BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
	)	
WATER QUALITY STANDARDS AND	)	
EFFLUENT LIMITATIONS FOR THE	)	R08-9
CHICAGO AREA WATERWAY SYSTEM	)	(Rulemaking - Water)
AND THE LOWER DES PLAINES RIVER:	)	
PROPOSED AMENDMENTS TO 35 Ill.	)	
Adm. Code Parts 301, 302, 303 and 304	)	

PRE-FILED TESTIMONY OF SCUDDER D. MACKEY

Introduction

My name is Scudder D. Mackey and I am an Environmental Consultant specializing in aquatic habitat mapping and characterization in both riverine and lake systems. I am the owner of Habitat Solutions NA, which is an independent environmental consulting firm. I currently hold dual appointments as a Visiting Research Professor in the Departments of Biological Sciences and Geological Sciences at the University of Windsor, Ontario, Canada. I hold a Bachelor of Science Degree in the Geological Sciences from Hobart College and a Master of Science in Geology from the University of Wisconsin – Madison. I received a Doctor of Philosophy Degree in Geology (fluvial sedimentology) from the State University of New York at Binghamton.

My areas of technical specialization are in aquatic habitat characterization and mapping; developing biophysical linkages to habitat; surface and watershed hydrology; nearshore, coastal, and riverine processes; and application of geospatial data and analyses (GIS) to Great Lakes aquatic ecosystems. I served as Supervisor for the Lake Erie Geology Group for the Ohio Department of Natural Resources and worked for the Great Lakes Governors as Project Implementation Manager with the Great Lakes Protection Fund (GLPF). I currently serve as a member of Lake Erie Habitat Task Group for the Great Lakes Fisheries Commission and the AIS

Barrier Advisory Panel and Rapid Response Team for the USACE Chicago Waterway electric field barrier project.

In 1995, I received the Outstanding Paper Award for the Journal of Sedimentary Research. In 2001, I received letters of commendation from the Ohio Senate and the U.S. House of Representatives for services to the People of the State of Ohio and the Natural Resources of Lake Erie. In 2005, I was retained by the Water Quality Board of the International Joint Commission to fully explore the role of physical integrity as part of a comprehensive ongoing review of the Great Lakes Water Quality Agreement. Also in 2005, I was the co-editor of a Special Issue of the Journal of Great Lakes Research entitled *Nearshore and Coastal Habitats of the Laurentian Great Lakes*, a collection of 14 peer-reviewed papers focused on the physical, chemical, and biological characteristics of Great Lakes nearshore and coastal habitats. In 2006, I was a co-investigator on a USFWS Great Lakes Fisheries Restoration Act funded project to create a framework and develop a process to systematically identify, coordinate, and implement aquatic and fish habitat restoration opportunities in the Lake Huron to Lake Erie Corridor (St. Clair River, Lake St. Clair, Detroit River). This project considered potential restoration opportunities within a context of long-term effects of global climate change.

Current ongoing projects include: Identification and mapping of potential lake trout spawning habitat in the Eastern Basin of Lake Erie in cooperation with the Ontario Ministry of Natural Resources and the New York Department of Environmental Conservation; river mouth mapping and instream aquatic habitat assessments for three urban rivers in the Toronto area in cooperation with the Toronto Regional Conservation Authority; riverine fish habitat assessments in the Sandusky River and Sandusky Bay areas in cooperation with Ohio State University and

Ohio Department of Natural Resources; and removal of the Ballville Dam on the Sandusky River in cooperation with the Ohio Department of Natural Resources.

Review of my resume (Attachment 1) will reveal that my work has been focused on developing linkages between physical processes, physical habitat, and the organisms that use those habitats. My work is based on first principles and considers habitat function, pattern, and connectivity; and includes the use of remote sensing technologies (sidescan sonar) in addition to more traditional habitat assessment techniques. This experience brings a unique perspective to the Chicago Area Waterway System.

Overview

The testimony presented here today will be focused primarily on the aspects of *physical habitat* related to the Aquatic Life Use designations proposed in IPCB rulemaking R08-9 and the methodology that IEPA used to designate those Aquatic Life Uses. My testimony has three components: 1) I will demonstrate that the data and methodology used by IEPA is inaccurate, flawed, and does not adequately consider all of the key elements necessary to assess the condition of aquatic habitats, 2) I will show that it is unlikely that the current proposed standards will significantly improve fish community structure and diversity in the Chicago Area Waterway System, and 3) I will suggest an alternative strategy that integrates all of the fundamental habitat characteristics necessary to maximize the productive and ecological capacity of the waterway, a strategy that the Metropolitan Water Reclamation District of Greater Chicago is currently pursuing.

From the perspective of physical integrity, *physical habitats* are defined by a range of physical characteristics and energy conditions that can be delineated geographically that meet the needs of a specific species, biological community, or ecological function. To be utilized as habitat, these physical characteristics and energy conditions must exhibit an organizational pattern, persist, and be "repeatable" – elements that are essential to maintain a sustainable and renewable resource. For example, seasonal changes in flow, thermal structure, and water mass characteristics create repeatable patterns and connections within tributaries and lakes. These patterns and connections, in part, control the seasonal distribution and regulate the timing, location, and use of aquatic habitats.

Also critically important is the pattern and juxtaposition of different types of habitat. For example, successful recruitment of fish will not occur if spawning habitat is not connected to suitable nursery and forage habitats. Nursery and forage habitats provide sheltered areas where larval and young-of-the-year (YOY) fish can feed and grow with minimal disturbance. Without access to adjacent nursery areas, potential spawning sites are nothing more than substrate areas with physical characteristics that mimic those of active spawning sites.

There are three major classes of variables that must be considered when assessing aquatic habitat – 1) energy (flow regime), 2) substrate (composition, texture, structure), and 3) water mass characteristics (water chemistry, water quantity). All of these variables must be spatially and temporally connected by physical and biological *processes* in ways that support diverse aquatic communities (see Figure 1 – Attachment 2). Biological characteristics are also an important element of aquatic habitat, but will not be discussed in detail in this testimony and are not included in Figure 1.

In a paper published in 1998, Yoder and Rankin made the point that the almost myopic focus on water chemistry, point sources, and contaminants by many regulatory agencies has led to an "incomplete foundation in water resource policy and legislation." Yoder and Rankin 1998 go on to state:

> "Because biological integrity is influenced and determined by *multiple* chemical, physical, and biological factors, a singular strategy

> emphasizing the control of chemicals *alone* does not assure the restoration of biological integrity."

This statement serves as an appropriate backdrop for the testimony to follow.

UAA Methodology

The identification of Aquatic Life Use designations and the classification of waterway reaches into the appropriate use categories are crucial to the successful conduct of a Use Attainability Analysis (UAA) process. The process by which the Aquatic Life Uses are defined and applied to waterways undergoing a UAA is the foundation for establishing appropriate water quality standards. Ideally, the UAA provides a scientific basis to develop attainable designated water uses that are based on a comprehensive integrated assessment of the physical, chemical and biological conditions of a water body (USEPA, 1994). This assessment should include an integrated analysis of current physical habitat, flow regime, temperature, water quality, and existing aquatic communities.

The purpose of this integrated assessment is to determine whether existing or improved conditions can be supported by changes in beneficial use and/or associated criteria. Thus, the methodology used in defining and assigning uses for a specific waterway should be transparent, scientifically based, and documented accurately, clearly, and completely. Unfortunately, the CAWS UAA Report and supporting documents submitted by IEPA in this rulemaking effort do not meet these criteria and contain data errors and flaws in the methodology used to develop the proposed Aquatic Life Use designations.

Aquatic Life Use Designations

IEPA has proposed to eliminate the current use designations that have been in place since 1972, and supplant them with a tiered system of Aquatic Life Uses supposedly based, in part, on inferred relationships between physical habitat as characterized by Qualitative Habitat

Evaluation Index (QHEI) scores, and the Ohio boatable Index of Biotic Integrity (IBI), which characterizes the health of the existing fish community. These new Aquatic Life Use tiers were based on a comparison of IBI percentile scores and QHEI scores at each sample location. Review of the QHEI and IBI scores revealed significant errors and uncertainties in the data, and the methods used to compare the QHEI and IBI scores found in Figure 5-2 of the UAA Report are not scientifically valid.

By focusing almost exclusively on the IBI metrics and percentiles, IEPA did *not* provide an integrated analysis of physical habitat, flow regime, temperature, water quality, and existing aquatic communities in their assessment of the CAWS. Specific issues that I will discuss include: (1) sampling design, (2) significant problems using the QHEI for CAWS, (3) errors and uncertainty in the data, and (4) fatal flaws in the Aquatic Life Use designation methodology.

1. There are significant limitations in the current sampling design.

In the physical habitat assessment summarized by Rankin in 2004 (IEPA filing Attachment R), QHEI values were calculated for 20 sites within the CAWS. These sites were selected based on the availability of long-term fish sampling data made available by the MWRDGC. The spatial distribution of these sites *was not* based on an appropriate statistical sample design or consideration of inferred physical habitat processes or characteristics. Distances between sampling sites ranged from 0.5 miles (0.8 km) to 15.8 miles (25.4 km), with a mean sampling distance of 4.3 miles (6.9 km). Clearly, gaps of up to 15 miles between sampling points in the waterway can not be considered to be a comprehensive assessment of physical habitat.

Moreover, portions of the CAWS were not included in the physical habitat assessment. For example, IBI and QHEI metrics for Bubbly Creek were *not evaluated at all*, and QHEI metrics were *not* calculated for the South Branch of the Chicago River. Even though the channel morphology and flow characteristics of Bubbly Creek and the South Branch of the Chicago River are *distinctly different* from each other, the CAWS UAA Report [on page 4-69] states that Bubbly Creek and the South Branch have "similar" environmental characteristics and are grouped together as the *same* channel in the Report.

Widely-spaced, traditional point sampling does not provide adequate data to document the type, area, pattern, or juxtaposition of different types of aquatic habitat that may exist in the CAWS. For example, in the Calumet-Sag Channel, only *two* sites were evaluated using the IBI and QHEI metrics, *and those sites were 10.7 miles apart.* These two sites form the basis for the habitat assessment and Aquatic Life Use designation for the entire 16-mile channel length. The limited number and wide spacing between habitat sampling sites is a *major* deficiency in the CAWS UAA Report and IEPA Statement of Reasons.

IEPA purportedly considered shoreline and bank-edge (littoral) conditions for each of the CAWS segments. This is surprising, because there has not been a comprehensive inventory and assessment of shoreline or bank-edge habitat conditions for the CAWS, nor have there been ecological studies of navigation or wave impacts on shorelines within the CAWS. Shoreline and bank-edge areas provide spawning, nursery, and forage habitats necessary to sustain healthy, propagating fish populations. As part of a comprehensive habitat assessment it would be important to know what the relative percentage, location, pattern, and distribution of shoreline types and bank-edge habitat are for each of the CAWS segments. This is particularly important when assessing the pattern and juxtaposition of different types of aquatic habitats, which was *not done* in the CAWS UAA Report or presented in the Statement of Reasons.

Even though bank-edge areas are regularly sampled by MWRDGC using electrofishing equipment, the results are integrated and summarized across the entire channel segment to calculate IBI scores at that sampling site. The reported IBI scores *may* be indicative of fish utilization of bank-edge habitat, but the coarse sampling interval and lack of bank-edge habitat data severely limits our ability to *draw any meaningful conclusions*. However, IEPA contends that these shallow water bank-edge habitats in the Calumet-Sag Channel should be considered to be spawning habitat, which is problematic given that *no direct data* are available to support that contention. The lack of a comprehensive physical and biological assessment of existing shoreline and bank-edge habitats is another *major* deficiency in the CAWS UAA Report and IEPA assessment methodology.

2. There are significant problems applying the QHEI to low-gradient urbanized rivers such as the CAWS.

The QHEI protocol was developed to provide a measure of physical habitat quality and is based on hydrogeomorphic metrics in a *natural* stream or river channel. There are six metrics that comprise this index: substrate, instream cover, channel morphology, riparian zone/bank erosion, pool/glide and riffle/run quality, and map gradient. The QHEI protocol is *not* designed for use in low gradient, non-wadeable streams and rivers, in part because traditional sampling approaches are inadequate to assess critical substrate, instream cover, or other metrics used in the QHEI assessment protocol. Within the CAWS, several of the key morphological metrics upon which the QHEI scores are based are held constant or are not present. As a result, the QHEI scores for the CAWS are calculated using sub-metrics that may be of *secondary importance* to the attainment of a diverse, sustainable fish population. Embedded within the QHEI scoring system is an *implicit* assumption that there is a relationship between flow hydraulics, channel morphology, and the type and distribution of substrate materials. This assumption is not valid for low gradient, urbanized, artificial channels such as the CAWS. Flows in the CAWS are regulated, controlled by man-made structures, and are not natural. The channels in the CAWS are stable (carved out of bedrock or artificially stabilized), and flows are generally decoupled from substrates, i.e. coarse-grained substrates observed in the CAWS may not be dependent on or controlled by flow. In summary, the QHEI protocol *was not* designed to be applied to a flow-regulated artificial waterway system such as the CAWS.

3. There are errors and uncertainty in the environmental data.

Careful review of the data and metrics calculated in the CAWS UAA Report reveals errors and uncertainty in the QHEI data and fundamental errors in how the boatable IBI scores were calculated. These errors call into question the reliability of the analysis and the resulting recommendations. First, there is considerable uncertainty as to what the *actual* QHEI scores are for the North Shore Channel and the Cal-Sag Channel. Unfortunately, due to transposition errors in the habitat assessment report by Rankin (IEPA Attachment R), the QHEI scores for the reference site at Sheridan Road on the North Shore Channel and for sampling sites on the Cal-Sag Channel were incorrectly stated (see Essig testimony, 4/23/08, page 192-193). If these QHEI scores were transposed, then the QHEI score at the reference site is considerably lower (42 instead of 54), which places the high-quality reference site in the "poor" habitat category. Given the significantly lower QHEI score, the Sheridan Road site *no longer* meets the criteria as an appropriate high-quality reference site, and the boundaries of the proposed Aquatic Life Use categories for the CAWS are invalid and should be redefined.

