Conceptual Frameworks and Great Lakes Restoration and Protection: A White Paper

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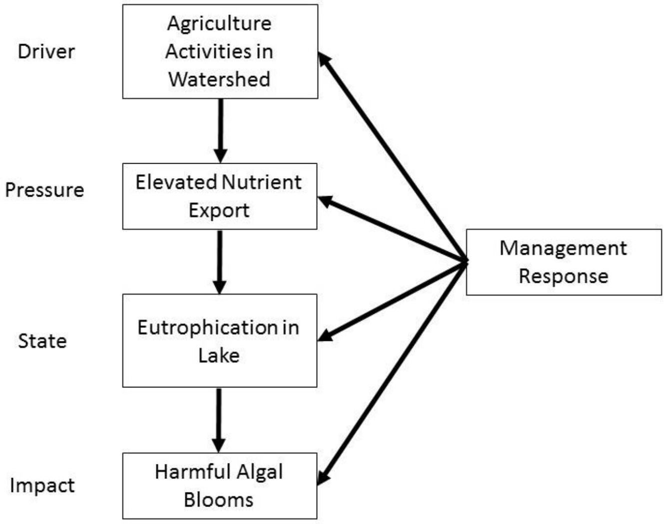

Conceptual Frameworks and Great Lakes Restoration and Protection: A White Paper

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In Memoriam

We honor the legacies of Dr. Alfred Beeton (1927 – 2019) and Dr. Jonathan Bulkley (1938 – 2019). Dr. Beeton was a leading Great Lakes researcher for decades, with early work focused on Lake Erie eutrophication and subsequent scientific leadership positions in both government and academia. Dr. Bulkley combined interest in science and technical issues and policy in over four decades' interdisciplinary research, education and outreach work at the University of Michigan. Both individuals were co-authors of the original *Prescription for Great Lakes Ecosystem Protection and Restoration* report which served as inspiration for this effort.

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Cover images: Top: Precipitation runoff from agricultural field (Natural Resources Conservation Service); Bottom: MODIS image of Great Lakes (NOAA/Great Lakes Environmental Research Laboratory).

Table of Contents

Executive Summary

The Great Lakes have been subjected to numerous stressors through the decades. A 2005 white paper (the "*Prescription*" report) highlighted the multiple stressors, introduced a simple conceptual model of stressor interactions, and recommended several approaches for addressing the stressors. Conceptual frameworks or models of ecosystems describe and visualize how these systems are structured and their component parts interact. They are especially useful in ecosystem restoration and protection work, as they can show how the major stressors interface with system attributes, allowing practitioners to 1) understand interactions in the biophysical and social arenas; 2) prioritize parts of the system where restoration investments may have the greatest impact; 3) identify where research gaps exist; and 4) generate new hypotheses about processes and effective intervention, among other benefits. While conceptual frameworks have been used to varying extents in restoration programs, projects, and research efforts in the Great Lakes region, it is not clear they have been used in planning and implementation to the same extent as in other large aquatic ecosystems. Particular programs where greater integration of conceptual frameworks could be fruitful include 1) the U.S. Great Lakes Restoration Initiative and 2) the Canadian Great Lakes Protection Initiative, and 3) the binational Lakewide Action and Management Plans.

In order to inform potential increased use of conceptual frameworks in Great Lakes restoration programs, the National Wildlife Federation (including a Steering Committee) organized a 2018 summit of 22 natural and social scientists sponsored by the National Oceanic and Atmospheric Administration Cooperative Institute for Great Lakes Research at the University of Michigan. The general objective of the summit was to identify one or more conceptual frameworks that could aid in restoration and protection planning in the Basin, building off of ideas in the 2005 *Prescription* report. This white paper provides an overview of conceptual frameworks, their characteristics, the extent to which they have been used previously in the region, a proposed general framework, and brief discussion on related issues, including governance structure and tying to decision support systems.

We determined that useful conceptual frameworks should have clearly defined terms, an appropriate level of complexity, scalable, explicitly identified management responses and human dimensions, and should be easily communicated to broader audiences. The general framework proposed for consideration in the region follows a hierarchical driver-pressure-state-impact-response model, which in turn would be applied to each lake and then to smaller areas (e.g., bays or connecting channels), as appropriate. Each diagrammatic model would have accompanying narrative material with references, allow for quantitative process-based models to be incorporated, and be tied to a decision support system. Regarding the process to formally develop and implement such models, we recommend that an intergovernmental or academic entity organize expert workshops to explore conceptual frameworks in greater depth, drawing on the general approach we present here. Managers of Lakewide Action and Management

Plans, as well as other agency programs (drawing on stakeholder input), could then refine and use the proposed models. Finally, an outside entity, whether an intergovernmental organization or academic center would be identified to periodically review use of conceptual frameworks in Great Lakes protection and restoration programs, potentially on the triennial cycle currently in place under the Great Lakes Water Quality Agreement.

1. Introduction

The Laurentian Great Lakes encompass approximately one-fifth of the world's surface freshwater. The region is home to over 40 million people, and contains diverse habitats including offshore rocky reefs, coastal wetlands and dunes, one of the world's largest freshwater deltas, and supports hundreds of fish and wildlife species.[1-2] The lakes provide significant ecosystem services, including provisioning (e.g. drinking water and commercial fishing), cultural (e.g. recreational), supporting (e.g. nutrient cycling), and regulating (e.g. water purification).[3] The Great Lakes have suffered from multiple stresses through the years, resulting from timber harvesting and overfishing in the 19th Century, and additional stresses over the past century that continue to this day, including aquatic invasive species, hydrological changes, eutrophication (associated with increased nutrients), toxic chemical loadings, and more recently, anthropogenic climate change.[1-2, 4]

There have been a number of studies through the years on stresses in the Great Lakes and potential approaches to address them.[5] A 2005 white paper (sometimes called the "*Prescription*" report)[6] discussed the various stresses in the lakes and recommended a four-pronged approach to improve their condition, consisting of: 1. Restoration, in particular of self-regulating mechanisms or processes; 2. Remediation, or addressing the causes of historic or existing stress; 3. Protection, or preventing new or further stress; and 4. Measurement, or assessing ecosystem condition via indicators. The *Prescription* report also included a simple conceptual model, in which multiple stresses were contributing to "ecosystem breakdown" (or a type of regime shift) in regions of the Great Lakes, though the report did not explore in detail stress-response mechanisms or more detailed conceptual models.[6] Though not published in the peer-reviewed literature, the *Prescription* report has informed Great Lakes restoration and protection efforts, including those of the Healing Our Waters (HOW) Great Lakes Coalition.[7]

Conceptual frameworks have been explicitly or implicitly considered in multiple research efforts in the region over the past two decades, including concerning stresses, ecosystem condition, and indicators.[8-9] In addition, there have been increasing management efforts to address the stresses, ranging from individual restoration projects to larger programs in both the U.S. and Canada.[10-11] However, it is not clear to what extent these efforts have incorporated conceptual frameworks, including models relating how management actions in aggregate might reduce stresses and subsequent impacts, and restore ecosystem functions and services. A recent paper from an expert workshop identified "grand challenges" for the Great Lakes across five topic areas, and at least two of the challenges – involving better understanding of ecosystem response to anthropogenic stresses, and identifying linkages between societal decisions and natural systems – could potentially be addressed through increased use of conceptual frameworks.[12]

Given this need, and under sponsorship of the National Oceanic and Atmospheric Administration (NOAA) Cooperative Institute for Great Lakes Research at the University of Michigan, the National Wildlife Federation (NWF) in June 2018 organized an expert summit to revisit the *Prescription* report and explore issues involving conceptual frameworks in Great Lakes restoration and protection planning.[13] The objectives of the summit were to:

- identify criteria (e.g., spatial scale) that can be useful in identifying or developing one or more conceptual frameworks that incorporate Great Lakes stresses;
- use the selected criteria to identify one or more conceptual frameworks addressing Great Lakes stresses that would be useful in restoration and protection planning; and
- identify information gaps relevant to the framework(s) selected to allow for improved research, monitoring, restoration, and protection planning.[14]

One of the desired outcomes of the summit was that it could help inform broader agency programmatic work in the region, including through the U.S. Great Lakes Restoration Initiative (GLRI) and the Canadian Great Lakes Protection Initiative.[10-11]

This white paper summarizes material developed from the summit[15] as well as subsequent discussions relating to conceptual frameworks and their value in improving restoration and protection planning and implementation in the Great Lakes region. Given the many questions the authors of this white paper believe may arise around the issue of conceptual frameworks and the Great Lakes, it was determined that a question-answer format would best summarize deliberations and outcomes of the summit, which is the approach employed for most of the remainder of this white paper.

2. Conceptual frameworks overview

2.1 What are conceptual frameworks and models, what are their benefits in ecological restoration and protection planning, and what types of decisions can be improved through their use?

One definition of ecosystem conceptual models from a report prepared through the U.S. Army Corps of Engineers Ecosystem Management and Restoration Research Program is: “descriptions of the general functional relationships among essential components of an ecosystem.”[16] Benefits of using conceptual models in ecosystem restoration and protection include helping with multiple aspects:

- Identify drivers of ecological processes and stressors (including anthropogenic), ecological effects, and attributes useful in monitoring and forecasting ecosystem response.
- Diagram qualitative explanations of how human activities alter ecosystems.
- Develop and communicate working hypotheses, improve understanding (including through more quantitative models), and develop consensus around key aspects of ecosystem stresses and response.
- Provide a framework for considering alternative actions and serve as a basis for implementing adaptive management strategies.
- Identify performance measures and develop monitoring activities to support restoration and management.[16-18]

Conceptual models can be grouped into several categories, including narrative, tabular, picture, box and arrow (stressor model), and input/output matrix (control model).[16, 19] Based on earlier work in the region and elsewhere that is summarized below, the assumption for this project from the start has been that one of the latter three formats would be most useful in informing ecosystem management in the region. One relatively common conceptual framework used in ecological restoration is the driver-pressure-state-impact-response (DPSIR) framework, a framework commonly used outside North America, including in Europe.[20] One schematic diagram for the framework, as used earlier in the State of the Great Lakes (SOGL) monitoring and reporting process (described in Question 3.1) is provided in Figure 1.

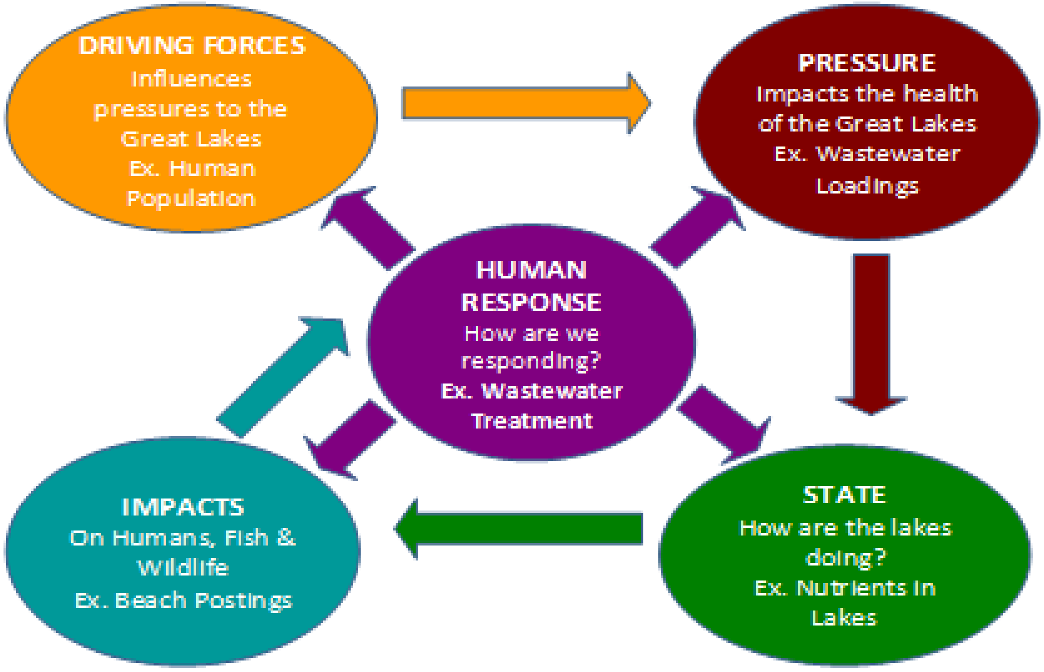

Figure 1. Driver-pressure-state-impact-response (DPSIR) framework as utilized in earlier State of the Great Lakes monitoring and reporting process.[21]

As indicated in Figure 1, driving forces (which can be natural or human-induced) lead to pressures, which lead to a change in state, with concomitant or resulting impacts, and potential human responses. Note that in this context *response* references a management or societal response to a stress, not an ecological response seen in a stress-response relationship. An example of this framework applied to one particular stress (involving elevated nutrients), in a more linear format, is provided in Figure 2.

