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Interactions between sediment processes and ecosystem responses in the Green Bay of Lake Michigan

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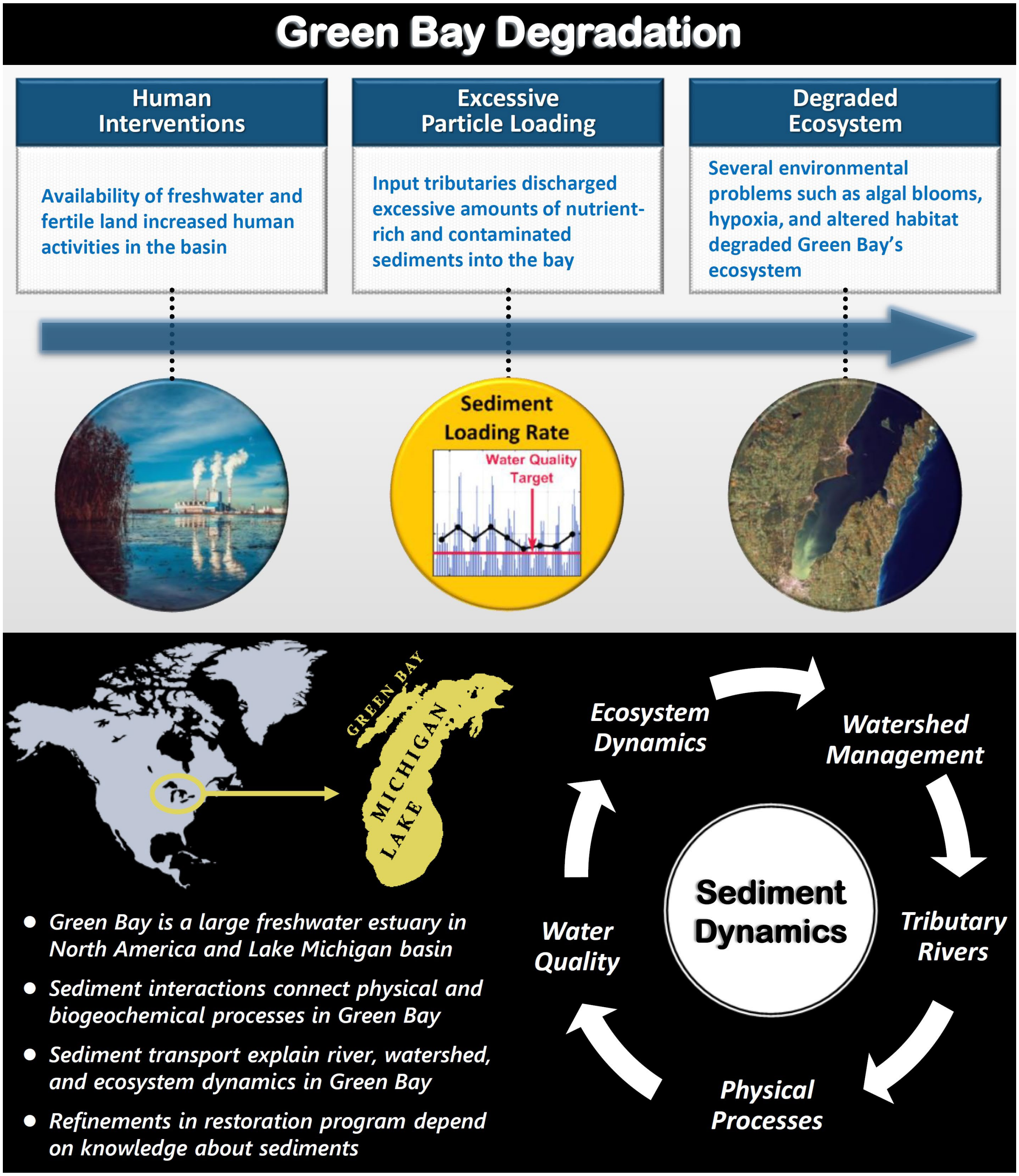
Abstract

Estuaries, in particular freshwater estuaries, provide valuable economic, social, and ecological services, but their ecosystems are often heavily stressed. Located in the Laurentian Great Lakes basin, Green Bay is a large freshwater estuary and a prominent example of a degraded ecosystem due to intensive human interventions and rapid development. Excessive amounts of contaminants and nutrients were discharged to the bay by inflowing tributaries for almost half a century, while in contrast Green Bay's seasonal-, morphological-, and physically-restricted mixing is unable to export a significant portion of those materials out of the bay, i.e., Green Bay behaves as an efficient retention basin for the Lake Michigan. Consequently, several environmental and public health-related issues have risen in Green Bay and turned the lower bay into an area of environmental concern since the 1980s. To address these challenges, restoration programs were developed, including the development of monitoring programs, scientific research, and remedial action plans. There is a consensus that accelerated loading rates of contaminated and nutrient-rich sediments are a major driver of the environmental crisis in the bay, yet the fate and transport patterns of Green Bay sediments are not clearly understood. While field observations in Green Bay are season-limited and costly, advanced computing techniques provided opportunities to refine our understanding of sediment dynamics in this estuarine system. This review of existing knowledge on Green Bay sediment processes can help to better understand the interplay between sediments, and physical/biogeochemical activities in estuarine systems and contributes conceptually to the restoration of degraded aquatic ecosystems.

Keywords: Green Bay, water quality, ecosystem restoration, estuary and lake systems, sediments and nutrients.

Graphical/Visual Abstract and Caption



Green Bay is a prominent example of degraded estuarine systems. Intensive human activities increased loading of nutrient-rich and contaminated sediments into the bay; resulting in decreased water quality and ecosystem degradation. Five decades of restoration efforts revealed links between sediment processes and ecosystem dynamics in Green Bay. Green Bay satellite imagery is from: www.ssec.wisc.edu/airportexhibit/slideshow/index.html?slide=10

1. Introduction

Estuaries, in particular freshwater estuaries, provide valuable economic, social, and ecological services, but their ecosystems are often heavily stressed due to intensive human interventions. Green Bay is the largest bay in the Laurentian Great Lakes, the biggest freshwater system on Earth. In the 1980s, the International Joint Commission (IJC) designated southern Green Bay and the Lower Fox River as an area of concern (AOC) due to several environmental and public health-related issues such as, hypoxia, eutrophication, toxic chemicals including polychlorinated biphenyls (PCBs), harmful algal blooms (HABs), reduced water quality, and lost or altered habitat (IJC, 1982). Due to rapid development and aggressive agricultural and industrial activities, nutrients/contaminants were discharged to Green Bay in excessive amounts beyond the bay's digestion capacity; leading to a significant disruption to the pre-existing hydrologic and nutrient budgets of the system (Klump et al., 1997).

Nutrient and contaminant particles attach to sediments (Tchounwou et al., 2012) and are transported along over land or in the water. Sediment processes can therefore affect the water quality, nutrient availability and recycling rates, eutrophication, and productivity of aquatic systems. High resolution information on Green Bay sediment dynamics is desirable for understanding the environmental problems, as well as to help formulate long-term solutions to those problems and improve management/restoration plans. Figure 1 provides an overview of the Green Bay's degradation, highlighting the links between sediment processes and different components of the ecosystem dynamics.

The restorations of similar freshwater and marine estuarine systems such as Saginaw Bay (Selzer et al., 2014), San Francisco Bay (Cloern & Jassby, 2012), and Chesapeake Bay (Mahoney & Bishop, 2017; Powledge, 2006) have been well studied and reviewed. Harris et al. (2018) examined the main causes of eutrophication and ecological disturbance in Green Bay, and reported achievements of the restoration program. Klump, Bratton, et al., (2018) described five disciplinary areas where science needs to be conducted for successful restoration. Even though the restoration of Green Bay depends on understanding of the interplay between sediment processes and ecosystem responses, restoration planning has not yet focused strongly on that theme.

The main purposes of this review are to fill that gap and synthesize the interdisciplinary research including fieldwork and computational efforts carried out since the early 1970s to study environmental degradation and restoration of Green Bay, with a focus on the role of sediment processes. Green Bay is a prominent example of degraded estuarine systems and reports of Green Bay restoration include a wealth of fieldworks, management plans, experimental, observational-based, and modeling efforts that have been conducted using significant investments and collaboration between agencies/institutions at local, regional, and national levels. We expect that this review will promote estuarine research and benefit the restoration of other estuarine systems elsewhere that suffer from similar environmental degradation problems.

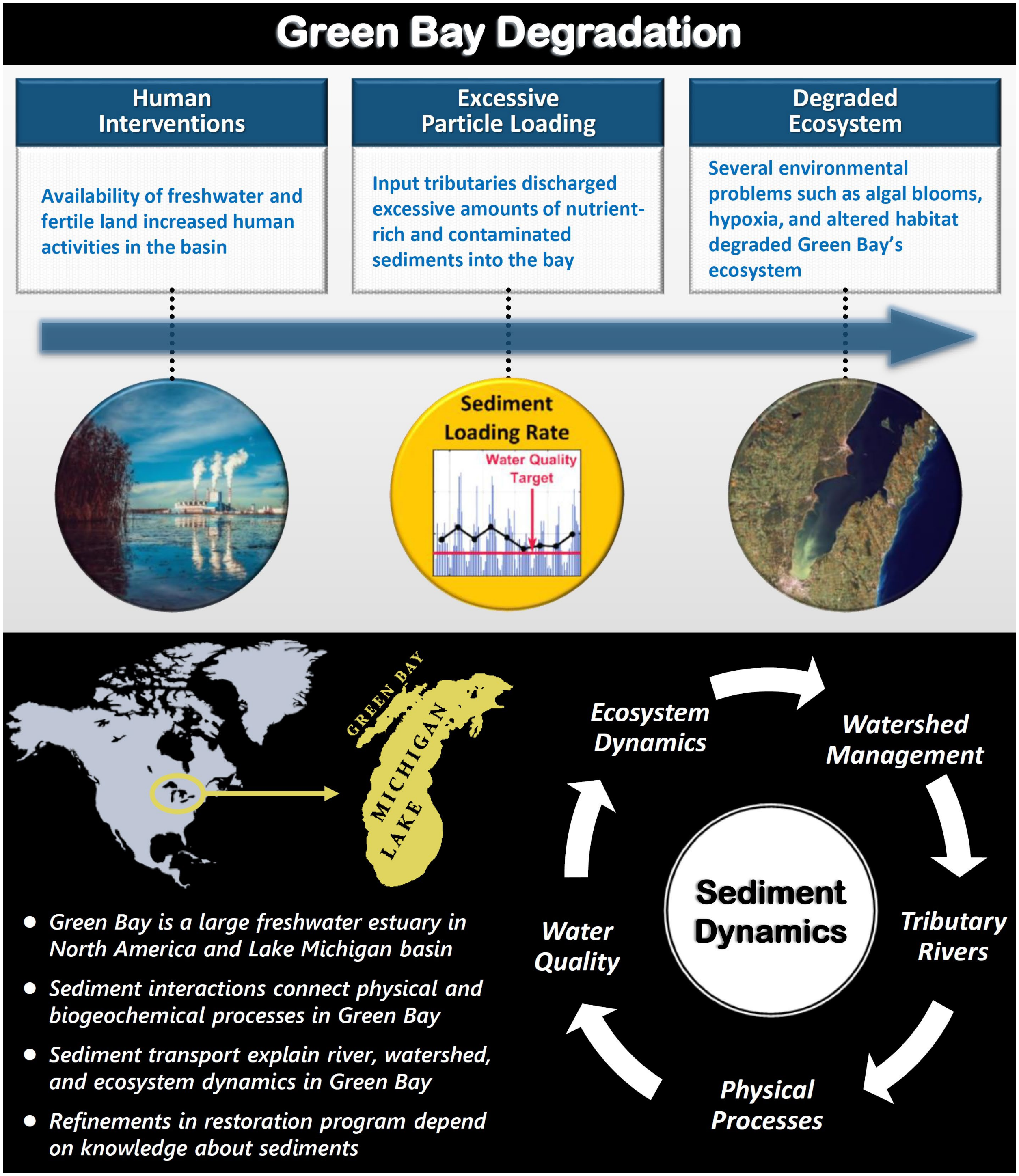


Figure 1. Motivations of the Green Bay restoration program and an overview of the interplay between sediment processes and ecosystem dynamics in the bay.

