Freshwater Ecosystems and Human Populations: Great Lakes Case Study

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ABSTRACT
The Great Lakes of North America were brought to the brink of ecological disaster and are now being returned to a healthier condition. This paper reviews the relationship of human populations to the Lakes’ ecosystem in broad terms and offers advice on go-forward strategies. The interaction of three major forces led to the Lakes’ decline: altering flow regimes by conversion of the landscape, biological pollution, and chemical pollution. Great progress has been made in restoring chemical integrity to the waters of the basin ecosystem, and modest progress has been made in managing the consequences of biological pollution. In the future, work within the basin must expand to include flow restoration strategies. Beyond work within the basin, new foreign policy instruments must manage the global problems of air and biological pollution.

INTRODUCTION
This is a personal account. I have spent the last twenty years learning about the Laurentian Great Lakes, the world’s largest freshwater ecosystem, identifying impairments and restoration opportunities, and aligning ideas, people, and resources to improve its ecological health. The opinions that follow are mine alone. They are not those of the Great Lakes Protection Fund, the Fund’s directors, owners or staff, or any other organization.

This paper uses a case study approach. A brief history of the interaction of human populations and the basin ecosystem is presented. In the pages that follow, I begin to unpack the case by summarizing the state of the Great Lakes ecosystem, through the lenses of physical, biological and chemical integrity. I briefly describe the key threats to the integrity of the ecosystem. I attempt to link those threats to sources related to various human populations. Finally, I suggest ways in which our collective conduct might be changed to avoid continued injury and better take advantage of the ecological restoration opportunities we now have.

By necessity, this paper focuses on key interactions, key systems, key stresses and key opportunities. In the space available, a comprehensive treatment is impossible, and I have not attempted it. I have also chosen to be provocative, and have written this as means of beginning a new conversation on how we can effectively govern our behavior – both within and outside of government – in a recovering freshwater ecosystem.

THE CASE – THE GREAT LAKES ECOSYSTEM
In search of a water route to Asia, Europeans came to the Great Lakes in the 16th century. Instead of the fabled Northwest Passage, they found beaver and began a robust fur trade. Forts were established on key water bodies to protect trade routes. Soon, the forts became towns and as the fur bearing animals became harder to find, the towns became more important than the trade they were established to protect.

Over the next three hundred years, the Europeans and their North American descendents wrested control of the land from the native people they had
found here. By the mid-1800s most of the native people were entreated from
their land, and confined to reservations. Westward expansion was facilitated by
the use of water transportation. The Erie Canal linked the Hudson to Lake Erie
by 1825. In 1829, the Welland Canal had bypassed Niagara Falls. Numerous
other canals, such as the Miami and Erie, linked the lakes to the Ohio and
Mississippi River basins.

By the 1830s, commercial logging had begun in the Canadian portions of
the basin. By the 1860s, the timber industry had started a logging boom in
Michigan, Wisconsin, and Minnesota. The vast virgin forests of the upper basin
fueled the growth of Chicago, Detroit, Milwaukee, Minneapolis, and St. Paul.
White pines in these forests could reach 200 feet in height and each produce
6000 board feet of lumber. Trees could be cut down in winter and floated to
river mouths on the snowmelt each spring. The cleared land allowed runoff to
reach streams without obstruction. Virtually all harvestable timber had been
cleared from the basin by the early 1900s.

As the cities grew, manufacturing became an increasingly important eco-
nomic force in the basin. The iron and steel manufacturing industry grew up
on the shores of the Great Lakes. Iron ore from Minnesota, limestone from
quarries throughout the basin, and coal from the nearby Appalachian plateau
were easily moved by barge to large, integrated steel making facilities. This
industry is still active on the south shore of Lake Michigan, at Sault St. Marie,
Detroit, on the south shore of Lake Erie, in Hamilton, and Nanticoke. The
sulfite paper making process was invented along the Welland Canal and the
industry took hold throughout the basin, and is especially concentrated along
Wisconsin’s Fox River. Significant concentrations of the chemical manufac-
turing industry are located along the Niagara River, the St. Clair River, and near
Michigan’s Saginaw Bay.

In 1950, the region’s population had reached some 28 million. Yet even in
the early 1950s, it became clear the freshwater ecosystem was not inexhaustible.
The basin fishery, once one of the world’s largest, collapsed. Within fifteen
years bulldozers were needed to remove dead fish from Chicago’s beaches. The
Cuyahoga River burned for three days. Lake Erie was unfit for human contact.
After almost half a century of focused work to restore the basin’s fishery, it
remains fragile – largely supported by hatchery-reared fish. After nearly
thirty-years of pollution control – the world’s toughest regulations and
largest expenditure of public funds for pollution control – the most noticeable
problems are gone...Yet problems remain.

What have the lakes taught us about how human populations should
govern themselves? What missteps have we taken in our relationship with this
freshwater ecosystem and how might we avoid similar missteps in the future?
Map of the Laurentian Great Lakes Region
BACKGROUND – AN INTRODUCTION TO THE GREAT LAKES

The Great Lakes ecosystem is the interacting components of air, water, land, and biota (including humans, of course) affecting the waters of the Great Lakes basin. This is a somewhat standard definition, appearing with minor changes in the Great Lakes Water Quality Agreement,\(^1\) the proceedings of the State of the Lakes Ecosystem conferences, and many scholarly articles.

The scale of the Great Lakes basin is difficult to comprehend, even for those who live and work in the basin. The five Great Lakes — Superior, Huron, Michigan, Erie and Ontario — themselves contain over 5,500 cubic miles of fresh water. This is 18% of the world’s available supply. The lakes cover an area of about 94,000 square miles. The watershed that drains into them covers just over 201,000 square miles. The system extends from roughly 41 to 51 degrees north latitude, and from 75 to 93 degrees west longitude.\(^2\) The drainage basin includes parts of eight U.S. states and two Canadian provinces.