Note: Proper application of the Ohio Boatable IBI requires identification of high quality reference streams which serve as yardsticks to measure the biological health in similar, regional water bodies. A high-quality reference stream will have suitable habitats and a diverse, well-balanced aquatic community using those habitats. These characteristics represent the highest level of physical, chemical, and biological integrity that can be attained within these regional systems.

If the QHEI scores that were originally reported *are correct*, then at the Cicero Avenue sampling site on the Cal-Sag Channel, the box plot of IBI scores falls *below* the minimum line for IEPA's Aquatic Life Use "A" waters, and a QHEI score of 37.5 is classified as a "poor" habitat. These data are consistent with the statement on page 4-92 of the UAA Report that the fish IBI scores in the Cal-Sag Channel are classified as "poor to very poor" and the QHEI scores are classified as "poor". At the Route 83 sampling site, the IBI score appears to be on the dividing line between IEPA's Aquatic Life Use "A" waters and Aquatic Life Use "B" waters, but the QHEI score of 42 is still in the "poor" range.

The Cal-Sag Channel and the Chicago Sanitary and Ship Canal share similar physical characteristics (for example, deep-draft waterway, limited shallow area along banks, high volume of commercial navigation) except that there is more weathering of the channel walls in the Cal-Sag Channel. The weathering of the bank walls provides a slight shallow shelf with limited habitat for fish. This difference explains the slightly higher QHEI scores in the Cal-Sag Channel compared to the Chicago Sanitary and Ship Canal. Nevertheless, both waterways are considered "poor" habitat according to the QHEI classification scale in Table 2 of Rankin's habitat assessment report (IEPA Attachment R). The small amount of rubble from the crumbling walls does very little to improve the overall physical habitat for fish and invertebrates in the Cal-Sag Channel.

The decision to include the Cal-Sag Channel as a higher Aquatic Life Use "A" water is *not* defensible, because the habitat indices for both monitoring stations were in the poor range, and the IBI percentile scores are below or at the bottom of the range established for IEPA's Aquatic Life Use "A" tier. In fact, the minimum IBI scores observed at the two monitoring stations in the Cal-Sag Channel are among the lowest in the CAWS.

Second, there are errors in the IBI scoring criteria listed in Table 4-11 of the CAWS UAA Report [page 4-27]. In this table, the scores for the "fish numbers" metric have been reversed. Instead of adding 5 points when there are less than 200 fish and 1 point when there are greater than 450 fish, the opposite should have been done. This error tends to inflate the IBI scores when fish densities are low. Moreover, a special scoring procedure was incorrectly applied to the CAWS data that is intended *only* for the Ohio *wadeable* IBI, *not* for the Ohio *boatable* IBI. Since the proposed Aquatic Life Use designations were based on these inflated IBI scores, *all* of the Aquatic Life Use designations proposed for the CAWS need to be reconsidered using the corrected IBI scores.

4. There are fatal flaws in the Aquatic Life Use designation methodology.

The method used to compare the QHEI and IBI scores found in Figure 5-2 of the UAA Report are not scientifically valid. First, by plotting the IBI and QHEI scores on the same graph, there is an implicit assumption that there is a one-to-one correspondence of IBI scores to QHEI scores, even though this is clearly not the case. Rankin in his 1989 paper states that "using the QHEI as a site-specific predictor of IBI can vary widely depending on the predominant character of the habitat of the reach".

Second, IEPA adopted the approach used in the CAWS UAA Report, and *in that report*, the lines used to delineate the Aquatic Life Use categories are *based solely on the percentile IBI scores*. Specifically, the Aquatic Life Use categories are delineated using the 75th percentile of the IBI scores at the reference site (NSC Sheridan Road) and the 75th percentile of the IBI scores from the entire waterway. Neither the CAWS UAA Report nor the materials supporting the proposed rule provide any justification (biological or otherwise) for using the 75th percentile IBI as a threshold.

Third, Figure 5-2 gives the impression that *both* biotic (IBI) and habitat (QHEI) indices were utilized in formulating the Aquatic Life Use tiers, and that observed IBI scores were consistent with the corresponding QHEI scores for selected reaches of the CAWS. However, the range shown on the vertical axis for the IBI score is 12-38, even though the entire range of possible IBI scores is from 12-60. On the QHEI score axis, the scale includes the entire range of possible QHEI scores from 0 to 100. By plotting the IBI scores in this way, it is possible to "adjust" where QHEI scores line up on the graph relative to the 75th percentile IBI line. In other words, the scale on the IBI axis can be adjusted or scaled up or down to *arbitrarily* fit the QHEI data to whatever IBI percentile is desired (what QHEI score would you like it to be?).

QHEI thresholds determined using this methodology are *arbitrary* and *scientifically invalid*. The ability to arbitrarily shift the IBI percentile lines relative to the QHEI data in Figure 5-2 invalidates the justification provided for IEPA's use of a QHEI score of 40 as a lower boundary for Aquatic Life Use "A" waters rather than a QHEI score of 45 as recommended by Rankin in 2004 (IEPA Attachment R). To summarize, even though Figure 5 -2 appears to be correct, any comparisons made between IBI and QHEI scores using this methodology are *not scientifically valid*.

Finally, it is stated in IEPA's Statement of Reasons that Aquatic Life Use "B" waters "are capable of maintaining aquatic-life populations predominated by individuals of tolerant types..." and Aquatic Life Use "A" waters "are capable of maintaining aquatic-life populations predominated by individuals of tolerant *or* intermediately tolerant types..." During cross-examination of IEPA, efforts to elucidate a more detailed description of desired aquatic communities for the CAWS were unsuccessful (see Smogor testimony, 3/10/08, pages 10-12). The lack of a desirable (or expected) fish and benthic invertebrate species list is somewhat surprising, because one would think that a description of the desired aquatic communities for Aquatic Life Use "A" waters and/or Aquatic Life Use "B" waters would be useful to determine if, and when, desired Aquatic Life Uses are actually attained. If we can't describe the biological community that is potentially attainable, then how do we know that it doesn't already exist?

In summary, based on the aforementioned deficiencies, the Aquatic Life Use categories and designations as proposed in IPCB R08-9 need to be reconsidered using a more transparent, scientifically-based methodology. At a minimum, the IEPA must first review and correct any inaccuracies in the environmental data *before* using that data to delineate proposed Aquatic Life Use waters for the CAWS. Further clarification is also needed regarding their approach and basis for defining Aquatic Life Use tiers and designations. IEPA's current methodology relies almost exclusively on the boatable IBI scores and does *not* adequately consider physical habitat, flow regime, or existing aquatic communities. If these elements are not incorporated into IEPA's analysis, the methodology must be judged as incomplete, arbitrary, and poorly founded in science.

The Proposed Water Quality Standards Will Not Achieve Designated Uses

In the Statement of Reasons, the IEPA hypothesizes that increased DO and reductions in temperature will significantly improve fish diversity and community structure within the CAWS. This implies that IEPA has determined that DO and elevated temperatures are the primary stressors limiting the biological potential of aquatic communities in the CAWS. In their submittals, the IEPA has not provided evidence that these are indeed the primary factors that limit the development of a diverse, sustainable fish community in the CAWS. I would ask why IEPA didn't compare readily available DO data with fish richness metrics from the CAWS to demonstrate that the proposed increases in DO would *indeed* result in a significant increase in fish richness and diversity. This is another deficiency in the IEPA assessment methodology.

Other non-water quality related parameters could also be limiting the biological potential of the CAWS. Examples include, but are not limited to:

- Physical limitations such as lack of shallow bank-edge habitats and riparian cover; lack of instream habitat cover and diversity; lack of suitable substrates and substrate heterogeneity; or altered flow regimes (flow and water levels);
- Biological limitations such as limited primary productivity, degraded macrobenthic communities (food supply), predation, or lack of appropriate spawning and nursery habitats;
- Chemical limitations such as legacy contaminants in the sediments; and
- Functional limitations such as navigation (prop wash and turbulence, sediment resuspension, waves) and conveyance of waste and flood waters (variable flow regime, water levels).

Other investigators have recognized these potential limitations as well. For example, the MWRDGC in Report 98-10 concluded that a lack of diverse aquatic habitats is one of the major limiting factors affecting fish diversity and richness in the CAWS. Conclusion 8 of the report states:

> "Even though water quality is generally good, the fish populations of the Chicago Waterway System are still dominated by omnivores, tolerant forms, and habitat generalists. This is primarily because water quality alone does not take into concern the condition of habitat, flow, or other outside factors. The waterways of the Chicago Waterway System were not constructed to be fishable streams with diverse habitat types. They were built for navigation and water reclamation. It is unlikely that these waterways can achieve the same stream quality for fish as a natural habitat-rich waterway unless desirable fish habitat is created..."

The CAWS UAA Report also found that a lack of suitable habitat may be a major factor that limits the attainment of diverse, sustainable fish communities. In fact the report on page 5-3 states:

> "Improvements to water quality through various technologies, like re-aeration may not improve the fish communities due to lack of suitable habitat to support the fish populations. Unless habitat improvements are made in areas like the CSSC, additional aeration may not result in the attainment of higher aquatic life use."

Multiple lines of evidence support the fact that water quality in the CAWS has *improved significantly* over the past several decades and is now good enough to support the passage of fish and other aquatic organisms to and from the Mississippi River and Great Lakes Basins via the CAWS. For much of the CAWS, fish richness and diversity has improved markedly since effluent chlorination was terminated in 1984, the Tunnel and Reservoir Plan (TARP) came online in 1985, and SEPA (aeration) stations improved DO levels in the Calumet River system.

Moreover, the existence of active angler groups and bass fishing tournaments on the waterway also suggests that for many species, water quality (DO and temperature) for much of the CAWS is *not a significant limiting factor*. Certainly there continue to be DO and temperature limitations for other desirable, less-tolerant species (which are not specifically identified in the UAA report or IEPA's statement of reasons), but if suitable habitats are not present, sustainable populations of these species will not become established in the CAWS, *irrespective of how much improvement there is in water quality.*

A diverse benthic community is an important food source for young and adult fish. Lack of an adequate benthic food supply could be a major limitation that is not necessarily related to water quality or DO, but instead is caused by limitations in physical habitat (unnatural flow, lack of suitable substrates, and poor sediment quality). In fact, fair to good Macroinvertebrate Biotic Index (MBI) scores from the "in-water column" Hester Dendy samplers and very poor MBI scores within CAWS sediments (Ponar grab samples) suggest that water quality improvements may *already be sufficient* to support a more robust and diverse macroinvertebrate community if suitable habitats were present in the CAWS (Wasik testimony).

In my opinion, the substantial investments needed for infrastructure to provide incremental increases in DO and/or reductions in temperature will *not* yield a proportionate biological response with respect to attaining sustainable fish communities and/or other beneficial uses. The lack of diverse bank-edge and instream habitats within the CAWS may be a much more significant limitation on the development of sustainable fish communities than current levels of DO or temperature. Without suitable habitat pattern and diversity, sustainable populations of these species can not be established *irrespective of how much improvement there is in water quality*. In fact, opportunities to improve physical habitat structure and increase habitat diversity in selected reaches within the CAWS may yield a much more significant biological response than system-wide improvements in DO and temperature.

Need for an Alternative Strategy to Generate a Comprehensive Habitat Assessment Integrating all Fundamental Habitat Characteristics Necessary to Maximize Productive and Ecological Capacity of the CAWS

After reviewing the CAWS UAA Report, IEPA's proposed rule R08-9, and supporting documentation, it becomes clear that there are major gaps in the CAWS environmental datasets, especially with respect to physical habitat, spatial and temporal sampling, and the need for new indices designed specifically to assess and summarize habitat and biological conditions in low-gradient, non-wadeable, highly altered, urban streams and rivers. Many of the major deficiencies in IEPA's approach are listed in Table 1 (Attachment 3)

Recognizing the data gaps and limitations in the CAWS UAA Report, the MWRDGC in the fall of 2007 issued a request for proposals entitled "Habitat Evaluation and Improvement Study" designed to address many of the data gaps and deficiencies listed in Table 1. This study, which is funded by the MWRDGC, is anticipated to be completed by summer 2009. As part of this project, historical environmental data and newly collected environmental data will be integrated into a comprehensive GIS package that will enhance accessibility and facilitate analysis of CAWS environmental datasets.

The Habitat Evaluation and Improvement Study that is currently underway will follow a scientifically sound, peer-reviewed, methodology for development of habitat indices in non-wadeable rivers (Wilhelm, *et al.*, 2005) to develop a CAWS-specific physical habitat index. This index will be designed to differentiate habitat quality in the CAWS, where habitat variability is relatively limited, especially within reaches. The study will make extensive use of existing biotic and habitat data collected by MWRDGC between 2001 and 2007, supplemented with detailed fish, macroinvertebrate, water quality, and habitat data from 30 CAWS sampling stations in 2008. These data will be further augmented by digital bathymetric and shoreline video covering the entire CAWS.

Robust multivariate statistical methods will be used to reduce the data and to identify the most important fish and habitat variables in the CAWS. This approach will provide the strongest relationships between fish and habitat, which is essential for understanding the ability of fish to thrive in the CAWS. When completed, the CAWS habitat index will be applied to the entire CAWS system. Furthermore, other important factors affecting fish will be considered in evaluating habitat quality in the CAWS, including sediment chemistry and navigation impacts.

This study will create opportunities to develop linkages between physical habitat, water quality, and aquatic communities in the CAWS. These linkages can then be used to systematically (and scientifically) evaluate and manage for potential Aquatic Life Uses for various segments of the CAWS, at scales much finer than had been previously possible.

Conclusions

Given the many deficiencies in the habitat data and lack of an appropriate science-based methodology to designate Aquatic Life Use waters, the IEPA filing of proposed rule R08-9 and associated DO and temperature criteria is premature. Moreover, in my opinion, the protections proposed in rule R08-9 are unnecessary and will not measurably enhance fish community structure, aquatic diversity, or beneficial uses within the CAWS. It is not at all evident that the substantial investments needed for infrastructure to provide incremental increases in DO and/or reductions in temperature will result in attainment of Aquatic Life Uses that are different from what already exist.

The ongoing Habitat Evaluation and Improvement Study is designed to address many of the deficiencies highlighted in this testimony. This study will be completed by the end of this calendar year with data and results available summer 2009. By integrating the results of this study with other CAWS datasets, it should be possible to perform a comprehensive, integrated assessment of the physical, chemical, and biological integrity of the CAWS. The objective would be to identify the most efficient and cost-effective means to further protect and enhance Aquatic Life Use waters and associated beneficial uses in the CAWS. It would then be appropriate to move forward once this work has been completed.

