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CLIMATE AND ENVIRONMENTAL DEGRADATION OF THE GREAT LAKES

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ABSTRACT

Climate is increasingly viewed as a critical variable that must be incorporated into planning and remediation activities to restore beneficial use of the Great Lakes. Recent efforts to characterize and remediate ecological degradation in particular locales around the Great Lakes shoreline have helped demonstrate the extent to which societal neglect of climatic influences has contributed to damage to environmental quality. An improved societal understanding of the role of climate in historical environmental degradation of the Great Lakes can help in the design and implementation of future regional environmental policy, particularly if scientific projections of global warming during the next century prove to be accurate. Even modest climatic changes will alter the region's hydrologic regime, leading to changes in net basin water supply, mean lake levels, and intensity and frequency of severe storms. Such changes could introduce new challenges for long-term management of the Great Lakes ecosystem.

INTRODUCTION

Restoration and protection of the inland waters and coastal zones of the Laurentian Great Lakes has become a major environmental concern in both Canada and the United States. Environmental restoration of the Great Lakes represents a very long-term undertaking. During the late 1960s and early 1970s, visible and tangible evidence of severe ecological degradation prompted U.S. and Canadian efforts to address a number of concerns about the future health of the Great Lakes and the basin's inhabitants. In 1978, the United States and Canada ratified the Great Lakes Water Quality Agreement, which committed the two

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national governments "to restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes Basin Ecosystem" [1, p. 8].[1]

As efforts to restore the ecological integrity of the Great Lakes have progressed, evidence has grown that many forms of environmental degradation are attributable to inadequate recognition of the region's climatic regime. A pattern of climate-related causes is now evident, and climate is increasingly viewed as a critical variable that must be incorporated into planning and remediation activities to restore the ecological integrity of the Great Lakes.

This article details the emerging awareness of the climatic connection to environmental degradation in the Great Lakes basin. The purpose is to help evaluate societal recognition of climate as a critical component in today's efforts to manage environmental resources—in this case, with a focus on a region of great importance to North America's two large neighbors, Canada and the United States. Climate is often neglected in environmental planning, yet many of the sources and causes of pollution in the Great Lakes basin are attributable to society's failure to respond appropriately to the region's climate.

ENVIRONMENTAL DEGRADATION OF THE GREAT LAKES

Described by one environmental historian as North America's "Fifth Coast" [2, p. 3], the Great Lakes are a vast freshwater resource. Eight U.S. states and the Canadian province of Ontario share the shoreline of the Great Lakes, as do more than one hundred counties in both countries; the St. Lawrence River, which drains the Great Lakes, passes through the province of Quebec to the Atlantic Ocean. More than twenty-seven million Americans and nearly eight million Canadians live within the Great Lakes basin, about 11 percent of the U.S. population and 30 percent of the Canadian population [3]. Many municipalities are dependent on the Great Lakes for their water supplies, as are one-third of Canadian and one-fourth of U.S. industry [4].

As a consequence of industrialization and urbanization around the Great Lakes' shoreline and agriculture and other land uses inland, serious pollution problems have developed in numerous harbors, rivers and embayments, and in the connecting channels between the upper and lower lakes. Pollutants entering the lakes from both point and nonpoint sources include volatile organic compounds, heavy metals, and industrial and agricultural chemicals.

As of 1987, 362 chemicals had been positively identified in the waters of the Great Lakes [3]. Many of these pollutants are "toxic substances" as defined by the

[1] The original water quality agreement was adopted in 1972 and was subsequently amended in 1978 and 1987. Lake Michigan was included in the 1978 agreement even though it is entirely within the political jurisdiction of the United States.

U.S.-Canadian Water Quality Agreement [1]. Of these toxic substances, the Water Quality Board of the International Joint Commission (IJC)[2] has designated eleven "critical pollutants" that are considered especially hazardous to terrestrial and aquatic species [3].[3]

Both the critical pollutants and other toxic substances identified by the IJC are an environmental concern because they contribute to an "impairment of beneficial use" of the waters of the Great Lakes. Impairment of beneficial use refers to "a change in the chemical, physical or biological integrity of the Great Lakes System" [1, p. 49] which is sufficient to cause conditions such as beach closings; deformities or reproductive problems in fish, bird or animal populations; loss of wildlife habitat; limitations on dredging activities; and restrictions on consumption of fish and drinking water.

The IJC has identified particular locales that are severely degraded as a consequence of the presence of toxic substances due to decades of contamination resulting from industrial, municipal and agricultural activities throughout the basin. Each of these locales has been designated by the IJC as an Area of Concern (AOCs), which is defined as "a geographic area that fails to meet the General or Specific Objectives of the [Great Lakes Water Quality] Agreement where such failure has caused or is likely to cause impairment of beneficial use or of the area's ability to support aquatic life" [1, p. 49].