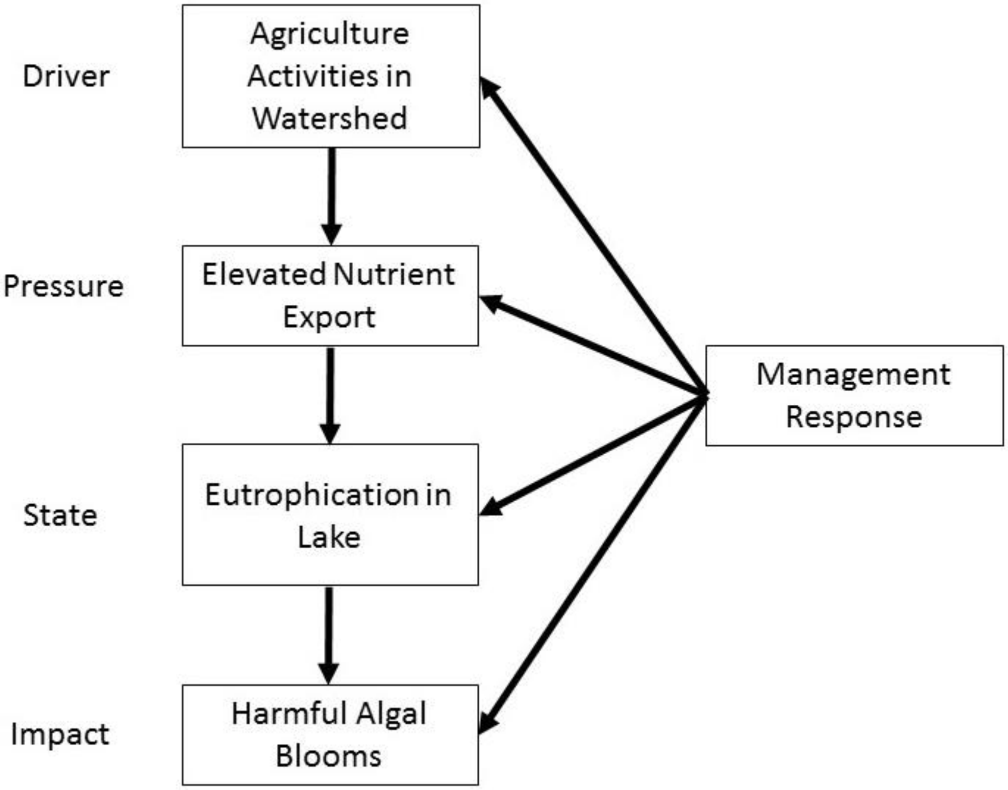

Figure 2. Example of a simple conceptual model using the DPSIR framework relating excessive nutrients and lake eutrophication.

In the model in Figure 2, the driver of agriculture activities can include excessive nutrient application or build-up in soils, leading to elevated nutrient export off the land (a pressure), which in turn can lead to elevated nutrients in a lake and resulting eutrophication (nutrient enrichment, or a change in state here) with potential impacts including harmful algal blooms (HABs). As implied in the figure, management responses on the right could be applied at any of the preceding four levels – e.g., changing agriculture practices (addressing the driver) vs. attempting to reduce HABs via some type of in-lake treatment (addressing the impact), or intervening in other ways to address the pressure or change in state. Although this model is highly simplified, this type of model can form the basis for more complex (including quantitative) models, lead to hypotheses that can be tested, allow for qualitative predictions, and help in evaluating different management options, ranging from nutrient management on farm fields to chemical treatments to reduce impacts in the lake.

While the potential value of conceptual models in ecosystem restoration is clear, there are also limitations, including that they are simplified depictions of reality, they are not comprehensive, but focus on parts of an ecosystem deemed most relevant, and they are not final system descriptions, but rather should be seen as consisting of a flexible framework.[16] Indeed in the simplified model shown in Figure 2, there will actually be a number of complicating factors at play within each of the boxes, with important factors including crop rotations and other management decisions (affecting the driver), soil properties, slope, subsurface drainage, and climate (affecting the pressure), size, basin morphometry, and other nutrient sources in the lake (affecting the state), and sunlight, temperature, and mixing (affecting the impact). But an initial simplified conceptual model can still form the basis for more mechanistic, complex, and quantitative models that better describe the system under consideration.

3. Overview of conceptual frameworks in Great Lakes restoration and protection planning and implementation, and frameworks used in other regions with relevance to the Great Lakes

Conceptual frameworks addressing Great Lakes stresses have been increasingly developed and/or used over the past two decades by agency managers, researchers, and practitioners, including private firms and nongovernmental organizations (NGOs). As stated in the Introduction, the *Prescription* report proposed a very simple framework in which stresses (e.g., aquatic invasive species, hydrologic alterations) could interact to lead to a regime shift in parts of the Great Lakes.[6] This section briefly reviews other work over the past two decades, including agency programmatic work, that of researchers, and efforts in other regions that may have relevance to conceptual framework development for the Great Lakes.

3.1. How have conceptual frameworks been incorporated recently in Great Lakes program work?

A significant portion of Great Lakes program work over the past five decades has occurred in support of objectives of the Great Lakes Water Quality Agreement (GLWQA), first signed by the U.S. and Canada in 1972 and amended most recently in 2012.[22] Under the GLWQA, the governments (or the Parties, through the U.S. Environmental Protection Agency (USEPA) and what is now Environment and Climate Change Canada (ECCC)) developed a coordinated monitoring and reporting process in the early 1990s,[23] which eventually led to the current State of the Great Lakes reporting process. The process has involved identifying indicators (which themselves have changed through time, particularly in number), collecting data through routine monitoring and regular reporting. Just prior to the most recent amendments to the GLWQA, the agencies were utilizing a DPSIR framework in the monitoring process, as illustrated in Figure

1. As implemented at the time, each of the five components of the framework had top-level stress categories (e.g., within pressures, there were pollution and nutrients, invasive species, and resource use and physical stressors), and multiple indicators within each top-level category.[21] Following renegotiation of the GLWQA in 2012, the DPSIR framework was dropped, and indicators were linked with specific GLWQA objectives.[24]

Conceptual models have also been utilized in the Great Lakes Inventory and Monitoring Network initiative coordinated by the National Park Service. An earlier report included an overview of conceptual models and development of models for six ecosystems or areas, including the Great Lakes nearshore region, large rivers, inland lakes, and other systems. The models were based on a simple box and arrow framework, involving drivers, stressors, effects, attributes (often relatively general), and measures, where the last were measures of attributes (e.g. species composition and abundance and nutrient cycling in the case of the nearshore region). The model diagrams themselves did not incorporate any explicit management response to address stressors.[19]

Regarding the large-scale restoration and protection programs for the Great Lakes that are currently operating in both countries, to our knowledge there has been limited use of a formal conceptual framework process to help guide overall program direction. For the U.S. GLRI, Action Plan II (covering fiscal years 2015-19) organized projects around five focus areas, with objectives, commitments, and measures of progress for each. The plan did include general conceptual approaches for several broad stresses or areas, including, for example, an approach to address runoff that included identifying sources, using modeling to target focus areas, implementing projects and evaluating effectiveness, and continuing monitoring. In addition, the plan included a science-based adaptive management process as part of Focus Area 5, with interwoven cycles, including development of the action plan on a five-year cycle as well as annual planning, with the process overall including funding of projects, assessment of project effectiveness on multiple scales, assessment of overall ecosystem health, communication of results, and prioritization of identified problems for targeting in the annual planning process.[25] Hence, there was a type of conceptual framework for programmatic work, but no apparent overall conceptual model of the ecosystem itself. GLRI Action Plan III was released in spring 2019, and in draft form, follows the same general approach as Action Plan II.[26] Concerning efforts on the Canadian side, it is not clear to what extent any type of conceptual framework is guiding restoration work; there is no overall action plan available similar to the GLRI Action Plan, although eight priority focus areas are included with five pertaining to ecological stressors or stressed habitats.[11]

Conceptual frameworks have also been utilized through the Lakewide Action and Management Plan (LAMP) process under the GLWQA. In particular, efforts led by The Nature Conservancy starting over a decade ago resulted in the development of biodiversity conservation strategies for each Great Lake,[27] though it is not clear to what extent the approaches used in developing those strategies are still referenced in current implementation of the LAMPs. In addition, the

International Joint Commission (IJC) has explored issues around indicators extensively, and a work group report in 2013 referenced use of the DPSIR approach described above.[28] (See elaboration on binational work in Appendix B).

In summary, though conceptual models have been incorporated to various extents in agency program work in the Great Lakes, there appear to be significant opportunities to revisit or expand development or modification and use of such models in restoration and protection planning and implementation.

3.2. What other research efforts over the past 10-15 years in the Great Lakes have explicitly or implicitly utilized conceptual frameworks that can inform Great Lakes restoration and protection planning and implementation?

