Prescription for Great Lakes Ecosystem Protection and Restoration

Avoiding the Tipping Point of Irreversible Changes

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(Endorsements as of May, 2006)

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OVERVIEW

There is widespread agreement that the Great Lakes presently are exhibiting symptoms of extreme stress from a combination of sources that include toxic contaminants, invasive species, nutrient loading, shoreline and upland land use changes, and hydrologic modifications. Many of these sources of stress and others have been impacting the lakes for over a century. These adverse impacts have appeared gradually over time, often in nearshore areas, in the shallower portions of the system, and in specific fish populations. Factors such as the size of the lakes, the time delay between the introduction of stress and subsequent impacts, the temporary recovery of some portions of the ecosystem, and failure to understand the ecosystem-level disruptions caused by the combination of multiple stresses have led to the false assumption that the Great Lakes ecosystem is healthy and resilient.

Because it has taken the Great Lakes four centuries of exposure to these human-induced stresses to get to this point, some argue we have decades to control these and other sources of stress and promote the lakes' recovery.[1] From this perspective, protecting the Great Lakes is not particularly urgent and action can wait until we conduct more studies, while taking small corrective measures when the opportunity or need arises. However, if not addressed with great urgency, the Great Lakes system may experience further – and potentially irreversible – damage.

In large areas of the lakes, historical sources of stress have combined with new ones to reach a tipping point, the point at which ecosystem-level changes occur rapidly and unexpectedly, confounding the traditional relationships between sources of stress and the expected ecosystem response. There is compelling evidence that in many parts of the Great Lakes we are at or beyond this tipping point. Certain areas of the Great Lakes are increasingly experiencing ecosystem breakdown, where intensifying levels of stress from a combination of sources have overwhelmed the natural processes that normally stabilize and buffer the system from permanent change.[2]

Although the specific episodes of ecosystem breakdown have been unpredictable and alarming, few Great Lakes researchers are surprised by these occurrences. A number of papers were published in the 1980s describing stresses in various areas of the Great Lakes, including Lake Erie and shallow embayments in lakes Michigan, Huron, and Ontario. These papers described the symptoms of the Great Lakes ecosystem under distress, and laid the foundation for a conceptual ecological framework for understanding the changes that were occurring at that time. Rapport et al. (1985) discussed ecosystem self-regulating mechanisms (such as responses to invasive species) and the process by which stresses can give rise to early warnings, coping mechanisms, and ultimately lead to ecosystem breakdown if the overall stress is sufficiently prolonged and/or intense. The ecosystem adaptation syndrome discussed in the paper can be used to help formulate a systematic ecosystem approach to environmental management of the Great Lakes. This ecosystem breakdown concept helps explain the scope,

[1] Great Lakes Interagency Task Force, Report to the President on the Implementation of the Great Lakes Executive Order, undated, available at: http://www.epa.gov/glnpo/collaboration/final_rttp_10282005.pdf

[2] This is analogous to discussions of resilience and catastrophic change in ecosystems as presented in Scheffer et al. (2001), whereby assuming alternative stable states are available, sufficient perturbation in any ecosystem can shift it to an alternative (and potentially "unwanted") stable state.

intensity, and speed of the ecosystem changes that have occurred in the Great Lakes since the 1980s.

Examples of ecosystem breakdown or major changes in the lakes include: (1) persistence of the anoxic/hypoxic zone in the central basin of Lake Erie and other stresses in the eastern and western basins; (2) continued symptoms of impairment (including eutrophication) in Saginaw Bay and Green Bay; (3) well-documented rapid disappearance of the once abundant amphipods in the genus *Diporeia* in sediments of large areas of all the lakes (except for Lake Superior), and concomitant food web disruptions; (4) recent declines in growth, condition and numbers of lake whitefish in Lake Michigan and portions of Lake Huron; and (5) elimination of the macrophyte (i.e. rooted plant) community and simplification of the benthic food web, in Sandusky Bay on Lake Erie and Cootes Paradise in Hamilton Harbour on Lake Ontario, due to sediment and other pollutant loads.

The major cause of ecosystem breakdown is the severe damage that has been done to the Great Lakes' self-regulating mechanisms. In the past, healthy nearshore communities and tributaries helped reduce the impact of many stresses on or entering the lakes. Over time, the combined effects of a whole suite of stresses from a variety of human-induced sources have overwhelmed the ecosystem's self-regulating mechanisms. This diagnosis suggests that it is appropriate and necessary to address multiple sources of stress in order to reverse the trend toward widespread ecosystem breakdown. The following is a list of Great Lakes management objectives based on this diagnosis.

- *Restore*

Restore critical elements of the *ecosystem's self-regulating mechanisms*. To the extent possible, reestablish natural attributes of critical nearshore and tributary communities so they can once again perform their stabilizing function. Where full restoration of natural attributes is not possible, improve desirable aspects through *enhancement* of important functions.[3]

- *Remediate*

Remediate abusive practices that create *sources of stress.* Reduce or eliminate physical habitat alterations, pollution loadings, pathways for invasive species, and other stressors or their vectors into the lakes.

- *Protect*

Protect the functioning portions of the ecosystem from *impairment*. Preserve those portions of the ecosystems that now are healthy, and those that can be restored or enhanced, through sustainable development practices within the Great Lakes basin.

- *Measure*

Building on existing efforts, measure ecosystem health through a set of agreed-upon integrative indicators that can serve to assess current conditions and monitor the progress of restoring the lakes.

[3] Establishment of restoration goals obviously needs to acknowledge ecological constraints (e.g., the presence of numerous invasive species – including introduced fish – that are currently important components of food webs) as well as consider other human use objectives (e.g., maintenance of sport fisheries that include introduced species) (see, for example, discussions in Kitchell et al., 2000; Mills et al., 2003; Sproule-Jones, 2003).

The conceptual model here indicates the importance of immediate and sustained action. It advocates using the principles of ecosystem-based management to restore and protect the Great Lakes. Without such action, the lakes could potentially suffer irreversible and catastrophic damage.