To date, the IJC has designated forty-three AOCs around the shorelines of the Great Lakes that are within the coastal jurisdictions of different American states, the province of Ontario, numerous counties, large metropolitan areas and smaller municipalities (see Figure 1). A Remedial Action Plan (RAP) is being developed for each AOC with the active participation of governments, the private sector, environmental interest groups and interested citizens [5]. According to the IJC,

> Remedial Action Plans . . . shall embody a systematic and comprehensive approach to restoring and protecting beneficial uses in Areas of Concern or in open lake waters [1, p. 51].

According to the Great Lakes Water Quality Board,

> The emphasis of RAPs is on remediation. RAPs are intended to identify when specific remedial actions will be taken to resolve the problems and which organizations or agencies are responsible for implementing those actions [6, p.1].

[2] The IJC is a binational institution created by the 1909 Boundary Waters Treaty to resolve disputes over the waters shared by Canada and the United States. The IJC has offices in Washington, D.C., and in Ottawa and Windsor, Ontario.

[3] The critical pollutants are 2,3,7,8-TCDD (dioxin); 2,3,7,8-TCDF (furan); benzo[a]pyrene (b[a]p); DDT and breakdown products (including DDE); dieldrin; hexachlorobenzene (HCB); alkylated lead; mirex; mercury; polychlorinated biphenyls (PCB), and toxaphene. See [3], pp. 22-23 for further discussion.

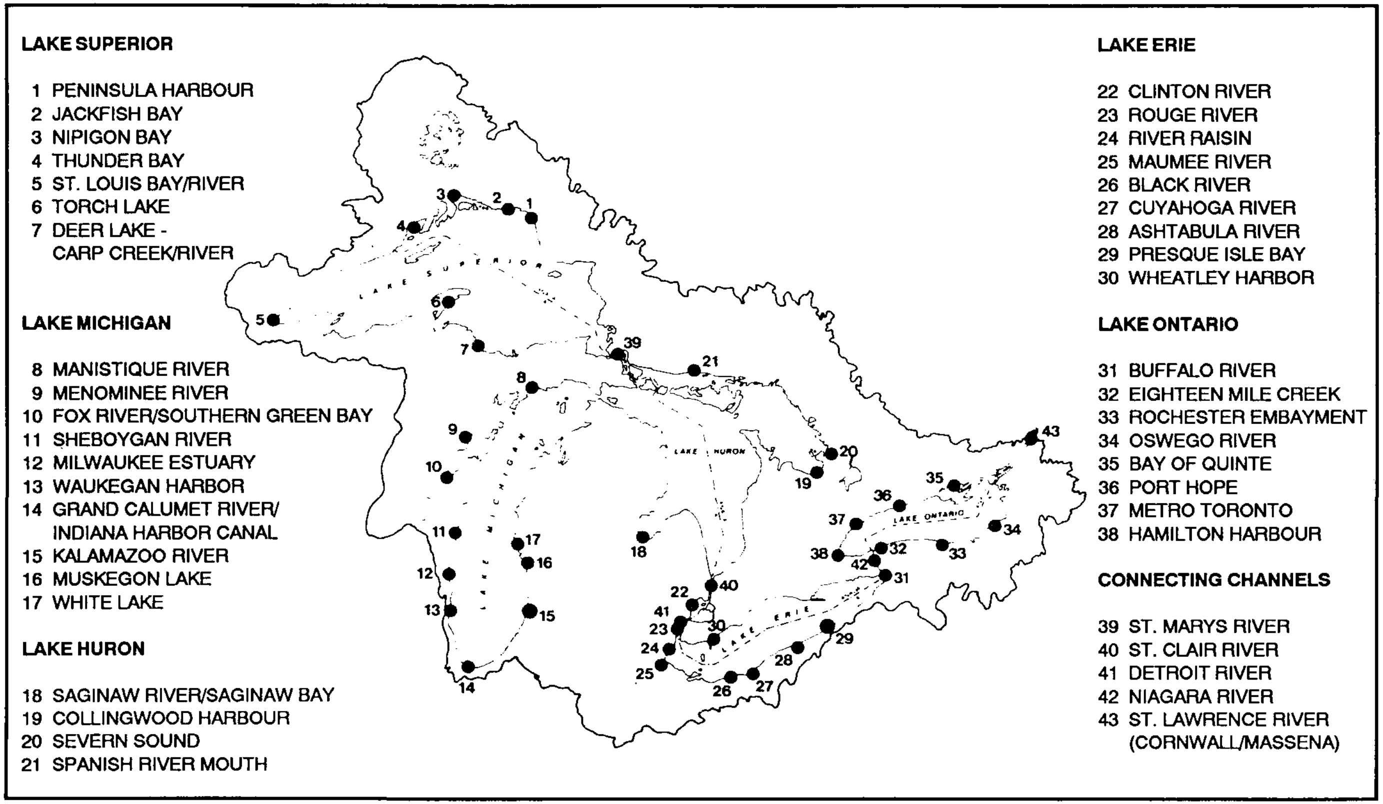

Figure 1. Forty-three areas of concern identified in the Great Lakes Basin. **Source:** International Joint Commission.

