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The Green Bay saga: Environmental change, scientific investigation, and watershed management

Hallett J. Harris [a,*], Robert B. Wenger [a], Paul E. Sager [a], J. Val Klump [b]

[a] *University of Wisconsin-Green Bay, 2420 Nicolet Dr., Green Bay, WI 54311, United States of America*
[b] *School of Freshwater Sciences, Great Lakes WATER Institute, University of Wisconsin-Milwaukee, 600 E. Greenfield Ave., Milwaukee, WI 53204, United States of America*

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ABSTRACT

The Green Bay watershed, draining a total area of approximately 40,468 km^2, comprises about a third of the Lake Michigan drainage. In the early years, fur trade was the dominant economic activity within the watershed. Later, when timber harvesting, papermaking, and agriculture came on the scene in the 19th and early 20th centuries, major environmental changes occurred in a relatively short period of time. Nutrient and sediment loadings, accompanied by organic wastes from sawmills and paper mills, resulted in a pollutant overload in the Fox River and in the eutrophication of the waters of lower Green Bay. Citizen complaints about these severely degraded conditions initiated a period of scientific investigation. Starting slowly with a few studies and surveys in the first half of the 20th century, serious investigatory work began at mid-century with support from the University of Wisconsin Sea Grant Institute. Examples of topics that have been investigated since then with support from numerous sources are: biological oxygen demand (BOD), phosphorus and total suspended solids loads, trophic status and food chain efficiencies, coastal wetland characterization, dynamics of the benthic layer, algae and abiotic solids, phosphorus cycling and mass balance, PCBs, seasonal hypoxia, and climate change impacts. These studies have provided the scientific foundation for government-led programs such as the Green Bay Remedial Action Program, the PCB clean-up program, and the TMDL program. Progress has been made—reduction in BOD is an example—but a fuller rehabilitation of this large-scale ecosystem remains an elusive goal. The saga goes on.

The Green Bay saga

The head of Green Bay receives water from the lower Fox River that drains from Lake Winnebago, the largest inland lake in Wisconsin. Lake Winnebago receives water from the Upper Fox River, the Wolf River and their respective watersheds. The total Green Bay watershed drains approximately 40,468 km^2 and, as such, it comprises about a third of the total Lake Michigan drainage. The name Green Bay is a bit of an enigma. The early French explorers referred to this water body as Baye Des Puans during their period of occupation. In 1778, in a publication by Jonathan Carver, it was given the name Green Bay (Kraft, 1984). The renaming was apparently due to the early spring greening of the extensive marshes and forested wetlands that were particularly prominent on the west shore of the bay. Clifford Mortimer, a noted limnologist/oceanographer, believed Green Bay was "somewhat misnamed as a 'bay'" and characterized it as a relatively shallow "gulf" connecting into the northwest part of Lake Michigan (Mortimer, 1978). Green Bay has also been referred to as the largest freshwater estuary in the world (Smith et al., 1988). However it may be characterized, Green Bay and its watersheds have had a long history of exploitation and a shorter but significant period of scientific exploration (Fig. 1) (Bertrand et al., 1976; Harris et al., 1987; Smith et al., 1988; Kraft and Johnson, 1999).

Early on, the economy of the region was based on the fur trade. During this period—which lasted through the early part of the 19th century until about 1834—little environmental change occurred in the watershed, river, or the bay. A federal land survey was conducted during the period from 1834 to 1836, after which land sales were opened by the United States Government. This opening marked the beginning of major changes in the watershed. The lumber industry came to the fore, and by the early 1880s one billion board feet of virgin timber had been harvested. Soon thereafter, from 1870 to 1930, economic development shifted to papermaking and manufacturing. The paper mills were essentially unrestricted in their use of the river as a source of water and power, and as a waste-disposal outlet. The agricultural economy began in the mid-1800s with the growing of wheat as the dominant farming activity, to be followed later by the start of the dairy industry. By 1900, much of the land in the lower Fox River watershed was under cultivation or utilized for grazing. In a relatively short period of time, from 1840 to 1900, these large scale changes in the watershed resulted in increased nutrient and sediment loadings into the river and bay. These

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* Corresponding author.
E-mail address: harrish@uwgb.edu (H.J. Harris).

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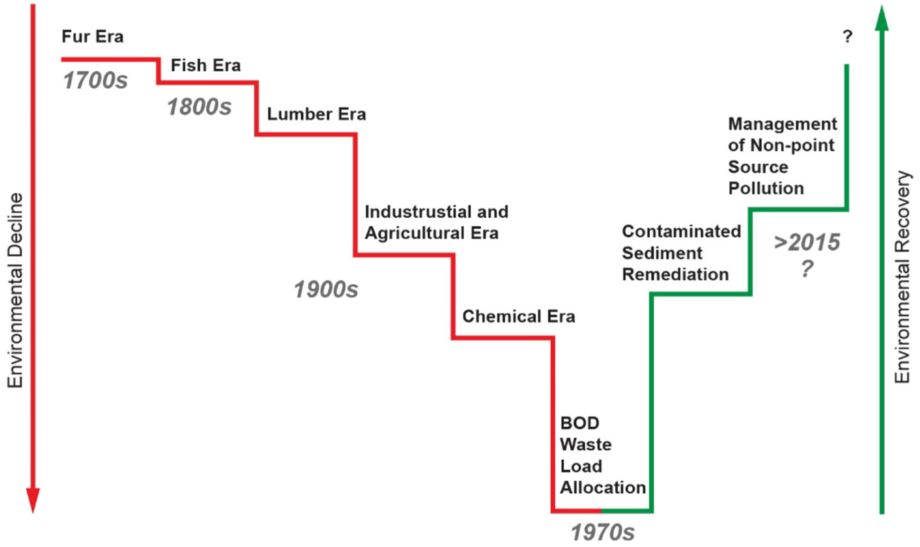