There have been multiple efforts by research groups exploring Great Lakes stresses and responses since the release of the *Prescription* report. Researchers at the University of Minnesota-Duluth and other academic centers established the Great Lakes Environmental Indicators (GLEI) project in the 2000s, involving aggregating spatial information on 86 variables grouped into five major stress categories, with an emphasis on coastal areas of the U.S. portion of the Great Lakes Basin. Though a more formal conceptual framework was not presented, the process was based on considering stressor-response relationships in the Basin, where the x-variables are stressors (or pressures) and the y-variables are ecological responses (or states).[29] Note in this nomenclature, *response* references ecological response, rather than management response as utilized in the DPSIR framework. Through multivariate statistical analysis, information was integrated into a smaller number of stress measures, ultimately leading to a cumulative stress index.[8] A recent analysis by this group utilized a similar GIS-based approach to categorize Great Lakes coastal habitats based on level of disturbance or degradation.[30]

The Great Lakes Environmental Assessment and Mapping (GLEAM) project utilized spatial analysis of environmental stressors with ecosystem services information to map stressors in the lakes. The assessment considered 34 individual stressors at high resolution (1 km^2), and entailed development of a cumulative stress index, where individual stressors were weighted based on outcomes of an expert elicitation process, as well as mapping of ecosystem services by synthesizing available data on human uses of the lakes. The overall analysis showed that cumulative stress was particularly high in nearshore areas throughout most of the Basin, while also extending offshore in Lakes Michigan, Erie, and Ontario.[9] As with the GLEI effort, this project did not provide a conceptual framework relating stressors to ecological conditions, though the analysis (including an approach for assessing cumulative stress) is relevant to conceptual approaches relating stresses and impacts. A recently published review on Great Lakes stressor interactions drawing on the GLEAM project included a conceptual model with boxes for stressors, states and responses, and arrows depicting processes, contributing stressors, and mechanisms.[5]

Several other stress-response research efforts in the Great Lakes have explicitly included conceptual frameworks. At the smaller scale, a comprehensive environmental assessment for Mona Lake, a small urbanized watershed in west Michigan, considered multiple stresses, and a conceptual model was developed, both for inflow and lake subsystems, showing relationships between stresses and ecological conditions.[31] A case study on the Lake St. Clair region explored natural and socioeconomic components of the system, with intensive work on four "pathways" (water use and discharge, land use, tourism and shipping), and the use of causal loop diagrams at varying scales showing relationships between various components.[32] At the larger scale, the Great Lakes Aquatic Habitat Framework (GLAHF) has been a multi-year project involving a database, framework, and classification system. The GLAHF includes hierarchically-nested geospatial grid cells with data across a number of categories, and though the system considers drivers, it has an emphasis on fundamental natural drivers as expressed through variables and "supervariables" (e.g., temperature and energy), though they can be altered by human activity.[33-34]

Two recent research synthesis efforts involving Great Lakes fisheries are also relevant. A review considering climate change and other stressors affecting Great Lakes fisheries included a hierarchical conceptual framework. In the nested framework (moving to smaller circles with each step), external drivers such as air temperature and precipitation would lead to changes in abiotic conditions in the lakes, which in turn would influence relevant biotic components (including predation and prey density), which would influence fish recruitment and growth of the species of interest, and ultimately the fish community composition more broadly.[35] Another recent review explored food web structure and ecosystem function in large lakes, including how such systems respond to changes (including human-induced), and included a conceptual framework based on three broad habitat compartments – nearshore, pelagic (offshore, shallower), and profundal (offshore, deeper portions of the lakes). The framework considered energy and nutrient flow into, within, and between compartments, and in addition to structural attributes of each compartment, considered natural and human modifiers, which in some cases may affect multiple compartments.[36]

3.3. What are key outcomes of use of conceptual frameworks in other large-scale aquatic ecosystem restoration projects, and how can these lessons be applied to the Great Lakes?

There have been multiple large-scale aquatic ecosystem restoration programs developed in recent decades, including several in the U.S. that were the focus of presentations and/or more intensive deliberations at the *Prescription* summit. Brief summaries of the use of conceptual frameworks in four such efforts are provided here, and additional background (including conceptual model diagrams) is provided in Appendix C.

Chesapeake Bay has been affected by stresses including excessive nutrients and sediment loads for decades. The regional science and policy communities have utilized modeling, including development of conceptual models relating key stressors to the system response, including hypoxia (low oxygen) and loss of aquatic life. These models, including box and arrow models, have both informed more quantitative models, as well as helped explore possible alternative scenarios of how the system might respond to management actions. For example, with reduced nutrient loads, will there be a linear response of algae, hypoxia, and turbidity? Or is it possible historic stresses have led to a shifting baseline that might preclude this type of linear response? Using both conceptual and appropriate quantitative models can help predict how the system will likely respond to management actions, especially when the latest science has been incorporated into management protocols through an iterative process. In addition, an executive order tying performance to funding provided additional incentive for utilizing conceptual and quantitative models.[37]

The Kissimmee-Okeechobee-Everglades (KOE) ecosystem in Florida has also experienced multiple stresses as well as been the target of large-scale restoration efforts over the past four decades. As part of development of an applied science strategy starting two decades ago, conceptual models for 11 physiographic regions in the KOE ecosystem were developed. Through this framework (generally similar to the DPSIR framework), an external driver (e.g., a water management practice) causes a stressor, leading to an ecological effect, and finally a change in one or more ecological attributes (e.g. waterfowl populations).[38] This framework was applied to the various regions (e.g. Lake Okeechobee), with individual driver – ecological attributes links in parallel, though with the possibility for interaction. In general, use of conceptual models in the KOE ecosystem has helped inform decision-making, including through identifying restoration needs and providing a framework for integrating science and policy for the Comprehensive Everglades Restoration Plan.[39] Indeed, conceptual model development and use has been an integral part of the adaptive management framework used in the KOE system, including in the development of restoration targets, performance measures, a monitoring program, and adaptive assessment strategy for reaching long-term wetland restoration goals.[40]

Puget Sound has also seen extensive restoration planning and implementation work in the recent past to address various stresses, including a focus on nearshore areas. As part of the Puget Sound Nearshore Ecosystem Restoration Project, conceptual models relevant to better understand nearshore ecosystem processes and the response of the ecosystems to restoration were developed by a science team. The process had an emphasis on ecosystem processes, structures, and functions, and the models had a five-level nested architecture, with different emphases at different levels (including varying emphases on spatial vs. temporal scales). Importantly, the process considered impairment and restoration from two directions. For example, the Level 3 conceptual model included external forcings of energy and matter affecting three abiotic compartments, which in turn had interactions with biota. Level 4 of the architecture had a number of submodels addressing specific stresses or impacts, but starting from a restoration activity. For example, in the case of wetland habitat restoration, a restoration action (e.g., dike breaching) would lead to expanded habitat availability for salmon, increased habitat edge, and finally increased juvenile salmon residence time (or a functional response).[41] Efforts in the region have more recently included use of *results chains*, which describe the sequence of outcomes following implementation of strategies, and this general approach was noted at the summit as a key feature of restoration implementation in Puget Sound (see Appendix C).

The Sacramento-San Joaquin Delta ("Delta"), whose watershed drains a large area in California, has seen both significant degradation for decades through demands on the water, as well as restoration work involving many partners, both federal and non-federal, including the Delta Stewardship Council (a California state agency).[42] State law stipulated that the Delta Stewardship Council develop a Delta Plan, to include a formal adaptive management strategy, which in turn should include components such as conceptual and quantitative models.[43] Conceptual models have been incorporated into restoration planning and implementation, as noted in a 2012 paper, whereby restoration actions were evaluated and ranked via use of conceptual models (involving drivers, linkages, and outcomes), an action evaluation procedure, and a decision support tool. Individual conceptual models were developed for specific aspects of the system, with potential linking of one to another, and graphical components providing other information (such as related to the character and direction of an effect – see example in Appendix C).[44] Each model was accompanied by narrative background, references, and other material. Other work in the Delta is also applicable to the Great Lakes as well, including the approach to categorizing stressors as current, legacy, global, or anticipated future.[45] Concerning conceptual model use in projects, a recent review by members of the Delta Independent Science Board of adaptive management implementation within Delta plans and projects found use of conceptual models in the majority of projects or plans reviewed.[43]

4. Steps in developing new conceptual frameworks for use in the Great Lakes

The summit participants came to general agreement that conceptual frameworks could be useful in informing protection and restoration programs and projects in the Great Lakes. In developing new conceptual frameworks for the region, other issues were identified as important, including identifying ecosystem objectives for which conceptual framework use can be valuable, identifying characteristics of a useful framework, having a science-based process that allows for adaptation and learning, and linking to an appropriate governance structure. These and related issues are considered in individual questions below.

4.1. What are key objectives in the Great Lakes that may more readily be met via the use of conceptual frameworks?

Objectives concerning environmental conditions in the Great Lakes can be broken down in several ways, including by: jurisdiction (e.g., local, state or provincial, federal, and binational), program type (e.g., regulatory and voluntary), stress (e.g., chemicals in water or sediments) and potentially by individual components of the system (e.g., by Great Lake, or by resource such as fisheries). Furthermore, many of these objective domains can be overlapping. As noted in Question 3.1, a key management driving force promoting the health of the system is the Great Lakes Water Quality Agreement (GLWQA) signed by the U.S. and Canada, with a purpose to "restore and maintain the chemical, physical, and biological integrity of the Waters of the Great Lakes" [22]. Relevant binational objectives include:

- General objectives (narrative in form) and specific objectives (e.g. concentrations for specific chemicals in water) under GLWQA Article 3.[22]
- Delisting targets for Areas of Concern (AOCs) under Annex 1 of the GLWQA, whereby all beneficial use impairments are removed for a particular AOC following remediation work.[46]
- Lake ecosystem objectives through individual Lakewide Action and Management Plans (LAMPs) under Annex 2 of the GLWQA, a process still underway following the renegotiation of the GLWQA, though other efforts have been addressing long-standing problems in individual lakes, such as nutrient loading and eutrophication impacts in Lake Erie.[47]

Other objectives are specific to chemical or biological pollutants, including meeting water quality standards adopted by states and Ontario for specific chemical substances, targets in place as part of total maximum daily load (TMDL) plans for impaired water bodies under the U.S. Clean Water Act, and sediment quality criteria or guidelines, which provide an indication of risks to benthic organisms and inform sediment remediation activities. There are also fish community objectives developed for each lake under "A Joint Strategic Plan for Management of Great Lakes Fisheries", through the Great Lakes Fishery Commission.[48] Finally, the U.S. GLRI has specific objectives associated with individual focus areas, such as "Remediate, restore, and delist Areas of Concern", "Prevent introduction of new invasive species", and "Reduce nutrient loads from agricultural watersheds".[26]

In general, it is likely that conceptual models could assist in implementation of activities to meet many of these objectives. In some cases, conceptual models may already be explicitly or implicitly incorporated. For example, meeting a water quality target through the TMDL process under the U.S. Clean Water Act entails an understanding of sources (both point and nonpoint) and cycling for a chemical within a water body, as well as implications of load reduction and time frame for meeting the target. Setting lake ecosystem objectives through LAMPs under the new 2012 GLWQA, including considering the multiple stressors affecting the lakes, can clearly benefit from use of conceptual models, as has been documented in an earlier effort referenced in Question 3.1 to identifying approaches to meeting certain biodiversity targets.[27]

In addition, conceptual models can be of value in understanding broader threats to parts of the ecosystem. For example, conceptual models likely could help suggest additional areas of research needed to address any ongoing structural or functional limitations in AOCs following completion of management actions or delisting. Similarly, having a comprehensive conceptual framework for the Great Lakes can help situate program activities (e.g., in the GLRI) in the context of the broader condition of the Lakes, including their chemical, physical, and biological integrity, and clarify complementarity of proposed actions by states, provinces, or other entities, and help avoid duplication or even unintentional consequences.

Finally, conceptual models can be useful in mapping out future scenarios. For example, how might effects associated with climate change (e.g. warmer temperatures, changed stratification patterns, more intense storm events) affect attainment of conservation objectives directly or indirectly related to these changes in future years? Conceptual models can be very helpful as a visual tool around which stakeholders from various sectors can speak a common language, including how management actions can address predicted stressors in order to attain particular attributes or agreed upon objectives, for example through climate adaptation planning.