I would like to thank the Illinois Pollution Control Board for the opportunity to present this testimony. I hope that the Board will carefully consider this testimony and act accordingly.

Testimony Attachments

1. Resume: Scudder D. Mackey, Ph.D.
2. Figure 1 Physical Characteristics of Aquatic Habitat
3. Table 1 Data Availability, Metrics, and Methods
4. Written Report: Scudder D. Mackey, Ph.D.

References

MWRDGC. 1998. A Study of the Fisheries Resources and Water Quality in the Chicago Waterway System 1974 through 1996. Report 98-10

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Respectfully submitted,

By: *Scudder Mackey*

Attachment 1

Scudder D. Mackey, Ph.D.

Habitat Solutions NA

Habitat Solutions NA

QUALIFICATIONS

- Demonstrated management abilities and leadership skills
- Excellent concept generation and synthesis skills – innovative solutions to complex problems
- Experience dealing with multiple stakeholders and partners during project planning and design
- Strong facilitation and communication skills

EXPERTISE

- Conservation Geology
- Aquatic Habitat Characterization
- Nearshore Coastal Processes
- Fluvial Sedimentology
- Hydrology
- Aquatic Invasive Species
- Geospatial (GIS) Mapping

EDUCATION

B.S., Geology, Hobart College, Geneva, New York, 1971

M.S., Geology, University of Wisconsin, Madison, Wisconsin 1977

Ph.D., Sedimentology, State University of New York, Binghamton, New York, 1993

AFFILIATIONS

International Association of Great Lakes Research

Geological Society of America

American Water Resources Association

Wisconsin Wetlands Association

American Fisheries Society

American Shore and Beach Preservation Association

Dr. Mackey is Principal and Owner of Habitat Solutions NA, an environmental consulting firm based in the Chicago, Illinois region. Habitat Solutions NA is an environmental consulting firm specializing in aquatic habitat assessment, protection, and restoration; riverine and coastal physical processes and habitat dynamics; and Great Lakes water resource issues. Dr. Mackey holds a Doctorate in Geology (fluvial sedimentology) with areas of technical specialization in aquatic habitat characterization and mapping; development of biophysical linkages to habitat; surface and watershed hydrology; nearshore, coastal, and riverine processes; and application of geospatial data and analyses (GIS) to Great Lakes aquatic ecosystems.

Dr. Mackey has considerable experience working with multiple stakeholders and has been directly involved with policy development and numerous protection and restoration initiatives focused on a broad range of environmental issues, including: Great Lakes water resources and diversions (Annex 2001), aquatic invasive species (ballast water introductions and Asian Carp), natural flow regime restoration (dam removals and watershed flow-path analyses), and the mapping and characterization of fish and aquatic habitats in large riverine and nearshore systems of the Great Lakes. He has collaborated with many key environmental groups and resource management agencies in both the U.S. and Canada and has an excellent rapport with agency, academic, and NGO organizations within the Great Lakes basin. Dr. Mackey has strong facilitation and communications skills and has considerable experience developing innovative solutions to complex environmental problems within the Great Lakes basin.

Dr. Mackey served as Supervisor for the Lake Erie Geology Group for the Ohio Department of Natural Resources and worked for the Great Lakes Governors as Project Implementation Manager with the Great Lakes Protection Fund (GLPF). Dr. Mackey developed, reviewed, and participated in numerous aquatic habitat protection and restoration projects in both coastal and riverine settings. He currently holds a dual appointment as an Adjunct and Visiting Research Professor in the Departments of Biological Sciences and Earth Sciences at the University of Windsor, Canada.

RELEVANT AGENCY EXPERIENCE

Dr. Mackey served as the Supervisor of the Lake Erie Geology Group from 1992 through 2003. This field office provided technical support and services to lakefront property owners, local communities, and local, State, and Federal agencies. The primary focus of this office was to develop a better understanding of coastal erosion and sediment transport processes along the Ohio Lake Erie coastline, and how to manage those processes in a sustainable way that benefits the people of the State of Ohio. The Lake Erie Geology Group worked closely with the U.S. Army Corps of Engineers on numerous coastal issues and assisted with the technical evaluation of projects proposed for Ohio Lake Erie waters. This office reviewed applications for new shore protection projects as part of a multi-agency review process, with a strong focus on sand resource conservation and management.

From 1992 though 1996, Dr. Mackey was a co-PI with the USGS National Coastal Center as part of major study to document and understand the underlying framework and processes influencing coastal erosion along the Ohio Lake Erie coastline. Dr. Mackey also initiated a comprehensive inventory of shore protection structures and a comprehensive assessment of the distribution of lakebed materials in coastal margin and nearshore zones in Ohio waters. Working with coastal stakeholders, the Lake Erie Geology Group developed and implemented the protocols to systematically map and quantify Coastal Erosion Areas as part of the Ohio Coastal Management Program.

Dr. Mackey also initiated habitat-related projects in cooperation with both State and Federal agencies, with a specific emphasis on developing linkages between physical habitat structure, the processes that create and maintain those habitats, and the biological organisms that relay on those habitats. Examples include the Metzger Marsh wetland restoration project, an assessment of Walleye spawning habitat over the Western Basin Reefs, mapping of potential small-mouth bass habitat around the fringes of the Lake Erie Islands, and numerous dam removal and stream habitat assessment and protection projects in tributaries flowing into Lake Erie.

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RELEVANT PROJECT EXPERIENCE

TRCA – Toronto Region Conservation Authority – Restoration and Naturalization of Lower Don River, Toronto, Ontario (ongoing) In cooperation with Staff from Applied Ecological Services and the Toronto Regional Conservation Authority, Dr. Mackey is mapping channel morphology and potential fish habitat structure in three urban rivers in the Greater Toronto area. Two of these rivers are being used as reference sites to establish habitat-fish community relationships from areas that have not been severely degraded. It is anticipated that this information and data will be used to guide a comprehensive restoration and naturalization effort in the Lower Don River.

The Ohio State University – Aquatic Habitat Mapping and Assessment – Sandusky Bay and Sandusky River, northern Ohio (ongoing) In May 2008, Dr. Mackey working in collaboration with a Graduate Student from the OSU Aquatic Ecology Laboratory and Fisheries Biologists from the ODNR mapped the distribution of aquatic and fish habitats in the Sandusky River and Sandusky Bay using sidescan sonar. This ongoing work is supported by the ODNR – Division of Wildlife. This study is part of an ongoing project to establish baseline data in anticipation of the removal of Ballville Dam on the Sandusky River in Fremont, Ohio.

ODNR - Division of Wildlife – Reconnaissance Sidescan Sonar Data Acquisition – Mentor/Fairport area (ongoing) In May 2008, Dr. Mackey working in collaboration with Fisheries Biologists from the ODNR – Division of Wildlife, collected more than 50 line miles of sidescan sonar data from nearshore and offshore waters in Lake Erie as part of a regional fish habitat characterization project. These data will be integrated with older data collected by the ODNR – Division of Wildlife to develop linkages between fish communities and nearshore habitat distributions. These data are being used to identify and guide potential fish habitat restoration and protection projects within Maumee Bay.

OMNR – Lake Erie Fisheries Management Unit - Lake Erie nearshore Mapping and Lake Trout Rehabilitation (ongoing) In July 2007, Dr. Mackey working in collaboration with Fisheries Biologists from the Ontario Ministry of Natural Resources (OMNR), initiated a project to collect sidescan sonar data from nearshore areas of the Canadian Lake Erie coastline to identify and characterize potential lake trout fish spawning habitat in the eastern basin of Lake Erie. The OMNR, USFWS, NYDEC, ODNR, and USGS are working to rehabilitate native lake trout populations in Lake Erie through habitat protection and rehabilitation efforts combined with an intensive stocking effort to begin in the fall of 2008. These habitat data will be used to locate potential stocking sites in both Canadian and U.S. Lake Erie waters.

U.S. EPA - Nearshore and Coastal Margin Habitat Assessment Project (completed)
In cooperation with Michigan State University, Dr. Mackey was a co-PI on a project to characterize nearshore habitat zones and develop biophysical linkages between nearshore habitats and the aquatic organisms that use them. Dr. Mackey used sidescan sonar and underwater video to identify and map nearshore and coastal margin habitats off the Lake Michigan coastlines of Wisconsin and northern Illinois. He continues to work with aquatic ecologists and fishery biologists from Michigan State University to characterize the biophysical linkages and heterogeneity of nearshore substrates. Ultimately, the results of this work will be used to assess the potential impact of changing water levels (climate change) and shoreline modifications (armoring) on nearshore habitat distribution and structure. The Wisconsin DNR and Regional Planning Commissions will use this information to guide development of new rules for shoreline development to protect and restore fish and aquatic habitats in Lake Michigan nearshore waters.

U.S. EPA – Lake Erie Binational Map Project (completed)
In cooperation with the University of Minnesota, the University of Windsor, Great Lakes Commission, and the U.S. Geological Survey, Dr. Mackey was a co-PI on a project to develop a unified habitat classification system and map for the entire Lake Erie basin. This project developed tools to assist the Lake Erie Lakewide Management Plan (LaMP) to develop a bi-national inventory of the status and trends in the quantity and quality of fish and wildlife habitats in the Lake Erie basin. The integrated habitat map will be used to track improvements in habitat quantity and quality resulting from preservation, conservation, and restoration efforts and to guard against further loss or degradation from land-use alterations. The project team is developed a strategy to revise and expand the classification scheme to the rest of the Lake Erie Basin and also developed a binational habitat map data exchange website which includes links to geospatial metadata and habitat coverages in the basin. The Lake Erie habitat classification and mapping project serves as a model for the development of a comprehensive basinwide habitat classification system and inventory for the entire Great Lakes basin.

ODNR - Division of Wildlife – Reconnaissance Sidescan Sonar Data Acquisition - Maumee Bay (completed)
In early May 2007, Dr. Mackey working in collaboration with Fisheries Biologists from the ODNR – Division of Wildlife, collected more than 75 line miles (121 line km) of sidescan sonar data from shallow-water areas of Maumee as part of a regional fish habitat characterization project. These data will be integrated with older data collected by the ODNR – Division of Geological Survey that characterizes nearshore substrate distributions along the entire 262-mile Lake Erie shoreline and more recent data collected by Environment Canada in deeper-water areas of the Western Basin. These data are being used to identify and guide potential fish habitat restoration and protection projects within Maumee Bay.

SEWRPC – Racine County Shore Structure Inventory and Assessment Project (completed)
In cooperation with the Southeast Wisconsin Regional Planning Commission and the Wisconsin DNR, Dr. Mackey developed and implemented a set of field protocols to identify, characterize, map, and inventory shore protection structures along the Racine County Lake Michigan shoreline. This pilot project included extensive field work and data collection using portable GPS equipment and development of a geospatial database and GIS to assess the current state of shoreline armoring along the Wisconsin Lake Michigan shoreline. As part of this project, the condition and integrity of structures were assessed along with the potential of these structures to modify nearshore coastal processes and habitats. In part based on this work and a similar inventory of shore protection structures along Wisconsin Lake Michigan shoreline, Dr. Mackey recently developed a new shoreline alteration index (SAI) that assesses not only the physical impacts of shore protection in the nearshore zone, but potential biological impacts as well. Ultimately, the results of this work will be combined with results from the U.S. EPA project (described above) to assess the impact of shoreline armoring on coastal processes and nearshore habitat distribution and structure.

USFWS - Restoration Act Sponsored Research (completed)
In cooperation with the University of Windsor and The Ohio State University, Dr. Mackey was a co-PI on a recently completed project designed to create a framework and develop a process to systematically identify, coordinate, and implement aquatic and fish habitat restoration opportunities in the Lake Huron to Lake Erie Corridor (Huron-Erie Corridor, HEC) within a context of water-level change resulting from potential long-term effects of global climate change. This project summarized existing datasets and initiatives and developed a comprehensive strategy to identify and implement sustainable aquatic and fish habitat restoration opportunities within the Corridor. Components of this restoration strategy are currently being implemented by the U.S. Geological Survey, U.S. Fish & Wildlife Service, Michigan DNR, Environment Canada, and the Great Lakes Commission.

International Joint Commission – Great Lakes Water Quality Agreement (completed)
In 2005, the Water Quality Board of the International Joint Commission retained Dr. Mackey to explore more fully the role of physical integrity as part of a comprehensive ongoing review of the Great Lakes Water Quality Agreement. Currently the GLWQA is a "water chemistry" agreement that does not adequately define or incorporate the critical elements of physical or biological integrity. Dr. Mackey's work succinctly defined physical integrity and provides specific examples of the importance of physical integrity to both the environmental and economic health of the Great Lakes basin. This work provides the conceptual underpinnings for a suite of developing projects focused on the protection and restoration of fish and aquatic habitats within connecting channels and waters (St. Clair and Detroit Rivers) and Lake St. Clair. Moreover, this work may form the basis for delisting criteria for Benthic Habitat and Fish and Wildlife populations within the St. Clair and Detroit River AOCs. Incorporating physical integrity into the GLWQA will provide new policy guidance and broaden the scope of the Agreement to include heretofore unrecognized protection and restoration opportunities within the Great Lakes basin.

SERVICE

Dr. Mackey currently serves as a member of **Lake Erie Habitat Task Group for the Great Lakes Fisheries Commission** and the **AIS Barrier Advisory Panel and Rapid Response Team** for the USACE Chicago Waterway electric field barrier project.

HONORS/AWARDS

Letters of Commendation – Ohio Senate, U.S. House of Representatives, Spring 2001: For services to the People of the State of Ohio and the Natural Resources of Lake Erie.

Speaker, Plenary Session - International Association for Great Lakes Research, 1999: *Cumulative Impacts: Physical and Biological Linkages to Habitat.* 42nd Conference on Great Lakes Research, Cleveland, Ohio, May 24-28.