Fig. 1. An abbreviated timeline of the environmental history of the Green Bay ecosystem from the 1700s to present.

loadings were accompanied by the discharge of organic waste from sawmills and paper mills and the discharge of sewage from developing communities. In combination, these inputs led to an overloading of the river, resulting in a rapid eutrophication of the waters of Green Bay.

How did the river and the bay come to such a degraded state? On the surface, the answers to this question are fairly clear. When it comes to the question of why the resource was allowed to degrade, the answers are more difficult. Perhaps it is another case of “the tragedy of the commons”, a situation in which users of a common resource keep claiming larger shares until the carrying capacity is exceeded and the system shifts to another state, one that is less beneficial (Hardin, 1968). It could also have been a matter of indifference resulting from society's movement along a “progressive path” in which fewer and fewer people involved in this collective endeavor were directly dependent on the bay and its resources. What mattered was that progress was, defined primarily as economic growth and development, largely through natural resource exploitation. The case of Green Bay, as was no doubt true of other systems in the Great Lakes, appears to “reflect historic allocation of resources toward those uses and beneficiaries who were not dependent on maintaining high environmental quality or sensitive species” (Harris et al., 1990).

The degradation does not end in this period, however. By the 1920s, the river and the lower bay as far as Red Banks (about 15 miles north of the mouth of the Fox River) were in such a degraded state that people took note and began to complain. In the decades that followed, reports of dying fish and offensive stenches arising from the East River and the lower Fox River were common. A newspaper account in 1961, for example, tells the story of workmen using a powered scow to remove tons of dead fish from the waters of the Fox River. Homes along the west bank of the river were said to be seriously affected by strong odors. Mysteriously, an accompanying photograph purports to show health department officials spraying DDT on the waters of the river (Green Bay Press Gazette, 14 June 1961).

This nadir of the period of degradation stimulated the first actions to determine the causes, calling into use the relevant science that was available at the time. A pollution survey conducted by the Bureau of Sanitary Engineering in 1925 revealed that depressed oxygen levels existed in the water over the last 15 miles of the river to its mouth at the bay. The survey also demonstrated that the dissolved oxygen concentration in the river was dependent on flow and temperature, two variables that were to be used in the waste load allocation model a half century later (WSBOH, 1927). A 1938 comprehensive study, jointly conducted by the State Committee on Water Pollution (SCOWP) and the newly formed Green Bay Metropolitan Sewerage District (now named NEW Water), reported the occurrence of blue-green algae blooms (*Aphanizomenon*) and linked the blooms to organic waste and nutrient loads (WSCOWP, 1939). Additional surveys that were conducted in 1955–56 and 1966–67 on the lower Fox River and Green Bay again implicated oxygen depletion. Benthic surveys conducted by SCOWP in 1938 (Surber and Cooley, 1952; Balch et al., 1956; Howmiller and Beaton, 1967; Harris, 1998), revealed the impact of hypoxia on the lower bay *Hexagenia* populations, an impact that resulted in the extirpation of these populations by 1967.

The evidence between cause and effect had been clear for several decades, but it was not until 1972 with the passage of the Federal Clean Water Act that action was taken to address the problem (Harris et al., 1987). Focused research by the Wisconsin Department of Natural Resources (WDNR) led to the development of a waste load allocation model that was used to partition waste loads from individual dischargers based on the river's flow and temperature and its assimilative capacity (Patterson, 1973; Patterson, 1980; Patterson, 1984).

Some $338 million ($1.9 billion in 2017 dollars) was invested in wastewater treatment facilities by both municipalities and industries, with the largest single expenditure of $80 million incurred by the Green Bay Metropolitan Sewerage District (GBMSD). The decrease in the average total discharge of biochemical oxygen demand from 1971 to 1978 was just over 90%. This action resulted in a marked increase in dissolved oxygen in the waters of the lower bay (Sager, unpublished data; Harris et al., 1987). The reduction in BOD was achieved through the Wisconsin Pollution Discharge Elimination System (WPDES), a program that was established in response to the Clean Water Act. While this was a remarkable success, the waters of lower Green Bay remained highly eutrophic. As a result, it had become clear to some in the science community that a more comprehensive understanding of Green Bay was needed.