4.2. What characteristics would make for useful conceptual frameworks for the Great Lakes?

The 2018 summit included discussion on characteristics helpful in identifying or developing conceptual frameworks for use in the Great Lakes, including drawing on previous work on the topic.[49] Fischenich (2008) identified characteristics ideally present in "useful" conceptual models, which include the following:

- Key physical, chemical, and biological attributes are identified.
- Mechanisms by which drivers cause change (in particular anthropogenic drivers or stressors) are provided.
- Critical thresholds of ecological process and environmental conditions are identified.
- Assumptions and gaps in knowledge (including in relation to restoration outcomes) are acknowledged.
- Current characteristics of system that may limit feasibility of achieving outcomes are identified.
- Adequate references to substantiate model are provided.
- Models are relevant to the problem at hand.
- Models are directed at appropriate spatial and temporal scales.
- Models strike a balance between over-simplification and over-sophistication.[16]

On the last point, a relatively simple model can have value in emphasizing key components and processes in a system as well as being easily communicated. On the other hand, while an extremely complex model may more accurately depict the system, there can also be limitations, including applying only in limited circumstances, data limitations, the possibility of erroneously modeled relationships, and challenges in communicating with broader users.[16]

The summit also included discussion on the above and related characteristics; key considerations identified are summarized in Table 1 on the following page. As indicated in the table, summit participants noted the importance of: use and assignment of terms (driver, pressure, etc.); incorporating human dimensions; having flexibility in incorporating management response; and being able to address complexity and varying types of pressures and drivers. In addition, it was noted that given the inherent simplification with any type of conceptual diagram, narrative text (including with references) would need to accompany each diagram.

Table 1. Considerations Involving Key Components of Conceptual Frameworks for Use in Great Lakes.

Component/Aspect	Considerations
Drivers	• Distinguish natural vs. anthropogenic
Pressures	• Consider categorizing (e.g. extractive, assimilative, physical alteration) • Consider spatial scales (e.g. more lakewide for atmospheric deposition of toxic chemicals, vs. more nearshore for botulism toxin)
Complexity	• Likely need for more detailed, mechanistic models to better describe system, which may be embedded in more general framework • Explicitly recognize potential ecological complexity (e.g. trophic cascades) • Potential for multiple interactions; avoid maintaining stressors in silos
Management responses	• Have explicitly identified within diagram • Can occur at different levels (drivers, pressures, state, etc.) • Active vs. passive • Achieving objectives via remediation vs. prevention • Utilize adaptive management • Incorporate climate change adaptation principles
Human dimensions	• Approaches to incorporate, such as through latent variables relevant to multiple other components (e.g. attributes) • Ensure consideration of communication potential to broader audiences, including general public
Component definitions, assignment, overall design	• Clearly define terms in framework • Recognize potential ambiguities – e.g. whether a particular component is a stressor (e.g. pressure) or a response (e.g. a state or attribute) • Actual design and functioning becomes clearer when considering particular stressors (or category)

Based on these considerations, key features that one or more conceptual frameworks for use in the Great Lakes should have include the following:

- Use clearly defined terms, including addressing potential ambiguities concerning particular components, group stressors together as appropriate, and distinguish natural vs. anthropogenic drivers.
- Explicit consideration of most appropriate scales, both spatial and temporal.
- Recognize potential ecological complexity, and address through incorporation of more detailed, mechanistic models within a more general framework.
- Ensure management responses are explicitly identified (within diagram, and as part of narrative), utilize adaptive management and climate change adaptation principles, and consider varying approaches.
- Explicit consideration of human dimensions, potentially as part of process for prioritizing management responses, and also the importance of communicating the process to broader audiences, including policymakers and general public.

4.3. What are conceptual framework architectures that may be particularly useful in the Great Lakes (nested, hierarchical, etc.), and what is the appropriate spatial scale for developing and using conceptual frameworks in the Great Lakes?

There was general agreement at the summit on the value of a general, higher level DPSIR-type diagram (or schematic) as a starting point for conceptual frameworks in the Great Lakes. Both plenary and breakout discussions at the summit tended to produce general box and arrow diagrams, with often more linear versions of the DPSIR framework of the type depicted in Figure 2.

Although the DPSIR framework has multiple values, challenges were noted at the summit, including for example difficulty in incorporating feedbacks and addressing stressor interactions. In addition, there was discussion around the value of exploring restoration activities via two pathways – i.e., from a driver to pressure to state to impact, and from a restoration action leading to a reduction in stressors (or pressures) and ultimately a change in state, and meeting a restoration target. To some extent, the challenge has to do with ongoing or future drivers and stressors vs. legacy stressors embedded within the system, where the management response may be different – e.g., prevention for the former, and restoration for the latter, an issue raised generally in the original *Prescription* report.[6] A related issue is the possibility of hysteresis, whereby ecosystem recovery may not retrace the pathway of decline.

Concerning spatial scale, discussion at the summit highlighted both the positives of a single framework – relatively simpler, and ideally applicable for multiple stresses across five large lakes – as well as the challenges, including accounting for significant physical, chemical, and biological differences in the lakes, and even within a lake. One solution would be to start from a single broadly applicable framework, and then apply to an individual lake and then parts of the lake, where particular components of the framework may be less relevant (e.g., related to excessive nutrient loadings and eutrophication impacts), but the framework overall still has value.

4.4. What approach to developing and using conceptual frameworks is best suited to support Great Lakes restoration and protection planning and implementation, including taking into account historic degradation, current, and potential future stresses?

In light of summit outcomes and subsequent considerations, we propose the following approach to developing and using conceptual frameworks in the Great Lakes:

- A multi-level framework with box and arrow-type models, with a hierarchical structure, and accompanying narrative text and references.
- An overall basin-wide general framework incorporating individual models for each of the five Great Lakes, which in turn would encompass models for smaller regions, including connecting rivers, bays, embayments, and harbors.
- The lake-based and finer resolution models could be coupled with appropriate quantitative, process-based models
- Coupling of the overall framework with a decision support system to aid in planning and management decisions

The architectural scope of the models we propose is indicated in Figure 3 on the following page. As noted, a generic model would overlay five lake models, which in turn would encompass more localized models. The right side of the diagram indicates entities involved in governance, management and research at the various scales, and some elaboration is provided in the next section.

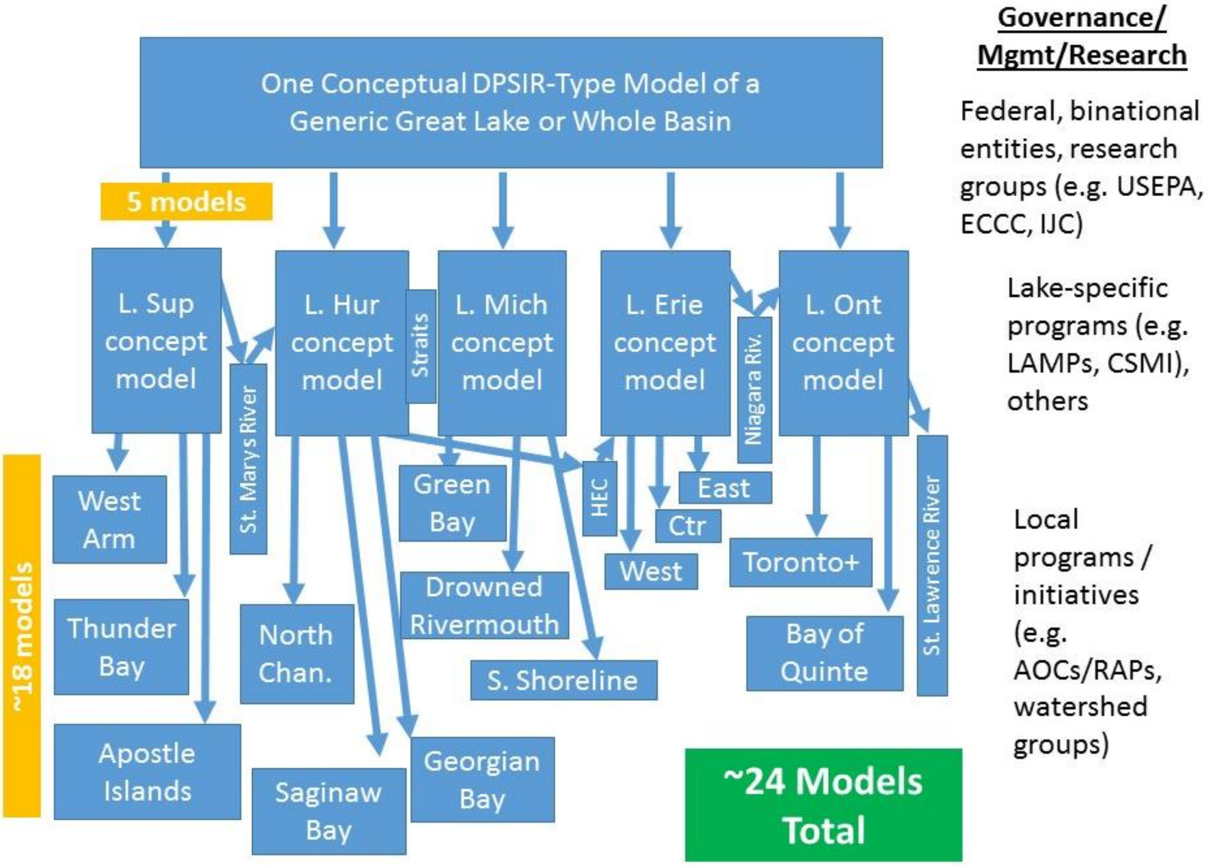

Figure 3. Architectural scope of conceptual models proposed for the Great Lakes, with individual lake models underlying a generic model, and more localized models underlying the lake-based models. Discussion of agencies and other entities involved in governance, management and research is included in Question 4.5. HEC: Huron-Erie Corridor; CSMI: Cooperative Science and Monitoring Initiative

In terms of a generic conceptual model diagram, we are proposing a modification of the approach used in the KOE (Kissimmee-Okeechobee-Everglades, Florida) ecosystem, entailing drivers, stressors, effects, and attributes, as described in Question 3.3 (also see elaboration in Appendix C). In addition, the diagram draws on the stressor categorization approach used in the Sacramento-San Joaquin Delta system. A generic conceptual model diagram is provided in Figure 4 on the following page.

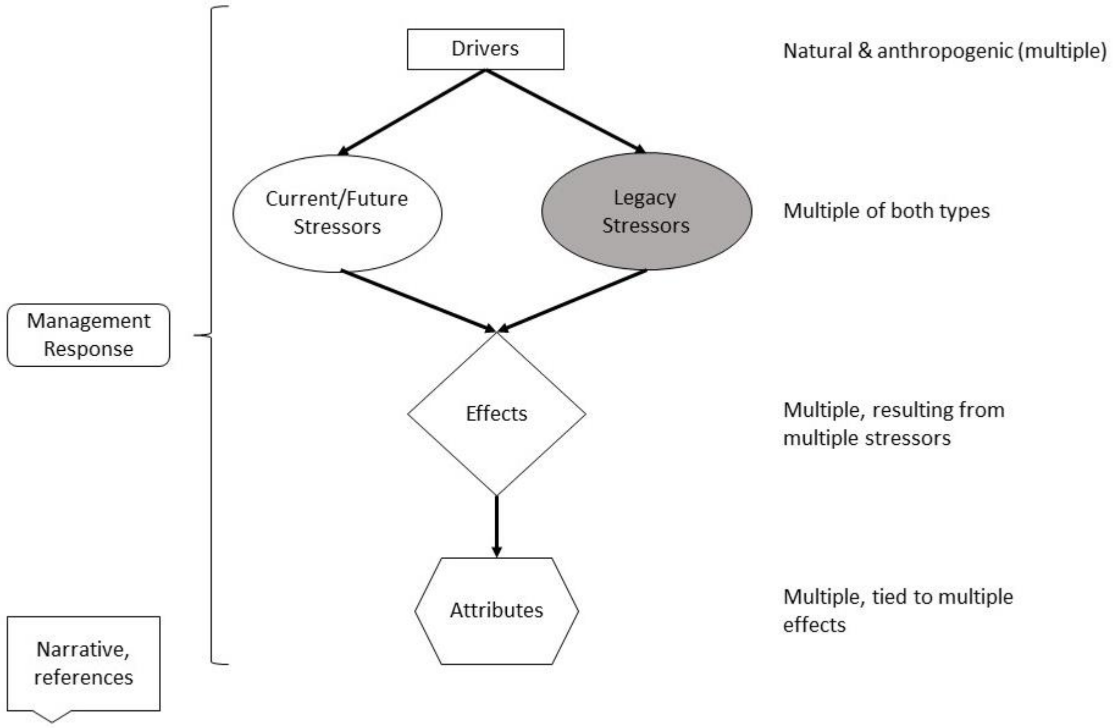

Figure 4. Generic conceptual model diagram proposed for the Great Lakes, drawing on box and arrow approach used in KOE (Florida) ecosystem.