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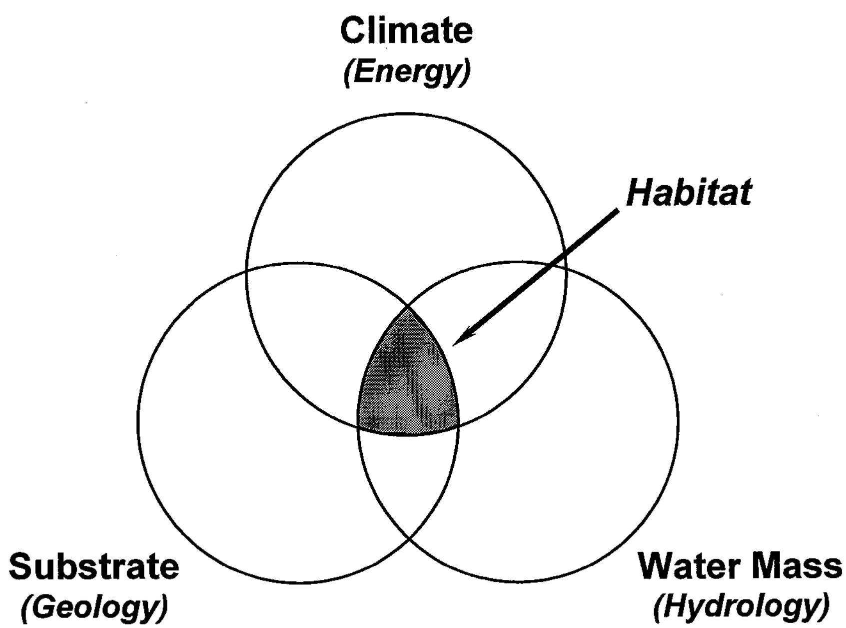
Attachment 2

Physical Characteristics of Aquatic Habitat



- *Energy* – estimated from hydraulic calculations for both oscillatory and unidirectional flows, flow regime
- *Substrate* – bedrock, composition, texture, hardness, stability, porosity, permeability, roughness, contaminants, macrophyte/woody debris.
- *Water Mass* – depth, temperature, turbidity, nutrients, contaminants, dissolved oxygen, and water quantity.
- *Habitat* – physical characteristics and energy conditions that meet the needs of a specific species and/or biological community for a given life stage.

Figure 1. Fundamental Characteristics of Aquatic Habitat

Attachment 3

Table 1. Data Availability, Metrics and Methods

Assessment Factor	Applicability	Rankin (2004), CAWS UAA, Statement of Reasons	Habitat Evaluation and Improvement Study
Number of Instream Sampling Sites	Natural and artificial systems	**20 sampling sites based on availability of fish data, no consideration of physical habitat**	**30 sampling sites based on consideration of physical habitat, geospatially integrated with continuous monitoring stations and shoreline/ bank-edge inventory and assessment**
Distance between Sampling Sites	Natural and artificial systems	**Min: 0.5 miles (0.8 km)** **Max: 15.8 miles (25.4 km)** **Mean: 4.3 miles (6.9 km)**	**Min: 0.25 miles (0.4 km)** **Max: 9.6 miles (15.3 km)** **Mean: 2.9 miles (4.7 km)** **Continuous shoreline/bank-edge inventory and assessment**
Type and Extent of Substrates	Natural and artificial systems	Numerous sediment samples available - ***not used in Aquatic Life Use designation Analyses***	**Geospatial integration of historic and new sediment sampling data**
Substrate Quality	Natural and artificial systems	Sediment chemistry and contaminant data available – ***not used in Aquatic Life Use designation Analyses***	**Review and evaluation of sediment quality data, including organic and inorganic chemical data, as well as sediment toxicity data; geospatial referencing of historic sediment chemistry and contaminant data**
Type and Extent of Instream Habitat Cover	Natural and artificial systems	**Data at 20 sampling sites, sites located based on available fisheries data**	**Data at 30 sampling sites, sites located based on physical habitat characteristics**
Type and Extent of Shoreline and Bank-Edge Habitats	Natural and artificial systems	***Unknown, not surveyed or inventoried.* Qualitative observations only.**	**Geospatially referenced, continuous digital shoreline video for both banks of the entire CAWS, for inventory and assessment**
Type and Extent of Riparian Cover	Natural and artificial systems	***Unknown, not surveyed or inventoried.* Qualitative observations only.**	**Geospatially referenced, continuous digital shoreline video for both banks of the entire CAWS, for inventory and assessment**
Flow Regime and Water Levels	N/A to CAWS as flows and water levels are regulated for flood control, conveyance of wastewater, navigation	Flow, water level, and hydraulic modeling data available – *not used in Aquatic Life Use designation*	Flow, water level, and hydraulic modeling data available, potential for analysis of conveyance, navigation impacts of proposed restoration activities
Water Quality	Natural and artificial systems	Complete suite of water quality data available – **no evidence that proposed increase in DO will yield significant biological response**	**Rigorous evaluation of continuous DO data, supplemented with the DO profiles conducted at the 29 habitat sampling stations surveyed during 2008 season; analysis of other water quality data; integration with biotic data**
Physical Habitat Metric	Metric for natural systems, Metric for low-gradient artificial systems	**QHEI – *not designed for low-gradient, urban streams or rivers***	**Developing new physical habitat index designed specifically for the unique conditions within the CAWS and other similar low-gradient urban streams and rivers**
Habitat Pattern and Juxtaposition	Natural and artificial systems	**None – not considered**	**Geospatial integration of discrete sample data and continuous sampling data**
Fish Community Metrics	Metric for natural systems, Metric for low-gradient artificial systems	**Boatable IBI – *incorrectly calculated***	**Selection of fish metrics will be based on CAWS fish data and new CAWS-specific fish metrics will be developed if appropriate**

Assessment Factor	Applicability	Rankin (2004), CAWS UAA, Statement of Reasons	Habitat Evaluation and Improvement Study
Macroinvertebrate Community Metrics	Natural and artificial systems	**MBI – *not used in Aquatic Life Use designation***	**MBI geospatially integrated with historic and current datasets**
Science-based Integrative Methodology and Metric(s)	Natural and artificial systems	***IBI percentile scores and best professional judgment used to delineate Aquatic Life Use categories and waters***	**Apply existing and new methods to geospatially integrate environmental data and to analyze and summarize condition of the CAWS using a new suite of metrics, potentially at a much finer scale.**
Navigation Impacts on Fish	Natural and artificial systems	**None – not considered**	**Navigation effects from commercial shipping activities may play a significant role in limiting near shore habitat potential and some aspects of water quality and those impacts are currently being evaluated using a combination of literature reviews and field observations from the 2008 season**

Note: - Red text indicates components that are considered to be deficient assessment factors.
- Green text indicates components of the ongoing "Habitat Evaluation and Improvement Study" that address those deficiencies.

Attachment 4

WRITTEN REPORT

Scudder D. Mackey, Ph.D.

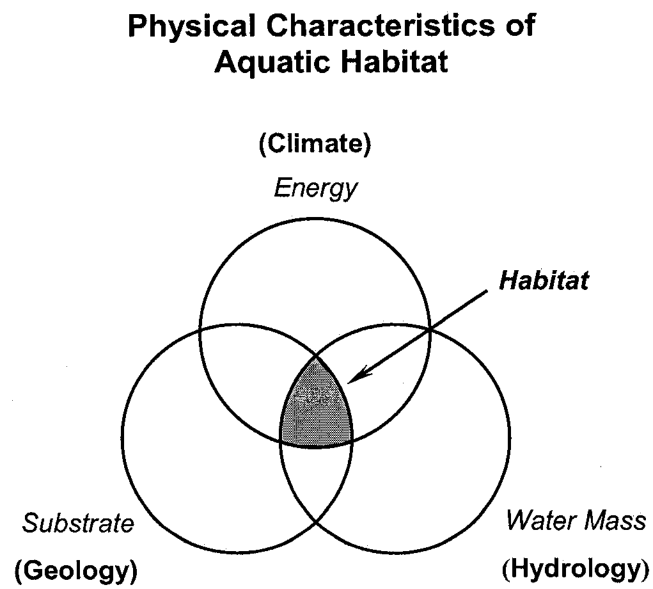
Physical Habitat Assessment – IEPA Proposed Rulemaking R08-9

Overview

This summary report is focused primarily on the aspects of *physical habitat* related to the Aquatic Life Use categories and designations proposed in IPCB rulemaking R08-9 and the methodology that IEPA used to designate those Aquatic Life Uses. Review of the Chicago Area Waterway System (CAWS) UAA Report and IEPA's Statement of Reasons reveals that the data and methodology used by IEPA is inaccurate, flawed, and does not adequately consider all of the key elements necessary to assess the condition of aquatic habitats. Moreover, it is unlikely that the standards proposed in IPCB rulemaking R08-09 will significantly improve fish community structure and diversity in the CAWS. Based on these deficiencies, an alternative strategy that integrates *all* of the fundamental habitat characteristics is needed to correctly assess the Aquatic Life Use potential in order to maximize the productive and ecological capacity of the waterway, a strategy that the Metropolitan Water Reclamation District of Greater Chicago is currently pursuing.

Habitat Integrity – A Framework for Sustainable Habitats and Ecosystems

Aquatic habitats are created when there is an intersection of a range of physical, chemical, and biological characteristics that meet the life stage requirements of an organism. Aquatic habitats are inextricably linked to physical integrity. Habitat is the critical component that links biological communities and ecosystems to natural processes, pathways, and the landscape. The pattern and distribution of habitats are controlled, in part, by the underlying physical characteristics of the basin and interactions between energy, water, and the landscape. Moreover, the physical characteristics and energy conditions that define aquatic habitats are created by the interaction of master variables – climate (energy), geology (geomorphology and substrate), and hydrology (water mass characteristics and flow) – the same variables and processes that maintain physical integrity (Figure 1). Biological characteristics are also an important element of aquatic habitat, but will not be discussed in detail in this testimony and are not included in Figure 1.



- *Energy* – estimated from hydraulic calculations for both oscillatory and unidirectional flows, flow regime
- *Substrate* – bedrock, composition, texture, hardness, stability, porosity, permeability, roughness, contaminants, macrophyte/woody debris.
- *Water Mass* – depth, temperature, turbidity, nutrients, contaminants, dissolved oxygen, and water quantity.
- *Habitat* – physical characteristics and energy conditions that meet the needs of a specific species and/or biological community for a given life stage.

Figure 1. Fundamental Characteristics of Aquatic Habitat

From the perspective of physical integrity, *physical habitats* are defined by a range of physical characteristics and energy conditions that can be delineated geographically that meet the needs of a specific species, biological community, or ecological function (Mackey 2005, Attachment M1). To be utilized as habitat, these physical characteristics and energy conditions must exhibit an organizational pattern, persist, and be "repeatable" – elements that are essential to maintain a sustainable and renewable resource (Peters and Cross 1992). The repeatable nature of habitat implies that the natural processes that create physical habitat must also be repeatable and may persist over a range of spatial and temporal scales.

For example, seasonal changes in flow, thermal structure, and water mass characteristics create repeatable patterns and connections within tributaries and lakes. Spatially, these patterns occur within the same general locations year after year and native species have adapted in response to these repeatable patterns. Moreover, movement of water, energy, and materials through the system (which depends on connectivity) also exhibits an organizational pattern, persists, and is repeatable. These patterns and connections, in part, control the seasonal distribution and regulate the timing, location, and use of aquatic habitats.

Also critically important is the pattern and juxtaposition of different types of habitat, i.e. habitat heterogeneity or diversity. For example, successful recruitment of fish will not occur if spawning habitat is not connected to suitable nursery and forage habitats. Nursery and forage habitats provide sheltered areas where larval and young-of-the-year (YOY) fish can feed and grow with minimal disturbance. Lack of suitable cover and/or limited productivity (lack of available food supply) will severely limit the ability of juvenile fish to survive. Without access to adjacent nursery areas, these potential spawning sites are nothing more than substrate areas with physical characteristics that mimic those of active spawning sites.

Thus, there are three major classes of variables that must be considered when assessing aquatic habitat – 1) energy (flow regime), 2) substrate (composition, texture, structure), and 3) water mass characteristics (water chemistry, water quantity). All of these variables must be spatially and temporally connected by physical and biological *processes* in ways that support diverse aquatic communities. These fundamental components are recognized in the Federal Water Pollution Control Act (Clean Water Act - CWA) where the principal objective is to restore the physical, chemical, and biological integrity of the nation's waters (33 U.S.C.§1251 [a]).

Traditional field assessment methodologies are generally site-specific and do not consider the *processes* or *connections* between physical habitat elements necessary to restore and maintain robust biological communities and sustainable ecosystems. The almost myopic focus on water chemistry, point sources, and contaminants by many regulatory agencies has led to an "incomplete foundation in water resource policy and legislation" (Yoder and Rankin 1998, pg 62-63). They go on to state:

> "Because biological integrity is influenced and determined by *multiple* chemical, physical, and biological factors, a singular strategy emphasizing the control of chemicals *alone* does not assure the restoration of biological integrity."

This statement serves as an appropriate backdrop for the discussion that follows.

General UAA Methodology

The identification of Aquatic Life Use designations and the classification of waterway reaches into the appropriate use categories are crucial to the successful conduct of a Use Attainability

Analysis (UAA) process. The process by which the Aquatic Life Uses are defined and applied to waterways undergoing a UAA is the foundation for establishing appropriate water quality standards. Ideally, the UAA provides a scientific basis to develop attainable designated water uses that are based on a comprehensive integrated assessment of the physical, chemical and biological conditions of a water body (USEPA, 1994). This assessment should include an integrated analysis of current physical habitat, flow regime, temperature, water quality, and existing aquatic communities.

The purpose of this integrated assessment is to determine whether existing or improved conditions can be supported by changes in beneficial use and/or associated criteria. Thus, the methodology used in defining and assigning uses for a specific waterway should be transparent, scientifically based, and documented accurately, clearly, and completely. Unfortunately, the CAWS UAA Report and supporting documents submitted by IEPA in this rulemaking effort do no not meet these criteria and contain data errors and flaws in the methodology used to develop the proposed the Aquatic Life Use designations.