An effort toward an improved understanding began in 1969 when the University of Wisconsin Sea Grant Institute initiated a more comprehensive research effort on Green Bay. The program was funded at a level of $579,107 ($3.86 million in 2017 dollars) over a four-year period (1970–1974); both federal and state dollars provided the source for these funds. This initiative occurred at the same time as the establishment of a new University of Wisconsin campus—the University of Wisconsin-Green Bay—on the eastern shore of Green Bay and in the city of Green Bay. These significant undertakings and events took place early in the so-called environmental movement in the United States. The first Earth Day occurred on 22 April 1970. The Clean Air

Act was passed in 1970, the Clean Water Act in 1972, the Endangered Species Act in 1973, and the Safe Drinking Water Act in 1974. The new University of Wisconsin-Green Bay, with its unique interdisciplinary programs and environmental focus, was very much in tune with these times and, in some quarters, was seen as a leader in environmental education at the collegiate level. Dubbed “Eco-U” in its early days——the record would go on to show that the new university and its faculty would play a major role over the next half century in addressing problems of the river and the bay.

The four years of Sea Grant-sponsored research produced an array of new information about the bio/physical dimensions of Green Bay. The results from two specific projects identified two issues that would occupy researchers and watershed managers for a half century and beyond. The first project dealt with investigations into the environmental chemistry of polychlorinated biphenyls (PCBs) (Veith, 1971; Veith, 1972). The second project was a quantitative assessment and partitioning of sources of phosphorus making their way into Green Bay (Sager and Wiersma, 1972; Sager and Wiersma, 1975). An assessment of the four years of research work was undertaken in 1974 in which the aim was to summarize research findings and identify potential future directions (Bertrand et al., 1976). Following an evaluation by UW Sea Grant Director Robert Ragotzki, UW Sea Grant staff members and advisors, a decision was made to go forward with a more structured program to guide a new research effort on Green Bay. A research coordinator and outreach person were hired and an agreement was reached to house the UW Sea Grant Green Bay Sub-Program on the UW-Green Bay campus.

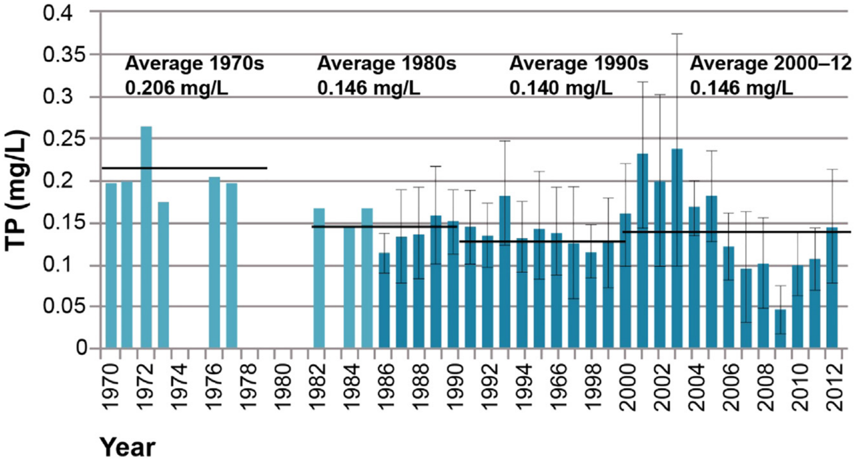
The new program was initiated in 1978. A Green Bay Workshop was held in September of that year with the purpose of reviewing past research, identifying priority research needs, and fostering the development of cooperative research efforts (Harris and Garsow, 1978). The outcome resulted in a ten-year blueprint for research on Green Bay and its watersheds. Twenty-four individual projects were completed between 1978 and 1986 at a cost of $2.1 million (approximately $4.7 million in 2017 dollars). The largest allocation, 30%, was for fishery investigations, while a nearly equal amount, 30%, was allocated to a study of the chemical/physical aspects of waters and sediments of the bay. Projects exploring the trophic dynamics of the system attracted 20% of the funding. Only a combined 10% was allocated to studies of the watershed and socio/economic aspects of Green Bay. Information transfer and the program operation required the remaining 10% of the funding.

The Sea Grant-funded program attracted other interests. In 1979, the Great Lakes Fishery Commission chose Green Bay to further its investigations into ecological rehabilitation of aquatic ecosystems (Francis et al., 1979). From 1979 to 1981 a series of workshops, identified under the rubric of Great Lakes Ecosystem Rehabilitation (GLER), was held with the ultimate objective of designing a preliminary plan for the rehabilitation of the Green Bay ecosystem (Harris et al., 1982; Magnuson, 1992). GLER workshop participants identified and ranked stressors on the Green Bay ecosystem (Harris et al., 1994); identified interactions between users and stressors (Wenger et al., 1999); defined technical, socioeconomic, and institutional elements of rehabilitation; and structured a preliminary rehabilitation plan for Green Bay. In research projects supported by Sea Grant, investigators examined the fate and transport of select chemicals (Marti and Armstrong, 1990), identified trophic dynamics and food chain efficiencies (Sager and Richman, 1990, 1991; Smith and Magnuson, 1990), and characterized the response of coastal wetlands and avian populations to lake-level fluctuations (Sager et al., 1985; Harris et al., 1981, 1983; McLaughlin and Harris, 1990; Fewless, 1986; Brazner, 1997) In other projects, water mass structures and exchanges in Green Bay were characterized, the populations of several important fishes were identified, and the role of micro-contaminants in the reproductive failure of Forster's terns in Green Bay were examined (Kubiak et al., 1989; Harris et al., 1993). The list of projects also includes a delineation of the physical, chemical, and biological dynamics of the benthic boundary layer of Green Bay and a characterization of the trophic status of Green Bay (Sager et al., 1984; Richman et al., 1984), including the epiphytic macroinvertebrate communities of four coastal marshes located along the west shore of the bay (Schneider and Sager, 2007).