SYMPTOMS

Many of the changes the Great Lakes have experienced in response to sources of stress have been documented for decades. Examples of symptoms and sources of stresses to the lakes include:

- Extirpation or major declines in important native species (such as lake trout and deepwater ciscoes) due to overfishing and effects from aquatic invasive species (such as sea lamprey predation on lake trout, and competition with deepwater ciscoes by introduced alewives and rainbow smelt);
- Widespread reproductive failures of keystone, heritage, and other (both native and introduced) fish species, including lake trout, sturgeon, lake herring, coaster brook trout, and Atlantic and Pacific salmon;
- Fouling of coastlines, resulting in beach closings and loss of habitat for fish and waterfowl;
- Toxic contamination of fish, which threatens the health of people, wildlife, and some fish species themselves, and results in fish consumption advisories throughout the Great Lakes and inland lakes and rivers;
- Loss of coastal wetlands, including over 90% of the presettlement wetlands along the Lake Huron/Lake Erie corridor;
- More recent introductions of aquatic invasive species (e.g., zebra and quagga mussels, round gobies and predatory zooplankton such as *Bythotrephes cederstroemi* and *Cercopagis pengoi* (two species of water fleas)) leading to declines in valued/important native aquatic species (including certain plankton, unionid clams and certain native fish species);
- Decreased populations of benthic organisms in many locations, causing decreased health in lake whitefish and with the potential to impact other species; and
- General water quality degradation, associated algal blooms, Type E botulism in fish and waterfowl, and contamination of drinking water (e.g., Johnson et al., 1998; Beeton et al., 1999; IJC, 2000; IJC, 2002; IJC, 2004; Whelan and Johnson, 2004).[4]

[4] In some cases, policies designed to address these stresses have been effective. Most notably, the passage in the United States of the Clean Water Act in 1972 and subsequent amendments initiated the National Pollutant Discharge Elimination System for point sources and resulted in billions of dollars in investments by federal, state, and local governments to upgrade, improve, and extend wastewater collection and treatment systems directly tributary to the Great Lakes; similar scale investments were made in Canada. The ban on the use and manufacturing of certain toxic chemicals, and strict protections put on others, has helped allow key indicator species (eagles, herring gulls) to return to health. However, even with substantial investments over the past three decades, wastewater treatment plants and sewer systems are in need of substantial new capital expenditures for major repairs, upgrades and, in some cases, replacement, and it is clear that local funding alone will not be adequate to the task. In addition, though a subject of research and policy focus for a number of years, nonpoint source pollution – including urban runoff, agricultural runoff, air deposition, and contaminated sediments – continues to be a significant contributor of pollutants to Great Lakes waters.

Historically, these and other symptoms were attributed to six major anthropogenic or human-induced sources of stress to the ecosystems in each lake.[5] The symptoms may appear stepwise like a chain reaction or self-organize in a complex, ecologically degraded manner. Listed in no particular order are those anthropogenic sources of stress: (1) **overfishing** (i.e., extracting larger quantities of fish than the system can sustain naturally); (2) **nutrient loading** (i.e., addition of phosphorus and nitrogen in excess of natural levels, usually via human waste and urban and agricultural runoff); (3) the release of **toxic chemicals** (e.g., mercury, polychlorinated biphenyls (PCBs) and other chlorinated hydrocarbons), including many that are both persistent and bioaccumulative;[6] (4) increased sediment loading as well as other sources of stress associated with **land use practices** (e.g., physical changes including alteration of vegetative land cover, wetland filling, modification of shorelines); (5) introduction of invasive (nonnative) **exotic plant and animal species** (e.g., purple loosestrife, sea lamprey, and zebra mussel); and (6) **hydrologic alterations** in tributary and connecting waterways, diversion and/or alteration of flows through the construction of dams, channels, and canals, alteration of natural drainage patterns (e.g., leading to increased surface water runoff and stream flows in urban areas with increased imperviousness).

Many of the symptoms of stress on the Great Lakes are attributable to a combination of these six sources of stress. Fouling of coastlines and near-shore areas arises from sewage overflows and contaminated runoff. Historically, valued species of fish declined in number or disappeared as a result of overfishing and, to varying degrees, invasive species, lost habitat connectivity, and toxic chemicals. Presently, invasive species and concomitant food web changes as well as lost connectivity of tributary spawning habitat play a larger role in affecting fish populations. Toxic chemical contamination in fish, which also threatens the health of humans and fish-consuming wildlife, is a direct result of historical and current toxic chemical releases. The loss of coastal wetlands stems from changes in land use practices and hydrologic alterations. Changes in water quality are caused directly by toxic chemical, nutrient, microbial and sediment pollution, as well as through actions of some invasive species (e.g., zebra mussels). Invasive species are the most likely principal source of food web disruptions now occurring in the Great Lakes, and are implicated in reproductive failures of some fish species (e.g., walleyes, lake trout, yellow perch, and lake herring) (McDonald et al., 1998; Fielder and Thomas, 2005).[7]

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[5] Although we often speak of a "Great Lakes ecosystem," in most cases each lake basin has its own ecosystem, further divided into sub-basin ecosystems.

[6] In addition to chemicals that have been of longstanding concern in the Great Lakes, increasing attention is being directed at chemicals of emerging concern, including those found in products such as pharmaceuticals, personal care products, and flame retardants. Some of these and other chemicals may act as endocrine disruptors or otherwise alter regulatory systems in biota, and potentially add to the stress caused by toxic chemicals of principal focus in the region.

[7] One example of reproductive effects on salmonids involves the action of the enzyme thiaminase, which transforms the essential vitamin thiamine. In a recent study, lake trout fed diets with substantial amounts of thiaminase (either in bacterial form or with alewives (an introduced species with naturally elevated levels of the enzyme)) produce eggs more susceptible to embryonic early mortality syndrome (Honeyfield et al., 2005).