2. Green Bay estuary and its input tributaries

Green Bay conveys to Lake Michigan major tributary rivers that carry considerable amounts of contaminated and nutrient-rich sediments. The Fox River is one of the largest tributaries to Lake Michigan, with an average annual discharge of ~150 m^3/sec (based on United States Geological Survey, USGS, gage station 040851385 records between 1989-2022) and a main supplier of sediments to the bay. Figure 2 shows the location of Green Bay in Lake Michigan and in the Great Lakes basin, Green Bay AOC, and the Fox River. The Lower Fox River begins at the north end of Lake Winnebago where it picks up about 20%

of its sediment loads (Beversdorf et al., 2018) and flows 64 km northeast towards Lake Michigan, draining an area of 16,395-km^2. On average, Fox River loads ~350 tons of total suspended solids (TSS) per day into Green Bay (Khazaei, Hamidi, & Nabizadeh, 2018). Among the eleven major tributaries that drain into Green Bay, the Fox River alone accounts for roughly 50% of the inflowing discharge (Khazaei et al., 2023), two-thirds of the nutrients loading, and 70% of the total phosphorus (TP) load into the lower bay (Harris & Christie, 1987; Qualls et al., 2007). The Menominee River is the second largest tributary into lower Green Bay by discharging volume, yet nutrients and particles loading is one order of magnitude less than the Fox River (Figure 3).

Sidebar 1

Green Bay: a prominent example of a degraded ecosystem

Located in the Laurentian Great Lakes basin, Green Bay is a large freshwater estuary and a prominent example of a degraded ecosystem mainly due to intensive human interventions and excessive loading of nutrients and particles to the bay. Long ice-cover duration, restricted mixing, massive freshwater intrusions from Lake Michigan, and system morphology limit exchange between lower and upper bay areas and Lake Michigan, resulting in increased residence times and reduced efficiency in transporting particles out of the bay. Significant efforts were made to understand and address these bio-environmental problems and revive Green Bay. Existing literature on Green Bay restoration includes a wealth of reports on field and remedial works, management and conservation plans, as well as experimental, observational-based, and modeling efforts that are conducted using significant investments and collaboration between multiple agencies/institutions at local, regional, and national levels in more than five decades. Design and planning for the Green Bay restoration is a multi-faceted task that requires deep understanding of the various aspects of system dynamics including physical, biogeochemical, hydrological, and ecosystem processes.

Figure 2. Green Bay and major lower bay tributaries. Bottom insets show locations of Lake Michigan in the Great Lakes basin, the Green Bay and Fox River Area of Concern (AOC), and the Chambers Island cross-section that defines the boundary between lower and upper Green Bay areas.

For decades, human activities in the watershed has intensified soil erosion and production of contaminants in the watershed, leading to an increase in pollutants and nutrients in the river (Klump et al., 1997; Qualls et al., 2013). Between 1954 and 1971 paper companies discharged to the Lower Fox River high concentration of PCBs used to make carbonless copy paper.

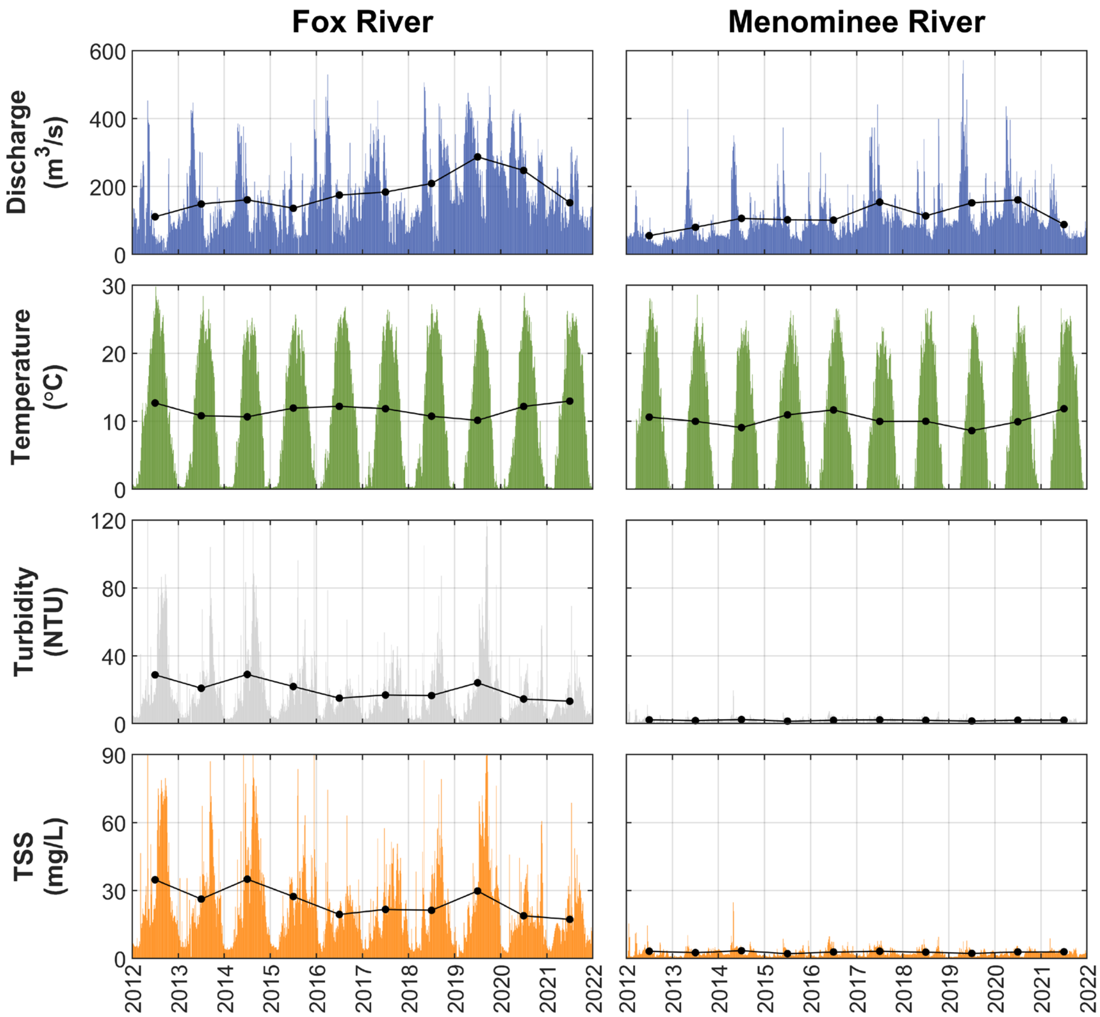


Figure 3. Daily observed inflowing discharge, temperature, turbidity, and simulated total suspended solids (TSS) at the mouth of the Fox and Menominee Rivers during the 2012-2022 period based on the observations of USGS gage stations 040851385 and 04067500, respectively. Black dots show yearly averages.

3. History of Green Bay degradation and restoration efforts

Green Bay has a long history of environmental degradation and recovery since 1700s. According to Harris et al. (2018), the ecosystem remained mostly unchanged during the fur trade and fishing-based economy of the 1700s and early-1800s. However, with the growth of the lumber industry and land sales between 1834-1836, natural resource exploitation began. The industrial and agricultural expansion between 1870-1930 increased nutrient, sediment, and organic waste loadings into the tributaries, resulted in strong eutrophication and degradation of Green Bay. The Federal Clean Water Act of 1972 provided opportunities to address the issue (Harris et al., 1987) by reducing waste loads and discharge of biochemical oxygen demand through the Wisconsin Pollution Discharge Elimination System, but eutrophication still remained high in Green Bay.

In the late 1960s, the University of Wisconsin Sea Grant Institute started a program to better understand biogeochemical and physical processes in Green Bay, which resulted in establishment of a sub-program in the University of Wisconsin-Green Bay campus in 1978. Significant investments were made on multiple projects to better understand the fisheries ecology, sediments, trophic dynamics, chemical, physical, and socio-economic aspects of Green Bay. Those activities brought Green Bay to the attention of a broader audience such as the Great Lakes Fisheries Commission and Great Lakes Ecosystem Rehabilitation program and was resulted in designation of Green Bay as one of the 43 AOCs in the Great Lakes basin by IJC in the late 1980s. Later, a Remedial Action Plan (RAP) was established by WDNR that identified 16 key actions for ecosystem recovery and 14 beneficial use impairments, six of which were pertinent to excessive loading of phosphorus and suspended solids.

As a part of the RAP, Green Bay Metropolitan Sewerage District, now NEW Water, established the Aquatic Monitoring Program (AMP; www.newwater.us/programs/aquatic-monitoring) in the 1980s to collect and analyze water quality parameters in the Fox River, East River, and lower Green Bay. That program supports research on the Fox River total maximum daily load (TMDL) assessments, restoration efforts for Green Bay AOC, and watershed management projects. A 1993 comprehensive analysis of Secchi depth and its relationships with Chl and abiotic solids in Green Bay AOC highlighted the need for an in-depth understanding of phosphorus and TSS in the bay, and a 1992 study found that most of the phosphorus and TSS in the lower bay are originated from rural sources (Harris et al., 2018).