Aquatic Life Use Designations

IEPA has proposed to eliminate the current use designations that have been in place since 1972, and supplant them with a tiered system of Aquatic Life Uses supposedly based, in part, on inferred relationships between physical habitat as characterized by Qualitative Habitat Evaluation Index (QHEI) scores, and the Ohio boatable Index of Biotic Integrity (IBI), which characterizes the health of the existing fish community. IEPA adopted the data and methodologies used in the CAWS UAA Report to develop and delineate two new Aquatic Life Use tiers ("A" and "B" waters) within the CAWS (IEPA Statement of Reasons and Sulski testimony 3/10/08, pages 14-18). These new Aquatic Life Use tiers were primarily based on a comparison of IBI percentile scores and QHEI scores at each sample location (Figure 5-2, CAWS UAA Report, page 5-9). Review of the QHEI and IBI scores revealed significant errors and uncertainties in the data, and the methods used to compare the QHEI and IBI scores in Figure 5-2 are not scientifically valid.

By focusing almost exclusively on IBI metrics and percentiles, IEPA did *not* provide an integrated analysis of physical habitat, flow regime, temperature, water quality, and existing aquatic communities in their assessment of the CAWS. Specific issues that I will discuss include: (1) sampling design, (2) significant problems using the QHEI for CAWS, (3) errors and uncertainty in the data, and (4) fatal flaws in the Aquatic Life Use designation methodology.

1. Sampling Design

In the physical habitat assessment summarized by Rankin (2004 – IEPA filing Attachment R), QHEI values were calculated for 20 sites within the CAWS. These sites were selected based on the availability of long-term fish sampling data made available by the MWRDGC, and typically occur at locations immediately above, or below a major discharge point source into the waterway. The spatial distribution of these sites *was not* based on an appropriate statistical sample design or consideration of inferred physical habitat characteristics. Distances between sampling sites ranged from 0.5 miles (0.8 km) to 15.8 miles (25.4 km).with a mean sampling distance of 4.3 miles (6.9 km Clearly, gaps of up to 15 miles between sampling points in the waterway can not be considered to be a comprehensive assessment of physical habitat. In fact, inferred physical habitat conditions were extrapolated considerable distances within the CAWS. For example, in the Calumet-Sag Channel (CSC), only *two* sites were evaluated using the IBI and QHEI metrics *and those sites were 10.7 miles apart.*

Moreover, portions of the CAWS were not included in the physical habitat assessment. For example, IBI and QHEI metrics for Bubbly Creek were *not evaluated at all*, and QHEI metrics were *not* calculated for the South Branch of the Chicago River. Even though the channel morphology and flow characteristics of Bubbly Creek and the South Branch of the Chicago River are *distinctly different* from each other, the CAWS UAA Report on page 4-69 states that Bubbly Creek and the South Branch have "similar" environmental characteristics and are grouped together as the *same* channel in the Report.

Other than at the locations sampled for the CAWS UAA Report, there are no data currently available to assess location, distribution, and pattern of potential instream habitat structure in the CAWS. Surveys in other natural and urban streams using sidescan sonar and underwater video suggest that the distribution and pattern of substrate and instream structure can be highly variable with patterns and complexity at much finer spatial scales than sampled in the CAWS UAA Report (IEPA did not collect new field data). Certainly, with up to a 15 mile sampling gap and a limited number of sediment samples, there is a considerable area within the CAWS where instream habitat structure (either natural or anthropogenic) could exist.

As stated in the beginning of this testimony, the pattern and juxtaposition of different types of habitat is a critical element that is rarely considered in most habitat assessments. Widely-spaced, traditional point sampling as described in Rankin (2004) and the UAA CAWS Report does not provide adequate data to document the type, area, pattern, or juxtaposition of different types of aquatic habitat that may exist in the CAWS. The limited number and spatial distribution of substrate and instream structure sampling sites is a *major* deficiency in the CAWS UAA Report and IEPA Statement of Reasons.

In testimony provided by Sulski (testimony in response to a question from the MWRDGC, 1/28/08, pg 103), IEPA purportedly considered shoreline and littoral conditions for each of the CAWS segments. This is surprising because there has not been a comprehensive inventory or assessment of shoreline or bank-edge habitat conditions for the CAWS, nor have there been ecological studies of navigation or wave impacts on shorelines within the CAWS. Shoreline and bank-edge areas provide spawning, nursery, and forage habitats necessary to sustain healthy, propagating fish populations. As part of comprehensive habitat assessment, it would be important to know what the relative percentage, location, pattern, and distribution of shoreline types and bank-edge habitat are for each of the CAWS segments. This is particularly important when assessing the pattern and juxtaposition of different types of aquatic habitats, which was *not done* in the CAWS UAA Report or IEPA Statement of Reasons.

Moreover, Yoder and Smith (1999) recommend that in channels where there are differences in left and right bank-edge habitats (IEPA's littoral zones), that additional sampling be done to calculate bank-edge IBI scores to document the potential difference in fish communities. Even though bank-edge areas are regularly sampled by MWRDGC using electrofishing equipment, the results are integrated and summarized across the entire channel segment at that sampling site (CAWS UAA Report, page 4-16). The reported IBI scores *may* be indicative of fish utilization of bank-edge habitat, but the coarse sampling interval and lack of bank-edge habitat data severely limits our ability to *draw any meaningful conclusions.*

Irrespective, IEPA uses the presence (or absence) of shallow water bank-edge habitat to justify a Aquatic Life Use designation "A" for the CSC and lack of shallow water bank-edge habitat is used by IEPA to justify an Aquatic Life Use designation "B" for the Chicago Sanitary and Ship Canal (CSSC). IEPA contends that these shallow water bank-edge habitats in the CSC should be considered to be spawning habitat, which is problematic given that *no direct data* are available to support that contention (Smogor and Sulski testimony, 3/10/08, pages 74-78).. The lack of a comprehensive physical and biological assessment of existing shoreline and bank-edge habitats is another *major* deficiency in the CAWS UAA Report and IEPA assessment methodology.

2. Problems and Short-Comings of Using QHEI for the CAWS

The QHEI was developed to provide a measure of physical habitat quality and is based on hydrogeomorphic metrics in a *natural* stream or river channel. There are six metrics that comprise this index: substrate, instream cover, channel morphology, riparian zone/bank erosion, pool/glide and riffle/run quality, and map gradient.

For example, within the CAWS, several of the key morphological metrics upon which the QHEI is based are held constant or are not present. As a result, the QHEI scores for the CAWS are calculated using sub-metrics that may be of secondary importance to the attainment of a diverse, sustainable fish population. Map gradient and watershed area were held constant for all of QHEI sampling sites (Rankin 2004 page 1 – IEPA filing Attachment R). Shallow-water riffles and runs are not present, and all of the CAWS channels are channelized, stable, have vertical walls, and have limited to no sinuosity (Rankin 2004 Table 2 – IEPA filing Attachment R). Virtually all of the CAWS channels can be classified as a series of interlinked pools or glides (Yoder testimony in response to question by MWRDGC, 02/01/08, pg 184-185) with channel/pool depths greater than 40 cm, which is the threshold water depth for higher quality pool/glide habitat (Rankin 2004 Table 2) Mean current velocities are low (significantly less than 1 foot/sec) and additional testimony will be provided on flow regimes and flow regime modeling within the CAWS demonstrating that due to very low channel gradients, minimum flow and/or flow reversals within the system are not an uncommon occurrence within certain segments of the CAWS (Melching testimony). The remaining QHEI metrics are substrate and instream cover, and submetrics within channel morphology, riparian zone/bank erosion, and pool/glide quality habitat. It is the differences in these remaining metrics that determine the QHEI scores in the CAWS.

Embedded within the QHEI scoring system is an *implicit* assumption that there is a relationship between flow hydraulics, channel morphology, and the type and distribution of substrate materials. This assumption is valid for natural rivers and streams, but not valid for low gradient, urbanized, artificial channels such as the CAWS. The channels in the CAWS are "naturally stable" (carved out of bedrock or artificially stabilized), and the flows in the CAWS are regulated, controlled by man-made structures, and are not natural. Flow hydraulics do not control or alter the location or pattern of channels within the CAWS.

With respect to substrate, coarse-grained substrates (coarse sand, gravel, cobble, and boulder substrates) are considered to be a positive habitat attribute due to increased habitat complexity and the assumption that coarse-grained sediments are transported and deposited by fast-flowing water. The inference in the QHEI scoring is that water and sediment "quality" will be higher in these areas as well. This inference is also supported by higher IBI scores in natural reaches with fast-flowing water and coarse-grained substrates (Rankin 1989, page 24). However, in systems where flows are effectively *decoupled* from the substrate (such as in the CAWS), this inference may not be correct. Flow decoupling means that substrate distributions observed in the CAWS are not dependent or controlled by flow. Consideration must be given to the processes and origin of substrates within the CAWS (i.e. is it anthropogenic or natural). If coarse-grained material is dumped (or are leftover construction debris) in the CAWS, higher QHEI scores *may not be appropriate or valid* because the assumption of fast-flowing water and/or natural processes implicitly built into the QHEI scores may not apply.

In highly urbanized waterways such as the CAWS that drain large impervious areas, the lack of a readily available, erodible sediment supply limits the type and grain size of sediments available to be transported and deposited. If there are no coarse-grained sediments available, then none will be transported (assuming the flow velocities are adequate to transport coarse-grained sediments). For the CAWS, average flow velocities are less than 1 foot/second and for 60% of the CAWS, the average flow velocity is less than 0.4 feet/second (Melching testimony). It takes and average of up to eight (8) days for water to transit the system (Melching testimony). Thus, due to a lack of an available sediment supply and low flow velocities, *naturally derived* coarse-grained substrates are limited and rare in the CAWS.

In the case of bank-edge areas (for example, littoral areas along the banks of the CSC), the dominant substrates are coarse construction debris, large limestone/dolomite blocks, and rock rubble that has spawled off the channel walls. Due to the grain size of the substrates (boulders and rock fragments), the potential for use by fish as spawning habitat is extremely limited (spawning is implied in the proposed the DO standards, Statement of Reasons, page 60). In fact, these areas would likely provide cover for tolerant predator species that would consume small YOY fish if they were available (Thoma 1998; 2004).

Finally, in non-wadeable streams and rivers, traditional sampling approaches are inadequate to assess critical substrate, instream cover, and other metrics used in the QHEI assessment protocol. In fact, most of the traditional assessment protocols are designed and applied almost exclusively to wadeable streams and rivers, with a strong bias towards medium to high-gradient streams (Wilhelm *et al.* 2005 – Attachment M2). This bias is reflected in how various habitats are ranked, and many of these habitat types do not exist in low-gradient streams and rivers (*or in artificial waterways such as the CAWS*). Wilhelm *et al.* 2005 summarizes these issues in detail and explores an alternative approach to assess habitat and biological response in non-wadeable rivers in Michigan. The work by Wilhelm *et al.* 2005 demonstrates that habitat assessment and the development of associated biocriteria is a problem that is *not* unique to the CAWS. There is an increasing recognition that alternative sampling and analytical approaches are needed to assess habitat and associated biocriteria in large non-wadeable rivers *and waterways*.

In summary, the QHEI protocol is *not* designed for use in low gradient, non-wadeable streams and rivers, in part because traditional sampling approaches are inadequate to assess critical substrate, instream cover, and other metrics used in the QHEI assessment protocol. Within the CAWS, several of the key morphological metrics upon which the QHEI is based are held constant or are not present. Embedded within the QHEI scoring system is an *implicit* assumption that there is a relationship between flow hydraulics, channel morphology, and the type and distribution of substrate materials. This assumption is not valid for low gradient, urbanized, artificial channels such as the CAWS. The channels in the CAWS are stable (carved out of bedrock or artificially stabilized), and flows are generally decoupled from substrates. Habitat assessments and the development of associated biocriteria in low-gradient non-wadeable streams and rivers are problematic and new protocols need to be developed specifically for these types of systems.

3. Errors in Environmental Data and Improper Use of Methodology for Designating CAWS Aquatic Life Uses

An analysis of the CAWS UAA Report, IEPA's proposed rule R08-9, and associated attachments reveals significant errors in the data and flaws in the methodology used to define and designate the proposed Aquatic Life Uses within individual CAWS segments. Most troubling is the difficulty in understanding the analytical process and methodology used by IEPA, which does *not* follow the process outlined in Figure 5-1 (CAWS UAA Report, page 5-7) which describes the States 305(b) reporting criteria for attainment in Illinois streams and rivers (IEPA 2004). Below is a summary that lists concerns about the CAWS data and flaws in the IEPA methodology:

A. IEPA failed to integrate physical habitat, fish, and benthic invertebrate metrics in their analysis.

IEPA used Figure 5-2 on page 5-9 of the CAWS UAA Report as the initial basis for proposing a two-tiered Aquatic Life Use system for the CAWS. In this figure, the geographic distribution of the Ohio boatable IBI is plotted and compared with QHEI scores calculated for the same geographic locations. The upper boundary for proposed Aquatic Life Uses is defined by IBI scores from the reference site and the lower boundary is defined by IBI scores from all of the sampling sites. A more detailed description is presented in the CAWS UAA Report (page 5-8). Contrary to the testimony of Sulski (3/10/08, pages 14-18), examination of Figure 5-2 clearly shows that differentiation of the two CAWS Aquatic Life Use tiers was based *solely* on the IBI percentiles, which is a measure of fish community structure and health. Scaling and plotting errors in Figure 5-2 negated the usefulness of the QHEI habitat scores, and macroinvertebrate data and sediment chemistry data were not considered or incorporated into the Aquatic Life Use designation methodology (Sulski, Essig testimony in response to questions from the MWRDGC, 3/10/08. pg 19 - 21). Additional testimony will be provided on these important habitat elements (Wasik, Melching).

B. A revision of the thresholds for the CAWS Aquatic Life Use designations may be required due to a significant reduction in the habitat (QHEI) score for the Sheridan Road reference site.

Proper application of the Ohio Boatable IBI requires identification of high quality reference streams which serve as yardsticks to measure the biological health in similar, regional water bodies. A high-quality reference stream will have suitable habitats and a diverse, well-balanced aquatic community using those habitats. These characteristics represent the highest level of physical, chemical, and biological integrity that can be attained within these regional systems. Since the CAWS is not a natural channel, it is acknowledged in the CAWS UAA Report, page 5-6, that the CAWS is unique and that no regional high-quality reference water bodies have characteristics similar to the CAWS.