Each RAP is to be prepared in three stages, with the IJC authorized to review and provide recommendations as each stage is completed by state/provincial and local jurisdictions [1]. Stage one involves definition of the forms and causes of impairment of beneficial use, which includes identification of the types and sources of pollutants causing such impairment(s). Stage two entails identification and selection of remedial and regulatory actions to reduce or eliminate future pollution and to restore the beneficial use(s) that were identified as impaired in Stage one; Stage 2 also involves establishing a schedule for implementing the remedial and regulatory measures as well as identifying individuals and agencies responsible for their execution. Stage three involves post-regulatory and post-remediation monitoring assessment of environmental conditions designed to demonstrate that beneficial use of the Great Lakes has been attained [1, 3].

For the forty-three currently designated AOCs, the RAPs are in various stages of development. Implementation of the RAPs will be costly and lengthy. The financial demands of designing and implementing RAPs "will test severely public and political commitment to the Water Quality Agreement" [3, p. 206]. While the RAPs continue to be developed, some remedial actions to restore specific beneficial uses in individual AOCs have been and are being implemented independently of the more comprehensive plans.

The AOC RAP activities are intended to be pursued in the context of an "ecosystem approach" for restoring beneficial uses of the Great Lakes. The U.S. and Canadian governments, the shoreline states and the province of Ontario all agreed to this strategy, which was defined in the Great Lakes Water Quality Agreement of 1978 to include human beings and their institutions as critical components of the environment, not just as inputs. The Water Quality Agreement defined the Great Lakes ecosystem as:

> the interacting components of air, land, water and living organisms, including humans, within the drainage basin of the St. Lawrence River at or upstream from the point at which this river becomes the international boundary between Canada and the United States [1, p. 4].

The ecosystem approach to environmental restoration and management should also explicitly include climate, which incorporates the interactions of air, land, and water. Thus, climate is accepted as an integral component of the ecosystem.

THE CLIMATE AND RESOURCES OF THE GREAT LAKES BASIN

Various efforts have been made to formulate a climatic classification system for different regions on different continents based on several variables. The most generally used was developed in the early years of this century by Wladimir

Köppen, an Austrian who was trained as a botanist. He devised a system for classifying regional climates around the world based on temperature, precipitation and vegetation [7]. According to Köppen's scheme, the Great Lakes region was classified as "humid continental cool summer." More specifically, the Great Lakes climate has the following characteristics: the average temperature of the year's coldest month is below –3°C (26.6°F), average temperature of the year's warmest month is above 10°C (50°F), summers are cool, and there is normally no dry season during the year [7, 8]. Any one or sequence of months, seasons or years can be warmer or colder than the average specified by Köppen.

Average annual precipitation in the Great Lakes region ranges from approximately 700-1000 mm (27 to 40 inches), increasing from west to east across the basin [9]. There is virtually no difference in monthly precipitation from winter to summer months. However, total annual precipitation is highly variable. This is illustrated in Figure 2, which shows combined interannual precipitation on Lakes Michigan-Huron, St. Clair, and Erie for the period 1900-1987.

The lakes themselves exert a tremendous influence over the basin's climate; the lakes cover 245,000 km^2 (95,000 mi^2)—nearly one-third of the basin's total area of 766,000 km^2 (296,000 mi^2). Because of their great capacity to store heat, the Great Lakes only rarely freeze completely, and then only in late winter. According to Eichenlaub, the lakes and the prevailing westerly winds contribute to "warmer winters and shorter durations of cold temperatures to their east and south than to the west" [8, p. 246]. Prevailing winds over the Great Lakes generally originate