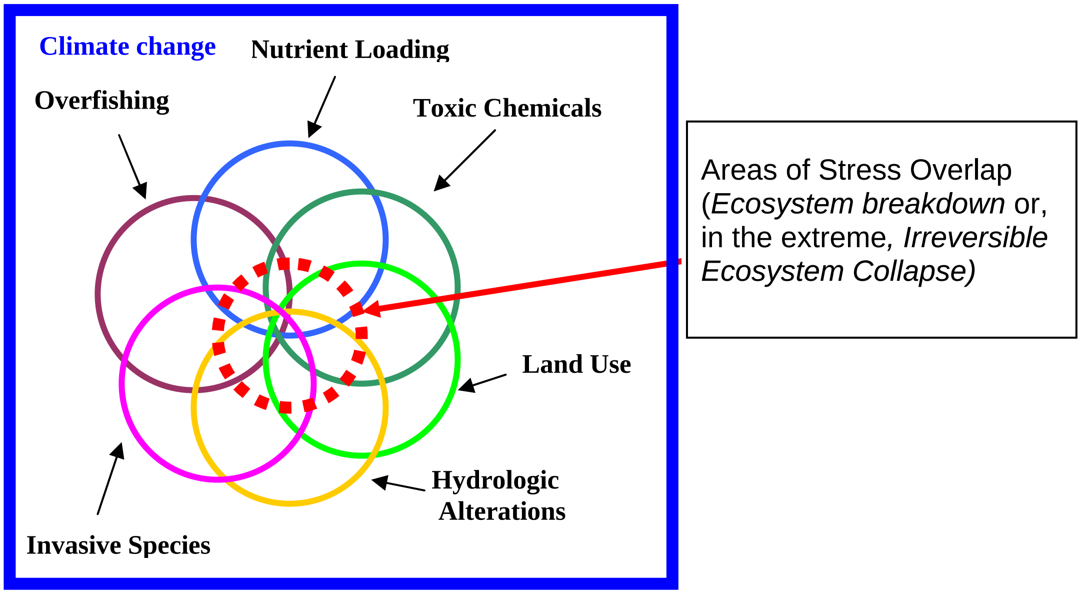
It should be noted that superimposed on these primary stresses are the broader, large-scale changes in global and regional climate. A recent analysis of the potential global warming and regional climate change impacts to the Great Lakes region included declining lake levels and the duration of winter ice, jeopardizing reproduction of some fisheries, and general lake warming that could negatively impact coldwater fish species, favor invasions of warm water nonnative species, and expand the duration of summer stratification and increase the potential for hypoxia ("dead zones") (Kling et al., 2003). These findings were generally consistent with earlier predictions for the Great Lakes in a scenario with a doubling of atmospheric carbon dioxide levels, although the researchers emphasized that the many complex interactions could lead to varied responses in individual ecosystems (e.g., thermal habitat changes in deep stratified lakes vs. shallow lakes and streams) (Magnuson et al., 1997). In addition to these potential compounding factors in the lakes proper, earlier ice breakup and earlier peaks in spring runoff will change the timing of stream flows, while increases in heavy rainstorms may cause more frequent flooding with potential increases in erosion, and additional water pollution from nutrients, pesticides, and other contaminants. While it is difficult to know how these changes will interact with the other six classes of stress identified above, there is little doubt that global warming will add yet another source of stress to the already perturbed Great Lakes ecosystem.

DIAGNOSING THE DISEASE

The Great Lakes ecosystem and the major human-induced sources of stress on it can be portrayed as a series of overlapping circles in a Venn Diagram, as shown in Figure 1 on the following page.[8] For areas where stresses act singly or jointly but not at intense levels, an ecosystem may change adaptively to an unhealthy state of diminished vigor and unpleasant aesthetics but not suffer major transformation to a disorganized critical state. Such a contrast could be analogous to a person feeling sick and redirecting vital efforts to recover at home rather than being taken to a crisis center for surgery or other intensive care. In an ecosystem in which only one stress acts intensely, positive (or reinforcing) or synergistic feedback loops can emerge, leading to a runaway or catastrophic breakdown process. However, such feedback loops are more likely to occur as the adverse effects of a number of stresses interact. The probability of disastrous ecosystemic breakdown appears to increase with the number of stresses acting on and interacting in the ecosystem. Thus, in this conceptual model, the probability of breakdown is likely to be highest at the center of the Venn Diagram where all types of stress act and interact to varying degrees. The prevention of this type of ecosystem breakdown should be the focus of attention in any restoration and protection efforts.

[8] The locations of stresses on the diagram is somewhat arbitrary, as the model is limited to working with stresses that are represented in two dimensions. It is possible that two or more stresses might interact in stronger ways (and others less coherently) that can be represented in the diagram.

Figure 1.



The magnitude (intensity), shape, and degree of overlap of the stresses have varied over time and space. For example, **overfishing** began in the late 1800s and continued into the 20th Century, while **invasive species** had significantly effected the ecosystem by the middle of the 20th Century. Other stresses have had significant effects more locally, such as **nutrient loading** in Green Bay, Saginaw Bay, and the western and central basins of Lake Erie, and **toxic chemicals** in the basin's industrial complexes such as along the Niagara, Detroit and Fox rivers (although due in part to diffuse loadings, many contaminants long ago become more widespread throughout the lakes themselves). In order to address these areas of overlap, there remains the need to better understand the salient features of these areas.

Conceptual Understanding of Ecosystem Stress Adaptation

The nearshore areas are important in the ecosystemic self-organization of the Great Lakes. Before the significant impact of humans (i.e., following European settlement), the nearshore areas were in equilibrium with surrounding areas. There was a healthy abundance and diversity of organisms interacting to various degrees with surrounding areas (from wetlands to offshore), and loads of nutrients and other constituents from land could be assimilated and/or transferred between communities without major disruptions to the functioning ecosystem. With development and industrialization in the Great Lakes, land use changes, increased pollution, and other factors have increased stress on these nearshore areas.

As the types and intensity of stress increased, two things happened. First, inflowing nutrients were shunted to the open waters of nearshore areas where photosynthetic energy fixation then erupted as plankton blooms. The blooms resulted in the loss of many valued, native species of nearshore communities and an increase in other species, native and nonnative, that favor open waters. Second, the entire ecosystem, including community abundance and composition, became unstable and began to undergo wider and more frequent fluctuations. Increased loadings of sediments from watershed runoff, toxic chemical inputs, oxygen depletion (following increased nutrient loads), hydrological alterations and other sources of stress created a hostile environment to bottom dwelling, pollution-sensitive species and to the eggs of most Great Lakes fishes (Rapport et al., 1985; Steedman and Regier, 1987). Some of these changes were concomitant with or followed upon earlier changes to the upper portions of the food web due to a combination of introduction of aquatic invasive species (such as the sea lamprey, rainbow smelt and alewives) and overfishing, leading to extirpation or significant depletions of open water species such as lake trout and deepwater ciscoes (Eshenroder and Burnham-Curtis, 1999).

More recently, the invasion of zebra mussels in Lake St. Clair in 1988 and later arrival of quagga mussels have altered this nutrient flow dynamic in the Great Lakes yet again. Extensive colonization by zebra mussels in nearshore areas of the lower lakes has resulted in the reduction of nutrient and energy supplies to the open waters (Hecky et al. 2004). The extreme filtering capacities of zebra mussels for plankton has transferred energy from the water column to the nearshore benthic areas, and diminished the transport of nutrients via currents to the deeper waters. Also, quagga mussels colonize deeper waters and out-compete other organisms for food resources directly. The increased nearshore retention of nutrients along with clearer water has led to an increase in undesirable species of algae. Organic material filtered by mussels is transformed into biodeposits (pseudofeces and feces) that while serving in part as a food source for some organisms, are not utilized as a food source by many other benthic organisms (see below). In addition, the zebra mussels themselves are undesirable prey for most native Great Lakes fish species, but are readily consumed by invasive round gobies. The introduction and spread of zebra and quagga mussels has not only led to declines in native mussels (Nalepa et al., 1996) and other benthic species (see, for example, Nalepa et al., 1998; Dermott, 2001; Lozano et al., 2001), but has also facilitated the spread of other invasive species (Ricciardi, 2001).