As indicated in Figure 4, the general approach follows that used in the KOE system, where drivers (such as land use) can lead to stressors (e.g., elevated nutrient export), in turn causing effects (e.g., eutrophication), which then can change attributes (e.g., fish habitat). An alternative approach is to first identify the system attributes of societal significance, and use those endpoints to help construct the conceptual model, which also was done for KOE models.

One modification we incorporated was the explicit distinction of current or future stressors from legacy stressors (done in the Sacramento-San Joaquin Delta,[45] as noted above), which is important in the Great Lakes, given the significance of legacy stressors.[50] In addition, the general KOE framework diagram did not explicitly incorporate management response, though management is incorporated at varying levels. In the proposed framework in Figure 4, management responses can occur at any level, though it is assumed that the more effective interventions will generally be higher in the framework – i.e., addressing drivers and/or stressors. In addition, the response will be different for current/future stressors (with an emphasis on preventive and control activities) vs. legacy stressors (with an emphasis on restoration). Regarding management responses more broadly, it is also important to keep in mind sustainability – e.g., to what extent interventions (such as fish stocking) might need to continue indefinitely. An additional important issue is societal values, including valuing of particular attributes, which can have significant implications for subsequent management actions, whether determined by, for example, program managers, a stakeholder process, or litigation outcomes.

One proposal for expanding this diagram to cover multiple drivers, stressors, effects, and attributes is provided in Figure 5 below. While drivers of change can be both natural and anthropogenic, the emphasis here is on anthropogenic drivers, including anthropogenic climate change. Drivers are not inherently a problem for ecosystems – indeed, natural drivers (such as variations in precipitation patterns leading to variable lake levels in the Great Lakes) can be important in maintaining a healthy ecosystem. Effects follow commonly identified impacts in the Great Lakes (including through State of the Great Lakes reporting). Attributes are identified at a high level (drawing on the GLWQA), but could be easily made more specific, such as reflecting native fish condition, clean beaches, clean drinking water, etc. At the same time, grouping at a given level could be pursued – for example, at the summit, one idea was that pressures (or stressors) could be grouped into extractive, assimilative, or physical alteration categories. In addition, as indicated in the lower left of Figure 5, the diagram would include accompanying pages with narrative details, including references.

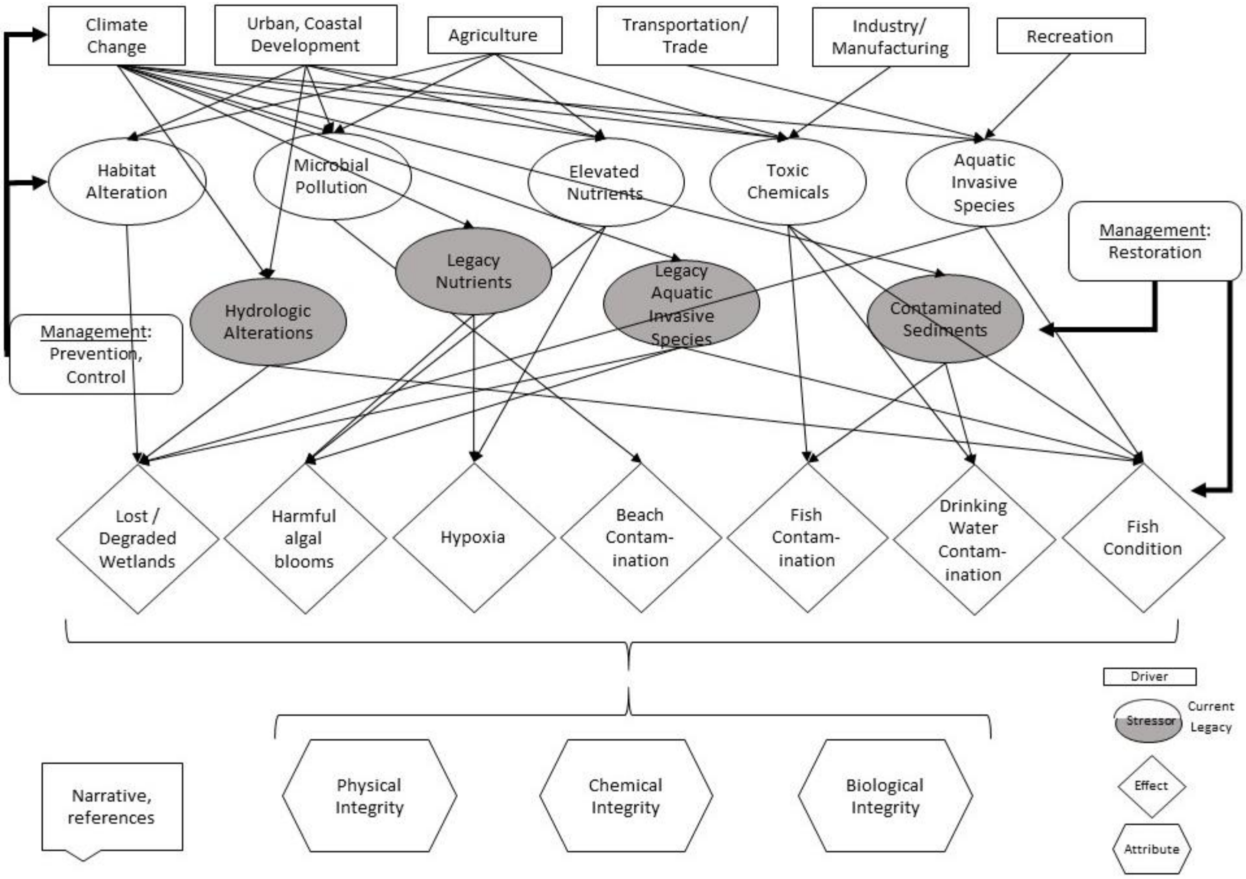

Figure 5. Example conceptual model diagram for the Great Lakes, drawing on *Prescription* report and other reviews. See further discussion in text.

Arrows link different components where some type of relationship has been clearly established. For example, agriculture can be a source of excessive nutrients, and larger storm events associated with climate change can lead to increased nutrient runoff and subsequent harmful algal blooms in particular areas (e.g., Western Lake Erie Basin), with the legacy of zebra and quagga mussel invasions in sediments potentially exacerbating the problem.[51-52] As noted above, the diagram illustrates the different management response approaches for current/future stressors (with an emphasis on preventive and control activities) vs. legacy stressors (with an emphasis on restoration). At the same time, as noted in endnote 50, some stressors may have components that are both legacy and contemporary, which can have management implications.

Though the diagram would ideally apply across the Great Lakes, it is not necessarily comprehensive – some components may be less prominent in some areas, whereas other stressors or effects not on the diagram may be important in other areas. In addition, for both stressors and effects, more refining is possible, so there would be multiple levels (as identified in the KOE system). For example, for aquatic invasive species, a nonnative fish introduction and establishment effect could, in turn, lead to another effect on fish community composition and structure.[38]

The diagram of the type shown in Figure 5 can be useful in higher level understanding of the system, including a general sense of how some stressors might interact, as well as overall management considerations. Note a current IJC project is examining approaches to addressing stressor interactions in the Great Lakes.[53] There would also be value in a diagram more specific to particular problems (e.g. eutrophication and impacts), whereby relevant drivers, stressors, effects and attributes are included, with the potential to modify (including adding new boxes or arrows) as scientific understanding improves, including on potential interactions. As indicated in Question 3.2 above, such an approach specific to key stressors in Mona Lake has previously been published.[31] In addition, the framework outlined in Figure 5 could lead to more refined, detailed quantitative models particularly useful in several ways, including testing hypotheses and identifying monitoring needs, including as management actions are underway. For example, if restoration work has been pursued at a particular location but desired attributes have not been attained, a conceptual model could be used (or revised) to help identify further research and monitoring work that may improve understanding of the system, including reasons for the delayed response, which can then inform revised management actions.

The management response (i.e., the two boxes on left and right sides of the diagram in Figure 5) would actually be more complex, entailing individuals at varying program levels and across multiple organizations, including watershed, local, state/provincial, and federal, and utilizing a decision support system to facilitate planning and implementation. A decision support system has been defined as an interactive computer-based tool or set of tools utilizing information and models to improve the process and outcomes of decision-making.[54] Such tools addressing threats in the Great Lakes Basin have been increasingly developed, including in support of management of coastal wetlands,[55-56] *Phragmites* control,[57] and riverine habitat and fisheries protection in light of vulnerabilities to climate change.[58] There was limited time for discussion of decision support tools at the 2018 summit. However, deliberations at subsequent workshops could identify an optimal approach for incorporating decision support tools as part of conceptual model use in restoration and protection planning in the Great Lakes, including the value of any single tool framework vs. individual stressor- or attribute-based tools.

4.5. What might a governance structure look like concerning conceptual frameworks in the Great Lakes, and how can such an effort be best integrated with existing research, monitoring, and restoration implementation efforts in the Basin?

Conceptual frameworks can be potentially useful across many administrative and operational levels in the Great Lakes, from small-scale restoration projects to large-scale restoration and protection programs. Given many individual projects will have been funded or otherwise fall within a broader administrative program, it is important that program managers and restoration practitioners be considering and using conceptual frameworks as well.