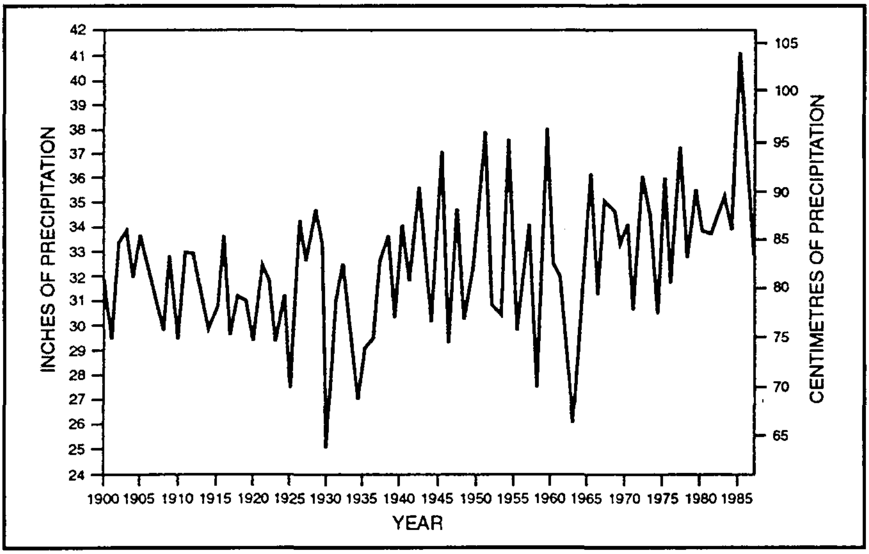

Figure 2. Combined Precipitation on Lakes Michigan-Huron, St. Clair and Erie.

from the west and southwest. Air masses passing over the lakes themselves may gain moisture from lake evaporation; consequently, average annual precipitation is greater in the eastern half of the Great Lakes basin than in the western half, and even more so when air masses accumulate moisture from the Gulf of Mexico and move northeastward toward the lakes [10]. During the early winter months, evaporation from open lake water contributes to what is called "lake effect" snowfall and enhanced snowbelts around the lakes' southern and eastern lee inland areas [11]. Eichenlaub reports that lake-effect snow can extend inland up to 40-48 km (25-30 mi), and that in certain Great Lakes areas a large percentage of annual total snowfall is generated by this phenomenon [8, 12].

The abundant natural resources of the Great Lakes basin attracted human settlement. Settlers were attracted to the region for its agricultural potential, forests, plentiful freshwater resources—all attributable to the region's climate. Minerals were discovered and mined, timber was cut, and farm produce harvested. The lakes also provided the opportunity for long-distance transport of ore, timber and farm produce from source to the basin's growing population and to markets outside the Great Lakes. The lakes were put to other uses, for both sources of drinking water and, eventually, for sewage disposal [2]. The region's abundant annual precipitation and runoff ensured that municipal sewage could be sufficiently disposed of, an early application of the concept that the solution to pollution is dilution. As the cities grew, water withdrawals from the lakes rose and urban runoff made its way into the lakes' tributaries, river mouths, embayments, harbors and connecting channels. Agricultural cultivation spread in the basin, and farm runoff eventually began to find its way into the lake's tributaries.

With the advent of industrialization in the latter half of the nineteenth century, the Great Lakes became a magnet for manufacturing, minerals extraction and power production. Factories, smelters and paper pulp mills were constructed around the shoreline of the Great Lakes, in part for access to commercial shipping and, equally importantly, for access to massive volumes of cooling and industrial process water. Electric generating power plants and oil refineries followed, then nuclear power plants in the 1970s. In one area of industrial concentration, numerous electric generating plants, factories and municipalities are situated along the banks of the St. Clair River between Lakes Huron and St. Clair. This connecting channel is now commonly referred to as "Chemical Valley" [13, 14].

Today the Great Lakes basin incorporates industry, substantially altered land uses and land cover, increased population, and urban/suburban sprawl. Elements of the Great Lakes ecosystem have been disrupted due to anthropogenic intrusions, which have given rise to the RAP efforts to reduce future pollution and remove the pollution of the past. Accompanying the individual RAP processes has been a growing awareness that human interactions with the region's climate have contributed to the degradation of the Great Lakes ecosystem. This should be encouraged while the RAPs are still in the process of being developed in order to ensure that climate is fully considered in terms of defining impairment of beneficial use and designing and implementing effective remedial actions to restore the Great Lakes ecosystem.

CLIMATE IMPACTS IN THE GREAT LAKES AREAS OF CONCERN

The Great Lakes' climate and other natural resources clearly were among the historical reasons why the basin attracted human settlement and subsequent industrial, agricultural, and commercial development. However, the manner in which the Great Lakes basin has been developed in the industrial age has contributed to environmental degradation. The result has been decades over which contaminants have reached the waters of the Great Lakes and their tributaries.