The Great Lakes are the only glacial feature visible from the moon. They were formed over several glacial episodes beginning some 500,000 years ago.\(^3\) The lakes began as lowlands, probably river valleys associated with the predecessor of the St. Lawrence River. Great lobes of ice, up to two miles thick entered these valleys. Contrary to what one might imagine, glaciers are not permanently frozen to their beds. Where they are in contact with the ground, the ice melts, enters cracks, and periodically freezes. Material of all sizes, from fine “glacial flour” to large rocks and boulders become entrained in the ice. When a glacial advance stops, the entrained material is deposited. This glacial drift became the soil and upper strata in the Great Lakes basin. Loose drift can hold vast amounts of groundwater. Areas having substantial deposits of well-sorted sands and gravel are usually significant groundwater storage and transmission areas, and are known as aquifers.\(^4\)

The present Great Lakes began to form with the retreat of the last glaciation — the Wisconsinan. The final substage of the Wisconsinan glaciation began retreating some 14,000 years ago and left the basin about 9,500 years ago. As the glaciers retreated, large lakes were formed at their edge. These “proglacial lakes” often deposited clays and other fine material, leaving patches of wet, poorly drained soils in the basin. These lakeplains are now home to unique biological communities in the basin.\(^5\)

THE MOVEMENT OF WATER WITHIN THE BASIN

Water moves within the basin in accord with the hydrological cycle — the dominant physical process at work in the basin. Air carries water vapor over the basin, deposits it on the land, where it eventually enters the lakes. Once in the lakes, water moves in currents along the shores, is pushed by winds and storms, and eventually leaves through evaporation or transport to the Gulf of St. Lawrence.

The water that replenishes the Great Lakes comes from precipitation. Precipitation is, in turn, driven by the global climate. Rain and snow fall directly

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on the lakes and on the lands drained by tributary rivers and streams. The majority of water that enters the system falls as rain or snow on the watershed, becomes ground water, and is discharged to the lakes through tributaries. Using new information, it has been estimated that approximately 53% of the new water entering the Great Lakes takes this ground water pathway. The second largest category, about 24% of new water on a system-wide basis, is surface runoff that drains into tributaries and, ultimately, to the lakes themselves. Over-lake precipitation, subtracting evaporation losses, accounts for about 20% of the new water entering the lakes. The remaining 3% of known inputs to the lakes are the diversions into the system from the Hudson Bay drainage that enter in Lake Superior.

On an individual lake basis, these contributions vary substantially due to local geology and the placement of the lake in the larger basin system. As one moves south and east in the system, the lakes increasingly depend on the waters flowing from the upper lakes. Lake Erie, on an average basis, receives nearly 90% of its new water supply from the outflow of the Detroit River.

The following is summary information on the movement of water through the Great Lakes basin. A lake-by-lake summary is provided to show how each lake is governed by several jurisdictions and remains connected to its own watershed while also being dependent on upstream sources of water.

LAKE SUPERIOR
Lake Superior, the largest, deepest, and highest in elevation of the lakes, borders Minnesota, Wisconsin, Michigan, and Ontario. Lake Superior contains 2,900 cubic miles of water and covers 31,700 square miles. Lake Superior has a drainage basin of 49,300 square miles. Three hundred and thirty-five tributary rivers and streams drain into the Lake (the Nipigon River flowing from Canada is the largest river and the St. Louis River flowing from Minnesota is the second largest), including large in-flows from the Long Lac and Ogoki diversions. Ninety-five percent of Lake Superior’s drainage basin is forested, and the remaining 5% is split between agriculture, urban and industrial land uses. Less than 2% of the entire population of the Great Lakes, or about 740,000 residents, live around Lake Superior. As a result, the Lake has avoided many of the pollution problems associated with the other lakes.

The majority of water entering Lake Superior, some 49%, is ground water transported to the lake via the network of tributary rivers and streams. The surface run off carried by these same tributaries accounts for just 17% of the water that enters the lake each year. The net contribution of over-lake precipitation (after evaporative losses are considered), accounts for 28% of new water each year. The remaining 6% of the water that refreshes Lake Superior each year comes from the diversions into the system from the Hudson Bay drainage at Long Lac and Ogaki. Water exits Lake Superior through the St. Mary’s River at a rate of approximately 78,000 cubic feet per second (cfs).
LAKES HURON AND MICHIGAN

Lakes Huron and Michigan are usually described as a single hydraulic system because they share a common outlet to the lower lakes and possess the same long-term water level.

The United States-Canada border divides Lake Huron almost in half. The Canadian portion of the lake is wholly within Ontario. The United States portion is located entirely within Michigan. Lake Huron contains 850 cubic miles of water and covers 23,000 square miles. Lake Huron has a drainage basin of 51,700 square miles, two-thirds of which is in Canada. Sixty-six percent of the area around Lake Huron is forested, 22% is agricultural land, 10% is urban and industrial land, and 2% is devoted to other uses.

Lake Michigan is the only Great Lake located entirely within the United States, bordering Wisconsin, Illinois, Michigan, and Indiana. Lake Michigan contains 1,180 cubic miles of water and covers 22,300 square miles. Lake Michigan has a drainage basin of 45,600 square miles. The northern portion of the lake has very little population, development, and water consumption, although most of the tributaries in the northern part of the lake’s drainage basin are dammed for power production. The southern portion is extensively urbanized with significant industrial, agricultural, and domestic water use, resulting in significant pollution, loss of wetlands, and other environmental problems. More than 10 million people reside on the lake’s shoreline.

The Lake Huron-Michigan system is dominated by the flow from Lake Superior, which provides an estimated 42% of the year’s water input. The contribution of ground water reaching the system through tributaries totals 35%-20% in Lake Huron and 15% in Lake Michigan. Surface runoff transmitted through tributaries totals 12% of the annual average amount of water entering the system – 8% in Lake Huron and 4% in Lake Michigan. The net contribution of precipitation is 22% of the annual water budget – evenly divided between the two lakes. The system drains into the St. Clair River at about 187,000 cfs.

LAKE ERIE

Lake Erie borders Michigan, Ohio, Pennsylvania, New York, and Ontario. The lake also receives surface and ground waters for the northeast portion of the state of Indiana. Lake Erie contains 116 cubic miles of water and covers 9,910 square miles. The shallowest of the Great Lakes, Lake Erie undergoes wide temperature swings, warming rapidly in the spring and summer and often freezing over in the winter. Lake Erie drains 30,000 square miles – 59% of that land is agricultural, 17% is forested, 15% is industrial and urban, and the remaining 9% is used for other purposes. Thirteen million people live within the Lake Erie basin, 86% of them in the United States. Despite its small size, the Lake Erie basin is the most populated of the Great Lakes and has the most agriculture. Lake Erie also has historically suffered significant damage from pollution.

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Despite its small size, the Lake Erie basin is the most populated of the Great Lakes and has the most agriculture. Lake Erie also has historically suffered significant damage from pollution.
Eighty-eight percent of the water entering Lake Erie in a given year is, on average, from the upper lakes via the Detroit River system. The remaining 12% is evenly divided between surface run off and ground water transmitted via the lakes’ tributaries. The precipitation falling on the lake is, on average, equivalent to the amount that evaporates from its surface. Lake Erie drains into Lake Ontario through the Niagara River and Welland Canal at a rate of 212,000 cfs.