For the U.S. portion of the Great Lakes, the Interagency Task Force (IATF, with USEPA as Chair and its Regional Working Group) leads the overall GLRI effort, with ECCC and the Ontario Ministry of the Environment having lead roles on restoration work in the Canadian portion of the Basin. The GLRI also includes a Great Lakes Advisory Board (GLAB), re-established in late 2018, and with the potential to form subcommittees.[59] In addition, binational Great Lakes efforts are ongoing, including under the GLWQA, which in addition to addressing AOCs (Annex 1) and LAMPs (Annex 2) includes a focus on Science (Annex 10). Work under Annex 4 (Nutrients) has entailed use of quantitative and conceptual models for Lake Erie. Furthermore, as noted for Question 3.1, coordinated monitoring is done as part of the State of the Great Lakes effort (which previously involved use of the DPSIR framework for a brief period, as noted above), and in addition, intensive annual monitoring of one Great Lake is carried out through the Cooperative Science and Monitoring Initiative (CSMI) on a five-year rotation.[60]

As noted for Question 3.3 above, approaches to conceptual framework use in other large aquatic ecosystems around the U.S. may be applicable to the Great Lakes. In Chesapeake Bay, for example, three committees (including a Scientific and Technical Advisory Committee (STAC)) report to the Executive Committee and the Principals’ Staff Committee. The STAC has been involved with other committees, goal implementation teams, and workgroups in developing and applying models.[37] In the Sacramento-San Joaquin Delta, an independent science committee has been involved in developing and/or reviewing science components of restoration planning and implementation in the Delta.[43]

In light of the existing governance structure in the Great Lakes and lessons from other aquatic ecosystems, we recommend the development and use of conceptual models at all levels within the hierarchy of Great Lakes programs, including basin-wide, federal programs, lakewide and sub-basin, and project level, including to help inform research and monitoring needs as well as management decisions. Recommendations on approaches at specific levels include the following:

- Co-chairs of individual Lakewide Action and Management Plans (Annex 2 of the GLWQA) should emphasize development and use of conceptual frameworks in work under each LAMP, including drawing on experience of all stakeholders involved in each LAMP. This can include reviewing the approach used in development of the earlier biodiversity conservation strategies as well as considering the approach recommended here for addressing key stressors in the Great Lakes.
- Co-chairs of other GLWQA annexes should explore more formal use of conceptual frameworks, including in restoration in AOCs (Annex 1) and in considering broader science issues, including related to multiple stressors and monitoring (Annex 10).
- In the large restoration programs (U.S. GLRI and Canadian GLPI), USEPA and ECCC, respectively, should develop and/or use science advisory committees to explore development and application of conceptual frameworks, both for the programs overall as well as for use in projects, including by grantees. In the case of USEPA, such an effort could be through a subcommittee under the recently re-established GLAB.
- In joint monitoring through the SOGL program, USEPA and ECCC program managers should revisit the use of conceptual frameworks, along the lines of recommendations in this white paper. Such an effort may help inform use of indicators, including potential identification of new or modified indicators, or prioritization for monitoring in the case of limited resources. This work should include coordination with the International Association for Great Lakes Research, given its new role in hosting State of Lake conferences.
- CSMI program managers should ensure incorporation of conceptual frameworks in planning for intensive field sampling years, which can help in generating or testing hypotheses and otherwise contribute to increased understanding of the lakes.

4.6. Is there value in having a more independent developer or steward (e.g., inter-governmental organization, academic center, etc.) of conceptual models, including for periodic evaluation and update of frameworks?

Summit discussions around governance issues touched on the possibility of an independent entity (i.e., independent of the agencies involved in restoration and protection programs) to steward or manage conceptual frameworks for application in the Great Lakes. This entity might take the form of an inter-governmental organization (such as one of the IJC boards or Great Lakes Commission (GLC)) or an academic center, which could be chosen through an open bidding process.[61] Such an entity could organize a process for developing conceptual frameworks for use in the Great Lakes by the various program managers (as indicated in the previous question and response).

Concerning the other ecosystem restoration efforts reviewed above (Question 3.3), conceptual models were typically developed by teams or committees coordinated as part of the broader effort by the lead agencies, though outside experts could be brought into the process. This general approach has been used for years in the Great Lakes region as well, through advisory committees under federal, state, and provincial agencies, and intergovernmental organizations. For example, regarding the IJC, as an advisory body concerning water quality, its boards are exclusively made up of non-IJC scientists, policy analysts, and others, though staff are involved in managing and developing products.

Based on summit discussions and considerations noted here, we believe there is value in having an intergovernmental organization or other entity organize a process for developing conceptual frameworks for use in the Great Lakes, drawing on recommendations herein, as well as having an outside entity (whether the same, or potentially a separate academic center or other group) to periodically review use of conceptual frameworks in Great Lakes protection and restoration programs, potentially on the triennial cycle currently in place under the GLWQA.

4.7. What additional steps should be pursued in developing or refining conceptual frameworks for use in the Great Lakes?

There was general agreement at the summit on the value of further work to explore development and use of conceptual frameworks in the Great Lakes, including deeper exploration of topics such as potential framework types, ensuring applicability across a number of stressors and regions of the Great Lakes, and an approach to their development, use, and evaluation. Important related aspects include coupling of conceptual frameworks with more quantitative, process-based models to help advance understanding of the system and to inform monitoring, as well as development and maintenance of decision support tools that can assist in management actions.

Hence, we propose the following next steps concerning conceptual model development in the Great Lakes:

- A series of expert workshops should be organized by an intergovernmental entity or academic center to explore in more depth the issues around conceptual frameworks covered in this white paper, and determine the value of the proposed framework outlined in Question 4.4 or any other approach that may be most feasible for use in the Great Lakes. We recommend this process involve communication and coordination as appropriate with agency program managers to ensure there is support for the idea, as well as consideration of the broad human dimensions aspects of Great Lakes issues, including involvement of a wide range of scientists (including social) and other stakeholders.
- Drawing on the outputs of the expert workshops, Lake-based conceptual frameworks should be developed/refined through the LAMP process, and federal restoration

program managers develop or use such frameworks in appropriate programs (e.g. GLRI, GLPI), and incorporating input by agency scientific advisory boards as appropriate.
- An outside entity, whether an intergovernmental organization or academic center should be identified to periodically review use of conceptual frameworks in Great Lakes protection and restoration programs, potentially on the triennial cycle currently in place under the GLWQA.

5. Conclusions and recommendations

Conceptual frameworks can be useful tools in ecosystem restoration and protection work, including synthesizing understanding of how a given system works; simplifying complex systems; helping isolate cause and effect; providing a common framework from which to develop alternatives; serving as a tool for developing hypotheses and making qualitative predictions of ecosystem responses; and helping inform implementation of adaptive management strategies. Conceptual frameworks have been used in different programs and projects in the Great Lakes region in the past two decades, as reviewed above (and in Appendix B). However, it is not clear that they have not been used in larger-scale restoration planning and implementation to the same extent as in other large aquatic ecosystems considered in this review.

At the same time, a number of research efforts have implicitly or explicitly used conceptual frameworks in examining varying stressors and ecosystem responses in the Great Lakes region. It is critical that the research community continue to explore these issues, and that Great Lakes scientists from all sectors (including academic, agency, private industry, NGO) be involved, assuming more focused work on conceptual frameworks proceeds in the region. This is particularly important given the potential for greater numbers of stressor interactions in the coming years and decades, and challenges in both predicting and managing them.

Based on discussion and outcomes of the June 2018 Great Lakes conceptual frameworks summit as summarized here, recommendations for developing and more formally using conceptual frameworks in the Great Lakes are as follows:

- Conceptual frameworks developed should have a number of characteristics, including clearly defined terms, distinguish natural vs. anthropogenic drivers, appropriate level of complexity, explicitly identified management responses and human dimensions, and be easily communicated to broader audiences.
- A general framework proposed for consideration follows the general driver-pressure-state-impact-response diagrammatic model (with variations as applied in the Kissimmee-Okeechobee-Everglades system in Florida), with a general framework that would be applied to each lake and subsystem therein. Each diagrammatic model would

have accompanying narrative material with references, allow for quantitative process-based models to be incorporated, and be tied to a decision support system.

- Concerning moving forward with conceptual framework development and use in the Great Lakes, we recommend an intergovernmental or academic entity organize expert workshops to explore conceptual frameworks in greater depth, drawing on the general approach presented herein, and LAMP and other agency program managers (drawing on input from stakeholders and science advisory committees, as appropriate) then refine the proposed models as needed for lakewide and program-wide work.
- An outside entity, whether an intergovernmental organization or academic center be identified to periodically review use of conceptual frameworks in Great Lakes protection and restoration programs, potentially on the triennial cycle currently in place under the Great Lakes Water Quality Agreement.

In summary, increased use of conceptual frameworks in the Great Lakes can better ensure improved scientific understanding of the various stressors affecting the lakes, approaches to their management, and efficient expenditure of resources in protecting and restoring the Great Lakes.

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7. Appendices

Appendix A

Summit Approach and Participants

The summit was organized by the National Wildlife Federation (NWF) and sponsored and hosted by the Cooperative Institute for Great Lakes Research (CIGLR) at the University of Michigan, in Ann Arbor, MI, June 27-29, 2018. The summit lead was Michael Murray (NWF), with contributions by six additional members of a Steering Committee – David Allan (University of Michigan), John Bratton (LimnoTech), Jan Ciborowski (University of Windsor), Lucinda Johnson (University of Minnesota-Duluth), Alan Steinman (Grand Valley State University), and Craig Stow (NOAA-Great Lakes Environmental Research Laboratory). In addition, 15 Great Lakes natural and social scientists and practitioners from diverse disciplinary backgrounds took part in the summit – see full list at the end of this appendix. Brad Cardinale (CIGLR Director) and Mary Ogdahl (CIGLR Program Manager) assisted with different aspects of the summit.

The purpose of the summit was to consider if and how use of conceptual frameworks could aid in protection and restoration of the Great Lakes, including in light of themes identified in the earlier white paper *Prescription for Great Lakes Ecosystem Protection and Restoration* [6]. The specific summit objectives were 1. Consider and select criteria (e.g. architecture, spatial scale, stresses addressed, mechanistic details, complexity) useful in identifying one or more conceptual frameworks addressing Great Lakes stresses; 2. Using selected criteria, identify one or more conceptual frameworks addressing Great Lakes stresses useful in restoration and protection planning; 3. Identify information gaps (e.g., related to research, monitoring) relevant to the framework(s) selected needed to fill to allow for improved restoration and protection planning using the preferred conceptual frameworks. A background document (developed by the Steering Committee) reviewing conceptual frameworks, their use in the Great Lakes and elsewhere, and potential approaches going forward, was distributed ahead of the summit. The summit itself consisted of a mix of presentations, plenary discussion sessions, and breakout discussion sessions (nominal group method), with reporting back.

The formal working portion of the summit starting on June 28 began with overview presentations, including a welcoming address by Bradley Cardinale on CIGLR and the purpose of working summits, and by Michael Murray with a brief overview of NWF, a summary of the original white paper *Prescription for Great Lakes Ecosystem Protection and Restoration*, and objectives for the summit. These were followed by three brief overview presentations by David Allan on the Great Lakes Environmental Assessment and Mapping (GLEAM) project, Richard Batiuk on restoration efforts in the Chesapeake Bay, and Alan Steinman on restoration work in the Everglades, all in light of the summit objectives around conceptual frameworks. A facilitated discussion followed to clarify objectives and approach for the afternoon session.

For consideration of criteria useful in developing conceptual frameworks, it was determined plenary discussion would be most useful, so the group developed a list of criteria, building on a list developed from the literature. Then participants broke into three discussion groups to consider one or more general conceptual frameworks, drawing on the criteria identified previously, that could be useful in Great Lakes restoration and protection work. Diagrammatic frameworks were captured on flipcharts and computers, as well as accompanying notes elaborating on the diagrams. After the full group reconvened, reporters summarized outcomes from each breakout group, including diagrams produced, and following brief general discussion, the summit was adjourned for the day.

The next day started with a recap by Michael Murray of Day 1 activities, and after group discussion, it was determined that rather than turn to the original objective of identifying information gaps, it would be more productive to continue deliberations on key themes identified the first day. A full group discussion further considered these issues, which are summarized in Question 4.3 in the main body of this report. For the breakout session on Day 2, based on the previous discussion, it was determined the most fruitful activity would be applying a conceptual framework to a particular Great Lakes threat, so each group pursued this tack, with varying degrees of specificity – i.e., one group chose to consider microplastics in a DPSIR-type framework, another group explored issues of “blueness” (or good ecological conditions) and human wellbeing more generally, and the third group delved into the structure of a framework and related governance issues, with a more generic threat.

Following reporting back from each of the three breakout groups, Michael Murray facilitated a brief discussion and summary session on issues that had arisen over the two days, as discussed in several aspects of Questions 4 in the main body of this report, and summarized next steps. It was noted that outcomes of this effort could have multiple applications, including for agency program managers (including through federal restoration programs), for the Parties and International Joint Commission in work involving the Great Lakes Water Quality Agreement, for groups such as the Great Lakes Commission (and its Blue Accounting Initiative), restoration practitioners (both private for- and non-profit), and others interested in Great Lakes protection and restoration. Following acknowledgment of support from CIGLR and thanks to participants, the summit was adjourned midday. Subsequent Steering Committee calls, correspondence with attendees, and additional research further informed the content of this white paper.