With sufficient cumulative stress (including habitat loss, nutrient loadings, oxygen depletion, and invasive species), the capability of once healthy, resilient, and diverse coastal communities to buffer against natural and human perturbations can be overwhelmed. In essence, the health-sustaining system of the Great Lakes is seriously weakened. Once the resilient capabilities are exceeded the ecosystem organization abruptly and catastrophically changes, resulting in ecosystem breakdown. Under extreme circumstances where the suite of stresses become severely intense, the ecosystem adaptive responses in some cases move into another phase dominated by species that can tolerate and benefit from those sources of stress. The presence of surface scum, mats of fungi, strands of filamentous algae, and surface blooms of toxin-producing algae create this new phase in the water column. This surface association has appeared seasonally in certain bays and in the shallow waters of the Great Lakes, but has had adverse affects on both the nearshore and open water communities.

Scientists throughout the world are documenting the actual and expected damage that the loss of such ecosystem resiliency can cause. In March, 2005, the United Nations issued a final draft of a report endorsed by 1,200 of the world's leading scientists called the Millennium Ecosystem Assessment Synthesis Report (United Nations, 2005). One of the report's conclusions follows:

> **There is *established but incomplete* evidence that changes being made in ecosystems are increasing the likelihood of nonlinear changes in ecosystems (including accelerating, abrupt, and potentially irreversible changes), with**

> **important consequences for human well-being.** Changes in ecosystems generally take place gradually. Some changes are nonlinear, however: once a threshold is crossed, the system changes to a very different state. And these nonlinear changes are sometimes abrupt; they can also be large in magnitude and difficult, expensive, or impossible to reverse. (Emphasis in original, endnote omitted) (United Nations 2005)

The Millennium Ecosystem Assessment Synthesis Report conclusions are repeated in a "Scientific Consensus Statement for Marine Ecosystem-Based Management" recently adopted by over 200 scientists (Scientific Consensus 2005). The scientists signing the Consensus Statement on marine environments (as do the scientists endorsing this prescription paper) emphasize the need for a holistic, ecosystem-based management approach, including the dangers of managing only individual sources of stress or specific species:

> **Ecosystems can recover from many kinds of disturbance, but are not infinitely resilient.** There is often a threshold beyond which an altered ecosystem may not return to its previous state. The tipping point for these irreversible changes may be impossible to predict. Thus, increased levels of precaution are prudent as ecosystems are pushed further from pre-existing states. Features that enhance the ability of an ecosystem to resist or recover from disturbance include the full natural complement of species, genetic diversity within species, multiple representative stands (copies) of each habitat type, and lack of degrading stress from other sources. (Emphasis in original.) (Scientific Consensus, 2005)

While the same ecological principles cited for the world's oceans apply to the Great Lakes, the lakes may be less able to cope with stress than typical coastal marine environments. Ecosystems that have evolved in relatively unstable environments, such as those in the intertidal ocean communities that are exposed to frequent tidal movements and that have great diversity of species, are more likely to resist and/or recover from moderate human-induced stress. In contrast, the Great Lakes ecosystem is a relatively young (< 12,000 years), mostly oligotrophic system that has evolved in a relatively stable environment with a more limited number of species. The lakes represent a more closed system than coastal ocean waters, and respond more slowly to contaminant loadings (with longer hydraulic flushing times than coastal areas). Because of these differences, the lakes may be rapidly altered by even moderate stresses such as changes in water quality, system hydrology, or the introduction of invasive species (Rapport and Regier 1995). Thus, action to avoid the tipping point for irreversible ecosystem changes in the Great Lakes may be even more urgent than for coastal marine environments.

Great Lakes Ecosystem Response to Loss of Resiliency

In the Great Lakes, nonlinear changes are no longer a future threat – these types of changes are taking place now. While in some areas some indicators of ecosystem health have continued to improve over the past decade, other large areas in the lakes are undergoing rapid changes where combinations of effects of old and new stresses are interacting synergistically to trigger a chain reaction process of ecosystem degradation. The rapidness of this chain-reaction process, seen over the past five to fifteen years and involving sudden and unpredictable changes, is unique in the Great Lakes' recorded history. Some of the most significant changes observed include the radical food web disruptions occurring in Lakes Michigan, Huron, Erie, and Ontario; the reoccurrence of the anoxic/hypoxic zone in the central basin and other impairments (such as blooms of *Microcystis* cyanobacteria in the western basin) in Lake Erie; and ongoing problems related to invasive species and other impairments in Lake Ontario. A profile of components of these potentially devastating ecosystem responses follows.

Profiles of Ecosystem Breakdown

Food Web Disruptions

Invasions of aquatic nonnative species in the Great Lakes have been a concern since the mid-twentieth century when sea lamprey, combined with other sources of stress, decimated populations of lake trout in the Upper Great Lakes. Facilitations between a series of invasive introductions have resulted in a synergistic effect leading to significant alterations of critical ecosystem processes in the Great Lakes. For example, reductions in lake trout and other predator species due to sea lamprey predation in Lakes Michigan and Huron paved the way for explosive increases in the populations of other invaders (e.g., alewife and rainbow smelt) which, in turn, competed with and preyed upon native forage species (Holeck et al., 2004).

More recently, researchers have documented a dramatic decline in abundances of the amphipod *Diporeia* in sediments of Lake Michigan. *Diporeia* is a critical component of the food web, important in the diets of many fish species. Historically, it has been the dominant food source for species such as slimy and deepwater sculpin, bloater, and lake whitefish. In the early 1980s average abundances of *Diporeia* in bottom sediments from Lake Michigan were as high as 12,200 individuals/m^2. However, *Diporeia* numbers began declining by the early 1990s, and by 2000 became severely depleted from sediment samples from Lake Michigan in much of the southern and northern portions of the lake, in some cases disappearing altogether (Nalepa et al., 1998; GLERL, 2003).

Populations of other macroinvertebrates have declined significantly in Lake Michigan as well. Oligochaete worms and fingernail clams showed declines in parallel with those of *Diporeia* in nearshore areas from 1980 – 1993 (Madenjian et al., 2002). While researchers have not been able to establish a direct link, they have associated the decline of *Diporeia* with increases in the abundance of the nonnative zebra mussel in Lake Michigan beginning in 1989. *Diporeia* and other benthic organisms depend on diatoms and detritus from other phytoplankton as a primary source of food, the same source of energy that zebra mussels utilize (Nalepa et al., 1998). Recent research indicates that the loss of amphipods is having serious consequences for the fish of Lake Michigan, including whitefish (Pothoven et. al., 2001), sculpin and bloater (Hondorp at al. 2005), and alewife (Madenjian et al., 2002). Evidence also indicates that similar food web disruptions are occurring or have already occurred in Lakes Huron, Erie and Ontario (e.g., Nalepa et al., 2003; Dermott and Kerec, 1997; Lozano et al., 2001).