LAKE ONTARIO
The smallest of the Great Lakes, Lake Ontario borders New York and Ontario. Lake Ontario contains 393 cubic miles of water and covers 7,340 square miles. Lake Ontario has a drainage basin of almost 25,000 square miles. Forty-nine percent of the basin is forested, 39% is used for agriculture, 7% is urbanized or industrialized land, and the remaining 5% is used for other purposes. Lake Ontario suffers from agricultural runoff and pollution. One of the greatest stresses on the Lake is the regulation of water levels through mechanisms comprising the St. Lawrence Seaway.

Like Lake Erie, the majority of water entering Lake Ontario is from the upper lakes – about 85% of the average annual amount. Some 9% of the new water entering Lake Ontario is from groundwater carried to the lake in tributaries. Five percent is surface run off carried in tributaries. The net contribution of precipitation accounts for nearly 2%. On an average basis, approximately 251,000 cfs (or 162 billion gallons per day) leaves Lake Ontario via the St. Lawrence River.

Other Hydrological Issues
Because of the size of the system, it responds somewhat slowly to environmental changes. Each lake has a large total volume relative to the amount of water entering and leaving. For example, using simplifying engineering assumptions, it has been calculated that a single drop of water deposited in Lake Superior on average takes 190 years to leave through the St. Mary’s River. This relatively prolonged hydrologic process means that the Great Lakes can require a significant amount of time to process changes in chemical water quality. In addition, the large surface area of the lakes, covering 94,000 square miles, makes the lakes vulnerable to direct atmospheric pollutants that fall with rain or snow and as dust on the lake surface.

The system is also somewhat slow in responding to hydraulic changes. It has been estimated that up to 15 years is required for certain changes in the water inputs to the upper lakes to be fully felt in the lower lakes. Nevertheless, changes in the long-term average flows and levels of the Great Lakes are somewhat predictable based on current knowledge and tools. Flows in the channels that connect the lakes and the levels of the lakes themselves are of critical importance to various users of the lakes, most notably the hydroelectric power industry and navigation interests.
THE RELATIONSHIP OF HUMAN POPULATIONS TO THE GREAT LAKES

The integrity of a freshwater ecosystem such as the Great Lakes is dependent upon the condition of its physical, chemical and biological components. Human populations can have both direct and indirect impacts on these components through resource consumption; residential, commercial, agricultural and silvicultural development; and the production and disposal of waste products.

Physical Integrity – What Have We Altered?
The physical integrity of the Great Lakes ecosystem is driven by the movement of water across and through the land, in streams and rivers, and in the lakes themselves. While it too is a critical process, the vertical movement of water in the open lakes, and the thermal stratification that limits mixing during the summer months, are beyond the scope of this paper. Suffice it to say that human population pressure has not widely altered the seasonal stratification of the open lakes, nor limited the mixing of the layers when stratification breaks down in the fall. Population pressure and resource consumption can, however, be linked to significant alterations in how water, energy, and materials have historically moved through the basin. Just recently we have begun to recognize the ecological consequences of the hydrological alterations brought about by water uses, diversions, and physical modifications to the land and waters of the Great Lakes.

Current Water Uses
No single, accurate, comprehensive database has been complied on the uses of Great Lakes basin waters. Progress is being made to create a data repository that satisfies the commitment to develop and maintain a “common base of data and information regarding the use and management of basin water resources...” contained in the Great Lakes Charter. In 1995, the annual report of the Great Lakes Regional Water Use Data Base Repository was made available, summarizing water use information that was available for the 1992 calendar year. At that time, the states of Michigan and Pennsylvania supplied their best estimates for several use categories.

The largest single use of water in the basin is for the generation of hydroelectric power. The Great Lakes Commission reports that, in 1992, 908.7 billion gallons per day were used to generate hydroelectric power. This represents over 94% of the total water reported to have been used in the basin...The second largest use of Great Lakes water is to supply cooling water to the thermoelectric power industry...The remaining 2% of water used in the basin is divided among all other uses – industrial supply, public supply, domestic use where public supplies are not available, irrigation, livestock, and navigation.

12 Great Lakes Commission. 1995. Ibid.
The dominant ecological impact of hydroelectric operations is altered system hydrology. These hydrologic changes include increased peak flows downstream of operations, diminished flows downstream and near power houses, increased rates of change between flow stages, and altered timing and frequency of flow events both upstream and downstream of these operations. In addition to changes in the movement of water, dams and their reservoirs alter how materials move from headwaters areas to the open lake. These materials include inorganic matter like clays, sands, cobbles and other sediment, organic matter like woody debris, and living organisms such as fish. In some cases, the interruption of sediment movement has caused the loss of beaches.\(^{14}\) In the Great Lakes, the inability of fish to reach tributary spawning habitat has a significant impact on the health of open water fisheries.\(^{15}\)

The second largest use of Great Lakes water is to supply cooling water to the thermoelectric power industry. The Great Lakes Commission estimates that 40 billion gallons per day are used to cool reactors and condensers used in the generation of electric power. This represents roughly 4% of the total use reported by the Commission for calendar year 1992.

Potential ecological effects from this use of water are largely attributable to the near field alteration of thermal regimes due to increased temperature and the possible release of trace contaminants used as cooling water additives. In terms of hydrological alteration, the cumulative effects of losses in wet cooling towers may merit attention. In compiling data for the 1992 use report, the ten jurisdictions each estimated the losses of cooling water to predict consumptive uses. The estimates ranged from “negligible” to 14% of water used.

The remaining 2% of water used in the basin is divided among all other uses – industrial supply, public supply, domestic use where public supplies are not available, irrigation, livestock, and navigation. The majority of the water is used for cooling industrial operations.

Even though the total volume of water use in these remaining categories is small, ecological impacts can be significant. For example, in the upper watershed, municipalities or industries often can withdraw water from a stream, use it, and then return treated wastewater at a location significantly downstream. The intervening stretch of river or stream can be dewatered to some degree, affecting the viability of local and perhaps regional fisheries. Similarly, if withdrawals are made from ground water, and the water is returned directly to surface streams, the ecological integrity of the watershed can be degraded because of reduced base flows in the streams. Such streams can dry in the summer, and subject to erosion in wet weather and sedimentation during lower flow periods.

The cumulative impact of extensive ecological degradation of the basin’s headwater streams will be a more fragile open lake system that requires intervention to maintain a healthy fishery and adequate water quality.