Accompanying the industrialization and urbanization of the Great Lakes basin was the customary transformation of the land surface for farming, highways, roads, and parking areas. The impacts of adding impermeable surface have been known for generations by civil engineers and flood control agencies. Historically, however, this has been viewed as a drainage problem, not as a problem of climate-society interactions. More recently, the true extent of the climate connection to stormwater-borne pollution has become increasingly evident as the Stage one RAPs have helped characterize the impairments of beneficial use in the Great Lakes.[4]

Traditional perspectives on stormwater runoff have changed in concert with the evolution of environmental ethics and management, particularly with the IJC's formal adoption of the ecosystem approach to environmental protection in the Great Lakes basin [15, 16]. Indeed, a recent report on urban runoff notes that,

> Historically, urban stormwater has been managed on the premise that it is a nuisance and should be drained from developed areas as quickly as possible. Little consideration was given to the environmental impacts of stormwater [15, p. 4].

The impacts of stormwater runoff are now understood to be substantial, particularly in two respects of great importance for restoring Great Lakes beneficial uses. These are: 1) precipitation runoff contributions to the accumulation of the persistent toxic substances in bottom sediments in the AOCs; and 2) stormwater impacts on undersized, and often aging, wastewater treatment and sewer systems which result in the transport of bacterial and other contaminants to the lakes and their tributaries.

[4] Similar stormwater pollution problems obviously have been identified in recent years in other developed coastal zones, waterways and harbor areas. However, the extensive nature of the Great Lakes AOC RAP process has facilitated a broader regional understanding of the extent to which the basin's hydroclimatology contributes to undesirable pollution and water quality degradation.

Persistent toxic substances in lake bottom sediments are now considered a critical contributor to impairment of beneficial use of the Great Lakes. The Great Lakes Water Quality Agreement defines a toxic substance as "a substance which can cause death, disease, behavioural abnormalities, cancer, genetic mutations, physiological or reproductive malfunctions or physical deformities in any organism or its offspring, or which can become poisonous after concentration in the food chain or in combination with other substances" [1, p. 7]. Health effects of exposure to toxic substances involves the entire aquatic food chain in the affected AOCs, up to and including humans. Consequently, Great Lakes states and the province of Ontario routinely issue fish consumption advisories to warn the region's human inhabitants of any dangers associated with eating certain species of freshwater sport fish taken from the lakes [3].

Toxic substances have been detected in the sediments of forty-one of the forty-three designated AOCs (the two exceptions are Sturgeon Bay, Ontario, and Presque Isle Bay, Pennsylvania). Different toxics are present in the sediments of different AOCs, due to the type and degree of regional urbanization, industrialization and inland land uses. Consequently, toxics present in the sediments of Lake Superior AOCs are largely different from those found in the AOCs of Lakes Erie and Ontario.

Toxics concentrations and spatial distribution have been characterized in most of the AOCs in preparation for the implementation of future sediments remediation options such as dredging, bioremediation or "armoring," wherein toxics would be isolated from the aquatic environment through the application of artificial sedimentation materials [3]. Physical disturbance of contaminated sediments causes resuspension of toxics in the water column, which is undesirable for improving the health of the aquatic food chain. Nonetheless, navigation channels and harbors are routinely dredged by the U.S. Army Corps of Engineers and Canadian interests in support of commercial shipping.

Current estimates suggest that cleanup and disposal of toxic sediments in the presently designated AOCs may cost hundreds of millions of dollars. Treatment of contaminated sediments reportedly can cost from U.S.$40 to U.S.$2,350 per cubic meter (U.S.$30 to U.S.$1,800 per cubic yard), depending on type of treatment process selected (e.g., armor, dredge and landfill, dredge and incinerate) [3, 17]. Ten AOCs for which cost estimates were prepared as of early 1989 carried a total cleanup bill of between U.S.$2.8 billion and U.S.$5 billion. The majority of this cost reportedly would be for two particular AOCs, Rouge River (Michigan) and Grand Calumet River/Indiana Harbor Canal (Indiana) [3].[5]

[5] Congress has chosen the Rouge River AOC as the site of a federally-supported demonstration program called the Rouge River National Wet Weather Demonstration Program. This project will develop comprehensive plans and infrastructure designs to alleviate pollution inflows to the lakes caused by combined sewer overflows and snowmelt runoff. To fund the project, Wayne County, Michigan, has received $46 million from the federal government. The U.S. Congress appropriated an additional $82 million in the fall of 1992 [18].

The second adverse environmental impact of stormwater runoff in many of the Great Lakes AOCs is due to direct effects of municipal combined sewage systems and wastewater treatment plants (WWTPs) in particular AOCs. Combined sewer systems are designed to carry both sanitary sewage from municipal (often including industrial) sources and stormwater runoff in a single sewer pipe to either a discharge point or a wastewater treatment facility. Combined sewer systems are prevalent in the Great Lakes region, including in the designated AOCs.