By late 1980s, research was focused on the quantity and sources of nutrients and suspended particles, but lacked information on their fate and transport. One of the earliest efforts developed to address that gap was the Green Bay Mass Balance Program (GBMBP), a four-year comprehensive monitoring and research program initiated by the US Environmental Protection Agency (USEPA) in 1989 to investigate toxic chemicals in the Fox River and Green Bay ecosystem (USEPA, 1989; Velleux et al., 1995). Hawley and Niester (1993) conducted an analysis of horizontal sediment transport in Green Bay based on extensive field measurements. Researchers at the University of Wisconsin-Milwaukee (UWM) and UW-Green Bay collaborated between 2010 and 2014 to create an analytical tool that is useful for managers and stakeholders to monitor and visualize nutrient loadings into the bay, and ways it responds to changes in climate conditions, land uses, and management/restoration actions (NOAA, 2017). That project also included development of multiple models for monitoring water quality, circulation, thermal structure, and biogeochemical activities in the bay (Bartlett et al., 2018; Bravo et al., 2015; Bravo, Hamidi, et al., 2017; Grunert et al., 2018; Hamidi et al., 2015; H. J. Harris et al., 2018; Kaster et al., 2018; Klump, Brunner, et al., 2018; Klump, Bratton, et al., 2018; P. Lin et al., 2018; Zorn et al., 2018). More recently, an in-depth study of sediment transport in Green Bay and Lake Michigan was conducted using a 3D physically-based sediment transport model (Khazaei et al., 2021).

Fieldwork and remedial actions complemented research in addressing Green Bay degradation. WDNR partnered with USEPA to develop a dredging program as a part of the Sediment Management Unit 56/57 Demonstration Project to remove the PCB-contaminated sediments from the Fox River bed (McCallum et al., 2001; Steuer, 2000). In one of the largest sediment cleanups worldwide, nearly 5 million cubic meters of sediment were dredged in 17 years and led to removal of more than 95% of the deposited PCBs (https://dnr.wisconsin.gov/newsroom/release/37611).

In 2012, Brown County started a construction project in the southwestern part of the bay to restore Cat Islands ecosystem to their historical condition (www.portofgreenbay.com/cat-island-restoration-project/). The project was supported by geomorphic assessment, hydrodynamic, wind-wave, and sediment transport modeling. Important outcomes of the restoration project include 30-50 years' worth of disposal capacity, beneficial reuse of dredged material for construction of the islands that provide 272 acres of habitat for birds, fish and mammals, a wave barrier that protects 1,225 acres of shallow water and wetland habitat, and improved water clarity. It was hypothesized that re-introduction of islands would affect water clarity impairments related to Fox River and Duck Creek plumes, however, there might be a need to reduce particle loading from tributaries to historical levels of prior to 1970 (Baird and Associates Ltd., 2005).

Harris et al. (2018) identified two key areas of Green Bay restoration: contaminated sediment remediation, and management of non-point source pollutions. Evidence of these improvements are reported in analysis of sediment dynamics such as a 70% reduction of PCBs in the lower reaches of Fox River. A comprehensive analysis of the water quality data in Green Bay also showed that setting TMDL levels of 0.1 mg/L for TP and 20 mg/L for TSS will result in significant improvements of Secchi depth in the bay (Wisconsin DNR, 2012). Those findings show that better understanding the links between sediments and biogeochemical aspects of the Green Bay ecosystem are crucial in future management and climate scenarios.

4. Feedbacks between sediment dynamics, water quality, and ecosystems processes

The spatial and temporal distributions of biological fields are closely coupled with sediment transport in Green Bay. Those distributions, in turn, can cause beneficial use impairments such as water quality and benthos degradation, loss or degradation of wildlife habitat, eutrophication or undesirable algae (https://www.epa.gov/great-lakes-aocs/lower-green-bayfox-river-aoc). This section starts by summarizing relevant studies on the coupling of ecosystem processes (e.g., water quality, influence of nutrients and contaminants, hypoxia, and algal blooms) and physical environment in Lake Michigan. Subsequent subsections describe existing evidence of that coupling, specifically in Green Bay.

Chen et al. (2004) investigated the impacts of suspended sediment on the ecosystem in Lake Michigan, during plume events in 1998 and 1999. They found that nutrients were maintained through nutrient release from suspended sediments within the plume, while it was supplied by current advection and diffusion in the interior. The modeling experiment was supported by data on surface sediment concentration converted directly from cloud-free SeaWiFS R_{rs}(555) imagery, phosphorus concentration measured at five transects, satellite-derived Chl, and water samples and continuous records of a Plankton Survey System (PSS). Another 3D fate and transport model of Lake Michigan in the Milwaukee nearshore zone highlighted the importance of sediment deposition and resuspension events in phosphorus cycle and change in *Cladophora* population in coastal areas (Bootsma, 2009; Bravo, Bootsma, & Khazaei, 2019; Bravo, Bootsma, & Khazaei, 2017; Fillingham, 2015). Both of these modeling efforts in southern and eastern Lake Michigan showed that the sediment resuspension can affect the ecosystem in two opposite ways. While resuspension events can increase light attenuation, sediment plume increases nutrients availability after plume appearance.

Rowe et al. (2017) investigated the influence of invasive mussels, phosphorus loads and climate on patterns of productivity in Lake Michigan. For that study they used the Finite-Volume Community Ocean Model (FVCOM) to implement a nutrient-phytoplankton-zooplankton-detritus (NPZD) model with the addition of a fifth compartment to represent benthic filter feeder (dreissenid mussel) biomass. The model development was supported by observations of water surface temperature, continuous profiles of temperature, vertically-resolved temperature, Chl-a, TP, and dissolved phosphorus (DP), DP measurements during the EEGLE project (1998-2000), particulate organic carbon (POC) concentrations, zooplankton biomass, phosphorus in mussel tissue, and satellite-derived light penetration. Rowe et al.'s (2017) model did not include a sediment transport module.

Water quality, benthic characteristics, and the ecosystem of Green Bay have been the subject of studies for decades (e.g., Auer and Canale, 1986; DeVilbiss et al., 2016; Groff and Kaster, 2017; Harris et al., 1994, 1987; Howmiller and Beeton, 1971; Klump et al., 2009, 1997; Kubiak et al., 1989; Lin et al., 2016, 2018; Maccoux et al., 2013; Pearson et al., 1996; Qualls et al., 2007; Rygwelski et al., 2012; Zhang et al., 1993). There is a consensus in those studies on the importance of understanding the links between sediment loading into and transport across Green Bay, and the formulation of solutions for the environmental problems in the bay.

4.1. Green Bay water quality monitoring

Water quality directly demonstrates the severity of environmental problems. NEW Water’s AMP supports Green Bay restoration program by collecting water quality information on Northeast Wisconsin’s waters since 1986. The dataset is one of the most extensive water quality datasets in the Great Lakes and includes data on nutrients, contaminants, and numerous physical parameters including dissolved oxygen, temperature, light, suspended solids, and algal concentrations. Analyses of this dataset have shown relationships between suspended solids/sediments and various water quality parameters in lower Green Bay (Khazaei, Hamidi, & Nabizadeh, 2018; Khazaei, Hamidi, Houghton, et al., 2018; P. Lin et al., 2016; Qualls et al., 2007, 2013). Based on an initial analysis of that dataset, Figure 4 shows that Chl-a, turbidity (Tu), TP, and chloride (Cl^-) are significantly correlated with TSS. The main reason for those relationships is that pollutants and nutrients attach to sediments, and are then carried along or buried in the bottom. The availability of datasets like the NEW Water’s data can support the development of coupled physical and biogeochemical models discussed above.

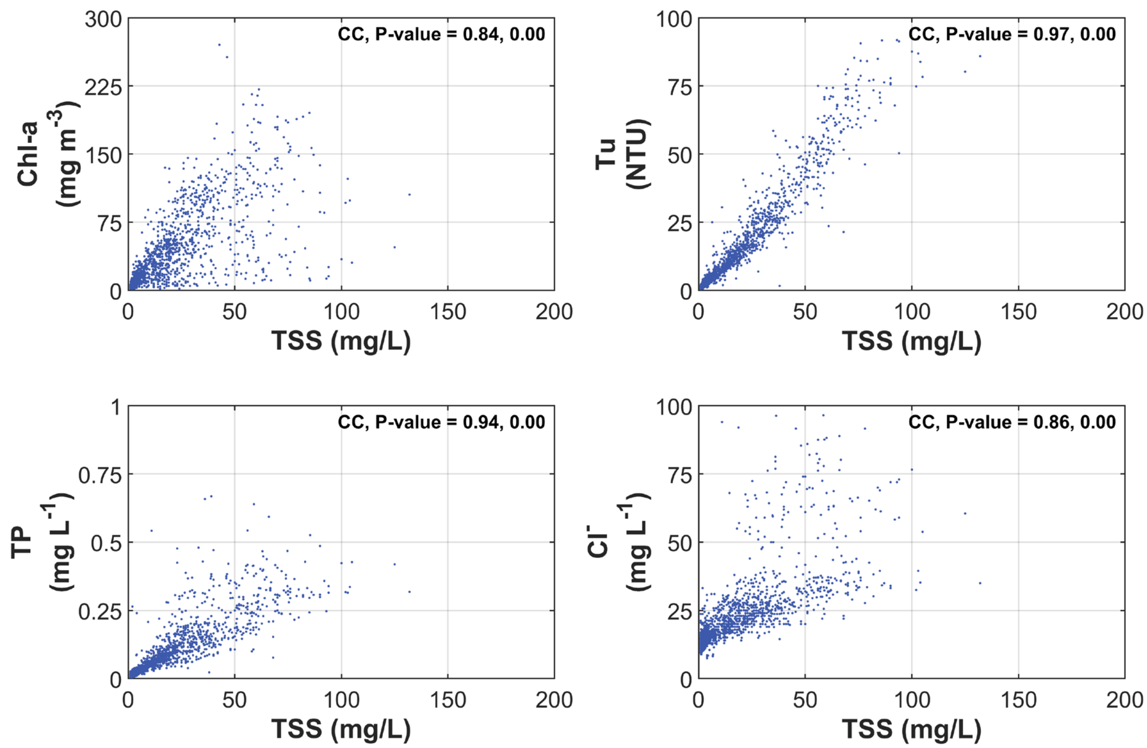


Figure 4. Relationships between concentration of total suspended solids (TSS) and water quality parameters. CCs denote Pearson's correlation and are calculated based on observations of TSS, Chlorophyll-a (Chl-a), turbidity (Tu), total phosphorus (TP), and chloride (Cl^-) in the Green Bay AOC during the period of 2011-2016 years.

4.2. Carbon and nutrients

Excessive loading has been reported as a primary cause of other environmental problems in Green Bay beyond contamination. Research has shown that nutrients and carbon are the limiting factor and the principal element of water quality control in freshwater estuaries globally and in the Great Lakes, including Green Bay, Saginaw Bay, Bay of Quinte, western Lake Erie, harbors, and urban coastal areas (Klump et al., 1997; Luo et al., 2017; Millard & Sager, 1994). As discussed in multiple articles, including Chen et al. (2004) and Rowe et al. (2017) studies, sediment-nutrient interactions, in particular, phosphorus loading is a key component in biological models of Lake Michigan.