\(^{14}\) A good example is the Elwha Dam complex in Washington State. See the summary of environmental impact statement in \textit{Smithsonian Magazine}, November 1998.

Existing Diversions
Presently, more water is diverted into the Great Lakes basin than is diverted out. No systematic evaluation of the ecological impacts of these diversions exists. Some of the hydraulic changes are understood, however. The net impacts of diversions, regulation structures, and channel dredging result in an estimated increase in the level of Lake Superior by four inches, a lowering of the level of Lakes Huron and Michigan by just over a foot, an increase in the level of Lake Erie by just over an inch and a decrease in the level of Lake Ontario by about two and a half inches.16

Although separate diversions, both the Long Lac and Ogaki diversions add water from James Bay in Canada to Lake Superior at varying rates between 2,500 to 8,000 cfs. These diversions are used to generate hydroelectric power and to transport pulpwood logs southward. The diversions have significant local environmental effects on fish habitat.

The Lake Michigan Diversion at Chicago diverts on average 3,200 cfs of Lake Michigan water to the Illinois River, which drains into the Mississippi River. The diversion consists of three components: (1) water supply withdrawn for domestic and industrial uses and then discharged into the Illinois River as treated sewage; (2) runoff that once drained to Lake Michigan but is now diverted to the Illinois River; and, (3) water diverted directly into the Illinois River and canal system for navigation purposes, connecting the Mississippi River to Lake Michigan.

The Welland Canal diverts water from Lake Erie to Lake Ontario for deep draft navigation and hydroelectric power generation, bypassing the Niagara River and Falls. The diversion also supplies water for industrial and municipal use, including sewage dilution. During the navigation season 9,050 cfs is diverted through Welland Canal. 7,950 cfs is diverted at other times. The diversion has lowered the level of Lake Erie by (less than) approximately six inches and dropped the levels in Lake Michigan and Lake Superior by about two inches and one inch respectively. The Welland Canal has resulted in the virtual disappearance of indigenous lake trout stocks by creating an entry point into the upper lakes for the sea lamprey.

The New York State Barge Canal system connects the Hudson River to Lake Ontario by diverting water from the Niagara River into Lake Ontario via a route that connects with the Erie Canal, which connects to the Hudson River. The diversion takes between 700 and 1,100 cfs primarily for navigation purposes.

Ecological Consequences of Physical Alteration
The Great Lakes, their connecting channels, and the lands they drain are part of a single, connected, ecological system. The major source of new water entering this system not only comes from the land, but moves through the land. Alterations in timing and amount of water supplied to the lakes not only impact downstream interests that desire to use the system’s water for economic purposes, but impact water dependent natural resources near to those alterations, and distant from them in space and time.
New scientific information tells us that all hydrological alterations of aquatic systems have ecological consequences. While these consequences depend on the exact nature of the specific alteration, they have more to do with how the water is used, where in the system it is used, and when water is used, than how many gallons of water are used. A relatively small volume of water permanently removed from a sensitive habitat may have grave ecological consequences. Similarly, the rapid addition of water to a stream reach during spawning season can eliminate a source of young fish for an important fishery.

Recent scientific investigations have identified that the biotic composition, structure, and function of aquatic wetland and riparian systems depend largely on the hydrologic regime. The hydrologic regime includes not only the absolute quantity of water at a given time, but also the frequency with which certain flows occur over a given time interval, the rate at which flow conditions change, the duration of various flow conditions, and the range of flows on a given system. The biologically important time intervals for these variables can be as short as an hour and as long as several years. All of these conditions describe the ability of a given aquatic system to move materials and to support species and natural communities that have evolved in response. Moreover, these conditions control critical biological events including the ability of exotic species to establish themselves; dispersal of native species; cues for spawning, hatching and migration of native species; and changes to food webs and encroachment of vegetation.

In addition to the waters of the Great Lakes basin themselves, the exhaustible natural resources that are threatened by future water development projects are those that depend on the basin’s waters in one way or another. They include the natural communities of the open lakes – phytoplankton, zooplankton, planktivorous fish, piscivorous fish and avian predators; natural communities on the coasts – wetlands, dunes, beaches, and shorelines; the plants, animals and natural communities of the rivers and streams tributary to the Great Lakes – species of fish, insects, plants, herps and mammals; riparian wetlands; embayment lakes; riparian plant communities; and upland pond and wetland communities fed by ground water. These natural resources are sustained not only by the waters of the Great Lakes basin but also by the movement of energy, materials, and biota in those waters.

Similarly, dams and other structures can also change the hydrology, and ultimately the ecology, of the basin. Depending on how they are operated, dams can dramatically alter the hydrologic regime. The magnitude, duration, frequency, timing, and rate of change of flow events can all be changed. For example, a hydroelectric dam designed to provide on demand peak power can almost instantly increase the flow in a river system from no flow to several times the historic annual maximum flow. Conceivably, this could happen on a daily basis. Further, such a facility can effectively “bury” historic spawning habitat beneath its reservoir. Demonstrated impacts of such operations include the loss of a self-sustaining fishery, loss of beaches due to sediment starvation, and fragmentation of aquatic habitat.

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When the hydrologic regime of open lake waters is altered through diversions, changes in outflows or other alterations in water supply, levels can change and the ability of the lake to support coastal wetlands can be diminished. For example, the International Joint Commission’s Levels Study Board concluded that regulation of Lake Ontario’s outflow has stabilized lake levels and caused “significant adverse damage” to coastal wetlands in the lake, and other adverse impacts on flood plain forest downstream. These impacts are strongly associated with changes in the frequency, timing, and duration of the periodic inundation that coastal wetlands require to maintain ecological integrity, rather than changes in long-term average levels or flows.

Chemical Integrity – What Have We Added?
Generally, two classes of chemicals are considered when evaluating the integrity of a freshwater resource: nutrients and toxics. Nutrients can be generally described as those compounds needed to support plant life. Toxics, on the other hand, are poisons that impair the ability of a system to support life. The Great Lakes have suffered problems from both types of chemicals.

