have had reductions in funding and staff, especially for freshwater topics like acid rain, climate warming, and invading non-native species. Department of Fisheries and Oceans groups like the Bayfield Institute and the Experimental Lakes Project were particularly targeted, as the department transferred almost all of its resources to dwindling cod and salmon stocks. Their justification is that freshwaters are provincial responsibilities. But at the same time, the Ontario Ministry of Environment's Dorset laboratory, which has done some of the world's best research and monitoring on acid rain and eutrophication, has had severe budget cuts and staff layoffs.

In the prairies and in the West, the situation is little better. Winnipeg's Freshwater Institute has closed all of its field stations except for ELA. The National Hydrology Research Institute and other Environment Canada installations have totally inadequate budgets. Parks Canada has poor capability to assess or protect aquatic resources in our national parks.

Again, provinces have made simultaneous cuts. In Alberta, many critical monitoring functions have been handed off to industries to monitor their own effluents. Research budgets are very low. Many activities that were formerly done by Department of Environment staff are now contracted to consultants or left to industry to police itself.

Politicians have hidden the critical nature of these cuts behind the standard caricature of lazy, overpaid, and underworked civil servants, causing the public to shout "hooray," without questioning what might be lost. I personally find the lazy civil servant image to be infuriating, for many government scientists are among the hardest working individuals in society. They view first-hand the rate at which Canadian natural resources are being squandered, which has focused them on their tasks in a way that can only be compared with wartime activities in other sectors of society. Many of my colleagues worked many long hours each week without additional pay because they believed that what we were doing was important.

Some have expected university scientists to fill the void left by the erosion of government science. But Canadian universities have a primary mandate to teach, with research only a secondary activity. Faculty members are recruited to teach required courses, not to fill niches in large research teams. Most university research is designed to educate graduate students, who are only present for a few years. They must demonstrate creative ability, not continue monitoring programs. University scientists are forced to obtain more and more of their research funds from industry. Even the Natural Sciences and Engineering Research Council of Canada now puts much of its money into cooperative research programs, where matching funds by industry are an important criterion. These programs are probably fine for applied sciences and engineering, where the production of useful and marketable commodities is an objective. But these programs are uncomfortable fits with most environmental science in the public interest. Looking back, I wonder how many detergent companies would have co-sponsored research on eutrophication that required them to totally change their products? How many coal companies would have co-sponsored research to show that they were causing an acid rain problem? The question must be asked: what agencies today do science to protect the public interest? Answers for different regions range from fewer than there used to be to near zero. This situation must be reversed if we are to have sustainable water resources in the next century.

Research on northern great lakes: a national disgrace

Many Canadian waters are currently jeopardized by human intrusion, without proper documentation of their baseline state and how humans have altered their communities and biogeochemical cycles. There are many examples, but the northern great lakes are most conspicuous. Great Slave Lake, Great Bear Lake, and other large northern lakes are among the most unstudied freshwaters of the world. Canada spends more money on great lakes research in Africa and the former U.S.S.R. than it does on its own northern great lakes. Great Slave and Great Bear lakes are the only remaining great lakes in the world where non-native aquatic species have not invaded.

Great Slave Lake was last studied in detail by Rawson (1950, 1956). With small boats and primitive hand-operated equipment, Rawson and his students discovered most of what we know about the lake, which is not very much by modern standards. The lake is now threatened by nutrients from burgeoning communities, industrial effluents from the Peace–Athabasca River system, pollution from gold and diamond mines, and exploitation of fisheries.

Great Bear Lake has never been comprehensively studied. There is not even a vessel on the lake that is capable of supporting research activity. The lake was polluted with uranium and radium from the Port Radium Mine in the early years of the last century. A few fishing lodges, the small indigenous community of Deline (formerly Fort Franklin), the abandoned mine facilities, and the ubiquitous inputs of airborne toxins are the only anthropogenic traces on the lake. At present, there are no roads or railways, but this will change rapidly. Clearly, it is the world's most pristine great lake at present. It is tragic that we know nothing about its aquatic communities and biogeochemical cycles, for if the twentieth century pattern of human activity continues, they will clearly be stressed in the present century. It is time that a major research institute focused on northern freshwaters and their problems.

How can a small country like Canada solve these problems?

It is well known that Canada's funds for research are a much smaller proportion of its national budget than in most First World countries. This must change for environmental science if we are to adequately protect Canadian resources from degradation (Peters et al. 1996).

Canadian universities, which are largely funded by provincial governments that see university education and research as being of peripheral value, will never be able to directly match the facilities of large American universities with enormous endowments or large environmental research facilities like Woods Hole or Scripps Institution. However, the combination of large federal and provincial environmental laboratories and universities offers some uniquely Canadian possibilities. Many government laboratories are on or near university campuses. Although individual government scientists often hold adjunct professorships and cooperate with university professors in research, such links have never been formalized. Universities have supplied much valuable research to ecosystem approaches at ELA and the Dorset field stations. In return, comprehensive government programs offer unique possibilities for interdisciplinary research and teaching, particularly at the graduate level. Some steps have been taken to explore these possibilities, for example, the linkages between Trent University and the Dorset Field Station of the Ontario Ministry of Environment and Laurentian University's Co-op Unit. But much more could be done.

Firstly, selection committees for new university scientists might be composed of both government scientists and university professors. With government scientists sharing some of the teaching load, scientists could be recruited with more emphasis on research specialty than is currently the case. The potential and inclination for interdisciplinary research and teaching could be among the selection criteria. Secondly, Natural Sciences and Engineering Research Council of Canada strategic grants and industrial grants or their equivalent might allow funding or in-kind support from government agencies to be used to "match" funds in its industrial and strategic grants programs, which currently only allow funding from industries to be counted. These would allow funds for research in the public interest, rather than only to support corporate agendas. Not only freshwater, but forestry, national parks, and other environmental programs could also benefit from such relationships.

I am optimistic that such arrangements might inject new life into aquatic and other environmental science in Canada. My experience with acid rain, eutrophication, and arctic research is that Canadian scientists generally do much more per dollar than their counterparts in other countries. Shoestring budgets are a tradition of environmental research in this country. But as we enter the twenty-first century, the shoestring is looking very worn. New programs in environmental science, particularly aquatics, are urgently needed if the destruction of Canadian freshwater ecosystems is to be prevented. Research must be much more focused on the cumulative effects of human activity than it has been in the past.

A national water strategy

Solving the water problem will require more than research. A national water strategy must be developed to get all levels of government to work cooperatively. Aboriginal people have been concerned about water issues for some time, for example, in the areas of Manitoba and Quebec flooded by large hydroelectric reservoirs and in the Peace–Athabasca drainage affected by pulp mills and oil sands developments. Corporations and the general public must become engaged. Until the Walkerton tragedy, the press paid little attention to water issues. The time to act is now, while there is widespread interest. Disappointingly, neither water nor other environmental issues have so far emerged in the political debates that have begun in anticipation of the election of a new national government. Unless there is a quick reversal of recent trends in water management, freshwaters will become Canada's foremost ecological crisis early in this century. I issue a challenge to future generations of aquatic scientists: the best thing that could happen to freshwaters in Canada is that you take steps to show that my predictions are wrong.

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