Lake Erie: Re-emerging Problems and New Threats

For the Lake Erie ecosystem, cautious optimism about restoration was expressed in the early 1990s as the result of reductions in phosphorus loadings, improved dissolved oxygen levels in the bottom waters of the central basin, and increased fish populations (Markarewicz, 1991). However, while improvements have continued by some measures (e.g., increased water clarity, establishment of rooted aquatic plants), other impairments have persisted and/or increased in intensity in recent years. For example, recent data indicate that since the early 1990s springtime phosphorus concentrations have increased, summertime dissolved oxygen levels in Lake Erie's central basin have decreased, and walleye numbers have begun to decline (IJC, 2004). Lake Erie nutrient loads and cycling, oxygen demand, dissolved oxygen levels and related issues have been the subject of a number of studies in recent decades, and it has been recognized that a combination of factors (including physical factors such as thickness of the bottom water layer, or hypolimnion) can affect deeper water dissolved oxygen levels.[9] Because of the number of factors involved, it is likely that no single factor explains the more recent periods of hypoxia (low oxygen conditions) in the central basin. Factors that could be influencing the persistent development of central basin summertime hypoxia include climate change and altered weather patterns (e.g., changes in temperatures and timing and intensity of storm events), changes in nutrient loadings (in particular from nonpoint sources – some data show increased phosphorus loadings from Ohio tributaries in the past decade), and altered internal cycling of phosphorus in response to the presence of zebra and quagga mussels (e.g., IJC, 2004; U.S. EPA and Environment Canada, 2004).

Avian botulism is another feature of the stress complex in Lake Erie (with cases also observed in Lakes Ontario and Huron), leading to episodic summertime die-offs of fish and fish-eating birds. The die-offs (which have included freshwater drum and birds such as common loons (*Gavia immer*) and red-breasted mergansers (*Mergus serrator*)) are linked to the generation of a neurotoxin produced by the anaerobic bacterium *Clostridium botulinum*. While the mechanisms leading to the outbreaks remain to be confirmed, the botulism toxin has been found in dreissenid mussels and invasive round gobies (a principal predator of zebra mussels), leading to the hypothesis that round gobies are transferring the toxin from zebra mussels to organisms higher in the food web (Domske, 2003; Ricciardi, 2005).

Another stress in Lake Erie is the return of blooms of the blue-green algae (or cyanobacteria) *Microcystis*. In addition to being a low quality food for other aquatic species, these algae can produce the microcystin toxin, which at sufficient levels can be harmful to fish, wildlife and humans. *Microcystis* are selectively expelled during feeding by zebra mussels, and thus zebra mussel colonization appears to be facilitating the re-emergence of these problem blooms (Vanderploeg, 2002). Another problem is the increasing frequency of algal mat development in nearshore areas (in particular in the eastern basin) by the filamentous green alga *Cladophora*. Blooms of this alga, which impair recreation and otherwise detract from beach aesthetic value, are linked to nearshore hypoxia/anoxia (U.S. EPA and Environment Canada, 2004).

Yet another significant potential threat to the ecosystem of Lake Erie and the other lakes is the presence of Asian carp in waters near the lakes. Several of these species have been imported to the southern U.S. to control unwanted organisms found in aquaculture facilities, and in some cases have escaped into the wild. While several individual Asian carp have been caught in Lake Erie, there are no established populations in Lake Erie or any of the other Great Lakes. However, at least two of the species have migrated up the Mississippi and Illinois Rivers and are within several miles of Lake Michigan. If the fish (which are planktivores and can range up to 40 kg) manage to breach barriers (such as the electric barrier on the Des Plaines River in Illinois), enter the Great Lakes, and become established, they could cause

[9] See for example Kay and Regier (1999) (and related papers in the State of Lake Erie volume) and Charlton (1987), Rosa and Burns (1987) and other papers in the same issue of the Journal of Great Lakes Research.

significant impacts on the ecosystem through competition with other fish that feed on plankton (U.S. EPA and Environment Canada, 2004).

Other emerging or ongoing symptoms of stress in Lake Erie include the continued presence of invasive species (including round gobies and quagga mussels), rising water temperatures, limited shallow water habitat due to hydromodified shorelines on the southern shore (in particular in the western basin), continuing presence of toxic chemicals (e.g., PCBs and persistent pesticides) leading to fish consumption advisories, and findings of pharmaceuticals, hormones and other chemicals of emerging concern in the Detroit River (IJC, 2004; U.S. EPA and Environment Canada, 2004).

Ongoing Impairments in Lake Ontario

Lake Ontario is also continuing to struggle with multiple sources of stress. While *Diporeia* declines have been reported since the 1990s following invasion by zebra mussels, as previously noted, the invasive quagga mussels have contributed to further alterations of the benthic community over broader areas in the lake. Other species that have invaded Lake Ontario in the past 10-15 years, with the potential to out-compete other native species, include the amphipod *Echinogammarus ischnus*, the New Zealand mud snail (*Potamopyrgus antipodarum*), and the predatory zooplankton *Cercopagis pengoi* (or fishhook water flea). The combination of a number of stresses over the past two decades (including oligotrophication, invasion by zebra and quagga mussels, fishery management practices, and climate change) has significantly altered the Lake Ontario fish community, with declines in alewife, native sculpin and whitefish, and increases in some native species associated with lamprey control (Mills et al., 2003). In addition, as with the other Great Lakes, numerous fish consumption advisories remain in place for Lake Ontario, including for PCBs, dioxins, mirex/photomirex and mercury (U.S. EPA, 2005; Ontario MOE, 2005).

PRESCRIPTION FOR RECOVERY

A number of management efforts (at local, state, national, and binational levels) directed at protecting and restoring the Great Lakes over the past three-plus decades have been developed and implemented, and there have been a number of successes. Sea lamprey control efforts starting in the 1950s have been relatively successful at controlling populations of this species, which has taken a significant toll on populations of lake trout and other native fish. Binational efforts following the signing of the Great Lakes Water Quality Agreement (GLWQA) in 1972 resulted in lowering of phosphorus loads to the lakes and improvements in a number of water quality indicators (in particular in the more heavily (nutrient) impacted lower lakes). Subsequent efforts under the GLWQA directed at toxic chemical contamination in Areas of Concern (AOC) (through Remedial Action Plans (RAPs)) have made some progress in addressing contaminated sediments, with two of 43 AOCs delisted. Implementation of Lakewide Management Plans (LaMPs) has also proceeded in recent years, with a number of efforts underway through the LaMP process in each lake to address numerous beneficial use impairments.[10] Other efforts have been ongoing over the past decade to address specific problems in the lakes or basin, such as the Canada–U.S. Binational Toxics Strategy (addressing mostly persistent, bioaccumulative, toxic (PBT) chemicals) and the Great Lakes Panel on Aquatic Nuisance Species. In addition, the development of indicators of ecosystem health has been conducted through the State of the Lakes Ecosystem Conference (SOLEC) process.