The Sea Grant Sub-Program and GLER laid the scientific foundation for two government-led programs yet to come: the Green Bay Remedial Action Plan (GBRAP) and the Green Bay Mass Balance Study (GBMBS). Green Bay was identified by the International Joint Commission (IJC) Great Lakes Water Quality Board as one of 43 Areas of Concern (AOC) in the Great Lakes region, which meant a rehabilitation plan was needed to identify means for correcting unacceptable water quality problems (IJC, 1985). From 1985 to 1987, a Remedial Action Plan (RAP) for the lower Fox River and lower Green Bay was prepared by WDNR, in cooperation with other agencies, researchers, and informed citizens (Harris, 1992). The plan was officially adopted by WDNR and the State of Wisconsin in 1988; as such, it was the first to be completed and the first accepted by the IJC Great Lakes Water Quality Board (WDNR, 1988). Attaining this distinction can be attributed in part to the research foundation provided by Sea Grant and GLER and a prototype plan that preceded the RAP development (Harris et al., 1987). The RAP contained 16 key actions for ecosystem rehabilitation and 120 specific recommendations. It also identified 14 beneficial use impairments, six of which are related to an excess of phosphorus and suspended solids. The combination of these two stressors led to poor water clarity in the AOC; the turbid water was due to excess algae and inorganic particles. The primary effect of this reduction in underwater light is the suppression or elimination of submergent aquatic vegetation (McAllister, 1991; Harris et al., 1991; Sager et al., 1996; Millard and Sager, 1994; Robinson, 1996).

A significant development that occurred just prior to the completion of the 1988 RAP was the establishment of a long-term water quality monitoring program for Green Bay. The program, which includes a comprehensive list of water quality parameters and 18 monitoring stations, was established by the GBMSD in 1986. The program has provided data for three versions of the *State of the Bay* report, the most recent of which came out in 2013 (Qualls et al., 2013). The importance and value of this program and the long-term database that developed from it cannot be over-emphasized. It provides the basis for assessing changes in the trophic condition of the bay in response to management efforts and is an important source of data for research work (Figs. 2 and 3). The 1988 RAP recognized the importance of the littoral community to the overall health of the Green Bay ecosystem, but did not at the time consider the combined effects of phosphorus and suspended solids on light attenuation. The RAP set a goal of 100–125 μg/L for average concentrations of phosphorus in the AOC over the summer, with the objective of reducing algae (chlorophyll *a*) concentrations to a point where Secchi disk transparency is 0.7 m. This is the depth where light requirements are just barely met for the submerged aquatic macrophyte *Vallisneria americana* (wild celery or eelgrass) (McAllister, 1991).

In 1993, the RAP was updated to meet a new set of requirements imposed under the 1990 Great Lakes Critical Programs Act, a legislative initiative which was, in effect, an amendment to the Clean Water Act. This updated version of the RAP (WDNR, 1993) included new data (P.E. Sager, personal communication) demonstrating that Secchi disk transparency in the AOC was significantly related to both chlorophyll *a* and abiotic solids. These results suggested that both phosphorus and total suspended solids (TSS) needed to be addressed. A study of several light-related variables was subsequently undertaken to more specifically evaluate the contributions of algae (chlorophyll *a*) and abiotic solids to light attenuation (Sager et al., 1996). The statistical procedure employed in this study yielded a model that defined the importance of both types of solids (Nutrient and Sediment Management Work Group, 2000). The results of this research provided the basis for setting numerical water quality targets for phosphorus and suspended solids when the Total Maximum Daily Load (TMDL) program for the Fox River watershed was developed a decade later.

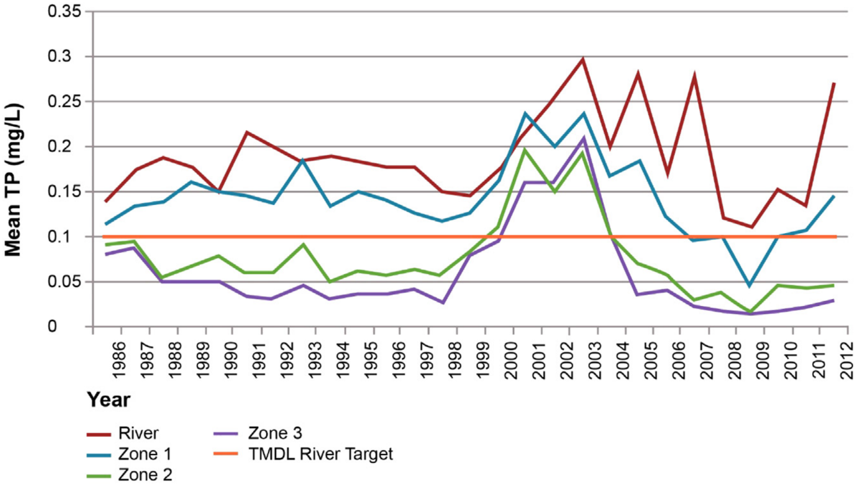


University of Wisconsin Sea Grant, State of the Bay 2013, data from Paul Sagar and GBMSD.