Based on the analysis of sediment samples, Klump et al. (2009) carried out carbon and nitrogen budget analysis for Green Bay through direct measurements of input fluxes and sediment burials, complemented with estimates of export to Lake Michigan and production rates obtained through the phosphorus cycle. That analysis showed input carbon from rivers is in balance with three major output fluxes—39% transport to upper Green Bay and exchanges with Lake Michigan, 26% sediment burial, and 35% release to the atmosphere in form of CO_2. Nitrogen recycling was also roughly estimated indicating 54% transport and 24% sediment burial of the total inputs with a 22% gap in the budget estimation.

Klump et al. (1997) reported that the Fox River sediment transport provides about 70% of the annual phosphorus load to the bay. Green Bay acts as an efficient nutrient trap and retains almost 70-90% of the external phosphorus before flowing into the main body of Lake Michigan. Most of this phosphorus is basically buried and reserved in the bottom sediment layers. Given that phosphorus is a principal water quality parameter in freshwater environments, it is important to obtain comprehensive knowledge on the phosphorus budget in these systems. That knowledge is dependent on the extent to which phosphorus will be held with the sediments, or recycled back into the water column. To reach an equilibrium state, in terms of no significant increase in phosphorus concentrations in the bay, it was suggested that at least 50% of the annual input must be exported out of the bay (Klump et al., 1997). WDNR has addressed the high phosphorus levels in Green Bay by analysis of phosphorus and TSS in the context of Fox River TMDL program. Statistical analyses have shown that reducing TP and TSS TMDLs could result in improvement of Secchi depth and water quality and provide favorable environment for aquatic vegetation and ecosystem (H. J. Harris et al., 2018).

4.3. Hypoxia

While the studies described in this section focus on formation of hypoxic zones in Green Bay, they contain relevant existing information on processes simulated by NPZD models, e.g., the relations among nutrient loading, light availability, primary production, phytoplankton, benthic respiration, and bacteria. There have been recent advances on the research on hypoxia in Green Bay. Sampling temperature and dissolved oxygen profiles during the 2009-2015 period has shown consistent summertime hypoxic zones in southern Green Bay benthic zone (Klump, Brunner, et al., 2018) with some locations in the southern bay experiencing dissolved oxygen concentrations lower than the water quality standard of 6 mg L^{-1} about 60% of the summertime stratification. During the May-September period, the hypoxic season could last two weeks to three months depending on thermal stratification, oxygen consumption near the bottom, organic carbon loading rates, and effective physical forcing drivers of the bay.

Klump et al. (2017) showed the process of the evolution of a dead zone in Green Bay (Figure 5). Excessive nutrient loading from the Fox River leads to persistent and massive algal blooms, including cyanobacteria. Shallow depths and rapid settling rates lead to the deposition of highly labile organic matter in bottom sediments, which in turn supports high rates of benthic respiration, driving hypoxia under stratified conditions in the mid to late summer period (Klump et al., 2017; Labuhn, 2017). High-resolution analysis of phosphate in Green Bay has shown consistency between increased rates of dissolved oxygen consumption and dissolved phosphate concentration in the bay (Zorn et al., 2018). Cold water that flows from Lake Michigan into Green Bay has also a significant role in the promotion of hypoxic zones (Grunert et al., 2018).

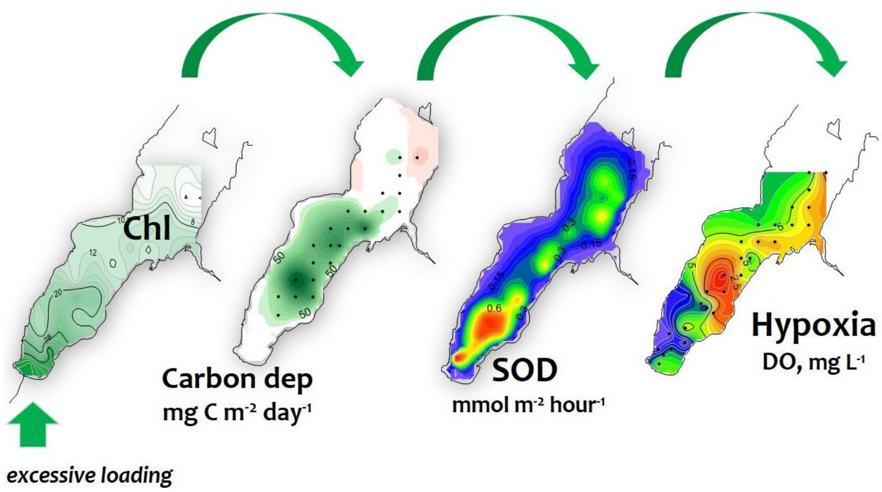


Figure 5. Evolution of a dead zone in Green Bay. From left to right: Chlorophyll (Chl) bloom, Carbon deposition, sediment oxygen demand (SOD), and Hypoxia patterns. Darker Green Colors indicate higher Chl concentration and Carbon deposition rates. Also, warmer colors indicate higher SOD and Hypoxic conditions.

Inconsistency between different components of the cycle in Figure 5 is due to a temporal disconnect between the occurrence of each event, as well as Fox River turbid plume along the eastern shorelines, formation of gyres, and thermal stratification that are all driven by wind, air-water interactions, and geomorphology of the system. Significant benthic respiration and higher deposition rates of fresh material indicates that such deposition drives sediment oxygen demand in the bay. LaBuhn and Klump (2016) showed that summertime primary production in Green Bay is a key driver of respiration in the benthos and at the sediment-water interface, which is a dominant cause of hypoxia. This recent information has become available by extensive fieldwork and analysis of sediment samples in Green Bay, Future field and models should focus more on detailed understanding of surface sediments for investigations of hypoxia and its major drivers.

4.4. Lost or altered habitats and harmful algal blooms

This section reviews studies on the relations among nutrients, invasive species, Chl-a concentration, algal blooms, and invasive species in Green Bay. Those processes are essential processes simulated by models such as the NPZD expanded to represent benthic filter feeder (dreissenid mussel) biomass implemented by Rowe et al. (2017).

A dramatic example of non-native species invasions is the population bloom of the zebra and quagga mussels in the Great Lakes since 1980s. Analysis of the pre- and post-invasion samples of water quality in lower Green Bay by Qualls et al. (2007) have shown that zebra mussel has changed Chl-a concentration due to their filtering activities. In addition, zebra mussels have imposed a strong trophic gradient and altered the chlorophyll-phosphorus relationship in the Green Bay AOC. Mussels alter the bacterial communities in lake sediments which are critical to nutrient regeneration and cycling in the lake habitat (P. O. Lee et al., 2015). Although, spatiotemporal distributions of nutrients are largely controlled by internal recycling and water-sediment dynamics, mussels' invasion have added to complexity of this issue (Shen, 2016; Shen et al., 2020). Particulate phosphorus (PP) that is excreted by mussels will be stored in sediments (Bravo et al., 2019). Zebra mussels typically use hard substrate for attachment, but they will attach to submergent vegetation when rocky substrates are not available. Research has shown that mussel invasion has changed patterns of algal growth in Green Bay in a way that Microcystis and Anabaena have increased in population leading to Cyanobacteria blooms in the system (De Stasio et al., 2014).

Cyanobacterial harmful algal blooms (cyanoHABs) have been observed in the Great Lakes since the mid-1990s (Boyer, 2008; Miller et al., 2017). Existence of cyanobacteria in Green Bay has been reported previously (De Stasio et al., 2008). A recent transect sampling of Green Bay in 2014 revealed that concentration of microcystins is on the verge of recreational risk levels in lower Green Bay (Miller et al., 2017). Given the reliance of HABs on nutrient availability, sediment transport plays a major role on the spatial distribution of cyanoHABs across the bay. Analysis of the cruise samples collected in 2014 and 2015 at the mouth of the Fox River and lower Green Bay indicates that existence of the cyanoHABs is positively correlated with Chl concentration (Bartlett et al., 2018). Also, as the distance from the mouth of the Fox River increases, the mean concentration of cyanoHABs decreases, because of the explicit relationship between the Fox River TSS loading and HABs in the lower Green Bay.

In contrast to cyanoHABs, green algae have decreased in abundance and biomass, while diatoms are increasing as a consequence of new conditions imposed by mussels. Zebra mussel invasion has also affected benthic invertebrate abundance and diversity in Green Bay (Reed et al., 2004). Invasion of the non-indigenous species such as Asian clam (Smith et al., 2018) or predatory Bythotrephes longimanus (Merkle & De Stasio, 2018) disturbs the ecological balance of the system. At the same time, some native species that used to be essential elements in the life cycle of the bay ecosystem went extinct. For instance, Hexagenia mayfly provides an important food source for fish species, however, it has not been observed since 1955 in Green Bay (Kaster et al., 2018). Hypoxia and PCB-contaminated sediments are the most predominant barriers to mayfly egg stockings in Green Bay. A congener-specific PCB analyses of Green Bay sediments showed that quagga mussel tissue and round goby PCB concentrations follows sediment PCB concentrations in nearshore areas of the lower bay (Macksasitorn et al., 2015). Findings of these studies highlighted the need to better understanding of trophic details through comprehensive analysis of benthos and sediment fields.

4.5. Influence of contaminants

Contaminants are introduced to the Fox River and Green Bay through different processes, in particular, anthropogenic activities such as agricultural and industrial operations (Wenger & Harris, 2010). A distinctive example of such activities in the Lower Fox River watershed was the release of ~120 tons of PCBs during the 1957-1971 period into the river by paper industry (Lick, 2009, p. 5). About 85% of the PCBs in the bay were delivered by the Fox River, while atmospheric deposition also contributed a small portion (Hermanson et al., 1991).

As part of the GBMBP, Manchester-Neesvig et al. (1996) found significant amounts of PCBs buried in the benthic layer of Green Bay, with the most abundant PCB-contaminated sediments found in the deposition zone that corresponds to the Fox River plume. The relationship between sedimentation patterns and spatial distribution of sediment-bound PCBs remained unanswered in that study due to lack of a sediment transport model. Combination of data from GBMBP and sampling nearshore sediments during August 2012 showed nearshore sediment dynamics and Fox River plume are still playing major role in PCB distribution in the bay's surface sediments (Macksasitorn et al., 2015). A collaborative effort that involved the WDNR between 2004 and 2009 reported a 70% reduction in PCBs in the water column (Wisconsin DNR, 2012), and a subsequent field survey showed an 83% reduction between 2006 and 2017 (Harris et al., 2018). Despite removal efforts, storm-driven resuspensions can quickly increase PCB concentrations in the water column as long as bottom sediments contain PCB.