The complexity of the jurisdictional management for the Great Lakes has long been recognized, involving management by two federal governments, eight states and two provinces, Native American and First Nation tribes, municipalities, as well as institutions such as the International Joint Commission, the Great Lakes Fishery Commission, and the Great Lakes Commission offering policy and management guidance. Challenges in implementing programs to protect the Great Lakes have been highlighted in recent reports, including a 2003 U.S. General Accounting Office (GAO) report. The report noted there were 148 federal (U.S.) and 51 state programs funding work on environmental restoration within the Great Lakes basin; a smaller number of federal programs (33) were focused specifically on the basin. The report also noted the lack of any overarching approach to coordinate program activities in support of Great Lakes restoration, as well as the lack of a coordinated monitoring program to determine basinwide progress toward meeting restoration goals (U.S. GAO 2003).

Indeed when faced with a particularly damaging human perturbation in the Great Lakes, our corrective response has generally been to focus on a particular cause of stress and not on the integrated sources of stress that allowed it to occur. For example, when excessive nutrients and associated algal blooms impaired Lake Erie, we focused on the major point sources of phosphorus that fed the algae and lead to oxygen depletion. For a short period, we dampened down that perturbation. However, now that similar degraded conditions have reappeared, we are uncertain if such conditions are due to insufficient control of excessive nutrients, are caused by invasive species, or the result of a combination of stress sources not effectively addressed when the problems were first identified. Compounding the issue, the Great Lakes ecosystem's adaptive responses, transforming into undesired, unhealthy states, seem to be increasing in a dramatic way, in particular due to the uncontrolled introduction of new invasive organisms that out-compete native species whose natural habitat has been severely degraded in a number of areas. In spite of some efforts at addressing invasive species introductions (such as ballast water exchange requirements in the Non-Indigenous Aquatic Nuisance Species Prevention and Control Act of 1990, which do not affect the large majority of ships entering the Great Lakes declaring "no ballast on board" but which in fact may contain residual ballast water), the rate of introduction of new aquatic invaders has remained high over the past 15 years, averaging over one new species every eight months since 1970 (Ricciardi 2001).

Two broad approaches for addressing Great Lakes problems by the policymaking and management communities are treating each symptom, or treating the disease. In addressing each perturbation individually, for example, one would look for approaches to control the spread of zebra or quagga mussels, approaches for reducing polluted runoff, and strategies for addressing existing contaminants and chemicals of emerging concern. Conversely, the Great

[10] For Lake Huron, the lakewide effort is the Lake Huron Binational Partnership, which is not nominally a LaMP.

Lakes community can address the unacceptable adaptive changes in the lakes by focusing attention on the multiple sources of stress that have led to wide-scale disruption of essential nearshore/tributary processes. While recognizing the difficulty in addressing a number of individual stresses (e.g., many years of efforts at suppressing sea lamprey populations), we believe focusing on the multiple sources of stress will lead to the best possible policymaking for and management of the Great Lakes ecosystem.

As we focus on multiple sources of stress, several critical ecosystem objectives should be maintained: (1) restore and enhance the self-regulating mechanisms of the Great Lakes by focusing on the health of key geographic areas. This includes major tributaries and key nearshore areas; (2) to the extent possible, remediate existing and prevent major new perturbations (e.g., stop the introduction of new invasive species and pollutants); (3) protect existing healthy elements by adopting sustainable land and water use practices in the basin that maintain the long-term health of the Great Lakes ecosystem and associated benefits; (4) better monitor ecosystem health and the progress of restoration and protection efforts.

Steedman and Regier (1987) outlined and defined a set of components for Great Lakes ecosystem rehabilitation and those definitions have been modified to formulate the following suggested four primary management objectives for the Great Lakes.

1. **Restore and Enhance Critical Nearshore Areas, Tributaries, and Connecting Channels**

   The ecosystem-based conceptual model should be applied to identify specific geographic areas where the combination of individual sources of stress have contributed or are likely to contribute to the degradation of the nearshore/tributary areas. These are areas where ecosystem breakdown is occurring or is likely to occur, and where action is most likely to restore resiliency to the Great Lakes. These consensus–targeted areas for coordinated restoration and protection efforts may well include those locations already identified as Areas of Concern by the International Joint Commission (expanded geographically to ensure they include the major sources of stress) as well as nearshore/tributary areas that are now showing symptoms or vulnerability to multiple sources of stress. This may require increased institutional focus (including increased emphasis within LaMP efforts) on these nearshore areas. The goal should be to reestablish the natural states critical to nearshore and tributary communities so they can once again perform their stabilizing function, or, if that is not feasible, enhance critical elements that play a role in stabilizing the communities.

2. **Remediate Basinwide Sources of Stress**

   Some of the major stress sources need to be managed through systematic, basinwide approaches. Impacts of stress are often lakewide, if not basinwide, and the remedies are not linked to a limited geographical area. Basinwide stress reduction recommendations include:

   - Support research on control of existing invasive species (e.g., round gobies, zebra and quagga mussels), and to the extent they are identified, implement any control measures
   - Prevent the introduction of new invasive species.

- Mitigate existing negative impacts and prevent significant future human alterations of tributary hydrology and Great Lakes shoreline structure. This can include promoting connectivity of habitat (such as wetlands or free-flowing rivers) important for many species.
- Reduce loadings of nutrients, sediments/dredged material, toxic chemicals, and microbial pollution to the Great Lakes and tributaries from all sources, including addressing continued development pressures and potential for increases in polluted runoff.

Actions such as these will be critical in preventing new perturbations as well as enabling the recovery process. Addressing nonnative species introductions is a key issue. Unlike chemical pollution (except in extreme cases of local pollution), nonnative species, if established, can be extremely difficult to control and have the potential to engineer the ecosystem to a significantly altered state.

3. Protect Healthy Functioning Elements

Sustainable development practices within the Great Lakes basin are required to preserve those portions of the ecosystem that now are healthy, and those that can be restored or enhanced. Recovery of healthy nearshore communities and tributaries, once begun, must be maintained; the conditions that caused the impairments in the first place must be addressed. Watershed-based approaches to land use management provide the best opportunity to minimize negative impacts on the surface water and groundwater essential to the sustainability of the Great Lakes ecosystem. Actions should support and expand activities that employ holistic, watershed-based approaches to land and water use decisions.