Fig. 2. The Green Bay Metropolitan Sewerage District has maintained a water quality monitoring program nearly continuously since 1986. Prior to that Sager and co-workers collected data in what has been designated as "Zone 1" in the lower bay – an area essentially contiguous with the Area of Concern outside of the river itself. Shown here are the average values for total phosphorus (mg/L) (whiskers are standard deviations) collected during the recreational period ~May–September.

By the 1990s, attention was being focused on the diverse sub-watersheds within the basin. The goal was to gain an understanding of these sub-watersheds as sources of nutrients and sediments that caused the highly eutrophic conditions in the bay. In early 1992, a small group of citizens brought together by Jack Day, an engineering professor at UW-Green Bay, formed a nonprofit organization called Northeast Wisconsin Waters for Tomorrow. This initiative by Professor Day was an outgrowth of his nearly three decades of service as a member of the Green Bay Metropolitan Sewerage Commission, in many of those years he was president of the commission. Northeast Wisconsin Waters of Tomorrow raised $400,000 ($696,000 in 2017 dollars) from local sources and recruited scientists and policy analysts to form an interdisciplinary analysis team. The goal was to devise a cost-effectiveness analysis methodology and apply it to determine relative costs and outcomes of different courses of action designed to improve water quality in the Green Bay watershed. A significant portion of the analysis team's overall effort was devoted to estimating phosphorus and total suspended solids loads in runoff from rural areas throughout the watershed. To obtain these estimates, the basin scale model, Simulator for Water Resources in Rural Basins Water Quality (SWRRBWQ), was applied to each of 41 sub-watersheds. The analysis was conducted using 1990 weather and land-use conditions (Analysis Team Report, 1994). The results from the simulations revealed that 74% of the phosphorus and 91% of the total suspended solids reaching the lower bay came from rural sources. When considering cost, the analysis team concluded that the unit cost of reducing phosphorus and TSS loadings from agricultural sources was significantly less than the cost for reducing loadings from municipal sources.

A UW-Green Bay soil scientist and his graduate students assessed the utility of several "runoff" models to estimate TP and/or TSS loadings from watersheds to the Lower Fox River. SWRRBWQ was one of the models evaluated, but eventually the USDA Soil and Water Assessment Tool (SWAT) was selected. SWAT was calibrated for use in the Lower Fox River basin (McIntosh et al., 1993; Sugiharto et al., 1994; Baumgart, 1998). The SWAT model (Baumgart, 2000; Baumgart, 2005) became the primary tool for developing the Lower Fox River total maximum daily loads (TMDL) for TP and TSS some 15 years later. Paul Baumgart has continued to provide much needed expertise in refining and calibrating the SWAT model for use in management applications in the Fox-Wolf basin.



University of Wisconsin Sea Grant, State of the Bay 2013, data from GBMSD.

Fig. 3. Yearly average total phosphorus concentrations (mg/L) by zone as measured by the GBMSD monitoring program beginning in 1986–2012 in four zones, the river and zones 1–3 stretching from the mouth of the Fox. Zone 1 is approximately from the mouth to km 7 (distance as measured along the major south to north axis of the bay), zone 2 from km 7 to km 20, and zone 3 from km 20 to km 25. The Total Maximum Daily Load target for the Fox River is 0.1 mg/L.

By the 1990s, considerable research had addressed the quantities, sources, and impacts of P and TSS, but little had been done to assess their fate once they reached the bay. A sedimentary phosphorus cycling and phosphorus mass balance study was initiated during this time. Results revealed, among other things, that recycled phosphorus represents about 30% of the total phosphorus reaching the bay, while 70% of the phosphorus that was deposited remained permanently buried (Klump et al., 1997). The southern portion of the bay behaves as an efficient sediment and nutrient trap for carbon and nitrogen, as well as phosphorus (Klump et al., 2009). Estimates of benthic recycling reveal that remineralization has been relatively rapid with approximately 50% of the carbon remineralized within less than fifteen years of deposition and a mean residence time for metabolizable sediment carbon and nitrogen of twenty years (Klump et al., 2009). These results suggest that if Fox River loading is curtailed, the bay may recover relatively rapidly from its present highly eutrophic state.

Another compounding factor impacting the nutrient/eutrophic condition arose in 1992 with the invasion of dreissenid mussels (Kraft, 1991–1997). Qualls (2003) and Qualls et al. (2007) used the spatially specific data set from GBMSD, collected from 1986 to 2001, to determine if zebra mussels (*Dreissena polymorpha*) have increased water clarity, affected nutrients, and impacted the chlorophyll-phosphorus relationship. In lower Green Bay the existence of a gradient was observed and was partitioned by GBMSD for data visualization and reporting into 3 zones, beginning at the mouth of the river and extending northward sequentially from the mouth to 7 km, 7 to 20 km, and 20 to 25 km along the major longitudinal axis of the bay.