***Prescription* Summit Participants**

J. David Allan, Ph.D., Professor Emeritus, School for Environment and Sustainability, University of Michigan

Jon Allan, Director, Office of the Great Lakes, Michigan Department of Natural Resources

Richard Batiuk, Ph.D., Associate Director for Science, Analysis and Implementation, Chesapeake Bay Program Office, U.S. Environmental Protection Agency

John Bratton, Ph.D., Senior Scientist, LimnoTech

Stephen Brandt, Ph.D., Professor, Department of Fisheries and Wildlife, Oregon State University

David (Bo) Bunnell, Ph.D., Research Fishery Biologist, USGS Great Lakes Science Center

Jan Ciborowski, Ph.D., Professor, Department of Biological Sciences, University of Windsor

Timothy Davis, Ph.D., Professor, Department of Biological Sciences, Bowling Green State University

Erin Dreelin, Ph.D., Professor and Director, Center for Water Sciences, Michigan State University

Mark Fisher, President and CEO, Council of the Great Lakes Region

Nicholas Georgiadis, Ph.D., Senior Research Scientist, Puget Sound Institute

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Donald Uzarski, Ph.D., Professor, Director of the CMU Institute for Great Lakes Research, Central Michigan University

Lizhu Wang, Ph.D., Physical Scientist, International Joint Commission

Mary Ogdahl, Program Manager, Cooperative Institute for Great Lakes Research (note-taking, logistics assistance)

Bradley Cardinale, Ph.D., Director, Cooperative Institute for Great Lakes Research (introductory presentation)

*: Steering Committee members in bold.

Appendix B

Conceptual Framework Use in Programs Under the Great Lakes Water Quality Agreement

Conceptual frameworks have been used as part of Lakewide Action and Management Plans (LAMPs) under the Great Lakes Water Quality Agreement (GLWQA). Prior to finalization of the amended GLWQA in 2012, The Nature Conservancy led efforts to develop biodiversity conservation strategies for each of the lakes, involving data synthesis and stakeholder input via workshops. As an example for Lake Erie, the process entailed assessing current biodiversity and developing medium-term targets, identifying critical threats, developing conservation strategies, identifying priority areas, and exploring implications of management actions for ecosystem services.[27] In addition, a general conceptual model (or "situational analysis") was used, in which indirect threats and opportunities affect sources of stress, which lead to stresses themselves, which then have implications for meeting conservation targets. The process also entailed development of conservation strategies, which schematically via a "results chain" indicated how implementation of a strategy leads to threat reduction, and ultimately the goal of meeting conservation targets. The process was involved – for example, agricultural non-point source pollution in the case of Lake Erie had 21 strategy boxes and 49 results boxes.[27]

In terms of current implementation of the LAMPs, based on the most recent LAMP annual reports,[62] there is understandably a focus on GLWQA objectives, though it is not clear to what extent implementation activities are taking into account the earlier biodiversity conservation strategies, or otherwise considering a conceptual framework relating management activities to stress reduction. On the other hand, there are cases of individual threats where more detailed work (including incorporating some type of conceptual framework) has taken place, such as involving addressing nutrients and harmful algal blooms (HABs) in Lake Erie, where there has been extensive modeling work relating nutrient loads to HAB impacts to management actions, including through domestic action plans.[47]

In addition, coordinated science work involving Environment and Climate Change Canada (ECCC) and U.S. Environmental Protection Agency (USEPA) occurs under the GLWQA Science Annex (Annex 10), which includes development or revision of indicators, monitoring, and reporting through the SOGL process, noted above.[63] In addition, coordination occurs through the Cooperative Science and Monitoring Initiative (CSMI), which entails intensive research and monitoring on an individual Great Lake on a five-year cycle, though based on publicly available material, it is not clear to what extent use of conceptual frameworks informs CSMI planning. Finally, the International Joint Commission has explored issues around environmental and human health indicators extensively in the past decade, and an earlier effort included a prioritization process for selecting indicators, to help identify "the fewest that tell us the most". That work group endorsed the use of the driver-pressure-state-impact-response framework briefly reviewed in Question 3.1.[28]

Appendix C

Conceptual Framework Use in Other Large Aquatic Ecosystem Restoration Projects

Ecological restoration has been underway in a number of large aquatic ecosystems over the past two decades, including several in the U.S. (see Question 3.3), and brief summaries of those broader initiatives are provided here.

Chesapeake Bay

Like the Great Lakes, the Chesapeake Bay is a large aquatic ecosystem with multiple jurisdictions and a region that has suffered from multiple stresses through the years. A major emphasis of both research and policy implementation for several decades has been addressing nutrient loading and eutrophication impacts, in particular hypoxia. As part of those efforts, a significant amount of modeling has been done, including developing conceptual models relating dissolved oxygen to the nitrogen and phosphorus cycles, including scenarios of both lower nutrients and excessive nutrients (with hypoxic conditions).[64] As part of an earlier review, a general conceptual model/logic diagram included degradation and restoration trajectories, including with feedbacks involving nutrients and water clarity.[65] A simpler conceptual diagram for the Bay (see Figure C1 below) shows the impacts of increased nutrient loads, leading to increased algal production (and shading of rooted plants), death and decomposition of algae, and resulting anoxia in bottom waters with reduction of fish habitat.[66]

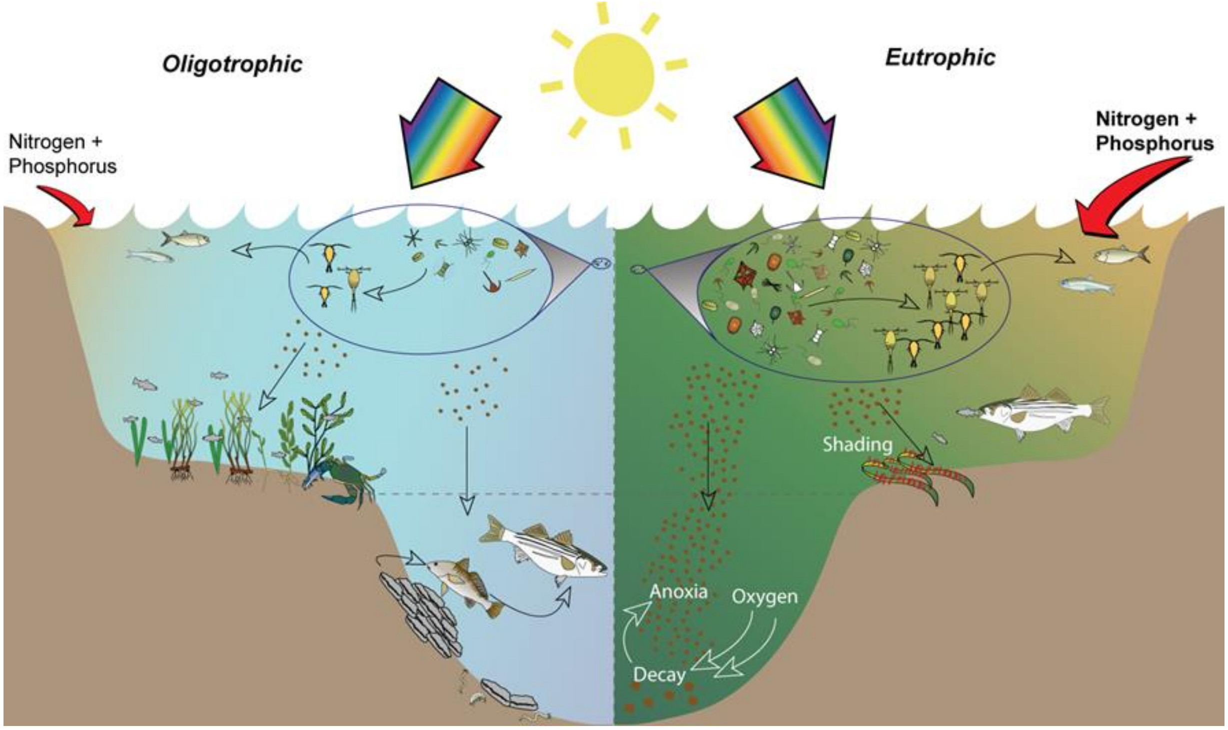

Figure C1. Conceptual diagram of Chesapeake Bay eutrophication.[66]

Kissimmee-Okeechobee-Everglades (KOE) Ecosystem in Florida

As with other large aquatic ecosystems, the KOE ecosystem (including the Everglades) has been historically subject to multiple stresses, ranging across hydrological alterations, development and other land use changes, and nutrient runoff from agriculture. The region has also seen systematic restoration efforts over the past several decades, including development of an applied science strategy starting in the late 1990s. This effort ultimately resulted in development of conceptual ecological models for 11 physiographic regions in the KOE region, with multiple objectives, including as planning tools and to provide general scientific support for the restoration effort. The general framework used is somewhat similar to the driver-pressure-state-impact-response framework described in Question 3, whereby an external driver causes an internal stressor, leading to an ecological effect, and finally a change in one or more ecological attributes (see Figure C2 below).[38] The framework was then applied to individual stressor-effect combinations, such as water management practices ultimately affecting waterfowl populations – see right side of Figure C2. For a given region, more comprehensive diagrams have been developed. For example, the Everglades Ridge and Slough model diagram includes four drivers, nine stressors, 21 effects, and six attributes, with in some cases, multiple sublevels – e.g., the effect of altered nutrient cycling and transport leads to another effect of reduced primary and secondary production, which in turn is coupled with other effects to affect plant community composition and structure.[67] Management actions resulting from the planning have addressed both water quantity (e.g. removing canals and levees to allow more natural sheetflow) and water quality (e.g. reducing nutrients through constructed wetlands).[39]

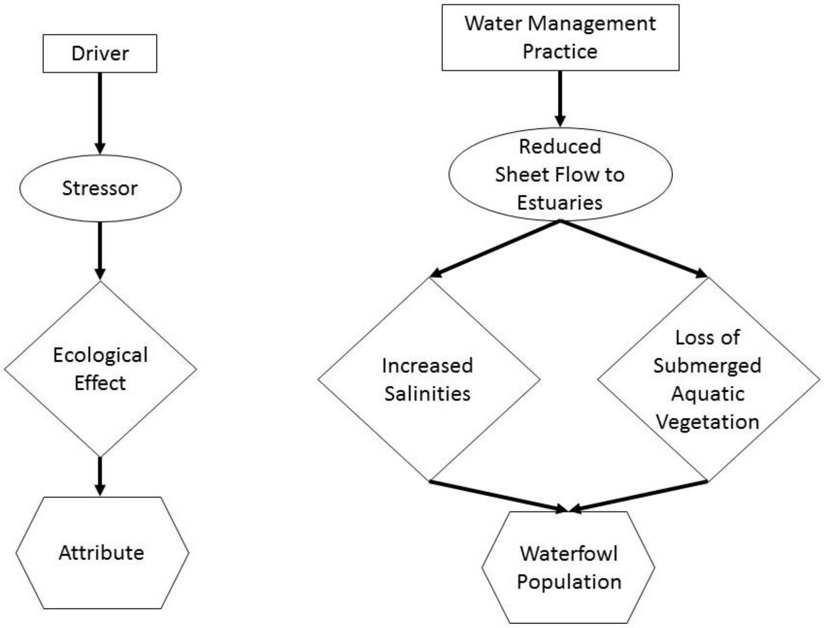

Figure C2. Generic conceptual diagram used in Everglades (left), and application to water management and resulting effects, including changes in waterfowl population (right). Redrawn from Ogden et al. 2005,[38] with permission from the publisher.