Combined sewer systems may be of insufficient capacity to transport elevated volumes of water generated by heavy rainfall or snowmelt runoff, resulting in overflows of untreated sewage reaching the lakes or their tributaries [15, 18]. These "combined sewer overflows" (CSOs) thus can carry untreated domestic sewage as well as municipal and industrial pollutants into the lakes [18]. The Center for the Great Lakes, a regional environmental interest group, reports that twenty-three of the forty-three AOCs experience impairment of beneficial use of the Great Lakes due to CSOs [19].

It is now very evident that the problem of CSO degradation of the affected AOCs could have been avoided if the capacity of these sewer systems had been appropriately sized as they were designed, constructed and expanded to properly accommodate the hydrologic characteristics of the Great Lakes basin's climate. The extent of the CSO contribution to Great Lakes water quality degradation in several AOCs is significant. For example, a report on the Rouge River (Michigan) AOC states that, "Recent water quality tests indicate that toxicity problems occur only after storms. The results suggest that CSOs and urban runoff are major sources of contamination" [20]. Similar connections between surface water contamination and CSOs are noted for numerous other AOCs [19].

In many AOCs, the CSO problem is sizable. For example, 111 CSO outfalls discharge raw sewage directly into three rivers that flow into the Milwaukee Harbor (Wisconsin) AOC as well as into the harbor itself during severe storms [21]. In the Rouge River (Michigan) AOC, 168 combined sewers overflow about thirty-five times annually during heavy storms [20]. In the St. Marys River (Michigan/Ontario) AOC, half of the fourteen CSO outfalls discharge directly into surface waters; during and following severe storms, the municipal water pollution control facility in Sault Ste. Marie (Ontario) is subjected to runoff that is more than three times the facility's design capacity [22]. In the Presque Isle Bay (Pennsylvania) AOC, a tunnel under the full length of the city of Erie collects CSOs from thirty-three sewer outfalls and discharges raw sewage into the bay waters [23].

In several AOCs, the CSO problem has been or is being corrected, in many cases at considerable expense. In the Clinton River (Michigan) AOC, annual CSOs have been reduced from about 150 to a current yearly average of twelve [24]. In the Rochester Embayment (New York) AOC, a network of CSO storage tunnels currently under construction will reduce annual sewer overflows from sixty per year to two; the storage tunnels are expected to cost $750 million to complete [25]. In the Milwaukee Harbor (Wisconsin) AOC, total federal and state grants for water pollution abatement (including construction of 27 km-long [17 mile], 8.5 m [28 ft] diameter CSO storage tunnels) exceeded $1 billion from 1978 to 1990, and the total cost of the abatement program will reach $2.2 billion by 1996; once completed, the relief tunnels will reduce annual CSOs from approximately seventy to less than two [21].

Storm runoff also overloads wastewater treatment facilities in many AOCs. Besides the twenty-three AOCs that experience CSO-related water quality degradation, several additional AOCs experience runoff-related water pollution problems due to inadequate wastewater/stormwater treatment capacity in local facilities [19]. Wastewater/stormwater treatment and associated temporary excess storage capacity are being or have been expanded in several affected AOCs.

Several other direct and indirect climate contributions to water quality degradation have been identified for individual AOCs, which have also helped raise awareness of the region's climatic regime as a critical environmental variable. Three examples illustrate the recently elevated recognition of the connection between regional climate and environmental quality. In the Ashtabula River (Ohio) AOC, winter ice flows are suspected of causing some toxics in sediments to migrate down the river into the harbor area and Lake Erie [26]. In the Grand Calumet River (Indiana) AOC, atmospheric deposition of toxic substances onto surface waters contributes to environmental degradation; the toxics are released into the atmosphere by fossil fuel burning to generate electricity, which is consumed in large quantities for heating and cooling to counter the seasonal climates in the Great Lakes basin [27]. In the Thunder Bay (Ontario) AOC, poor water quality in the Kaministikwia River and the Thunder Bay harbor is caused by high phosphorus concentrations and elevated bacteria levels; water quality is known to be degraded by drought years and associated low water conditions [28].

An unintended benefit of the multi-year RAP process in the Great Lakes Areas of Concern is a growing societal awareness of the region's climate as it relates to environmental degradation and long-term efforts to restore and protect the Great Lakes ecosystem. The RAP process has helped citizens and governments learn about the range of climatic influences on environmental quality. The RAPs have also helped inform the public about the tremendous socioeconomic costs of neglecting regional climate as it relates to natural resource management in the Great Lakes basin.