The highest nutrient concentrations and lowest Secchi disk depths are observed in Zone 1 and lowest nutrient concentrations and highest Secchi disk readings in Zone 3. Changes occurring after the arrival of the zebra mussel included a slight increase in Secchi disk depths in Zone 1, but no changes in Zones 2 and 3. Moreover, no changes were observed in the chlorophyll-phosphorus relationship in Zone 1, slight changes were noted in Zone 2, and a decoupling was observed in Zone 3. Other investigations carried out from 2000 to 2006 revealed actual changes had occurred in the bay following the invasion by zebra mussels (DeStasio et al., 2008). These investigators resampled established sampling locations in Green Bay during four years of the post invasion period. Secchi disk depth did not change significantly following the invasion, while chlorophyll *a* was significantly greater, as was phytoplankton biovolume. There also was a significant shift to greater and more frequent dominance of the phytoplankton community by Cyanobacteria. Another unforeseen impact of the invasion by exotic mussels was the impact on the Green Bay migratory diving duck population (Harris, 1998). During the post-invasion period, diving duck use steadily increased to 1.83 million duck use days by the fall of 1997, a 220% increase. The increase was due primarily to increases in the mollusk-feeding ducks: golden eye (*Bucephala clangula*), lesser scaup (*Aythya affinis*), and greater scaup (*Aythya marila*).

As noted earlier, research on PCBs was initiated in the 1970s. By the mid-1980s further work and documentation on the impact of PCBs on Green Bay had been completed (Sullivan and Delfino, 1982; Sullivan et al., 1983; Kubiak et al., 1989; Harris et al., 1990; Ankley et al., 1992; Harris et al., 1993; Ankley et al., 1993; Brazner and DeVita, 1998). In 1987, the U.S. Environmental Protection Agency, Region 5, identified Green Bay as the site for a PCB, cadmium, and lead mass balance study. The mass balance approach had been used in other systems, but never on a geographic scale the size of Green Bay. The effort involved dozens of investigators from multiple universities and agencies (USEPA, 1989). Several million dollars were budgeted for the program at the outset, but by the end the cost was approximately $11 million ($22.8 million in 2017 dollars). The modeling results and environmental data from the mass balance study verified the necessity of moving forward with a program to remediate erodible PCBs in the Fox River. WDNR officials felt the study and the models provided them with the basis for making technical and management decisions on contaminated sediment remediation in the Fox River.

A collaborative approach, involving WDNR and the responsible parties (paper mills), was developed for the PCB remediation program. Adding urgency to the start of the program was a threat by the USEPA to name the Fox River and Green Bay as a Superfund site (Kraft and Johnson, 1999). In 2004, dredging and capping operations began in Little Lake Butte de Morts located at the upstream end of the lower Fox River. Since completion of this phase of the remediation program in 2009, the lowering of PCB concentrations in walleye fillets from Little Lake Butte des Morts has been significant (Fig. 4; WDNR, 2012). In the 2012 *Long Term PCB Monitoring Report* (WDNR, 2012), another positive development reported was a 70% reduction in PCBs in the water column in the Little Rapids to De Pere segment of the Fox River (OU3). This reduction was in reference to the 2006 baseline levels. However, at that time, PCB concentrations in fish tissue ranged from 137 μg/L to 1840 μg/L, levels that were not significantly different from those in 2006. Sampling was again conducted in 2014 in the same segment of the river. The results showed. PCB concentration in the water column had decreased by 83% from the 2006 baseline levels. Again there were no significant reductions in walleye tissue, but concentrations in carp tissue showed a 47% decline and in gizzard shad tissue the reduction was 81%.

No recent studies have been conducted on PCB accumulation in fish-eating birds; e.g., Forster's terns. However, there have been studies on the tree swallow, an avian insectivore, which feeds on aquatic insects emerging from sediments in the river and the bay (Custer et al., 1998; Custer et al., 2016). According to these studies, in 1994 and 1995 total PCB levels in eggs and in tissues of newly hatched young from nests within the AOC had a mean value of 3.0 μg/g of wet weight. Tree swallow eggs were monitored again in the period from 2010 to 2015. For those eggs collected from an area of the river lying within the AOC, the average PCB level was 3.27 μg/g, while for those eggs from an area of the bay, also within the AOC, the average was 1.32 μg/g. It is important to note that "cleanup dredging" had not yet taken place in the area of the river that was sampled. Also of interest is the fact that the PCB levels observed in the eggs were an order of magnitude below what has been stated to be the lower limit of their effect on hatching (20.0 μg/g in the United States). It remains to be seen what effects remedial dredging will have in terms of exposure to PCBs and other toxic substances; e.g., dioxins and furans. Remedial operations to the mouth of the river are scheduled to be completed by 2018. To date, over 15

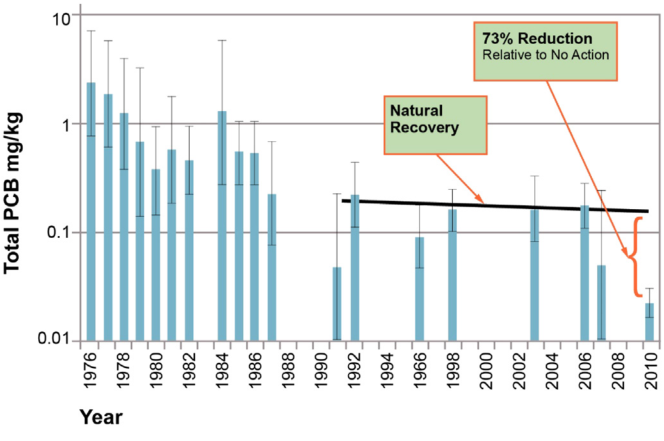


Figure from: WDNR, Lower Fox River OPerable Unit 1 Post Remediation Executive Summary

Fig. 4. Average PCB concentrations in walleye fillets (whiskers are standard deviation) from Little Lake Buttes des Mortes on the Fox River, showing decreased concentrations following remedial dredging to remove contaminated sediments (WDNR, 2012). Natural recovery (no action) refers to the modelled reductions that would have been achieved without remediation (dredging and capping).

million cubic yards of contaminated sediments have been treated and/or landfilled at a cost of over $1 billion.