In the late 1960s, Lake Erie was widely acclaimed to be “dead.” Actually Lake Erie was far too alive, choking on nutrients. In fresh water systems, the ability of phytoplankton, small plants at the base of the food chain, to grow, is limited by the availability of phosphorous compounds. Add phosphorous and you get more phytoplankton. Because Lake Erie is relatively small, and highly urbanized, it was susceptible to nutrient enrichment. At the time, most sewage and industrial waste was poorly treated. Laundry detergents, which were ultimately released to basin waters through septic and sewer systems, also contained high levels of phosphorous. The high concentrations of nutrients caused large growth of algae. As the algae died, it decomposed in the water column and in the sediments removing oxygen from the lake. The loss of oxygen killed fish, and left foul smelling water, even after it was treated for drinking.19

Such enrichment, called cultural eutrophication, was once common in the Great Lakes. While Lake Erie was the worst case, both Lakes Michigan and Ontario suffered from increased nutrient loading and were showing signs of eutrophication. Throughout the basin, river mouths and bays, including Green Bay, Saginaw Bay, the St. Louis River Estuary, the Muskegon River, the Bay of Quinte, and Hamilton harbor among others, were eutrophic because of the release of sewage and industrial waste.

Today, these problems are largely under control. Laws have been passed limiting the amount of phosphorous in detergents. Industries and cities have typically installed waste treatment systems. Where enrichment problems now exist they are largely localized and contained thanks to the efforts of the basin’s citizens, governments, and industry.

In contrast to managing nutrients, where efforts could focus on a single element like phosphorous, managing the impacts of toxics must focus on a large list of chemicals. Toxic substances are those known to have an adverse

impact on the living components of the ecosystem, that is, any substance which can cause death, disease, behavioral abnormalities, cancer, genetic mutations, physiological or reproductive maladies or physical deformities in one organism or its offspring, or which can become poisonous after concentration in the foodchain or in combination with other sources.\textsuperscript{20} Such compounds include heavy metals (copper, nickel, lead, chromium, cadmium, and mercury for example) and complex, usually man-made organic compounds (polychlorinated biphenyls or PCBs, pesticides, herbicides, polynuclear aromatic hydrocarbons, and tetrachloro-dibenzo dioxins (TCDDs)). Toxic compounds come from a variety of human activities and reach the lakes through a variety of pathways, including effluent discharges to streams, rivers and lakes, deposition from the atmosphere, or via groundwater contaminated by leaking landfills. Once these compounds reach the lakes, they are often sequestered in sediments and released over time into the water column.

The widespread presence of toxic substances found in the Great Lakes in the 1960s and 1970s was primarily the result of the increased commercial production and widespread use of organic chemicals and metals that started during World War II and accelerated afterward. Environmental records assembled from radio-chemically dated sediment cores from Lake Ontario revealed the presence of several chemicals starting as early as 1915, but sharply increasing in the late 1940s and reaching peak levels in the early 1960s.\textsuperscript{21} The IJC has verified that some 362 chemicals were present in the Great Lakes. One third of these may have toxic effects.\textsuperscript{22}

Several types of toxic effect are associated with chemical contaminants in the Great Lakes. The easiest to understand is lethality. Some compounds, at a sufficient concentration, are lethal to aquatic life. Several heavy metals, for example, kill fish by destroying the ability of the gills to extract oxygen from water. Effluents from certain industrial processes, such as electroplating, once contained a sufficiently high level of dissolved heavy metals to be lethal to aquatic organisms. All such discharges are now illegal on the U.S. side of the basin.

A variety of sub-lethal effects are also associated with toxic compounds. At very low levels, some heavy metals can interfere with kidney function, the ability of fish to locate prey, and can make organisms more susceptible to disease. Some organic compounds have similar effects.

Carcinogenesis—the induction of cancer or tumors—is another consequence of toxic exposure. Numerous fish collected from areas contaminated with organic pollutants have lesions and tumors.

Perhaps the most insidious consequences of chemical contamination are those that pass from generation to generation in utero, or through the food chain from prey to predator. Teratogenic compounds are those that interfere with the development of young. They can cause birth defects such as crossed bills in birds, development of extra limbs in amphibians, or developmental impairments in humans. Chemicals can also bioconcentrate or biomagnify through the food chain. In the Great Lakes, minute concentrations of PCBs in

\textsuperscript{20} GLWQA, 1987


\textsuperscript{22} Beeton et al., 1999 ibid.
the water column will concentrate some hundred fold in phytoplankton, thousands fold in zooplankters and planktivorous fish, hundreds of thousands fold in piscivorous fish, and up to six million fold herring gulls. 23

Because some chemicals both biomagnify and possess carcinogenic, mutagenic and/or teratogenic properties, threats to the top of the food chain often drive clean up efforts. Humans who consume Great Lakes fish can be at elevated risk levels. So can fish-eating birds, such as bald eagles, gulls and terns. Fish-eating mammals, including mink, fishers, and otters can also be at risk.

Great progress has been made in reducing the input of toxic chemicals to the Great Lakes, and the levels of toxic chemicals in Great Lakes biota. In fact, the populations of fish-eating birds have expanded greatly since the early 1980s. Since their use and or manufacture has been banned, levels of PCBs, dioxins, pesticides, and herbicides have dramatically declined. Other substances have been addressed in controls adopted in statutes in place in the U.S. and Canada, most notably the U.S. Clean Water Act and control orders issued by the Province of Ontario.

Significant contamination remains. Because chemicals can be sequestered in sediments, a reservoir of contamination resides at the bottom of most Great Lakes harbors. Of 43 areas of concern identified by the U.S. and Canada, all had contaminated sediments and only one has been cleaned up sufficiently to be removed from the list.

Of particular concern are chemicals such as mercury, whose levels have increased in the environment, and those such as DDT/DDE, whose concentrations have stopped declining.

Atmospheric transport of chemicals into the Great Lakes basin is an increasingly significant input. Transport by air masses and deposition by precipitation is believed to be a significant source of lead, arsenic, cadmium, polynuclear aromatic hydrocarbons, Lindane, Chlordane, DDT/DDE, Dieldrin, toxaphene, and PCBs entering the Great lakes watershed. 24 Some of the compounds, such as DDT/DDE and Lindane, whose use is banned in both the U.S. and Canada, are believed to be carried in air masses from sources as far away as China, India, the former Soviet Union, and Central America. 25

Biological Integrity – What is the Condition of the Living Part of the Ecosystem?
The basin ecosystem can be thought of as having seven biological compartments – the open lakes, the coastal shores, coastal wetlands, the lakeplains, tributary streams and rivers, the upland terrestrial communities and upland wetland communities. All are linked to one another, although the strength and importance of the relationships vary. For our purposes – evaluating the biological consequences of human population pressure on freshwater ecosystems – the biological condition of the open lake and tributaries is where we will focus. Closely associated are biological effects in both the coastal and inland wetland systems, as are changes in the abiotic features of the coastal shore and upland terrestrial communities.
The biological condition of the ecosystem has been significantly degraded. Some 145 non-native species have established themselves as permanent residents, often with disastrous consequences for the native species that they compete with or prey upon. Some of the more notorious invading species include the sea lamprey, carp, the Eurasian ruffe, alewife, and the zebra mussel.