Unfortunately, public education about climate and the Great Lakes ecosystem comes at a tremendous price. Generations of insufficient attention to the basin's hydroclimatology in the design and construction of the basin's wastewater and stormwater infrastructure have led to impairment of beneficial use of the waters of the Great Lakes. As a result, the public and private sectors and the region's citizens are expending considerable scarce resources to reduce runoff-borne pollution and improve inadequate sewer systems, and to consider appropriate actions concerning the presence of toxic substances in river, harbor and lake sediments.

LOOKING TO THE FUTURE

The growing recognition of climate's importance to environmental management in the Great Lakes basin comes at a critical time in light of projections during the past several years of a future global climate change attributable to the buildup of certain radiatively active trace gases in the earth's atmosphere. These gases include carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs) and nitrous oxide (N_2O). CO_2 is considered the trace gas of greatest importance because of the substantial increase in its atmospheric concentration as well as its probable continued rise due to global consumption of fossil fuels.

The atmospheric CO_2 concentration in 1990 was 353 parts per million by volume (ppmv), up from the pre-industrial (i.e., around 1800) level of about 280 ppm. Atmospheric CO_2 is increasing at a rate of 1.8 ppmv, or 0.5 percent, per year [29]. Continuous monitoring since 1958 at the Mauna Loa Observatory in Hawaii shows that atmospheric CO_2 increased by 12 percent from 1959 to 1990 [30]. Atmospheric concentrations of the other so-called "greenhouse gases" are also increasing rapidly [29, 30].

After extensive review of the scientific literature and research findings on the theory of climate change, the United Nations-sponsored Intergovernmental Panel on Climate Change (IPCC) has reported that at the current rate of increase in the atmospheric concentrations of radiatively active trace gases, mean global temperature will increase 1.5-4.5°C by the year 2100, with a greater rise in mean temperatures in the earth's polar regions and higher latitudes than in the mid-latitudes or tropics [29]. Assuming no significant reduction in global CO_2 emissions in coming decades, the IPCC concludes that global mean temperatures will rise on the order of 0.3°C per decade during the next century.

The global warming debate has been of interest to the IJC, as scientific research suggests that anthropogenically induced climate change could substantially alter the hydrologic regime of the Great Lakes basin. Computer modeling experiments of the earth's future climate indicate a likelihood of significantly reduced net water supply in the Great Lakes basin [e.g., 31, 32], which would translate into declining lake levels through the twenty-first century [33, 34]. The U.S. Environmental Protection Agency projects that the atmospheric concentration of CO_2 will double from its recent historical concentration (i.e., ~350 ppmv) sometime during the next century, and that with such a doubling the Great Lakes could eventually decline 0.5-2.5 meters (1.7-8.3 ft) from their present mean levels by the year 2100 [35]. A hydrologic impacts assessment of three widely used global climate computing models and their doubled CO_2 outputs by the U.S. Great Lakes Environmental Research Laboratory (GLERL) yielded similar findings.[6] GLERL

[6] The three global circulation models used were those developed at NASA's Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), and Oregon State University (OSU).

reports that under doubled atmospheric CO_2 conditions for a thirty-five-year simulation period, mean water levels could decline by 0.79-2.48 m (1.5-8.3 ft), with the least impact on Lake Superior; GLERL's study, however, finds that net basin water supply declines so significantly that the objectives of the lake level regulation plans currently used for Lakes Superior and Ontario could not both be met because of the degree of basin water supply deficiency [34].

In addition to the possibility of declining lake levels, global warming could cause substantial regional changes in wind directions, lake wave climate, stagnation episodes and the intensity and frequency of storms [36]. The combination of declining lake levels and storm-induced wave action could resuspend toxic sediments in the water column and reintroduce contaminants into the food chain in particular AOCs unless tainted sediments are removed, immobilized, or appropriately treated *in situ* to reduce their toxicity [17]. Further, declining lake levels could prompt the need for more dredging of navigation channels for commercial shipping; this would generate unanticipated volumes of contaminated sediments that would require proper disposal. Because the disposal facilities where dredged sediments are presently being placed are nearly full, new disposal facilities will have to be sited and constructed. Their disposal capacities should be designed to accommodate what may be a larger volume of future dredged sediments if lake levels do indeed decline as a consequence of climate change. New disposal facilities will be increasingly difficult to site, however [37]. Thus, with possibly declining lake levels, dredging in particular AOCs may have to be curtailed and toxics left in place.

Altered storm intensity and frequency could also cause future problems with respect to water treatment plants and sewer systems in particular Lakes AOCs despite infrastructure improvements that have been implemented or are planned to accommodate the current climate of the Great Lakes basin. Design capacities of treatment facilities and sewer lines may be exceeded by future runoff as storm intensities are altered. Since strong summer storms presently occur as a consequence of hurricane remnants passing close to the Great Lakes basin [38], changes in intensity or frequency of hurricane activity due to climate change could produce larger or more frequent heavy runoff episodes. Municipal water supply intakes could also require extension as lake levels were to decline. Drought, which periodically occurs in the Great Lakes basin, could further strain wastewater treatment and municipal water supplies [39].