Industrial release of PCBs in the aquatic environments has led to contamination of edible fish within the Great Lakes watershed and in particular Green Bay (Macksasitorn et al., 2015). Hg emitted by coal-fired power plants has also contributed to the contamination of freshwaters and is a public environmental health problem for decades. In addition to PCBs and Hg, analysis of the sediment cores showed the existence of toxic substances such as As, Pb, Zn, Cd, and Fe in Green Bay (Christensen & Chien, 1981; O'Loughlin & Chin, 2004). Those substances are primarily introduced by anthropogenic sources. A recent study showed that reduced human interventions and land-based activities could result in improvement of water quality in the Great Lakes estuaries (S. A. Hamidi, Abbasi, & H. Hamidi, 2021). Given the abundant presence of these contaminants within the Green Bay sediments, their resuspension and deposition and circulation could be understood through sediment dynamics.

5. Green Bay as an efficient sediment trap

Green Bay drains one-third of Lake Michigan watershed and receives approximately one-third of the total suspended matter entering the lake despite containing less than 5% of the Lake Michigan volume (Klump et al., 2009). The physical characteristics of Green Bay have made the sediment transport from the bay to Lake Michigan inefficient, i.e., limited mixing, long period of ice cover, lake water intrusion, and morphological condition, shape, and geometry of the bay (~20 km wide and ~190 km long) do not allow for a dominant northward transport to the lake.

Early investigations of mixing dynamics in Green Bay were conducted by Modlin and Beeton (1970) based on differences in the conductivities of the bay, Fox River, and Lake Michigan, They showed that Lake Michigan-Green Bay exchange has an important impact on flushing rates of the bay (Labuhn, 2017). Miller and Saylor (1993, 1985) described circulation regimes in Green Bay based on field measurements of currents and water temperature at several stations, including the four main passages between Green Bay and Lake Michigan: Death's Door, Rock Island, St. Martin Island, and Poverty Island. In addition to a counterclockwise circulation in the bay when dominant southwesterly winds were blowing, they found two-layered currents in Green Bay and strong stratifications during summer. The Fox River inflow runs at the surface layer while cold hypolimnetic lake water flows into the bay and extends southward, maintaining stratification and increasing residence times.

Hamidi et al. (2015) developed a 3D hydrodynamic model for Green Bay based on the Princeton Ocean Model (POM; Blumberg and Mellor, 1987). That model examined the spatiotemporal patterns of the atmospheric heat flux, the advective heat transport, and cold lake water intrusions. Compared to observation-based models, their research provided more details of the circulation patterns over the entire Green Bay. Their results, in particular Figure 6 in Hamidi et al. (2015), showed that, during July and August, southwesterly winds drive three clockwise and two anticlockwise gyres inside the bay and further north of the Chambers Island. Those results are compatible with cyclonic circulation patterns found for Lake Michigan (Beletsky & Schwab, 2008, 2001).

The circulation and thermal regime in Green Bay are dominantly driven by the momentum fluxes that are generated by wind, the heat flux at the air-water surface, Coriolis effects of the Earth's rotation, thermal stratification, and the topography of the basin (Bravo, Hamidi, et al., 2017). Analysis of the thermal regime by Hamidi et al. (2015, 2013) and Bravo et al. (2015) indicates continuous stratification between June and September in deeper waters of the bay. Mixing events occur due to the wind blowing from the west, which increases bottom temperature and dissolved oxygen concentration. Wind fields are one of the main forcing factors of circulation, which in turn drive biogeochemical processes in the bay such as sedimentation, residence and flushing times, thermal stratification, and evolution of hypoxic zones.

Wind-driven waves and upwelling-downwelling cycles play an important role in the hydrodynamic patterns of Lake Michigan (Beletsky et al., 2006). Waples and Klump (2002) showed that wind conditions can significantly affect water mass exchange between Green Bay and Lake Michigan, bottom water temperature, oxygen demand, and benthic biogeochemical processes. There is evidence that extreme winter conditions during 2013-2014 may have imposed a shift in the thermal regime of Lake Michigan (Gronewold et al., 2015). Grunert et al. (2018) analyzed the thermal structure of Green Bay during 2012-2013 years using field observations across the bay. They showed that cold-water intrusion from Lake Michigan affects thermal regime of the southern bay and the stratification event, and that the effect depends on the climate conditions on a year-to-year basis.

As mentioned above, ice periods in Green Bay restricts mixing and transport of sediments from south to north. Wang et al. (2018) found a high probability of ice cover in Green Bay during the December-April period, with annual maximum ice cover data indicating almost complete coverage in January-March. Analysis by NOAA Great Lakes Environmental Research Laboratory (GLERL) from 2012-2017 showed ice cover lasting from early November to late April (>150 days) in Green Bay. Although loading rates decrease significantly during this period, ice cover slowdowns the mixing activities in the bay; leading to more sediment deposition and nutrient burial in the benthos. Figure 6 shows ice cover in the Great Lakes in mid-February of four selected years since 1990, based on the NOAA's Great Lakes Ice Cover dataset (www.glerl.noaa.gov/data/ice/). Green Bay is almost covered by ice in all cases. Ice cover eliminates interactions with surface metrological drivers and shortens the period of effective mixing and transportation of loaded materials to the main body of Lake Michigan.

Bravo et al. (2020) used a POM-based hydrodynamic model, a Lagrangian drifter experiment, and a 3D particle trajectory model to estimate summertime transport timescales in lower Green Bay. They found that residence and flushing times are similar, and are roughly two and six months for the lower bay and entire bay areas, respectively. Similar flushing and residence times in lower Green Bay showed the important role of water exchange at the Chambers Island cross-section. Residence times in the Green Bay AOC and near the Fox River mouth exceeds 4 months, providing a rich pool of nutrients and organic matter that triggers summertime HABs and hypoxic events.

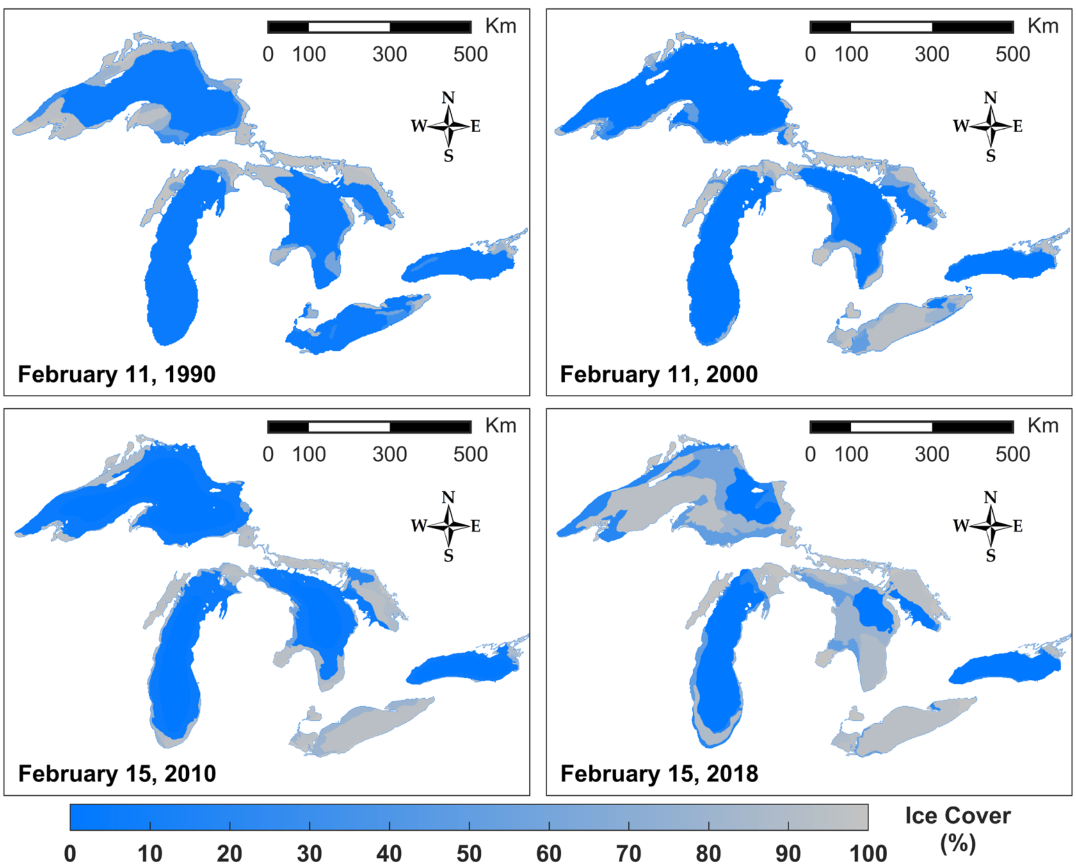


Figure 6. Spatial variability of ice cover in the Great Lakes and Green Bay based on the NOAA's Great Lakes Ice Cover dataset in the mid-February of 1990, 2000, 2010, and 2018 years.

Climate change could introduce further variability in the prediction of dynamicity of the lakes, and impose uncertainty in planning for remediation actions. Freshwater estuarine systems are vulnerable to a changing climate and its impacts, since they regularly host high population density. A study by Wenger and Harris (2010) suggests that projected climate scenarios could exacerbate the impacts of major stressors, such as agricultural and urban runoff, on Green Bay, hence the effects of climate change on environmental conditions in Green Bay require further investigation.

6. Sediment transport and dynamics in the bay

Restoration of Green Bay depends on a comprehensive understanding of sediment dynamics. Researchers have used various approaches to study sediment transport in Green Bay. The NOAA sediment trap study was part of the GBMBP initiated by USEPA (USEPA, 1989) and one of the earliest programs aiming at understanding sediment dynamics in Green Bay, including mass balance, seasonal fluxes, and sedimentation rates patterns (Eadie et al., 1991). That study also provided insight on mass fluxes and settling velocities which is important in understanding seasonal stratification patterns.

Hawley and Niester (1993) conducted the first measurement-based 1D sediment transport analysis for Green Bay. They measured water transparency in the passages on both sides of Chambers Island in 1989. Water transparency data was first converted into total suspended material and then combined with current measurements made by Miller and Saylor (1993) to analyze the net horizontal sediment flux from and toward lower Green Bay. They found that sediment flux is primarily due to a counterclockwise circulation transport around Chambers Island. During summer, transport out of the southern bay is small or negligible. However, roughly 10-33% of the tributaries loading is flushed out into the northern bay in the winter. Hawley and Niester (1993) recommended more extensive field surveys in future works.

Early analysis of sedimentation rates based on ^{210}Pb- and ^{137}Cs-dating techniques identified three major distinctive depositional zones in lower Green Bay, mostly reflecting the sediment loaded by the Fox, Oconto, Peshtigo, and Menominee rivers (Deering, 1985; Manchester-Neesvig et al., 1996). Sedimentation rates were found to be very negligible in the northern and central bay. That finding suggests sediment load into the bay deposits mostly in the southern bay, and the rest of the load that moves to the northern bay, is transported to Lake Michigan rather than being settled in upper Green Bay. Klump et al. (1997) also reported major depositional zones in the southern bay and characterized northern Green Bay as non-depositional zones of well-washed sands and glacial till. Jones (2000) used a combination of field observations and laboratory experiments to estimate physical characteristics for major sediment classes in the Lower Fox River. Jones (2000) also highlighted the significance of seiche motion that could significantly reverse and enhance the flow in the lower portion of the river and should be considered in estimations of daily loads from the Fox River.