The Open Lakes
The open lake biological community organizes itself around who eats whom. The base of the food chain begins with the phytoplankton, the small plant life discussed earlier. The phytoplankton convert sunlight and carbon dioxide into organic matter that serves as food. This food is consumed, for the purposes of our discussion, by zooplankton, tiny animals that graze on algae. The zooplankton, in turn, are eaten by small fish – planktivores. Larger fish, the piscivores, eat the small fish. The larger fish are eaten by birds, by mammals (including humans) or by “decomposers,” the garbage collectors of the natural world. Viewed simply, decomposers are the bacteria that turn dead fish and plankton back into nutrients, consuming oxygen in the process.

While the above relationships still exist in the open lakes, the organisms responsible for doing the eating have changed dramatically in the last 100 years. Candidly, very little is known about the species composition of the phytoplankton community in the Great Lakes. While species previously not known to be in the lakes are routinely encountered, it is not known whether these are new introductions or simply new identifications. A bit more is known about the zooplankton. Some key zooplankton appear to be disappearing. Dioporia, a shrimp-like animal that is a preferred prey item by many Great Lakes fish has drastically declined in recent surveys in Lake Michigan. Non-native zooplankton are increasing in the system.

The fish community has been altered by the accidental and intentional introduction of non-native species. Let’s use the members of the historic and present Lake Michigan food chain as an example. Historically, the planktivores included the lake herring and several species of deep-water ciscoes. Today, accidentally introduced species – alewife and rainbow smelt – fill their functional niche. The alewife is now believed to constitute most of the biomass in lake Michigan. The alewife was introduced to the lake when an impoundment being used to grow them as bait fish failed in a storm and washed its contents into the lake. The alewife succeeded because it has the ability to out feed the native species. Alewifes and smelt are prey for intentionally introduced pacific salmon, which now replace the native lake trout as the top fish predator. The salmon are hatchery raised, and used to keep the alewife in check.

The same story, sometimes with different species names, is true for each lake in the basin.
Tributaries and Connecting Channels
While it was not the case prior to European development of the waterways, most Great Lakes tributaries are largely separated from the open waters of the lakes biologically by dams and other structures. Historically, many fishes used tributaries as spawning and nursery habitat. Some 73% of common Great Lakes fish use river habitats for spawning. Today, the tributaries are often managed as fishery resources largely separate from the lakes they once served.

Several Great Lakes tributaries once supported a diverse unionid mussel fauna. The St. Clair-Detroit River system was once home to 39 species, one of the most diverse mussel populations on the planet. Because of channel modification, pollution, and the invasion of the zebra mussel, those populations were largely gone by 1992. Several relict populations remain, however. Fish Creek, in northeast Indiana, holds the only known population of the White Cat’s Paw Pearly Mussel.

Other Biological Features
In spite of massive land conversion, pollution, and exotic species invasion, the Great Lakes basin contains a wealth of unique biological features. The Nature Conservancy, using state agency data, identified occurrences of some 131 globally rare species and natural community types in the basin. Sixty-one of these have the global distribution limited to or predominantly within the basin. The vast majority of these globally significant features are supported by the basin’s hydrologic regime.

ANALYZING THE CASE: DEGRADING AND RESTORING THE GREAT LAKES ECOSYSTEM
When viewed in hindsight, through the lens of 21st century environmental science, it is evident that we conducted three simultaneous, large-scale, uncontrolled experiments with the ecosystem. First, we altered its plumbing by reshaping the land and rivers. Second, we altered its chemistry by introducing nutrients and poisons. Last, we fundamentally altered its biological composition by introducing – sometimes knowingly, but usually not – non-native species. These alterations were synergistic – reinforcing one another – and led to a collapse of the system’s ability to self organize and regulate itself.

These changes, and how we managed to do them, can be illustrated through a different (and equally highly simplified) telling of the case summarized at the beginning of this paper.

The clearing of the Great Lake’s forests at the end of the 19th century made possible the fishery and water quality collapses of the mid-20th. By altering how water moved across the land, and physical conditions of the tributaries that drained the basin, the harvest of trees not only fueled the westward expansion of the basin’s two countries, but prepared habitat for the most destructive invasive species the basin has yet encountered – the sea lamprey.


31 Rankin and Crispin, IBid.

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It is unclear if the sea lamprey was native to Lake Ontario or not. But the canals that connected the upper lakes to Lake Ontario, and Lake Ontario to the Hudson, made it possible for the lamprey to enter all of the Great Lakes. Lampreys are eel-like fishes that spend most of their long life cycle in the sediments of the streams in which they spawn. They spend their eighteen month parasitic phase patrolling open lake waters attaching themselves like giant leeches to the sides of large fishes and sucking them dry.

The tributaries that had transported logs and were subject to scouring during rain events were transformed into nearly ideal lamprey habitat. As they moved into their new homes after the logging was completed, they went largely unnoticed because of their small numbers and relatively long life cycle. But with abundant food, and no natural competition, they bred unchecked. Within two or three lamprey generations, the population of piscivorous fish started to decline dramatically.

With the fish-eating fish on the decline, there was no natural control for the planktivores – the fish that eat zooplankton. Their populations exploded. The faster one species could eat, the more that species could out-compete rivals. The introduced alewife, with its ability to use three feeding methods, not only grew its population, but also out-competed the native herring and ciscoes. And the population of zooplankton collapsed.

With no zooplankton to eat them, there was no natural control for the populations of phytoplankton in the lakes. At the same time, we humans – who until now had little reason to treat our sanitary or industrial waste – were fertilizing the rivers and lakes with nutrients. With all the nutrients they could consume and few natural predators, phytoplankton populations exploded – causing the now infamous death of Lake Erie, robbing Lake Michigan of oxygen, thereby killing millions of alewifes near Chicago, and strangling Green Bay.

None of this was done with malevolence and forethought. The men who spent winters in lumber camps did not set out to cause the collapse of the Great Lakes fishery. The commercial fishermen who stacked lake sturgeon like cordwood did not intend to drive the species close to extinction. The steel industry greatly expanded its operations in the basin to win the Second World War, not poison the lakes. Cities built sewers to protect their populations, not to over-enrich Lake Erie.