As a surrogate, the North Shore Channel at Sheridan Road was selected by the UAA team as a regional reference site due to high IBI and QHEI scores (CAWS UAA Report page 5-8). Unfortunately, due to transposition errors in Table 2, page 4 of the habitat assessment report by Rankin (2004), the QHEI value for the reference site at Sheridan road was incorrectly stated and is considerably lower than originally plotted in Figure 5-2 (see Essig testimony, 4/23/08, page 192-193). Based on this testimony, the high-quality reference site selected by the UAA team actually had a QHEI score of 42 (instead of 54), which would place that site in the "poor" habitat category based on Table 1, page 2 of the Rankin (2004) habitat assessment report. Given the significantly lower QHEI score, this site *no longer* meets the criteria as an appropriate high-quality reference site.

The testimony of Sulski (3/10/08, pages 14-18) confirms the importance of the Sheridan Road site as a high-quality reference site *and* as a determinant for the placement of boundary lines to categorize CAWS Aquatic Life Use waters. If the testimony of Essig is correct (Essig testimony, 4/23/08, page 192-193) and the QHEI scores have been transposed, then, a significant *revision* of the boundaries for the CAWS Aquatic Life Use designations may be required.

C. There is considerable uncertainty as to what the *actual* QHEI values are for the North Shore Channel and the CSC, and whether or not the *correct* QHEI scores were used when designating Aquatic Life Use waters.

Uncertainty exists as to whether or not the transposition error is real because if it is, the highest quality QHEI scores are now at Route 83 and Cicero Avenue sampling locations in the CSC. This very surprising considering that the CSC is a steep-walled, deep draft shipping channel carved out of bedrock that is used extensively for navigation. There may be some limited bank-edge habitat and limited riparian cover, but the median IBI scores for the CSC are 20 and 21 (poor), which does not suggest a diverse, well-balanced fish community or presence of high-quality habitat. Moreover, the CAWS UAA Report (page 4-92) states that the IBI scores in the CSC are classified as "poor to very poor," and the QHEI score is in the poor range (30-45), which would suggest that the CSC is not the highest-quality habitat in the CAWS.

If the QHEI values that were originally reported *are correct*, then at the Cicero Avenue sampling site on the CSC the box plot of IBI scores falls below the minimum line for IEPA's Aquatic Life Use "A" waters, and a QHEI score of 37.5 is classified as a poor habitat. These data are consistent with the statement on page 4-92 of the UAA Report, that the IBI scores in the CSC are classified as "poor to very poor" and the QHEI scores are classified in the "poor" range (30-45). At the Route 83 sampling site, the IBI score appears to be on the dividing line between IEPA's Aquatic Life Use "A" and "B" waters but the QHEI score (42) is still in the "poor" range.

The CSC and the CSSC share similar physical characteristics (for example, deep-draft waterway, limited shallow area along banks, high volume of commercial navigation) except that there is more weathering of the channel walls in the CSC. The weathering of the bank walls provides a slight shallow shelf with limited habitat for fish. This difference explains the slightly higher QHEI scores in the CSC compared to the CSSC. Nevertheless, both waterways are considered "poor" habitat according to the QHEI classification scale (Rankin 2004, Table 2). The small amount of rubble from the crumbling walls does very little to improve the overall physical habitat for fish and invertebrates in the CSC.

The decision to include the CSC as a higher Aquatic Life Use "A" water is *not* defensible because the habitat data for both monitoring stations was in the poor range, and the IBI percentile scores were not clearly in the range for IEPA's Aquatic Life Use "A" tier. In fact, the minimum IBI scores observed at the two monitoring stations in the CSC are among the lowest in the CAWS. It is recommended that additional fish and habitat data be collected in the CSC to augment the sparse sampling sites and to verify the appropriate IBI and QHEI scores for the CSC.

D. There are errors in the IBI scoring criteria listed in Table 4-11 of the CAWS UAA Report (page 4-17). If the proposed Aquatic Life Use designations were based entirely on these inflated IBI scores, then all of designations need to be reconsidered using the corrected IBI scores.

In Table 4-11 of the CAWS UAA Report (page 4-27), the scores for the "fish numbers" metric have been reversed. Instead of adding 5 points when there are less than 200 fish and 1 point when there are greater than 450 fish, the opposite should have been done. Footnote "c" also states that special scoring procedures are used when relative numbers are less than 200/0.3 km." That special scoring procedure is for the Ohio *wadeable* IBI, not for the Ohio *boatable* IBI. Special scoring is used to calculate the boatable IBI when relative numbers are less than 200/1.0 km, which is not uncommon in the CAWS. Due to these errors, true IBI scores would be lower (by as much as 10 units) than those reported in the CAWS UAA Report. Since these erroneous scores in Table 4-11 were used to calculate the IBI data in the CAWS UAA Report, *all* of the proposed categories and designations need to be reconsidered with the corrected IBI scores.

E. The QHEI and IBI data as plotted in Figure 5-2 are incorrectly presented, not scaled properly, and for comparison purposes are not scientifically valid. Any comparative interpretations between the IBI and QHEI metrics derived from Figure 5-2 are arbitrary and without scientific merit.

The two vertical axis scales presented in Figure 5-2 of the CAWS UAA Report are inconsistent. By combining the IBI and QHEI scores in this way, there is an implicit assumption that there is a one-to-on correspondence of IBI scores to QHEI scores, even though this is clearly not the case. Rankin (1989) on page 12 states that "using the QHEI as a site-specific predictor of IBI can vary widely depending on the predominant character of the habitat of the reach".

Moreover, while QHEI scores are included in Figure 5-2, they are *not* used to define the boundaries between Aquatic Life Use categories. The lines delineating the Aquatic Life Use categories are *based solely on the percentile IBI scores.* Figure 5-2 gives the impression that *both* biotic and habitat indices were utilized in formulating the Aquatic Life Use tiers, and that observed IBI scores were consistent with the corresponding QHEI scores for selected reaches of the CAWS. However, the range shown on the vertical axis for the IBI score is 12-38, even though the entire range of IBI scores is from 12-60. On the QHEI score axis, the scale includes the entire range of QHEI scores from 0 to 100. This inconsistency results in an inaccurate depiction of where QHEI scores would line up on the graph relative to the 75th percentile IBI line. The *only* meaningful delineations in this figure are for the IBI scores. The lines delineating the Aquatic Life Use categories are based on percentiles calculated from the IBI scores, and those values remain the same irrespective of the plotting scale.

More importantly, as presently plotted, the scale on the IBI axis can be adjusted or scaled up or down to *arbitrarily* fit the QHEI data to whatever IBI percentile is desired (what QHEI score would you like it to be? see the "sliding" discussion in Smogor's testimony, 3/10/08, page 33). As a result, even though Figure 5 -2 appears correct, it is scientifically invalid with respect to defining relationships between the IBI and QHEI. The ability to arbitrarily shift the QHEI data relative to the IBI percentile lines in Figure 5-2 also invalidates the justification provided for IEPA's use of a QHEI score of 40 instead of 45 (Rankin 2004 – IEPA Attachment R) as a lower boundary for Aquatic Life Use "A" waters (see Smogor testimony, 3/10/08, page 29-30).

In most assessment studies, QHEI and IBI data are compared in cross plots where QHEI scores are the independent variable (x–axis) and fish IBI scores are the dependent variable (y-axis). Even though there is considerable scatter and uncertainty in the data, statistical relationships can be derived from the QHEI and IBI scores and are calibrated *to appropriate regional reference sites*. This more traditional type of analysis is *not* presented in the CAWS UAA Report or in materials associated with IEPA's proposed rule R08-9.

F. <u>In IEPA's Statement of Reasons, the agency does not acknowledge that the 75th percentile IBI score was used in the Aquatic Life Use designations, nor does IEPA adequately explain the biological justification for doing so.</u>

On page 5-8 of the CAWS UAA Report, it is the 75th percentile IBI line in Figure 5-2 that distinguishes the Ohio-based Modified Warm-Water Aquatic Life from Limited Warm-Water Aquatic Life Uses. Use of the 75th percentile was described as having "no immediate regulatory implication" in the CAWS UAA Report. However, it appears that IEPA adopted the 75th percentile approach for designating the proposed CAWS Aquatic Life Uses as they were assigned exactly as the CAWS UAA Report recommended (page 5-14). Neither the CAWS UAA Report nor the Statement of Reasons supporting IPCB R08-9 provide any justification (biological or otherwise) for using the 75th percentile IBI as a threshold.

G. A description of the desired fish and benthic invertebrate communities expected to occur in both the Aquatic Life Use "A" and "B" waters are not included in the regulatory proposal.

There is limited text that describes the difference between Aquatic Life Use A and B waters in the proposed regulatory standards and IEPA's Statement of Reasons. It is stated in the regulatory proposal that Aquatic Life Use "B" waters "are capable of maintaining aquatic-life populations predominated by individuals of tolerant types..." Aquatic Life Use "A" waters "are capable of maintaining aquatic-life populations predominated by individuals of tolerant *or* intermediately tolerant types..." These descriptions are confirmed in the pre-filed testimony presented by Sulski. Efforts to elucidate a more detailed description of desired aquatic communities from IEPA were unsuccessful (see Smogor testimony, 3/10/08, pages 10-12). The lack of a desirable fish and benthic invertebrate species list is somewhat surprising, as one would think that a description of desired aquatic communities for Aquatic Life Use "A" waters and Aquatic Life Use "B" waters would be useful to determine if, and when, the desired Aquatic Life Uses were attained.

H. IEPA does not consider that within individual channel segments designated as Aquatic Life Use "A" waters, there are extensive areas where shallow bank-edge habitats *don't exist*, which supposedly should diminish the biological potential of those waters.

An important difference between the two Aquatic Life Use definitions is the physical description of Aquatic Life Use B Waters as "deep-draft, steep-walled shipping channels." Paradoxically, there are Chicago Area Waterways (for example, the CSC and the Little Calumet River) that are designated as Aquatic Life Use "A" waters in the regulatory proposal, despite the fact that they *are* deep-draft, steep-walled shipping channels.

Based on the pre-filed testimony of Sulski and in testimony by Smogor (3/10/08, pages 59-61), the lack of shallow bank-edge habitats should diminish the biological potential of those waters, which is, in part, the justification for proposing the Aquatic Life Use "B" designation. However, IEPA does not consider that within individual channel segments proposed to be designated as Aquatic Life Use "A" waters, there may be extensive areas where shallow bank-edge habitats *don't exist,* which should *also* diminish the biological potential of *those* waters. Finally, IEPA has not presented data that document the use of these shallow bank-edge habitats by fish and benthic invertebrates which is supposedly one of the primary justifications for developing and designating Aquatic Life Use "A" waters.

Widely spaced samples; uncertainties and errors in the data, and a scientifically invalid comparison of the IBI and QHEI scores leads to the conclusion that the proposed Aquatic Life Use designations in IPCB R-08-9 are inaccurate, not scientifically justified, and need to re-evaluated and revised using a more transparent, scientifically-based methodology. The IEPA failed to integrate physical habitat, fish, and benthic invertebrate metrics into their analysis. First and foremost, the IEPA must correct the deficiencies and errors in the environmental data described_previously and provide further clarification regarding their approach and basis for defining Aquatic Life Use tiers and designations. If not, the approach must be judged as arbitrary and poorly founded in science.

Proposed Water Quality Standards Will Not Achieve Designated Uses

In the Statement of Reasons, the IEPA hypothesizes that increased DO and reductions in temperature will significantly improve fish diversity and community structure within the CAWS. This implies that IEPA has determined that DO and elevated temperatures are the primary stressors limiting the biological potential of aquatic communities in the CAWS. In their submittals, IEPA has *not* provided evidence that these are indeed the primary factors that limit the development of a diverse, sustainable fish community in the CAWS. In their submittals, IEPA didn't compare readily available DO data with fish richness metrics from the CAWS to demonstrate that the proposed increases in DO would *indeed* result in a significant increase in fish richness and diversity. This is another deficiency in the IEPA assessment methodology.

Other non-water quality related parameters could also be limiting the biological potential of the CAWS. Examples include, but are not limited to

1. Physical limitations such as lack of shallow bank-edge habitats and riparian cover; lack of instream habitat cover and diversity; lack of suitable substrates and substrate heterogeneity; altered flow regimes (flow and water levels);

2. Biological limitations such as limited primary productivity, degraded macrobenthic communities (food supply), predation, and lack of appropriate spawning and nursery habitats;
3. Chemical limitations such as legacy contaminants and pharmaceuticals,
4. Functional limitations such as conveyance of wastewater and flood water, and navigation (prop wash and turbulence, sediment resuspension, waves).

Other investigators working on the CAWS also recognize the same limitations. The MWRDGC in Report 98-10 entitled "A Study of the Fisheries Resources and Water Quality in the Chicago Waterway System 1974 through 1996" (MWRDGC 1998 - Attachment M3) concluded that a lack of diverse aquatic habitats is one of major limiting factors affecting fish diversity and richness in the CAWS. Conclusion 8 of the report (pages xiv–xv) states:

> "Even though water quality is generally good, the fish populations of the Chicago Waterway System are still dominated by omnivores, tolerant forms, and habitat generalists. This primarily because water quality alone does not take into concern the condition of habitat, flow, or other outside factors. The waterways of the Chicago Waterway System were not constructed to be fishable streams with diverse habitat types. They were built for navigation and water reclamation. It is unlikely that these waterways can achieve the same stream quality for fish as a natural habitat-rich waterway unless desirable fish habitat is created…"

The CAWS UAA Report (page 5-3) states:

> "Improvements to water quality through various technologies, like re-aeration may not improve the fish communities due to lack of suitable habitat to support the fish populations. Unless habitat improvements are made in areas like the CSSC, additional aeration may not result in the attainment of higher aquatic life use."

Multiple lines of evidence support the fact that water quality in the CAWS has *improved significantly* over the past several decades (Melching testimony) and is now good enough to support the passage of fish and other aquatic organisms to and from the Mississippi River and Great Lakes Basins via the CAWS. For much of the CAWS, fish richness and diversity has improved markedly since effluent chlorination was terminated in 1984, the TARP came online in 1985, and SEPA stations improved DO levels to acceptable levels in the Calumet River system

(MWRDGC 1998). As a result of these improvements, the U.S. Army Corps of Engineers, with the support and participation of numerous State and Federal agencies and other groups, has constructed and activated a 12 million dollar electric field barrier north of Romeoville to prevent aquatic invasive species (primarily fish) from transiting the waterway.