Satellite imagery can be used as an alternative to measure surface sediment fields when field measurements data is unavailable, although such approach would be limited to relatively uncommon cloud-free sky conditions in Green Bay. NASA Landsat TM and NOAA AVHRR imagery was used in the 1980s to investigate the transport of the Fox River turbid plume in Green Bay (Lathrop et al., 1990). Results showed that the suspended sediment loads were transported northward along the eastern coast as a plume. Consistent with previous findings, that study showed inefficient transport of inflowing particles to the open waters of Lake Michigan. A recent study used the NASA MODIS imagery data to investigate the Fox River turbid plume during the period 2010-2014 (Hamidi et al., 2017) and found no significant difference sediment distribution patterns compared to the 1980s study—as the distance from the mouth of the Fox River increases, the concentration of suspended solids and turbidity decreases.

Satellite imagery data is only able to produce surface sediment fields and cannot capture important sediment interactions near the bottom and in deeper waters that are far from the vision capacities of satellite sensors. Developing 3D physical sediment transport models is therefore necessary to overcome limitations in ground- and space-based observations. While there have been multiple efforts to model sediment transport in the Great Lakes (Hawley et al., 2014; Lin et al., 2021; Niu et al., 2018; Valipour, Boegman, Bouffard, & Rao, 2017) and Lake Michigan (Hawley et al., 2004; C. Lee et al., 2005, 2007; Lou et al., 2000; Schwab et al., 2006), few studies have focused on Green Bay.

One of the earliest efforts in using physically-based computer models to investigate fate and transport of sediments in Green Bay was conducted by WDNR (HydroQual Inc., 1999). They used a POM-based 3D hydrodynamic model that was coupled with a wind-wave model to investigate the transport of PCB-contaminated sediments and included resuspension and deposition processes. Wave-induced shear stress at the bottom was simulated based on the NOAA GLERL's wave model (Schwab et al., 1984). Sediment loading was considered from three major sources: exchanges with Lake Michigan, tributary loadings, and shoreline erosion. They calibrated the input parameters for the sediment transport model based on previous studies by Burban et al. (1990) in freshwater systems and Lick et al. (1995) for the Fox River. The model showed acceptable performance in simulating sediment transport, however, was not implemented in future applications due to low computational efficiency, inability to represent complex geometry of Green Bay in the structured grid used, and difficulties in modeling shallow estuarine systems with POM-based models. The study also suggested that an ideal sediment transport model must be coupled with a eutrophication model to account for the internal loading processes rather than to only incorporate the loads due to hydrological and meteorological events.

Recently, Khazaei et al. (2021) developed a hydrodynamic, wind-wave, and sediment transport model for Lake Michigan with fine details of Green Bay using FVCOM. The model uses an unstructured grid that provides opportunity to include high-resolution features of Green Bay's peninsulas and islands (e.g., Chambers Island and Cat Islands). The model uses combined current-wave shear stresses to drive bottom sediment resuspension and forces the sediment actions using mixed bed conditions (i.e., mixture of cohesive and non-cohesive sediments). The Fox and Menominee Rivers were used as point sources of sediment load while the sediment budget of the system is also in balance with bottom and shoreline erosion/deposition. Their results for the 2016-2019 period showed high sediment activities and presence of resuspended particles near the mouth of the Fox River, in the Green Bay AOC area, and along the Fox River plume in the shallow waters of eastern shorelines. Khazaei et al. (2021) suggested that these physical actions in Green Bay should be studied jointly with the biogeochemical processes when relevant information such as loading rates of nutrients, distribution of algal biomass, and mussel areal density becomes available. Video 1 is an animation of 2018 daily- and depth-averaged TSS transport in Green Bay and inside the AOC, based on simulations of Khazaei et al.'s physically-based sediment transport model.

Video_1.mp4

Video 1. Animated daily- and depth-averaged snapshots of total suspended solids (TSS) in Green Bay during the period of May-October 2018. Right-bottom inset provides high-resolution details of TSS transport in the Green Bay AOC and near the mouth of Fox River (Khazaei et al., 2021).

While modeling efforts offer detailed information on sediment dynamics and biological/ecological processes in Green Bay, there is still need for fieldwork to obtain supporting data, improve modeling platforms, and gain better insight on mechanisms of the biogeochemical processes in the Green Bay ecosystem.

7. Remarks on sediment processes and perspectives of the Green Bay restoration: applications and next steps

For decades, particularly since the mid-20th century, Green Bay has suffered from environmental problems that were caused by excessive loadings of human-made nutrients and contaminants. Despite previous successful efforts that helped delisting some AOCs from the primary list of endangered ecosystems in the Great Lakes basin, Green Bay is still a major AOC and to achieve the delisting goal three main steps seems to be necessary in future refinements of a restoration agenda for Green Bay: 1) diagnosis of the root causes of the problem, 2) prescription and design of long-term solutions, and 3) evaluation of the effectiveness of the proposed solutions under different loading and climate scenarios.

The first step includes conducting research to investigate and diagnose the primary causes of the problems, both human-related and due to environmental variability in the bay and its watershed. There is a consensus among decision-makers that excessive nutrient loadings have disrupted the ecological balance of the system, while physical transport is not capable of exporting materials with the same rate that they are entering the bay. Climate change may also contribute to the problem, yet the role of climate variability is not well understood. The second step involves implementation of management tasks from different perspectives, including but not limited to, outflow regulations, nutrient/toxic management, and ecological flows assessment. While these management scenarios could have preventive impacts, there are alternative restorative actions such as the rebuilding of the Cat Islands and the Fox River dredging activities. These projects can provide short-term solutions but require careful consideration to avoid potential side effects. The endpoint of rehabilitation is to review and monitor system responses to restoration activities. Lessons learned from both successful and unsuccessful practices should be documented as a reference for similar cases worldwide. Scientific research can help to define efficient and sustainable solutions, and reduce costs. Research can help convince funding agencies and stakeholders to invest in sustainable and environmental-friendly infrastructures.

Experts and decision makers discussed various aspects and advances in Green Bay restoration during a conference in 2017 "*Summit on the Ecological and Socio-Economic Tradeoffs of Restoration in the Green Bay, Lake Michigan Ecosystem*" (Klump, Bratton, et al., 2018). Scientific planning of remediation was recommended to be organized around five focus areas: 1) Watershed modeling, 2) Biochemistry and hydrodynamics, 3) Ecosystem modeling and trophic dynamics, 4) Habitat and biodiversity—benthic, wetland, and land-margin interfaces, and 5) Socioeconomic and management issues. Future restoration actions should focus on improving knowledge on hydrodynamics, sediment transport processes, and biogeochemical interactions in Green Bay. That knowledge will advance the five disciplinary areas of restoration and has several useful applications for ecosystem management, including:

1) explaining sediment dynamics, deposition/resuspension rates, and water clarity under different loading scenarios
2) predicting the short- and long-term effects of the restoration plans under different loading scenarios
3) informing management strategies and beach advisories, providing simulations and early warning forecasts of the potential fate and tracking of contamination or material following a spill, accidental or deliberate discharges, or a lost object
4) predicting algal blooms and modeling the formation and persistence of hypoxic dead zones
5) improving nutrient transport and budget analysis
6) studying the transport and fate of contaminated sediments
7) planning of future monitoring programs and design of fieldwork

These applications can inform future development of sustainable conservation and management plans for other highly-dynamic marine and freshwater environments with similar ecosystem characteristics and environmental degradation problems.

Sidebar 2

Sediment dynamics: a key element of the Green Bay restoration agenda

Five decades of interdisciplinary scientific research and fieldwork addressed the restoration of Green Bay estuary. A synthesis of 100+ reports has shown that sediment dynamics explain ecosystem degradation in Green Bay and connects major physical and biogeochemical processes of the system. Physical processes such as sediment transport and resuspension events govern the movement, deposition, flushing rates, and availability of nutrients and contaminants in the bay. On the other hand, high concentrations of those contaminants and nutrients are the main drivers of biogeochemical processes in the system such as water quality variability, nutrient budgets, algal blooms, formation of low oxygen or hypoxic areas, invasive species, and altered habitat. Sediment dynamics is the key in better understating the nexus of such processes in Green Bay and refinement of the rehabilitation efforts. Additionally, it has several useful applications for improvement of the environmental management practices including the development of water quality monitoring and/or operational forecasting systems, sustainable river and watershed management, Total Maximum Daily Loads (TMDL) assessments, and climate mitigation and adaptation strategies.

8. Conclusions

The Laurentian Great Lakes provide invaluable environmental, social, and economic resources to Northern America. Human activities such as urbanization, agricultural, and industrial activities have stressed the lakes, in particular, estuarine systems like Green Bay. Lost or altered habitat, degraded water quality, hypoxia and HABs, and disturbed ecosystem are symptoms of dire ecological conditions in Green Bay. Restoration of AOCs is a top priority for the Great Lakes communities, requiring interdisciplinary management, modeling, and monitoring efforts. This article summarizes over 100 papers that investigated the limnology of the Great Lakes, the major causes of Green Bay degradation and addressed the restoration programs for almost five decades.

Water quality and ecosystem health are closely linked to sediment processes through contaminant transport and burial in the bay. Excessive nutrient loading, particularly phosphorus, has disturbed the lower bay's ecological balance. Sediment transport, deposition, and resuspension rates drive nutrient recycling and are important components of nutrient budget analysis in the bay. Deposition of organic matter is a major driver of oxygen consumption and formation of hypoxic zones in the benthic layer. Transport or resuspension of rich sediments spikes phosphorus concentration in the water column and triggers harmful algal bloom events such as cyanoHABs. Those conditions have forced migration or extinction of long-lived species in the bay, and provided opportunity for invasion of new species such as the zebra and quagga mussels with unfavorable ecological consequences. Restoring Green Bay is difficult because of its morphology and geophysical characteristics, such as significant hydrological inputs, inefficient hydrodynamic patterns, dominant summer thermal stratification, lake cold-water intrusions and two-layered flow conditions, long period of ice-cover, and climate variability. Those processes cause Green Bay to function as an efficient retention basin, holding ecosystem-disturbing particles for extended periods.

Sediment dynamics are generally at the root of ecological, environmental, and public health problems in inland aquatic systems like Green Bay. Advanced sediment analysis tools, based on observations, remote sensing, and models can improve our understanding of the circulation and transport mechanisms, impacts of tributary loadings, water and particle exchange, climate change/variability impacts, and the links with ecosystem processes and water quality problems. This review's holistic analysis of physical, sedimentary, and biogeochemical processes can be applied to improve conservation and restoration efforts of other deltas, estuaries, and coastal systems around the world.

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Conflict of Interest

All authors have no conflict of interest to declare.