Yet the results were clear, even if the causes were multiple. No one cause – deforestation, industry, domestic sewage, or biological pollution – could account for the magnitude and scope of the environmental damage visited on the Great Lakes. Each sector could effectively argue that its actions could not possibly account for the problems. In fact, each sector could correctly argue that its share of the damage was but a minor fraction of the total problem.

All of our actions were based in almost perfect ignorance of the ecological systems around us. As a people, we were acting without understanding that the Great Lakes were an ecological system, and we did so at our own peril.
includes hundreds of thousands of miles of lake surface area, it is slow to respond. Responses that are not immediate in time, or that are not near in space, go unappreciated and under valued by humans. Responses of ecological systems are frequently distant in time and space from the driving stimulus.

Different human populations interacted to the detriment of the ecosystem. First, the logging boom of the late 1800s was driven by the expansion of two countries. It wasn’t that logging was the problem, per se. Rather, it was the method by which it was done, and the rate at which it occurred that was the problem. Fundamentally, the fact that it altered the basin’s physical integrity, especially the hydrologic regime, is what matters most. But this change would have been far less important, if another group of individuals had not been busy unintentionally introducing non-native species by digging canals and increasing ship traffic. These two factors destabilized the system to such an extent that when a third population fertilized the Great Lakes nearly one hundred years later by adding untreated waste, the system virtually collapsed ecologically.

**Initial Progress in Addressing Human-Induced Alterations**

To address the state of the Great Lakes, an unprecedented response was mustered. In the 1960s, led by government agencies who largely lacked a clear statutory mandate, a coordinated resource and waste management strategy was launched. It was a “top-down, bottom-up” strategy driven by a scientific understanding of how the lakes operated as a system. The “top” and “bottom” in the strategy have not-so-much to do with people – they do not describe federal officials and local citizens – they describe the top and bottom of the food chain in the open lakes.

The “top-down” strategy was a two-part effort to restore top predators to the lakes. The lake trout population had been virtually wiped out by the sea lamprey. To restore its functional role in the system, it was decided to introduce pacific salmon. These fish could be raised in hatcheries and, once released into the lakes, could restore grazing pressure on the alewife. The second part of the strategy was to control sea lamprey populations. Spawning streams were chemically treated to kill lampreys. New physical barriers, called lamprey weirs, were installed in streams that had spawning habitat.

The “top-down” strategy had immediate pay-off. Government could and did act directly. Hatcheries began to produce salmon fry and release them to the lakes. This was a war of production, and the government had the means.

The “bottom-up” strategy was a bit more difficult to implement. The essence of the bottom-up approach was to tackle the base of the food chain by reducing the input of nutrient chemicals. Finding sources to control was no problem. Virtually no municipalities provided biological sewage treatment. Similarly, most industries provided virtually no treatment of their wastes. But there was little agreement on exactly which nutrients were the problem, which sources should install controls, what performance levels were required, and who was to pay for the treatment equipment. Further, there was no legal requirement to do anything.
Nevertheless, progress was made. By the early 1970s, it became clear that phosphorous was the chemical of concern, performance targets were identified, the federal governments on both sides of the basin committed to action, and the U.S. passed the Clean Water Act, creating legal obligations and funding programs to share the cost.

As the nutrients were cleaned up, and the system began to return to its normal trophic condition, attention was turned to the toxic pollutants whose effects had been masked by eutrophication. Most of the effects were subtle, non-lethal impacts, but disturbing nonetheless. Gulls and other water birds were born with crossed bills. Fish had tumors, lesions, and eroded fins.

The control of toxics was complicated by some of the same factors that made controlling nutrients difficult: which compounds to control was unclear, acceptable levels (if any) were not known, and how these compounds interacted in the environment was not known. What did exist in the U.S. portion of the basin was a set of statutes that could drive the elimination of these materials from water, air, and land sources. By nearly any measure, the amount of toxic chemicals released into the basin and their effects in the environment have been greatly reduced.

Future Needs and Opportunities to Restore Ecosystem Health

The overarching challenge facing the Great Lakes ecosystem is to create governance systems that support its recovery. The behaviors to be governed are different than those we have had success with in the basin. Government programs and private initiatives have slowed, and in some cases eliminated, near-field pollution. Government programs have successfully kept the fishery on life support. But these are reactions to threats, not actions to restore the ecosystem. Reactive government programs ossify. They are suited to “rifle shot” responses to clear and temporary problems. Restoration governance needs to support action in three areas, outlined below.

Restoring Natural Flows

First, the best restoration opportunity within the basin is to restore natural flow regimes to tributaries and coastal areas of the lakes. As discussed earlier, the tributaries need to re-connect to the open lakes, and also to the lands they drain. So-called non-point source pollution is not pollution in the classic sense – materials added to water. It is more usefully described as a result of changed flow regimes. Water moves across the land, into and through streams more quickly after rain events in altered landscapes. The high energy of moving water moves sediments more quickly and farther than it would if the landscape had not been altered. But the sediments being moved are not typically new materials – they are existing bed load being displaced in time and space. Bed load – in stream sediments – is not a pollutant. A pollution control framework will not succeed in restoring ecological health to these systems.
What is needed is a set of policies that value natural flows and support their restoration. To get there, we first need to encourage what I call “environmental hydrology,” the science of the movement of water and its role in ecological processes. To my mind, this is no different than how “environmental chemistry” emerged in the late 1970s – when scientists began to focus on how chemicals behave in ecological systems and think differently about chemistry as a result. When hydrologists routinely think of water budgets in biologically relevant time frames – hours, days, weeks and months – in addition to typical annual water budgets, environmental hydrology will have arrived.

Environmental hydrology will need to guide how we use land and water. The removal of dams that no longer have a useful purpose is one tangible step. The re-operation of hydroelectric facilities is another. Freeing waterways to use their floodplains is another flow restoration strategy. Agricultural areas can be tapped to increase the ability of their lands to recharge aquifers and slow the runoff of rain and snowmelt to surface waters. New residential and commercial construction needs to be encouraged, and perhaps required, to improve existing flow regimes.

Perhaps most importantly, the world will hold us to our own standards of water use. The Great Lakes hold nearly one fifth of the world’s supply of fresh water. As this becomes a scarce commodity throughout the world, increased pressure will be brought upon the basin to meet human needs, or market demand. International trade rules allow the governments of Canada and the U.S. to stop the sale of water only if it is done to conserve exhaustible natural resources and if the same rules apply to both domestic and international consumption. As it stands, water in the Great Lakes is presently free for the asking. If we are not able to export environmentally sensitive ways of using water and protecting supplies, we may be forced to export the water itself.