Moreover, the existence of active angler groups and bass fishing tournaments on the waterway also suggests that for many species, water quality (DO and temperature) for much of the CAWS is *not a significant limiting factor*. Certainly there continues to be DO and temperature limitations for other desirable, less-tolerant species (which are not specifically identified in the UAA report or IEPA's statement of reasons), but if suitable habitats are not present, sustainable populations of these species will not become established *irrespective of how much improvement there is in water quality*. Moreover, with activation of the electric field barrier just north of Romeoville, fish passage to and from the Illinois Waterway and Mississippi River systems is restricted (at least theoretically). Sources of new fish species for the CAWS are then limited to the Calumet River system, Lake Michigan, and the small tributaries feeding into the CAWS.

Other factors, in addition to water and habitat quality may also limit the attainment of Aquatic Life Uses. For example, primary productivity in the CAWS is very low, with mean concentrations of chlorophyll A ranging from 3 µg/L to 17 µg/L (Wasik *et al.* 2004). Based on macroinvertebrate data from the CAWS UAA Report (Section 4), the diversity and density of macroinvertebrates in sediments are generally low which would suggest that benthic productivity (and thus potential food supply for fish) is significantly degraded and limited in the CAWS. Lack of an adequate food supply could be a major limitation that is not necessarily related to water quality or DO, but instead is caused by limitations in physical habitat (flow, lack of suitable substrates, and poor sediment quality). In fact, higher macroinvertebrate species richness from the "in-water column" Hester Dendy samples versus the sediment grab samples within the CAWS suggest that water quality improvements may *already be sufficient* to support a more robust and diverse macroinvertebrate community if suitable habitats were present (MWRDGC benthic invertebrate reports, attached to Wasik testimony).

In my opinion, the substantial investments needed for infrastructure to provide incremental increases in DO and/or reductions temperature will *not* yield a proportionate biological response with respect to attaining sustainable fish communities and/or other beneficial uses. Without suitable habitat pattern and diversity, sustainable populations of these species can not be established *irrespective of how much improvement there is in water quality*. In fact, opportunities to improve physical habitat structure and increase habitat diversity in certain reaches of the waterway may yield a much more significant biological response than system-wide improvements in DO and temperature. The lack of diverse bank-edge and instream habitats may be a much more significant limitation on the development of sustainable fish communities than current DO or temperature limitations.

Need for a Comprehensive Habitat Assessment of the CAWS

After reviewing the CAWS UAA Report, IEPA's proposed rule R08-9, and supporting documentation, it becomes clear that there are major gaps in the CAWS environmental datasets, especially with respect to physical habitat, spatial and temporal sampling, and the need for new indices designed specifically to assess and summarize habitat and biological conditions in low-gradient, non-wadeable, highly altered, urban streams and rivers (summarized in Table 1 – Attachment M4). In reviewing this testimony, a number of major deficiencies were noted, including:

- Limited number of instream sampling sites;
- Large gaps between sampling sites (spatially and temporally);
- Lack of comprehensive instream habitat data;
- Lack of comprehensive substrate data;
- Lack of a comprehensive shoreline and bank-edge inventory;
- Lack of well defined science-based metrics and indicators designed for non-wadeable urban streams and rivers that characterize: habitat, fish, macroinvertebrates, water quality, sediment quality, flow regime, and water levels;

- Lack of well defined science-based methodologies that integrate and compare multiple metrics and indicators to assess the physical, chemical, and biological integrity of low-gradient, non-wadeable, highly altered urban streams and rivers; and

- Lack of a well defined science-based methodology that links multimetric indicators to stressors and prioritizes those stressors to guide protection and restoration activities.

Recognizing the data gaps and limitations in the CAWS UAA Report, the MWRDGC in the fall of 2007 issued a request for proposals entitled "Habitat Evaluation and Improvement Study" designed to address many of the data gaps and deficiencies listed above (Attachment M5). This study, which is funded by the MWRDGC, will directly address the deficiencies identified in this report (see Table 1 – Attachment M4) and is anticipated to be completed by summer 2009. As part of the contract, historical environmental data and newly collected environmental data will be integrated into a comprehensive GIS package that will enhance accessibility and facilitate analysis of CAWS environmental datasets.

The Habitat Evaluation and Improvement Study that is currently underway will follow a scientifically sound, peer-reviewed, methodology for development of habitat indices in non-wadeable rivers (Wilhelm, *et al.*, 2005) to develop a CAWS-specific physical habitat index. This index will be designed to differentiate habitat quality in the CAWS, where habitat variability is relatively limited, especially within reaches. The study will make extensive use of existing biotic and habitat data collected by MWRDGC between 2001 and 2007, supplemented with detailed fish, macroinvertebrate, water quality, and habitat data from 30 CAWS sampling stations in 2008. These data will be further augmented by digital bathymetric and shoreline video covering the entire CAWS.

Robust multivariate statistical methods will be used to reduce the data and to identify the most important fish and habitat variables in the CAWS. This approach will provide the strongest relationships between fish and habitat, which essential for understanding the ability of fish to thrive in the CAWS. When completed, the CAWS habitat index will be applied to the entire CAWS system. Furthermore, other important factors affecting fish will be considered in evaluating habitat quality in the CAWS, including sediment chemistry and navigation impacts.

This study will create opportunities to develop linkages between physical habitat, water quality, and aquatic communities in the CAWS. These linkages can then be used to systematically (and scientifically) evaluate and manage for potential Aquatic Life Uses for various segments of the CAWS, at scales much finer than had been previously thought possible

Conclusion

Given the deficiencies in the habitat data and lack of an appropriate science-based methodology to designate Aquatic Life Use waters, the IEPA filing of proposed rule R08-9 and associated DO and temperature criteria is premature. Moreover, the protections proposed in rule R08-9 are unnecessary and will not measurably enhance fish community structure, aquatic diversity, or beneficial uses within the CAWS. The substantial investments needed for infrastructure to provide incremental increases in DO and/or reductions temperature are better spent elsewhere.

Aquatic Life Use Designations

An analysis of the CAWS UAA Report, IEPA's proposed rule R08-9, and associated attachments reveals *significant errors in the data* and *flaws in the methodology* used to define and designate the proposed Aquatic Life Use tiers "A" and "B" within individual CAWS segments. Widely spaced samples; uncertainties and errors in the data, and a scientifically invalid comparison of the IBI and QHEI scores leads to the conclusion that the proposed Aquatic Life Use designations in IPCB R-08-9 are inaccurate, not scientifically justified, and need to be re-evaluated and revised using a more transparent, scientifically-based methodology. The IEPA failed to integrate physical habitat, fish, and benthic invertebrate metrics into their analysis. The IEPA must correct the environmental data described previously and provide further clarification regarding their approach and basis for defining Aquatic Life Use tiers and designations. If not, the approach must be judged as arbitrary and poorly founded in science.

Associated DO and Temperature Criteria

In their submittals, IEPA has not provided evidence that DO and temperature are indeed the primary factors that limit fish community structure and aquatic diversity in the CAWS. In fact, multiple lines of evidence support the fact that water quality in the CAWS has *improved significantly* over the past several decades and is now good enough to support the passage of fish and other aquatic organisms to and from the Mississippi River and Great Lakes Basins via the CAWS. In my opinion, the substantial investments needed for infrastructure to provide incremental increases in DO and/or reductions temperature will *not* yield a proportionate biological response with respect to attaining sustainable fish communities and/or other beneficial uses. Without suitable habitat pattern and diversity, sustainable populations of these species can not be established irrespective of how much water quality is improved. In fact, opportunities to improve physical habitat structure and increase habitat diversity in certain reaches of the waterway may yield a much more significant biological response than system-wide improvements in DO and temperature

Recommendation

The recently funded Habitat Evaluation and Improvement Study is designed to address many of the deficiencies highlighted in this testimony. The study will be completed by the end of this calendar year with data and results available summer 2009. By integrating the results of this study with other CAWS datasets, it should be possible to perform a comprehensive, integrated assessment of the physical, chemical, and biological integrity of the CAWS. The objective would be to identify the most efficient and cost-effective means to further protect and enhance Aquatic Life Use waters and associated beneficial uses in the CAWS. It would then be appropriate to move forward once this work has been completed.

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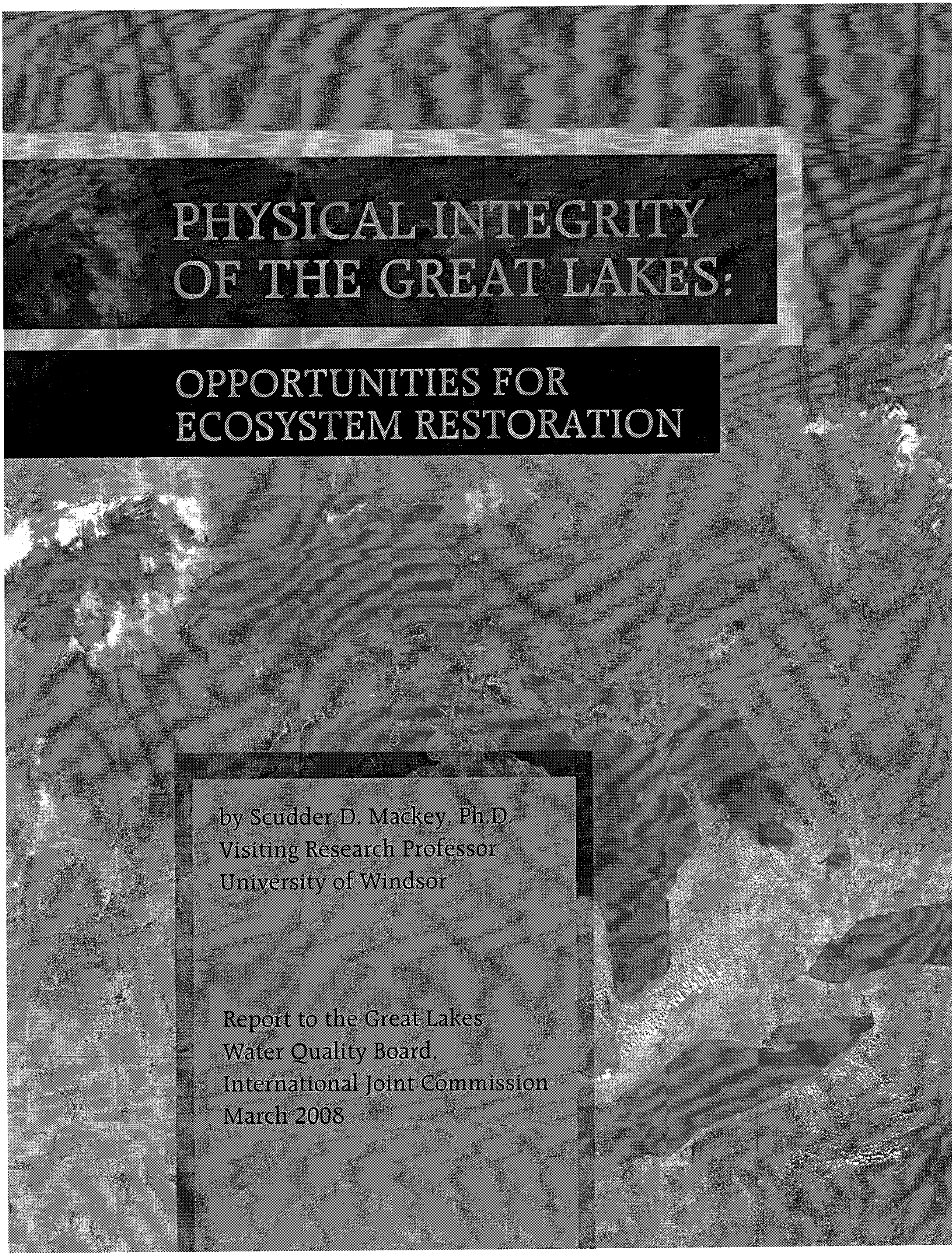
Attachment M1



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Report to the Great Lakes
Water Quality Board,
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DISCLAIMER

This report was solicited by the Great Lakes Water Quality Board to assist the board in developing its own advice on review of the Great Lakes Water Quality Agreement for the International Joint Commission. The comments, findings and recommendations in this report are those of the author and do not necessarily reflect the views of individual Board members, the organizations they represent, nor the International Joint Commission.

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"...by protecting, restoring, and enhancing the chemical, physical, and biological integrity of the Great Lakes - we will protect, restore and enhance the ecological integrity of the Great Lakes."

INTRODUCTION

The International Joint Commission (IJC) seeks to better define physical integrity in the Great Lakes with an emphasis on identifying and evaluating challenges and opportunities for ecosystem restoration, protection, and sustainability. Along with chemical and biological integrity, restoring and maintaining physical integrity is clearly identified in Article II as one of the primary purposes of the Great Lakes Water Quality Agreement (the Agreement) (IJC 1989). However, there are few references to physical integrity elsewhere in the Agreement. Physical integrity is implied in Annex 2 - restoration of beneficial uses (particularly fish and wildlife habitat) in Areas of Concern (AOC's) (IJC 2003). Several of the Lakewide Management Plans (LaMPs) have evolved beyond the critical pollutants language to include physical habitat protection and restoration in order to achieve ecological integrity (GLC 2004). Protection and restoration of physical integrity is also implied in the restoration of wetlands in Annex 13 and remediation of contaminated sediment in Annexes 12, 14, and 17.

Moreover, one of the biggest challenges to address in restoring naturally functioning systems is that there is no common vision of physical or ecological integrity for the Great Lakes ecosystem. Goal setting is further complicated by the limited understanding that we have of how the system functions as a whole. As a result, goals are not clearly defined, making it difficult to prioritize activities, programs, and budgets (GLPF 1998).

With the potential for review and revision of the Agreement, the timing is right for addressing the dynamic physical nature of the water resources and ecosystem function in the Great Lakes basin. Ultimately, the focus of the Agreement is to protect, restore, and enhance the ecological integrity of the Great Lakes (IJC 1989).

Purpose and Objectives

Currently, none of the Agreement boards are addressing physical integrity in their priority activities largely because Great Lakes water quality management has been mainly focused on chemical pollution and clean up. Our inability to develop approaches and programs for moving physical integrity from concept to action is in part due to the lack of a definition of physical integrity in the Agreement and a focus on pollution control programs that are designed to control what enters the system, not to control or alter the *energy, processes,* or *pathways* within the system. Meeting water quality targets and eliminating sources of pollution will only get us part way to restoring a sustainable ecosystem and achieving ecological integrity (e.g. Hartig *et al.* 1998).