Chlorinated hydrocarbons are not the only toxic chemical of concern in the Fox River and Green Bay; mercury has also been the subject of multiple investigations. The first studies were initiated in the early 1970s and continued intermittently through the late 1990s (see Qualls et al., 2013 for a summary). The highest total mercury concentrations found in Fox River sediments exceed the Ontario sediment quality guidelines by three times and the Wisconsin water quality criteria for wildlife by twenty-two times. While total and dissolved mercury concentrations are relatively high compared to other sites in Lake Michigan, the methyl mercury concentrations are no greater than or less than those at other sites. This apparent contradiction is due to less than optimal conditions for methylation in the Fox River and Green Bay (Hurley et al., 1998). Even so mercury levels in Fox River fish have exceeded consumption advisories in the past. Health concerns for mercury may be rectified by contaminated sediment removal for PCB remediation.

In 2003, a new effort to enhance knowledge and understanding of the watershed was initiated with the support of a $1.5 million grant from ARJO Wiggins Appleton, Inc.: the Lower Fox River Watershed Monitoring Program (LFRWMP). Partners in this program were UW-Green Bay, UW-Milwaukee, U.S. Geological Survey, GBMSD, Oneida Tribe, and six area high schools. Major program elements included continuous monitoring of sediment and P loadings, installation of real-time sensors, source-area studies, watershed modeling, and stream biotic integrity assessments. Monitoring results for the water years 2004 to 2006 characterize the seasonality of loads, the distribution of daily flows and loads, volumetric-weighted concentrations, and their comparisons among streams (Graczyk et al., 2011).

The LFRWMP continues to develop with additional funding from outside sources and by its partnering with the Fox/Wolf Watershed Alliance. Data gathered from many automated stations have provided a new and essential database to calibrate and validate the SWAT model in its application to the watershed. The SWAT model was a vital tool in the establishment of the phosphorus and suspended solids targets in the TMDL program for the lower Fox River basin (Baumgart, 2005). Presently, the LFRWMP provides technical resources and personnel to help assess the impact of management practices on several Demonstrations Farms in the basin. The LFRWMP is an integral part of a larger research effort to test the effectiveness of new conservation practices being implemented by agriculture producers. As the phosphorus issue was being addressed at the watershed scale another study examined phosphorus loading on a basin scale, increasing the impetus for action (Maccoux et al., 2013).

By the early 2000s, WDNR moved more aggressively to address P and TSS issues by retaining the Stratus Consulting firm to develop a TMDL program for P and TSS in the lower Fox River. In 2007, WDNR supported this effort by forming an ad-hoc science team whose purpose was to provide local data and contribute expertise in the setting of numerical targets for the TMDL program in the lower Fox River basin. The science team conducted a statistical analysis of a data set compiled by the GBMSD monitoring program with the objective of identifying a relationship between TP and TSS in the Fox River and light extinction rates (EPAR) in Zones 1 and 2 of the bay (WDNR (Appendix A), 2012). Subsequently, the derived statistical model was applied to six reduction scenarios, each of which was based on a specific assumption about the reduction in the levels of TP and TSS. From the six reduction scenarios WDNR selected the following TMDL targets for the lower Fox River: 0.1 mg/L for TP and 20 mg/L for TSS. These reductions from the baseline levels of 0.180 mg/L for TP and 36 mg/L for TSS were predicted to result in a specific EPAR value which, through a regression analysis, translates to a Secchi disk value of 1.14 m. This is a clear improvement over the baseline Secchi disk value of 0.70 m, an advancement that was judged to provide a favorable and realistic environment for aquatic plants and other ecosystem components (Robinson, 1996; E. Sager, personal communication). Once the targets were set, the consultants could employ the SWAT model as a tool to estimate TP and TSS reductions in the watershed needed to meet the targets for the lower Fox River and the bay. The TMDL targets were established in 2012. Identifying scientifically sound and socially acceptable means for achieving these targets is a multi-institutional task that is ongoing.

There is yet another concern that arises when considering actions to restore the integrity of the Fox River/Green Bay ecosystem: climate change. Climate change poses a new kind of threat to the Fox River and Green Bay because it may alter the impact of the already existing stressors on the system. A few years ago, as part of a larger statewide effort called the Wisconsin Initiative on Climate Change Impacts, a working group focused specifically on an assessment of climate-caused impacts on Green Bay that are likely to occur over the next 30 to 50 years. A methodology employing numerical methods was developed to assess the potential impacts (Wenger and Harris, 2010). The primary conclusion was that runoff from agricultural and urban sources, already a major ecosystem stressor, will be exacerbated in the future as a result of climate change impacts.