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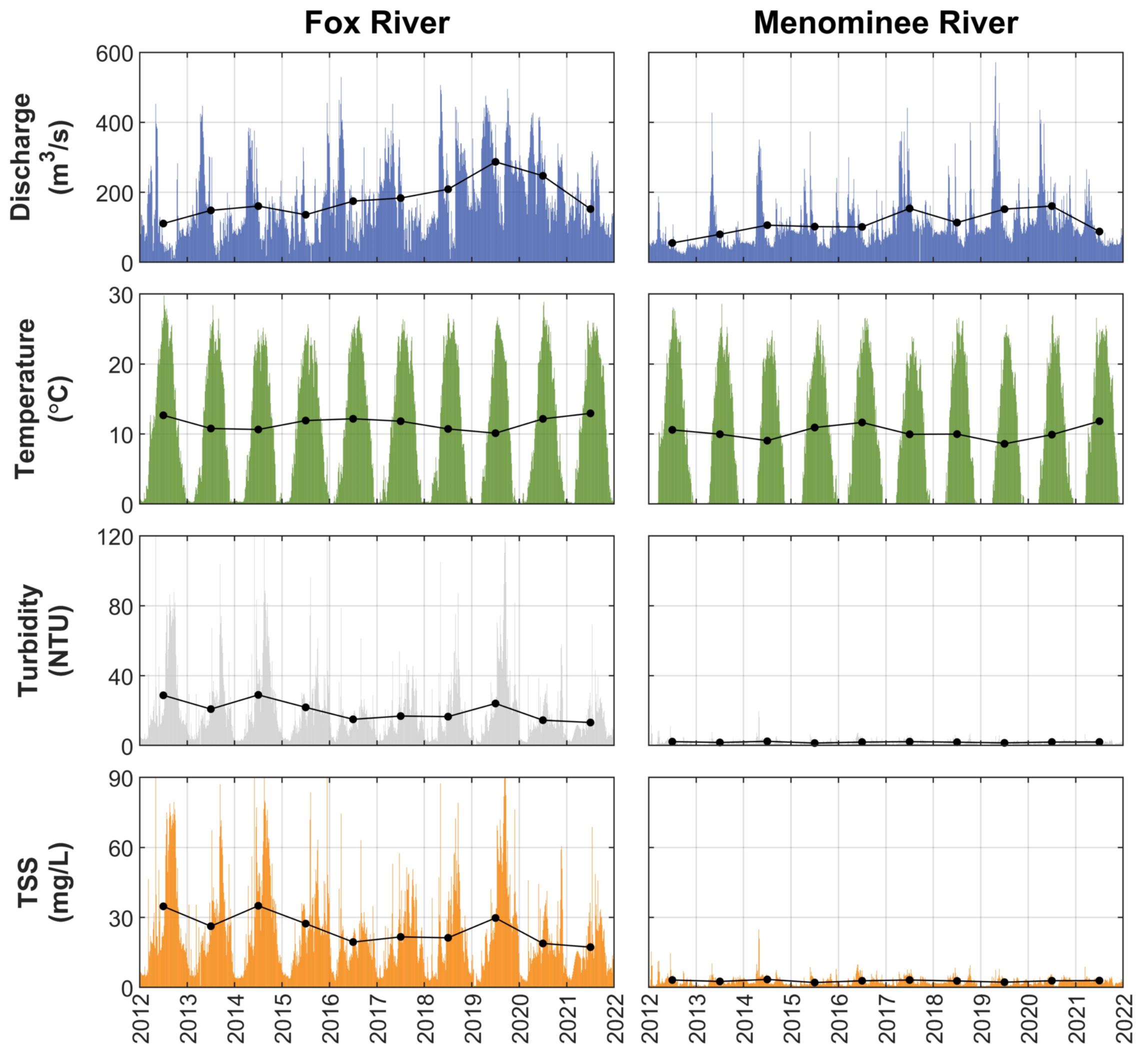

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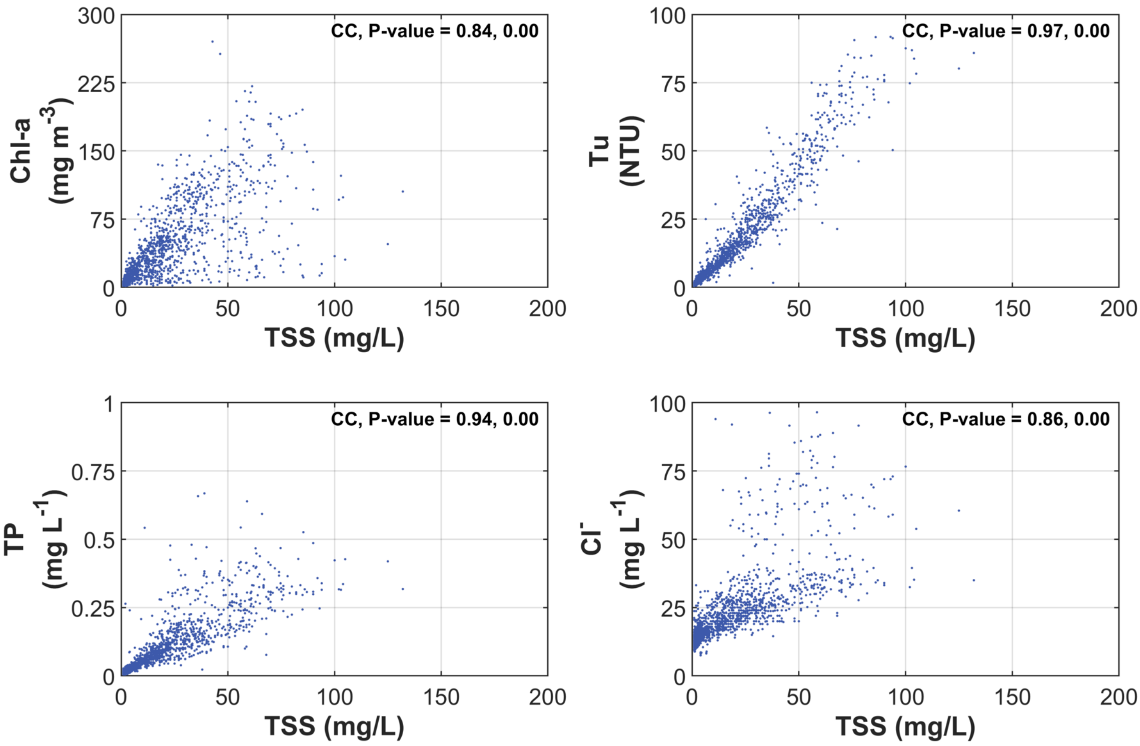

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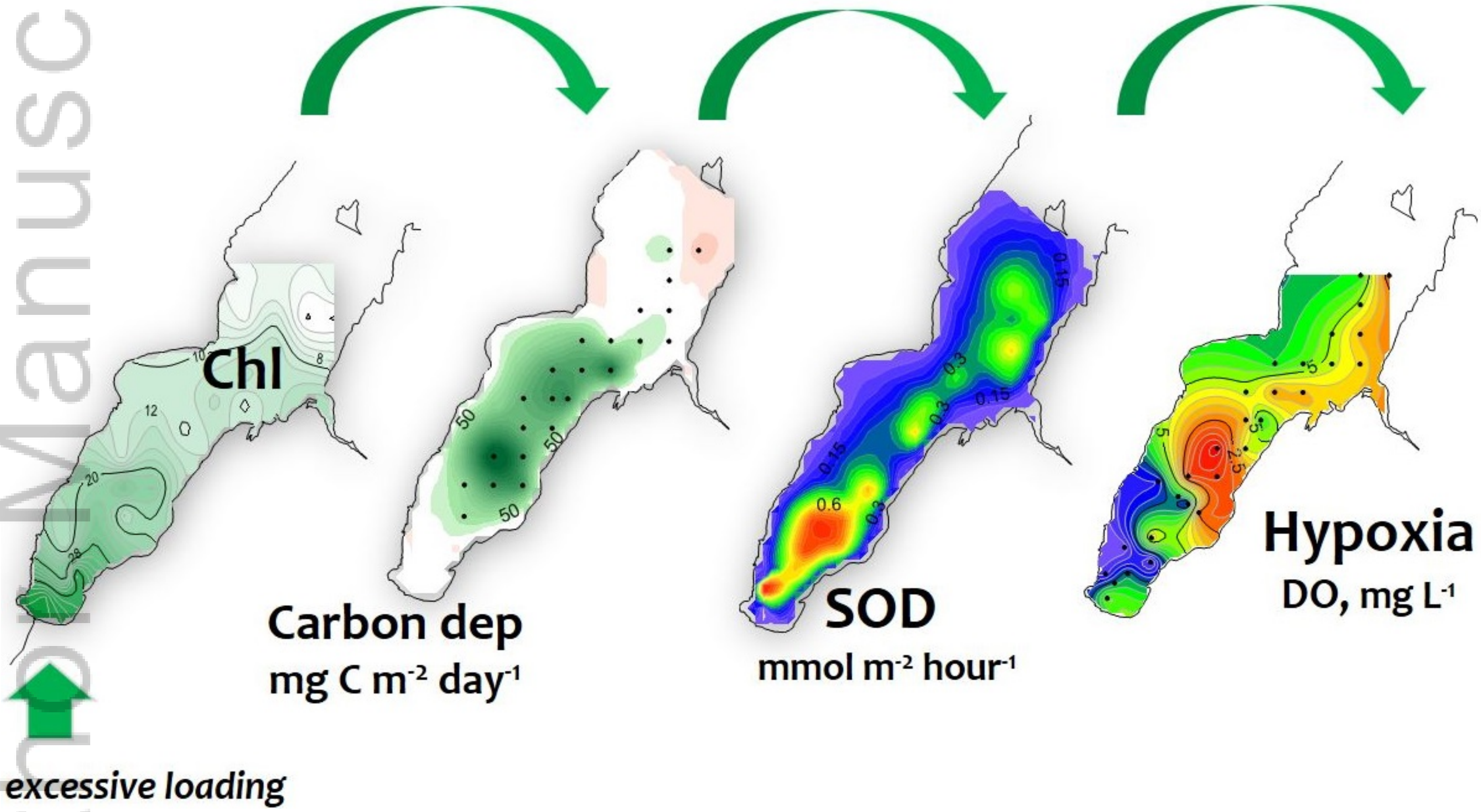