Drought could cause further pressure on Great Lakes water supplies, albeit indirectly. With warmer temperatures, higher evaporation rates and reduced soil moisture in other regions of North America due to climate change [40], new efforts could be expected to export Great Lakes water to such agricultural areas as the U.S. High Plains, west of the Mississippi and Missouri Rivers. Indeed, even in the absence of a possible future climate change, there have been serious proposals to divert Great Lakes water to help support the High Plains economy [2, 41] where "climate-free agriculture" has been driven for the past forty years or more by once plentiful groundwater resources.[7] In many areas of the High Plains, excessive mining of the regional aquifers has forced farmers to abandon or curtail their irrigation practices because of the rising energy costs of withdrawing the groundwater. A combination of further groundwater depletion, growing pressures for agricultural production and higher mean High Plains temperatures brought on by global warming could help resuscitate earlier proposals to divert large volumes of Great Lakes water. There could also be increasing pressure to divert water into the Mississippi River to keep it navigable for commercial shipping.

If global and regional mean temperatures were to rise, fossil fuel consumption could be expected to rise for indoor space cooling which could be expected to increase more than space heating would decline in a warmer climate. This could contribute additional deposition of contaminants, which are known to be transported into the basin by the atmosphere [43], into the waters of the Great Lakes. In sum, long-term changes in local water quality could occur because of global warming, although the rate and extent of water quality degradation remain uncertain.

It should be noted that recent and ongoing research on the impacts of climate change in the Great Lakes basin may lead to smaller projected changes in net basin water supply and/or lake level declines, or perhaps even to forecasts of rising lake levels. Either declining or rising water levels would produce shoreline and water quality impacts [9]. Moreover, depending on changes in storm frequency and intensity, the environmental impacts of rising lake levels could be substantial. With rising lake levels, for example, storm-generated wave action could damage shoreline landfills known as confined disposal facilities (CDFs), where contaminated sediments are placed after being dredged from navigation channels and harbors in many of the AOCs. While CDFs are considered acceptable temporary disposal sites for dredged sediments, they would be viewed as much less acceptable under conditions of rising lake levels and associated wave action because of the potential for leaching or widespread release of contaminants back into open lake waters.

The prospect of rising lake levels due to climate change also would suggest an increase in NBS, which would indicate increased runoff and perhaps more runoff-transported pollution. Thus, increased runoff could lead to future water quality degradation irrespective of improvements that are currently being achieved within individual AOCs.

[7] Speaking of the expansion of irrigation farming in the High Plains in the early 1970s, one U.S. Department of Agriculture official proudly declared, "We have achieved a climate-free agriculture on the plains" [42, p. 234].

CONCLUSION

As a consequence of generations of pollution of the North American Great Lakes, beneficial use of their waters has been impaired in numerous locales. The U.S.-Canadian International Joint Commission has designated forty-three critical zones—Areas of Concern (AOCs)—where water quality and beneficial use have been severely impaired. Remedial Action Plans (RAPs) are in various stages of completion to identify the causes and types of pollution, and to design and implement actions necessary to restore the environmental integrity of the AOCs.

Preparation of the RAPs has produced an unintended benefit among residents of the Great Lakes basin. These comprehensive assessments of the AOCs have helped illuminate the importance of understanding the importance of regional climate in ecosystem management and environmental restoration. The RAPs have demonstrated the extent to which environmental degradation in individual AOCs is now attributed to societal neglect of climatic variability. In many cases, the high cost of implementing corrective measures further emphasizes the importance of understanding the role of climate in regional environmental resource management. The RAP process has shown that local impacts of regional climate can be both ecologically and economically damaging. However, the rise in societal awareness of regional impacts on environmental quality should help improve the integration of climate information in future public policy.

Increased awareness of climate in the context of ecosystem management not only yields present societal benefits, but it is necessary for the formulation and implementation of future environmental policy in the Great Lakes basin. The prospect of a changing climate caused by a warming of the lower atmosphere through the next century suggests that long-term environmental policy for the Great Lakes must take into account a range of climate-related factors, including changes in regional hydrology and new climatic variability around a potentially changing mean.

The importance of increasing societal awareness of the climate-environment connection thus applies to both current and future climatic conditions. Changnon observes that, "In the past, we have operated with only limited information about how the climate affects us. As a result, we have often made incorrect economic, environmental and policy decisions" [44, p. 80]. This commentary should help guide long-term environmental decisionmaking and policy implementation in the Great Lakes basin.

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