Puget Sound

As with the other large aquatic ecosystems discussed here, Puget Sound has suffered from multiple stresses through the decades, while also being the target of extensive restoration work, through the activities of researchers, program managers, and others. One project that has been part of overall restoration is the Puget Sound Nearshore Ecosystem Restoration Project, and to help guide restoration work, a Project Nearshore Science Team explored conceptual models relevant to better understanding nearshore ecosystem processes and the response of the ecosystems to restoration. The effort included an emphasis on ecosystem processes, structures and functions, and the models had a nested architecture, with five levels, ranging from level 1 (considering the domain, including spatial scales and landscape context) to level 5 (considering time frame and variability). The level 3 conceptual model is provided below, in Figure C3. The diagram includes external forcings of energy and matter (water, particles, etc.) affecting three abiotic compartments within the nearshore domain (air, water, sediment), which in turn has energy and matter interactions with biota. Level 4 of the architecture includes a number of submodels addressing specific stresses or impacts – for example, in the case of wetland habitat restoration, a restoration action (e.g. dike breaching) would lead to restored processes (e.g. expanded habitat availability for salmon), then structural changes (e.g. increased habitat edge), and finally functional response (e.g. increased juvenile salmon residence time).[41] Restoration work has more recently included use of *results chains*, which describe the sequence of outcomes following implementation of strategies (which can occur at various points), as documented in addressing shoreline armoring in Puget Sound.[68]

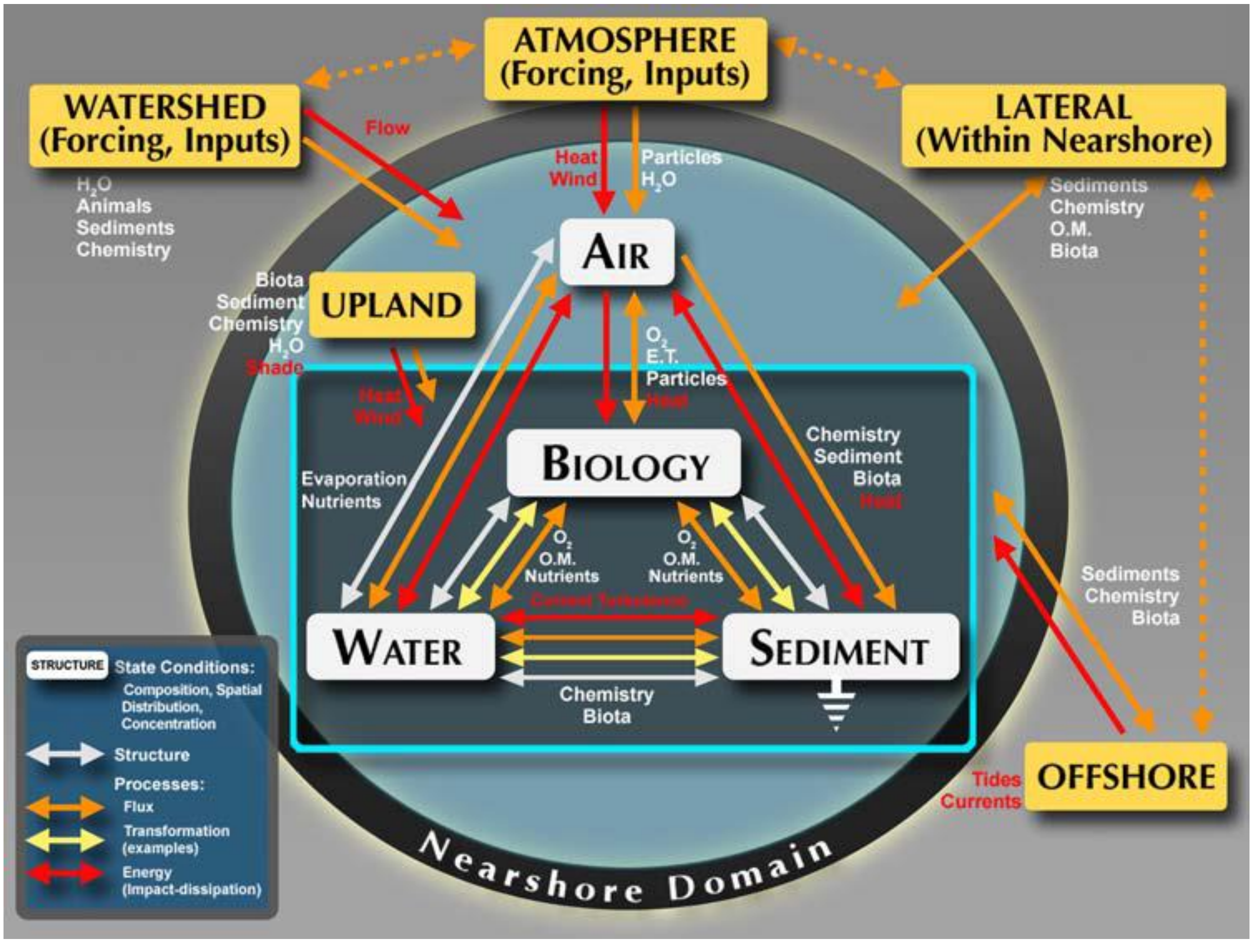

Figure C3. Generic conceptual diagram in level 3 of Puget Sound Nearshore Ecosystem Restoration Program, situated with the five-level modeling framework developed for the program, from Simenstad et al. 2006.[41]

Sacramento-San Joaquin Delta

The Sacramento-San Joaquin Delta ("Delta") watershed drains a large area in California, is important ecologically and to agriculture and other human uses in the area, and has been significantly degraded through the decades, with water supply and water quality impacts. Restoration efforts have also been underway for many years, with many federal and non-federal partners involved, including the Delta Stewardship Council (a California state agency) and other state, local, and regional agencies and nonprofit institutes.[42] State law stipulated that the Delta Stewardship Council develop a Delta Plan, to include "a science-based, transparent, and formal adaptive management strategy for ongoing ecosystem restoration and water management decisions."[43] Furthermore, the California Water Code stipulated coequal goals, referencing "two goals of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem. The coequal goals shall be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place."[69]

In their review of adaptive management in the Delta, members of the Delta Independent Science Board noted that conceptual models are a key component of the adaptive management process.[43] Such work has been carried out in the Delta, as part of the Delta Regional Ecosystem Restoration Implementation Plan. In this process, as noted in the 2012 paper, restoration actions were evaluated and ranked via use of conceptual models, an action evaluation procedure, and a decision support tool.[44] The conceptual models allowed for synthesizing information and making qualitative predictions about ecosystem function and restoration outcomes, while the other components provided additional tools, including considering factors such as the magnitude and certainty of ecological outcomes, risk of adverse outcomes, and finally integrating values into the decision support tool. The conceptual models themselves were based on drivers (which may be managed or not), linkages (e.g. cause-effect), and outcomes (environmental or species-response variables). The diagrams included visual indications of several attributes of linkages, including related to the character and direction of an effect, its importance, scientific understanding, and predictability. In addition, conceptual models were typically developed for more limited aspects of the system, with the potential for outcomes of one becoming a driver in another, and each conceptual model was accompanied by a narrative document with background, references, and other material. For example, the conceptual model for the splittail fish and the transition from resident adult to successful spawning adult is reproduced in Figure C4 below.

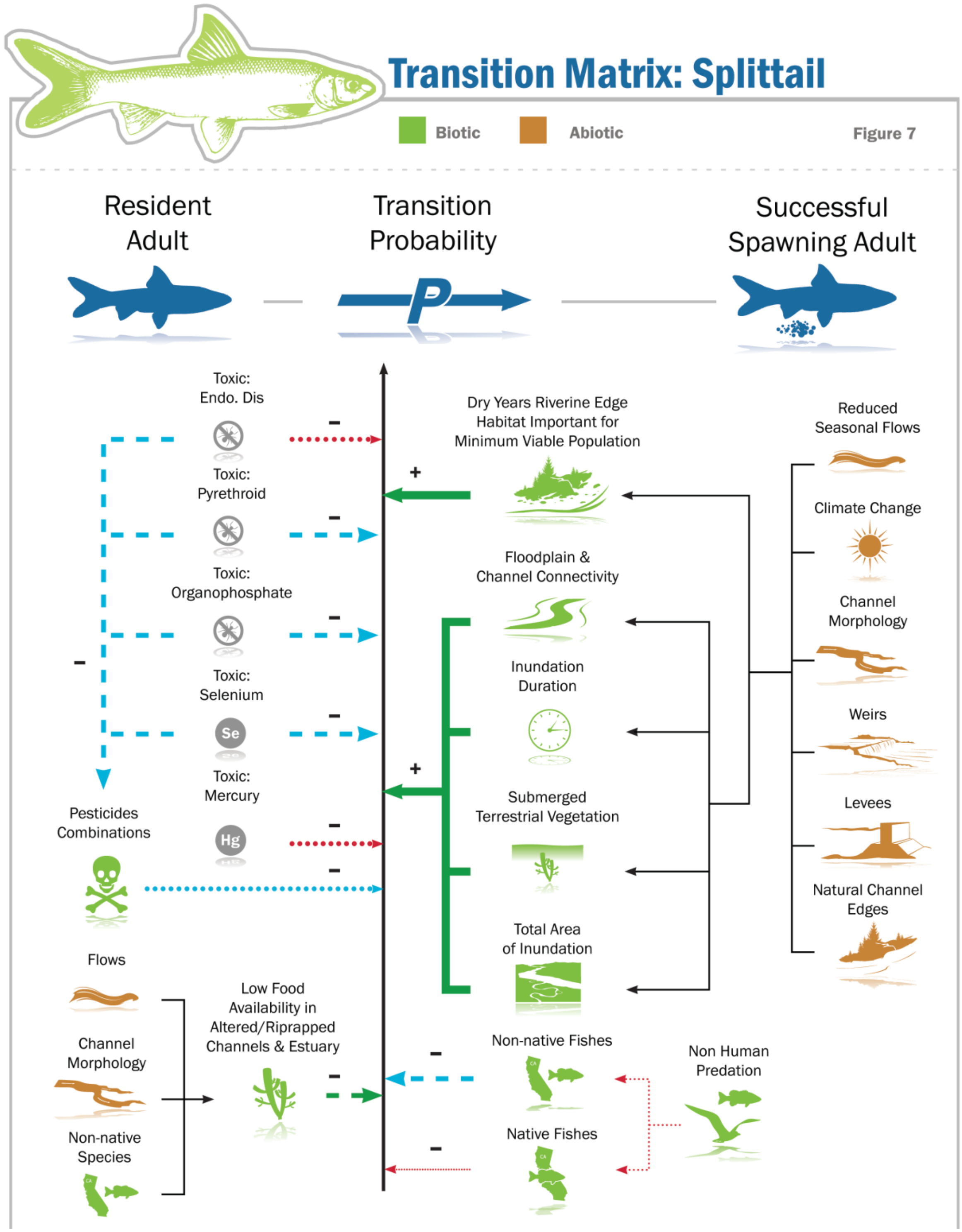

Figure C4. Generic conceptual diagram utilized in the Sacramento-San Joaquin Delta for transition of resident splittail adult to successful spawning adult, with arrows depicting the importance, level of understanding, and predictability of processes, and (+) and (-) signs indicating positive and negative impacts on transition probability, respectively. From DiGennaro et al. 2012.[44]