**Halting Biological Pollution**

A second need for the Great Lakes is to halt the biological pollution of the ecosystem. This is a need that differs in two fundamental respects from the flow restoration opportunity described above. First, it is a need to stop an ongoing insult. Second, it must be addressed at a global scale. The organisms appearing in the Great Lakes, as well as other aquatic and marine ecosystems, are coming from places half way around the world.

Biological pollution is different in character from chemical pollution. The most persistent chemical pollutants in the basin are those materials that degrade slowly in the environment. They can become trapped in sediments and re-released over decades to the lakes. Invasive species, on the other hand, never degrade; they in fact expand their numbers and impact over time. They change the biological, and in some instances, the physical and chemical fabric of the ecosystem. Once established, they are virtually permanent features of the ecosystem.

The primary vector for non-native species to enter the Great Lakes is the ballast operations of commercial shipping. Ships carry ballast water to ride low...
in the water, increasing the ships fuel economy and operating safety. Organisms may be sucked into ballast tanks in foreign harbors and released in the basin as the ballast water is pumped out when cargo is taken on. Alternatively, some organisms may be trapped in the sediment in bottom of ballast tanks and released at some later date when those sediments are mixed with ballast taken on in the basin.

Another threat is also presented by ballast operations. In addition to fish, algae and invertebrates, ballast water can contain pathogenic micro-organisms that present a disease threat to humans and other animals. These pathogens are often the result of poor sanitation in the world’s ports. Once added to a ballast tank, these organisms can greatly increase their numbers. Unlike most port cities in the U.S. and Canada, Great Lakes port cities typically use the lakes as drinking water sources. To protect the health of those who drink Great Lakes water, we have a vested interest in improving sanitation in port cities around the world.

The second most important vector for non-native species entering the Great Lakes is the series of breeches in the continental divide that separate the lakes for the Mississippi, Hudson Bay and Hudson River systems. These canal systems have been used by species as entry routes to the Great Lakes. Future public works project should look to restore the ecological separation of these systems, even if we maintain the ability to move goods in these canals. Clear operating standards should be developed to guide the present routine opening of the system to biological pollution.

**Promoting Clean Development**

The Great Lakes are linked to the rest of the planet not only by shipping routes but also by the atmosphere. The atmosphere is quickly becoming the most important pathway for chemical contaminants to enter the Great Lakes basin. Two sources deserve particular attention.

First, the combustion products from coal-fired power plants present a threat to this system. Recently, utility companies in Minnesota and Wisconsin have made commitments to reduce the emissions of mercury. This is an important step. Requirements may yet need to be tightened using the authorities of the U.S. Clean Water Act and Clean Air Act. Similar controls may be required in Canada.

But these sources do not likely pose the greatest long or medium-term threat to the health of the Great Lakes. That threat comes from the desire of Asian peoples to enjoy a standard of living comparable to that enjoyed in North America in the late 1940s. The electrification of China, India, and rural parts of the former Soviet Union is just underway. If they chose the same technology that we did – massive coal burning power plants – the impact will be felt in the Great Lakes because of atmospheric patterns that deposit residues from that part of Asia in the Great Lakes region. Mercury, polynuclear aromatic hydrocarbons, and other toxic materials will concentrate in the lakes. The expansion
of a commercial chemical industry will follow. Persistent, bioaccumulative toxics will also preferentially accumulate in the lakes and their resident biota. We need to promote a cleaner pathway of development than the one we chose. Distributed power, clean combustion, and efficient energy use are all exports that we can and should make.

The second source of concern is the expanding use of persistent, bioaccumulative pesticides in the developing world. DDT/DDE has been traced from the Great Lakes to use in the jungles of Central America. It is used to rid settlements of mosquitoes that spread malaria. A solution to a public health problem in one country is endangering subsistence anglers in another.

Again, these are problems of global scope. As we solve problems of local making in the Great Lakes basin, the lakes are increasingly affected by activities further away in space and time. The most important policy for the Great Lakes is likely to be foreign policy informed by ecosystem science, not domestic environmental policy. These are likely to take the form of aid, assistance and market-making policies, not regulatory policy.

CONCLUSION
This case demonstrates three key inter-related principles. First, that large-scale action that manipulates freshwater ecosystems should not be undertaken without consideration of the ecological impacts of those actions. Every choice has consequences. Some are beneficial, serving to help restore degraded systems. Some are detrimental to the ecological health of the system, but may need to proceed for other reasons. Most choices have elements of both, causing some ecological disruption over some time horizon, but having some positive ecological consequences as well. To govern ourselves effectively, we must be aware of the full range of consequences our choices generate.

Second, ecological consequences are often distant in both space and time from the action(s) that cause them. This case shows how loggers at the end of one century can impact swimmers in the middle of the next. Yet, this lesson cuts two ways. First, it teaches us to be careful about actions that have negative impacts that may not appear immediately, but occur downstream affecting our neighbors or in the future affecting our children. It also reminds us that distant populations matter. The Great Lakes will suffer cumulative adverse impact from the actions of distant peoples. Second, and this is the under-appreciated good news, cumulative positive consequences will also lag the actions that produce them. Seemingly isolated good works, such as restoring wetlands or returning natural flow regimes to tributaries, will generate increasingly positive returns once there is a “critical mass” of such activity. Consciously choosing restorative alternatives – those that create ecological wealth, over sufficiently long time and space scales – will produce synergies that truly make the whole greater than the sum of the parts. This is the nature of systems. Both the distant positive and negative effects need to be considered in governance decisions.
Third, it is necessary to think expansively about the relationship of human populations to freshwater ecosystems. It is tempting, for example, to think of only those humans who live near a lake or river system as the human population that matters. However, ecological systems do not necessarily work that way. While a complete analysis is unlikely to not consider such local populations, those who live far away geographically, or have yet to be born, may be the stakeholders that matter most, and will drive governance action. It depends on what those human populations are doing. Freshwater ecosystems have many different human populations that affect them, and that are effected by them. Usually, simple measures like amount of water consumed, land developed, or pollution produced, are not, by themselves, useful measures of ecological harm. Neither are acres of open space, area of buffer strips, or number of rare species, useful measures of ecological health. The key is to understand the relationship that a series, or set, of human populations has with the ecological system, and which key ecological processes are being compromised or restored to health in that relationship. Such processes can be thought of as master variables and include natural flow regimes, the full complement of native species and functional niches, and a natural chemical regime. We must minimize disruptions to intact, healthy processes, and restore those that have been adversely impacted.

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