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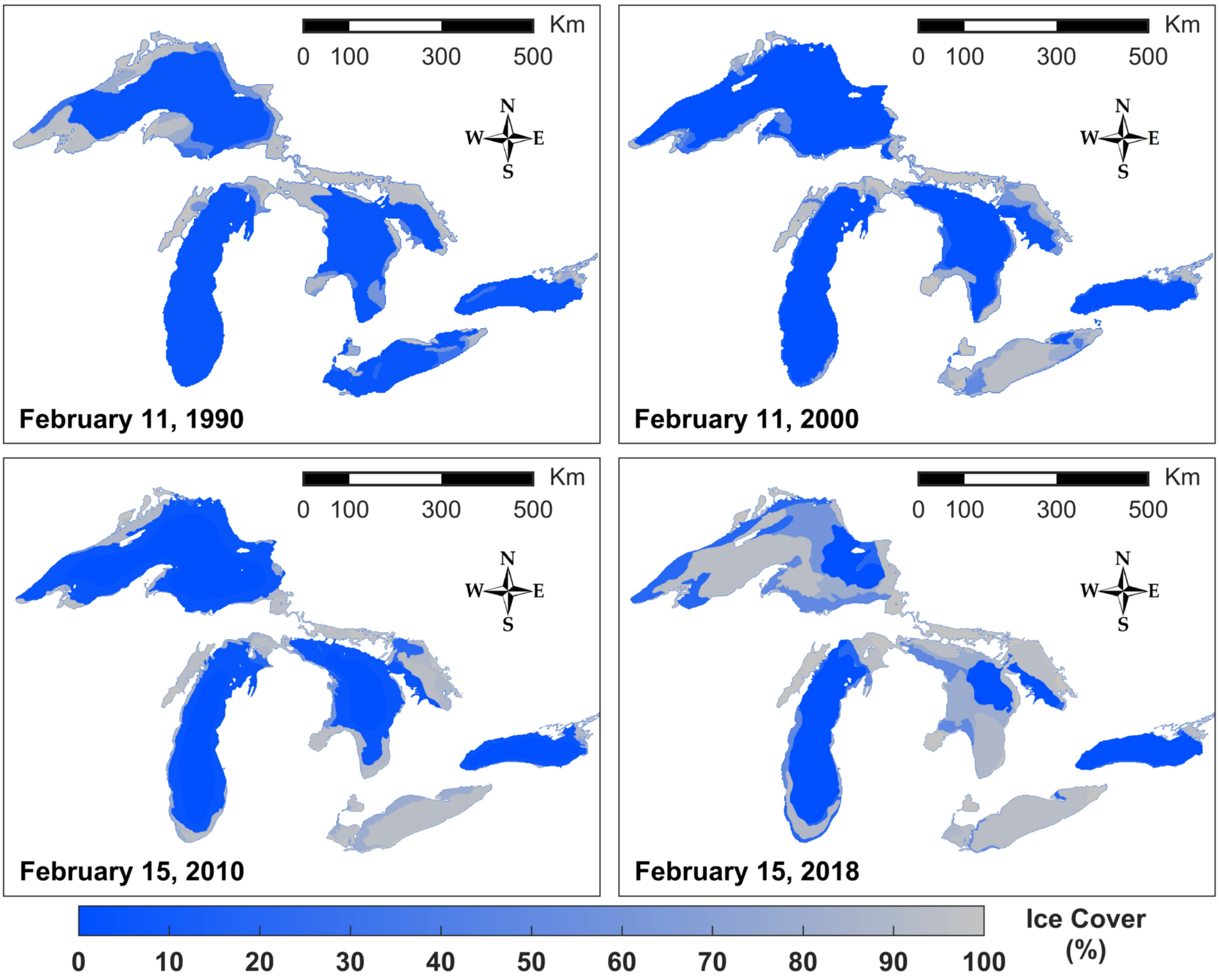

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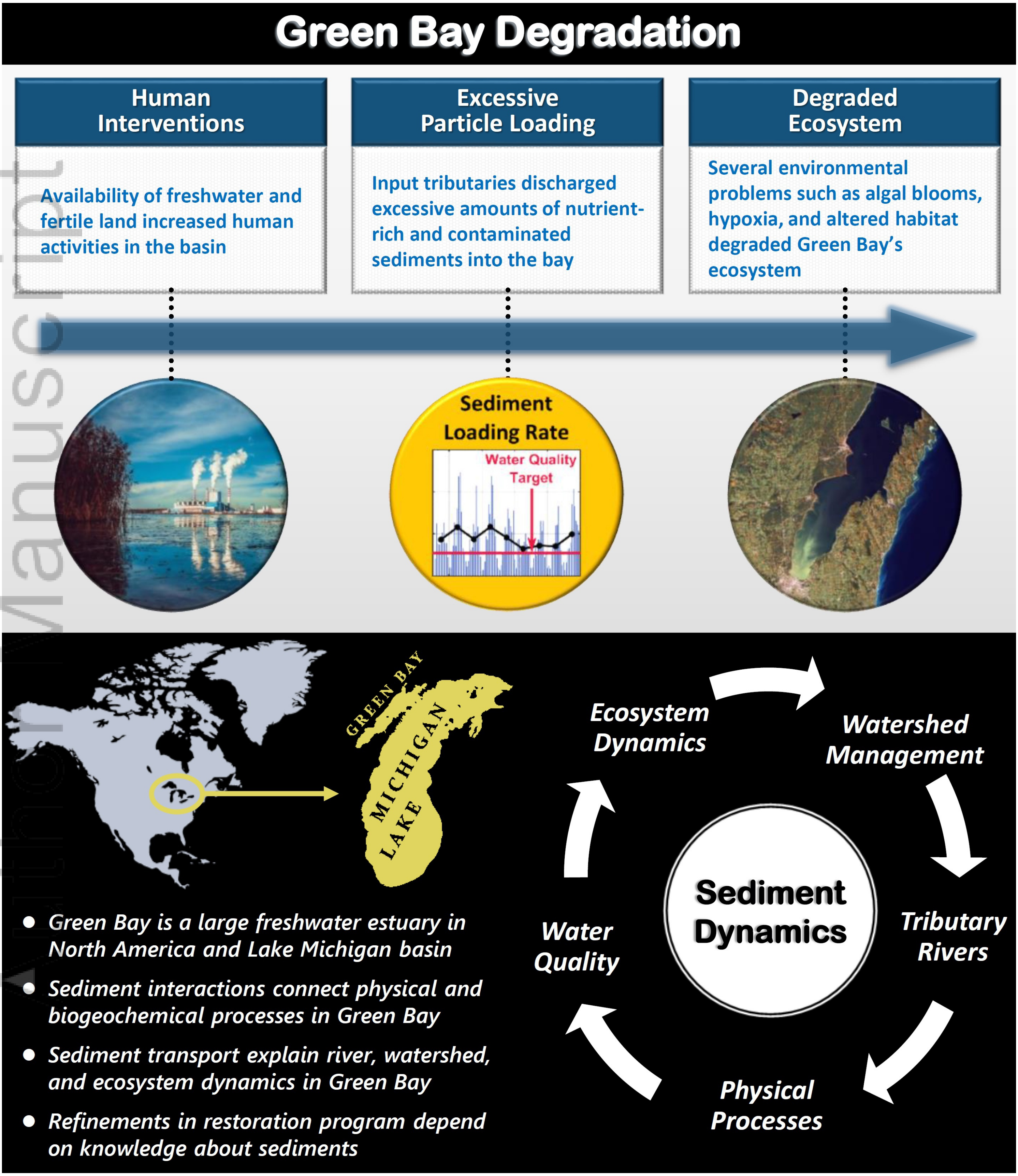

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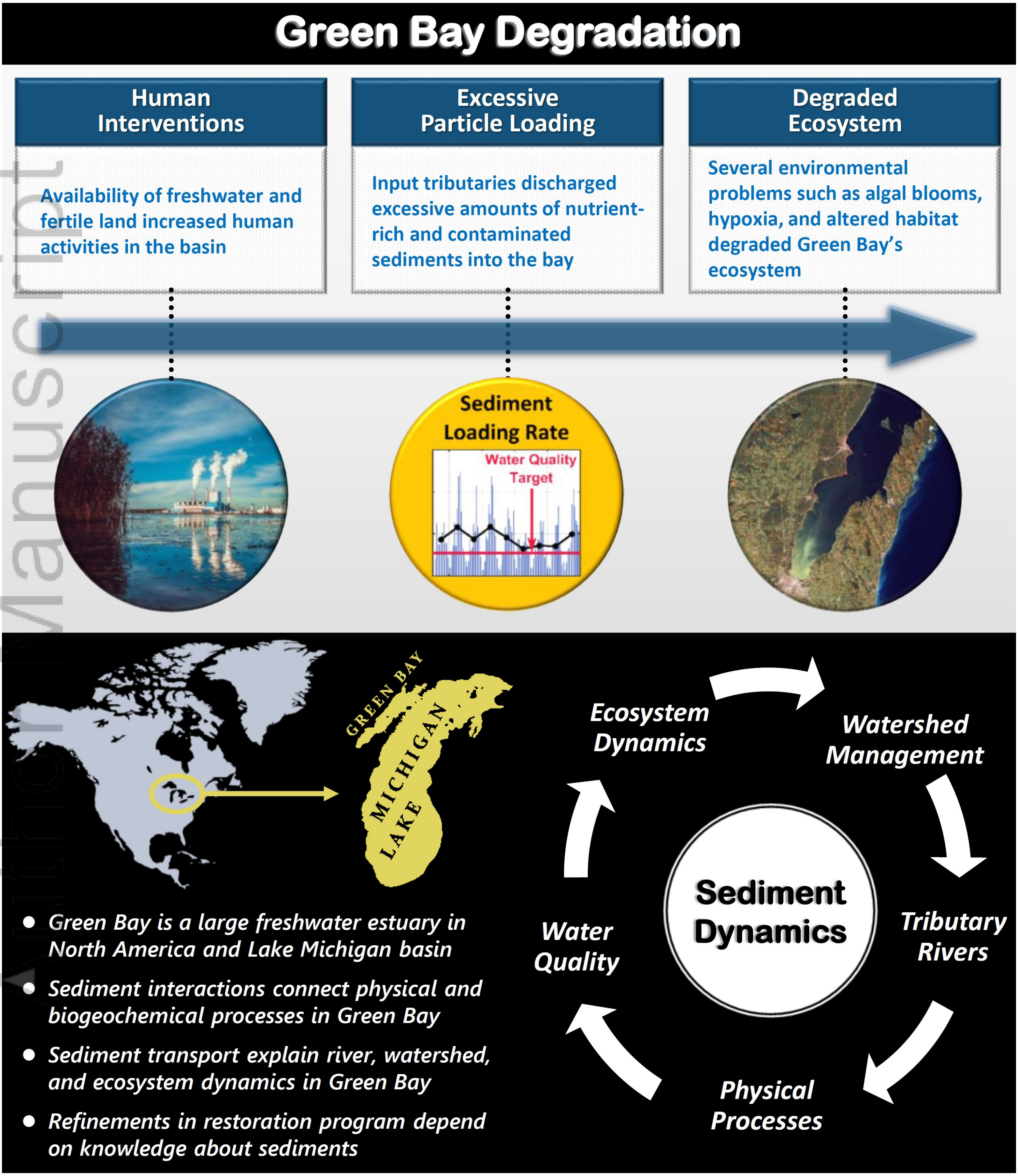

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