4. Monitor Ecosystem Health

Monitoring the ecosystem response through an agreed-upon set of integrative indicators will be an extremely important part of any Great Lakes restoration effort. This effort should build on ongoing efforts such as the development and application of SOLEC indicators. Major changes in the ecosystem are occurring while many of the indicators that governments have traditionally used to measure Great Lakes health (water clarity, ambient water pollution levels, and certain contaminant levels in wildlife) are actually improving. Because nonlinear changes, such as those the Great Lakes are currently experiencing, may confound expected relationships between sources of stress and the lakes’ response, traditional indicators may not be adequate descriptors of the health of the ecosystem and may not be useful in predicting future conditions. While some type of consensus on indicators is desirable, given the dynamic nature of the system and our understanding of it, flexibility must also be included in the development and use of indicators.

Certain features of the ecosystem appear to be particularly responsive to the seven sources of stress (including climate change) identified above. Emblematic species such as certain fish-eating birds and populations and reproductive health of key fish species (such as lake trout, lake herring, walleye, yellow perch, and lake sturgeon) as well as wetland sub-ecosystem complexes should clearly be part of any monitoring program. In addition, monitoring should include a strong human health component, in particular involving tribal/First Nation communities and other populations heavily dependent on Great Lakes fisheries and other resources. There have been varying degrees of research on integrative indicators of ecosystem integrity with most effort focused on emblematic species and wetland complexes. Some evidence suggests smaller organisms at the bottom of the food chain respond more quickly to change, and thus monitoring micro- and macro-invertebrates might well reveal the earliest signs of ecosystem disruption and/or recovery (Odum, 1985).

A key issue for any monitoring network is the ability for rapid detection and identification of new threats, in particular aquatic invasive species. This is particularly important given the difficulty in controlling invaders once established, and the significant economic costs and ecological disruption nonnative species can cause (Pimentel et al., 2000). Use of predictive tools based in part on an understanding of existing invasions can assist in monitoring for potential invasive species (Ricciardi, 2003).

SUMMARY

The health of the Great Lakes ecosystem is in jeopardy. While a number of remediation and other activities have been pursued through the years to address Great Lakes problems, additional actions are urgently needed to restore system elements, particularly in critical nearshore/tributary zones where a chain reaction of adaptive responses to a suite of stresses may be leading to catastrophic changes: ecosystem breakdown and potentially irreversible ecosystem collapse. Without at least partial restoration of these areas, the negative symptoms being observed in the Great Lakes will likely intensify and could degrade irreversibly. Concurrently, actions are needed to control or eliminate sources of basinwide threats to the essential biological, physical, and chemical components of the Great Lakes' ecosystem stability and health. Finally, large areas of the Great Lakes basin waters remain relatively healthy and productive and they provide a wide range of benefits to the people of the region. Protecting the remaining areas from further stress is significantly more cost-effective than attempting restoration after damage has occurred. In summary,

- Historically, when faced with a particularly damaging ecosystem impact, policy responses have focused on particular symptoms and not on the integrated sources of stress that cause these symptoms.
- To increase the effectiveness of policy and on-the-ground restoration, sources of stress and, especially, interactions between those sources need to be explicitly considered.
- One way to prioritize efforts is to focus on specific geographic areas that have experienced ecosystem breakdown and develop efforts to address the multiple sources of stress that have contributed to these impacts.
- Some major sources of stress to the Great Lakes have broad implications and need to be addressed basin-wide since the sources (and their impacts) are not always limited to single locations.
- Watershed-based approaches offer the best opportunity to protect existing basin waters by establishing sustainable land and water use development practices.

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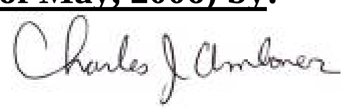
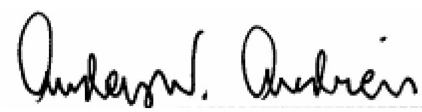


Dr. Charles Amlaner
Professor of Physiology and Behavior
Chairperson,
Department of Ecology and Organismal Biology
Indiana State University



Anders Andren, PhD.
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Joseph Atkinson
Professor
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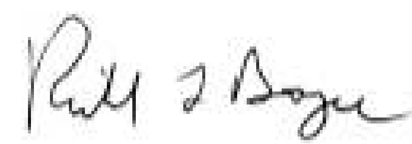

Richard L. Boyce
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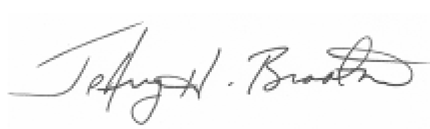

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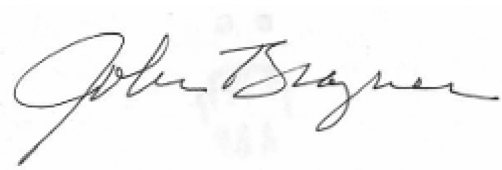

John Brazner
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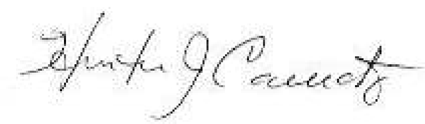

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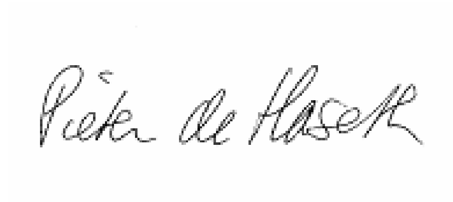

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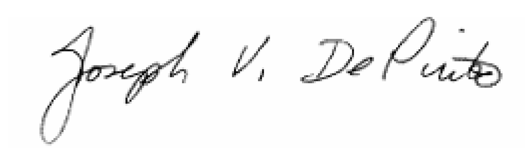

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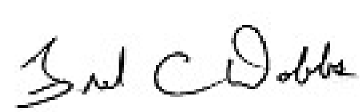

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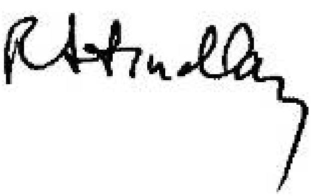

Rick Findlay
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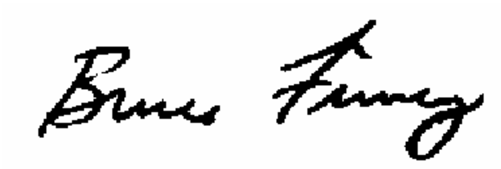

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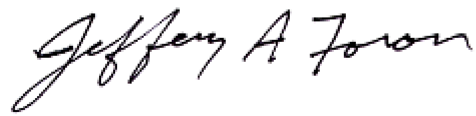