Another concern arising from a warming climate is its potential contribution to the formation of “dead zones”. As in other coastal environments subject to excessive nutrient enrichment and eutrophication, Green Bay has likewise experienced recurring seasonal hypoxia (Klump et al., this issue; Valenta, 2013). While oxygen depletion within the Fox River has been essentially eliminated as a result of the Waste Load Allocation Program, hypolimnetic oxygen depletion farther out into the bay has been observed as far back as the 1960s (Schraufnagel et al., 1968; Kennedy, 1982). Recent studies supported through NOAA's Coastal Hypoxia Research Program have provided a more comprehensive picture of bottom water hypoxia under stratified conditions in late summer (July–September) (Klump and Fermanich, 2017). Nutrient load-driven production of high organic matter inputs from both upstream sources and in-situ algal production in combination with the bay's estuarine-like circulation result in prolonged periods of thermal stratification and bottom water isolation (Hamidi et al., 2015). Evidence suggests that the summertime development of “dead zones” (regions with <2 mg/L dissolved oxygen) are a regular feature of the bay that could be exacerbated by warming climate and extended stratification, as well as by persistent or enhanced nutrient loading from the watershed (Klump et al., this issue).

Conclusions

What are the lessons that have been learned from the Green Bay saga? There are many, but the most important one is that we have come to understand how difficult it is to rehabilitate a large-scale ecosystem. Whether rehabilitation is even possible is a question that tends to arise on occasion. Interestingly, the difficulty of ecosystem management was foretold in 1984 by a UW-Green Bay political science colleague in a conference paper titled “The Dilemma of Ecosystem Management—The Green Bay Experience” (Yarbrough et al., 1984). Yarbrough and his co-authors noted that successful ecosystem management requires: a) a system-wide ecosystem approach, b) operational guides to management developed through research on the functional properties of ecosystems, and c) comprehensive planning and cooperation across a very broad range of institutions. In a succinct statement they postulate the dilemma as follows: “Ecological rehabilitation requires comprehensive ecosystem management but the existing institutional structure is biased against comprehensive management”. The comprehensiveness and coordination that are required to undertake successful ecosystem management are incompatible with a wide distribution of responsibility and decision making authority. What is the way out of this dilemma? Yarbrough and his co-authors contend that to bring about change a mandate is required – the force of law.

Reflecting on the Green Bay saga, in all cases where there appears to be progress in addressing specific problems—hypoxia in the river and the bay, PCB contamination, and eutrophication and light climate—we see some sort of mandate at work. With mandates in force and operational guidelines to management in place, guidelines that have been formulated from comprehensive scientific investigations, is that enough? The answer is no. Money is required—lots of it. In the case of Green Bay, considerable funding has come from private sources—funding for the PCB cleanup program and the Lower Fox River Watershed Monitoring Program are examples—and much has come from federal and state coffers. The funds have been used not only for remedial action, but also for research and educational outreach to the public. Will that support be forthcoming in the future? Our analysis of the question leads us to the conclusion that it may be more cost effective to adopt and support policies that prevent environmental degradations, rather than face the need to "fix" them later. Said another way, one cannot decouple economic sustainability from ecological sustainability and still have a sustainable society (Kubiszewski et al., 2017). This last observation highlights the need to include effective social science expertise in developing operational guidelines for ecosystem management. Such guidelines cannot be developed without broad-based societal support.

Be that as it may, the Green Bay saga continues. Committed individuals continue their work, and new people come on the scene with new ideas. New technology, which can be used to develop more sophisticated research and monitoring procedures, becomes available. Careful thought is given to the development of focused research agendas. An example of the latter occurred at a recent conference held at UW-Green Bay in July 2017. Attendees, consisting of experienced researchers and persons with knowledge of the Green Bay ecosystem, engaged in three days of deliberations and discussions leading to the development of a new long-term research agenda that covers the next decade. The title of the conference, Summit on the Ecological and Socio-Economic Tradeoffs of Restoration in the Green Bay, Lake Michigan Ecosystem, gives an indication of the scope and range of discussions that took place in generating the decadal research agenda. It calls for projects that demarcate the present state of knowledge, fill gaps in our understanding of the ecosystem structure and function, assess management policies and practices to determine their capability for meeting changing climatic conditions, and translate scientific information into a form that is useable by managers, policymakers, and others. The agenda is organized around five key focal areas:

1) Watershed modeling
2) Biochemistry and hydrodynamics
3) Ecosystem modeling and trophic dynamics
4) Habitat and biodiversity—benthic, wetland, and land-margin interfaces
5) Socioeconomic and management issues.

The new research agenda developed by the participants in the July 2017 conference, and the start for moving toward this agenda provided by the papers in this special issue, may mark a transition into a new era in the effort to rehabilitate the Green Bay ecosystem. If this is the case, clearly the past research era with its beginning some 90 years ago, has served as a prologue to what lies ahead. Here again it is important to highlight the factors that provided the momentum for this initial era: the public concern about the environment, pro-environmental legislation stimulated by the environmental movement in the 1970s, and, at the local Green Bay level, the establishment of the University of Wisconsin-Green Bay on the shores of Green Bay. Not only did the new university bring a faculty with scientific expertise for conducting research on the Green Bay ecosystem, but it also provided a focal point for the marshaling of scientific expertise from throughout the University of Wisconsin System, most notably UW-Madison and UW-Milwaukee. Central to this unfolding research process was the University of Wisconsin Sea Grant Institute.

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