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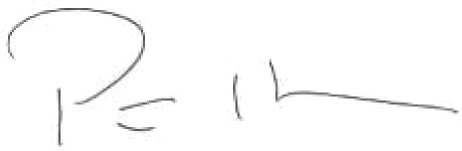

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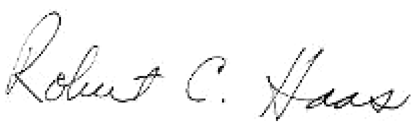

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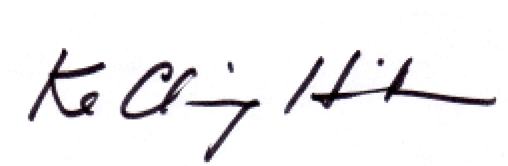

Ke Chiang Hsieh
Professor, Department of Physics, The University of Arizona

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Laura L. Jackson
Professor of Biology
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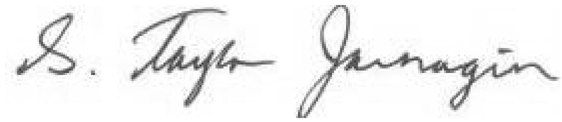

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Barbara J. Javor, Ph.D
Consultant
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Consultant, Environmental
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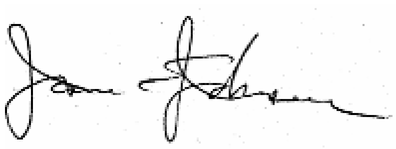

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Station Manager
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Eugenia Kalnay
Distinguished University Professor
Department of Meteorology
University of Maryland

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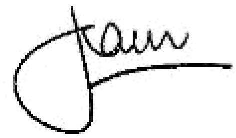
Professor of Biology, Boston University
Marine Program, Department of Biology



Jagjit Kaur, Ph.D.
Associate Scientist
CH2MHILL

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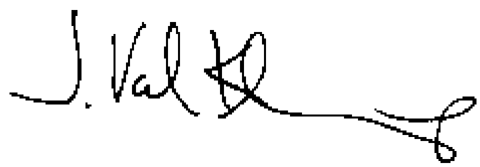
Terry Kinzel, M.D., FACP
Associate Chief of Staff for Geriatrics &
Extended Care, VAMC



Val Klump
Director, Great Lakes WATER Institute
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Gail Krantzberg
Professor and Director
Center for engineering and Public Policy
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Irvin Lindsey
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Catherine Masson
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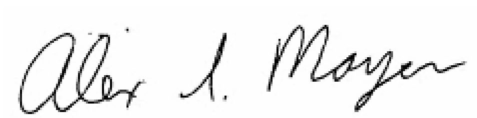

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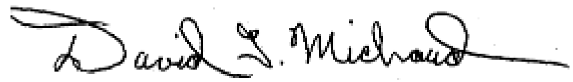

Dave Michaud, Principle Environmental Scientist, Wisconsin Energy Corporation

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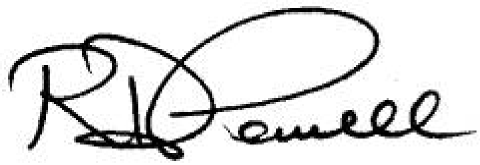

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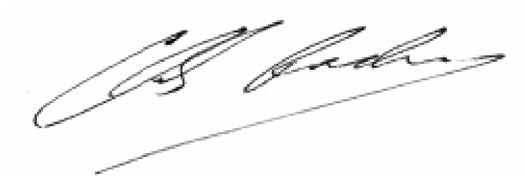

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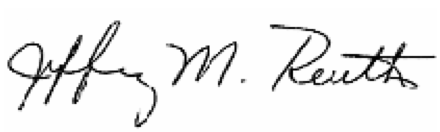

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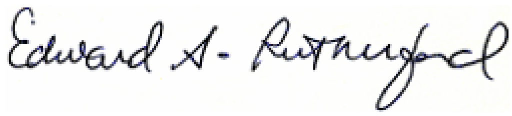

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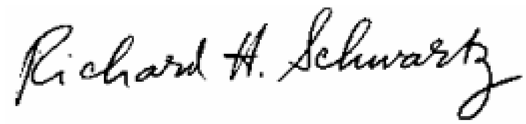

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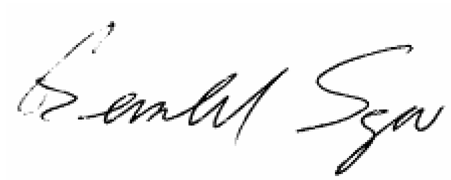

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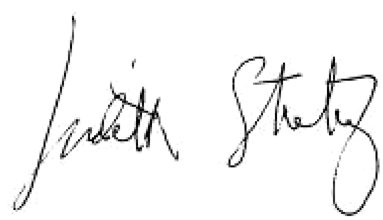

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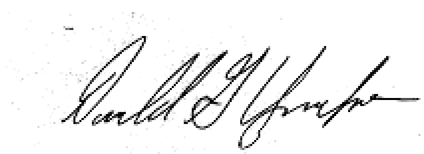

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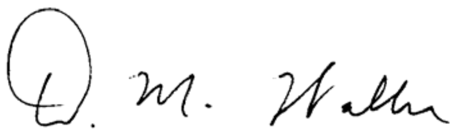

Don Waller
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Leroy S. Wehrle
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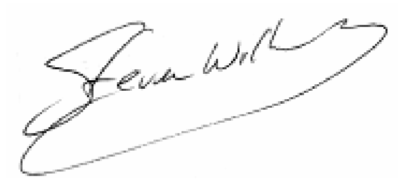
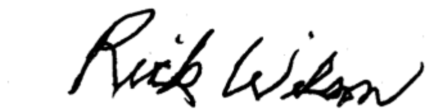
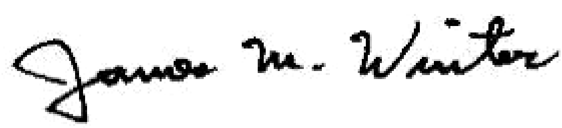
Signature Not Available
Julie L. Whitbeck
Assistant Professor – Research,
University of New Orleans



Steven Wilhelm, Ph.D.
Associate Professor
University of Tennessee



Rick Wilson
Coastal Management Coordinator
Surfrider Foundation, CA



James M. Winter
Professor Emeritus
Wentworth Institute of Technology, MA

Signature Not Available
Michael Wollman
Professor Emeritus of Electrical Engineering Cal Poly, CA

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Donald J. Wuebbles
Executive Coordinator, School of Earth, Society, and Environment
Professor, Department of Atmospheric Sciences, University of Illinois