The lack of a common vision for physical and/or ecological integrity has impacted our ability to develop and implement a comprehensive restoration agenda. For example, "Restoring the Great Lakes" has recently become the focus of considerable discussion and debate among resource managers and agencies within the Great Lakes (U.S. EPA 2004; U.S. Policy Committee 2002). Clarity and a sense of purpose has been lacking in the discussion up to this point, and there is a need to establish a shared vision or goal that captures what is meant by "Restoring the Great

Lakes". Fortunately, the Great Lakes Water Quality Agreement already identifies the fundamental system components necessary to achieve ecological integrity – *chemical*, *physical*, and *biological* integrity. The importance of these components to the concept of ecological integrity can be expressed in the following hypothesis:

Hypothesis

If chemical, physical, and biological integrity are necessary and fundamental components of ecological integrity; then protecting, restoring, and enhancing the chemical, physical, and biological integrity of the Great Lakes will protect, restore, and enhance the ecological integrity of the Great Lakes.

If the above hypothesis and associated concepts are validated and found to be true, then the logical conclusion is that "Restoring the Great Lakes" means protecting, restoring, and enhancing the chemical, physical, and biological integrity of the Great Lakes - and the natural processes, pathways, and landscapes that maintain them. This discussion paper will define and explore one of the three fundamental components identified in the Agreement – *physical integrity* – and will suggest an operational concept for physical integrity that is based on a somewhat different perspective – a perspective based on process and function rather than an ongoing assessment of system components and status. This perspective is based on the concept that sustainable waters and a sustainable ecosystem require protection and restoration of natural processes, pathways, and landscapes.

"...sustainable waters and a sustainable ecosystem require protection and restoration of natural processes, pathways, and landscapes."

Major elements to be considered in this discussion include: natural processes and restoration of natural flow regimes; pathways, flow paths, and connectivity; landscapes; linkages to habitat integrity and ecosystem function; potential long-term stressors including water levels and climate change; and recommendations to incorporate these principles and concepts into an Agreement to provide a binational framework for the development of a comprehensive protection and restoration strategy for the Great Lakes. However, it is beyond the scope of this work to provide specific recommendations as to the most appropriate binational strategy to develop or implement that framework (see discussion by Bowerman *et al.* 1999; Minns and Kelso 2000).

"Restoring the Great Lakes means protecting, restoring, and enhancing the chemical, physical, and biological integrity of the Great Lakes - and the natural processes, pathways, and landscapes that maintain them."

Irrespective, it is necessary to consider embedding within the Agreement an overall *vision* of ecological integrity; definitions of chemical, physical, and biological integrity; and a set of *guiding principles* designed to protect, maintain, and enhance the Basin's chemical, physical, and biological integrity. Moreover, in addition to guiding principles, a *binational strategy* needs to be implemented to develop new protection and restoration *standards* that are balanced between assessing fundamental structural components of the ecosystem and protecting and restoring the functional processes that maintain them. Only in this way will we be able to protect, restore, and maintain the Great Lakes water quality and quantity, support natural biodiversity and ecosystem function, and achieve ecological integrity.

FUNDAMENTALS

Master Variable Concept

Master variables are fundamental characteristics that structure, organize, and define a system, influence the distribution and abundance of energy and materials, and regulate processes that have a profound effect on the physical, chemical, and biological integrity and the ecosystem function. When altered or changed, the effects of these master variables cascade through the physical, chemical, and biological systems, altering processes and the ecosystem function. There are six master variables and each of those master variables are linked to specific system components within the Agreement (Table 1.).

Table 1. Master Variables

Natural Variables	**GLWQA System Component**
• *Climate* (energy)...	*Physical* Integrity
• *Geology* (materials, soils, geomorphology, bathymetry)...	*Physical*, *Chemical* Integrity
• *Hydrology* (water quantity, quality, surface and groundwater flow, hydrography)...	*Physical*, *Chemical* Integrity
Anthropogenic Variables	
• *Chemical Pollution*[1] (what enters the system)..................	*Chemical* Integrity
• *Biological Pollution*[1] (what enters the system)..................	*Biological* Integrity
• *Resource Utilization* (what is anthropogenically removed, consumed, or altered within the system)........................	*Physical*, *Chemical*, & *Biological* Integrity

The first three are natural variables that structure, organize, and define the fundamental physical and energy characteristics of the landscape and the processes that act on that landscape. The second three are anthropogenic variables that impact the structure and organization of the landscape and the processes that act on that landscape - but are directly linked to anthropogenic activities from within, or outside, the Great Lakes Basin. It is important to recognize that there are attributes of these master variables that cannot be manipulated and are therefore not actionable. Examples would include climate (temperature, precipitation); geology (bedrock and surficial materials); or regional basin geomorphology. However, other attributes are actionable and can be altered to obtain a desired result. Examples would include hydrology (flow regime, flow paths and hydraulic connectivity, diversions, breaching of watersheds); chemical pollution (pollutant and nutrient loadings); biological pollution (introduction and dispersion of invasive species); or resource utilization (land cover, water diversions, consumptive use). By focusing on these master variables and working to restore them to a more natural condition, we allow *natural system processes* to maintain and restore essential ecosystem functions over the long term with

[1] Not explicitly considered in this document.

minimal anthropogenic management (or interference). This approach is both economically and ecologically efficient.

Landscapes, Processes, and Pathways

Landscape Concept

For the purposes of this discussion, the system under consideration is the entire Great Lakes Basin as defined by water tributaries to the Great Lakes, including both surface and ground waters. However, the discussion will be focused on landscapes – specifically, the land and water areas that are encompassed by the entire Great Lakes basin. Unlike watersheds, which are usually delineated by surface-water hydrology, *landscapes* are defined by, and include the integrated components of land and water area (i.e. geology, geomorphology, and land cover) upon which natural processes act within the Great Lakes Basin. Watersheds are a subset of landscapes and are defined (and limited) by the area that collects surface waters that feed a main stream and associated tributaries. Even though landscapes are typically considered to represent areas of regional extent, the term is applicable to multiple scales. The following definitions apply:

- *Geology* – surface and subsurface distribution of geologic materials; soils; hydrophysical characteristics (permeability, porosity, aquifers, aquatards…).
- *Geomorphology* – shape, pattern, distribution, and physical features of the land surface; landforms and drainage pattern (topography, slope, hydrography, channel morphology and bathymetry, connectivity and pattern).
- *Land Cover* – shape, pattern, and distribution of biological and anthropogenic features on the land surface; Land Use.

Landscapes - **Integrated components of land and water area (i.e. geology, geomorphology, and land cover) upon which natural processes act within the Great Lakes Basin.**

Landscapes and watersheds are linked to the Great Lakes via hydrology, i.e. surface and groundwater flows and the pathways that water takes to enter the Great Lakes. Landscape stressors create hydrologic impairments – by altering flow characteristics and/or the functional connections and pathways between fundamental system components within the system. These impairments alter natural flow regimes, degrade water quality, and affect the benefits that water provides to the ecosystem.

Natural Processes and Pathways Concept

Physical characteristics and natural processes structure, organize, and define aquatic systems and regulate the biological and chemical elements of the system (Poff *et al.* 1997; Richter *et al.* 1998; 2000; Baron *et al.* 2002; Ciruna 2004). With respect to physical integrity, *processes* are mechanism(s) by which energy and materials are transferred or conveyed through a system. Examples of such natural processes include:

- *Physical Processes* – mechanisms that transfer of energy, water, and materials across and through the landscape into the Great Lakes
- *Biological Processes* – mechanisms that transfer energy and nutrients upwards through the food web.

Processes - **Mechanism(s) by which energy and materials are transferred or conveyed through a system.**

Conceptually, it is convenient to consider the natural processes within the context of fundamental system components – chemical, physical, and biological integrity. Natural processes can be grouped by the systems through which those processes act – abiotic systems and biotic systems – which translate directly into physical and/or biological integrity (Table 2.)

Table 2. Processes, Pathways, and Fundamental System Components of Integrity

	Abiotic (Physical Integrity)	***Biotic (Biological Integrity)***
Processes	Physical Processes Geochemical Processes	Biological Processes Biochemical Processes
	Conveyance of energy and materials through physio-chemical systems	Conveyance of energy and materials through biological systems
Energy Source	Climate/Thermal Regime Potential/Kinetic Energy	Photosynthesis/Primary Productivity Microbial Activity
Pathways and Connectivity	Hydrogeomorphic processes: transfer of water, energy, and materials over and through the landscape.	Predation: transfer of energy and nutrients upwards through the food web.

For example, within the Great Lakes, the movement of water across the landscape is the primary mechanism by which energy, water, and materials are conveyed through the system. Hydrologic flows are created by the interaction of precipitation (weather and climate), topography (geomorphology and geology), and surface water slope (the earth's gravitational field). Hydrologic flows are an example of abiotic or physical processes that are controlled by the laws of physics. Predation, the consumption of organisms by other organisms represents an important biological (or ecological) process by which energy and materials (nutrients) are conveyed from lower trophic levels to upper trophic levels within the food web. Predation and predator-prey interactions are controlled by complex relationships and interactions between populations and the life-stage requirements of different species (e.g., Haas and Schaeffer 1992; Ryan *et al.* 1999; Eshenroder and Burnham-Curtis 1999). Note that the chemical and bio-geochemical processes have both abiotic and biotic components. Chemical integrity is a crosscutting element that is related to all three fundamental system components – chemical, physical, and biological integrity (Table 2). By focusing on chemical integrity, the framers of the Agreement were able to address stressors and associated impairments that included both abiotic and biotic components of Great Lakes ecosystem. Three decades ago when point sources of pollution and degraded water quality captured public attention, a focus on the chemical integrity of the Great Lakes was certainly appropriate.

Current pollution control and water management paradigms rarely consider the linkage between water quantity (flow regime) and water quality. Improvements in water quality have been the primary goal behind many regulatory programs in the basin (e.g. IJC 1989; summary by Charlton and Milne 2004). More recently, there is a growing recognition that *how* we use water in the Great Lakes basin and our impacts on the water quantity may be as important to the ecological integrity of the basin, as maintaining water quality (IJC 2000; Annex 2001). In fact, the quantity and quality of water conveyed through the Great Lakes system represents "two sides of the same coin" - where degraded water quality reduces the *quantity* of water available to provide essential ecosystem functions and services. Degradation of water quality and/or removal of water from the system (through consumptive loss or diversion) have the same effect – these changes alter the physical integrity of the Great Lakes and the natural processes that structure, organize, and in part, regulate the aquatic ecosystem.

> *Pathways* - **Paths along which the natural processes act, so as to convey energy, water, and materials through a system.**

With respect to natural processes and physical integrity, *pathways* are defined as the paths along which the natural processes act, so as to convey energy, water, and materials through a system. Implied in this definition are: 1) functional pathways, which include functional and physical connections between fundamental physical components of the system, and 2) hydrologic pathways, which include flow paths, hydraulic connectivity and continuity, and patterns of flow. Examples of natural processes, the hydrogeomorphic areas and pathways along which they act, and the types of functional and/or hydrologic connections include (see also Table 3):

Table 3. Physical Integrity - Natural Processes, Pathways, and Connectivity

Natural Process	***Attributes***	***Pathways/Area***	***Connectivity***
Surficial Processes	• Weathering, mass wasting, overland and sheet flow • Highly dynamic • Spatially and temporally variable and episodic	• Generally unidirectional (down slope) flow • Acts across broad landscape surfaces	• Lateral hydraulic connectivity with adjacent floodplain and watershed surfaces
Fluvial Processes	• Channelized flow • Highly dynamic • Spatially and temporally variable and episodic	• Generally unidirectional (down slope) flow • Acts within or along linear stream corridors and/or drainage networks within watersheds	• Lateral hydraulic connectivity with adjacent floodplain and watershed surfaces • Longitudinal hydraulic down-slope continuity and connectivity within stream channels
Groundwater	• Infiltration and groundwater flow • Highly dynamic • Spatially and temporally variable and episodic	• Unidirectional and/or bidirectional flows • Act across broad landscape surfaces and/or within stream channels or lakes	• Hydraulic continuity (groundwater-surface water connections) and recharge area • Potentiometric surface (water table elevation) - surficial geology and soils (aquifers)
Coastal Margin and Nearshore	• Wave and storm-generated currents and flows • Intermittent fluvial influence near river mouths • Highly dynamic • Spatially and temporally variable and episodic	• Oscillatory bidirectional and/or unidirectional flows • Act within or along both shore-parallel and shore-normal linear corridors with seasonal onshore-offshore components • Water-depth dependent	• Shore-parallel hydraulic connectivity (littoral processes) • Shore-normal hydraulic connectivity (deltaic, estuarine, wetland, barrier connectivity)
Open Lake	• Wave and storm-generated currents and flows • Superimposed over broad-scale hydraulic (riverine) or thermally driven (seasonal) flows • Spatially and temporally variable and episodic	• Oscillatory bidirectional and/or unidirectional flows • Broad-scale regional unidirectional flows • Act within and between lake sub-basins, major connecting and tributary channel inflows and outflows	• Lateral hydraulic connectivity with adjacent water masses • Hydraulic connectivity with major connecting and tributary channel inflows and outflows

- *Surficial processes* – Processes associated with weathering, mass wasting, and overland and sheet flow. These processes are highly dynamic, are spatially and temporally variable and episodic, are generally unidirectional (down slope), and act across broad landscape surfaces;
- *Fluvial processes* – Processes associated with channelized flow. These processes and flows are highly dynamic; may be spatially and temporally episodic; are generally unidirectional (down slope); and act within or along linear stream corridors and/or drainage networks within watersheds. Fluvial processes are highly dependent upon lateral hydraulic connectivity with adjacent floodplain and watershed surfaces, and longitudinal down-slope hydraulic continuity and connectivity within stream channels;

- *Groundwater processes* – Processes associated with infiltration and groundwater flow – hydraulic continuity. These processes and flows may be dynamic; spatially and temporally episodic; unidirectional and/or bidirectional; and may act across broad landscape surfaces and/or within stream channels or lakes. Groundwater processes are highly dependent on potentiometric surface (water table elevation), surficial geology and soils (aquifers), hydraulic continuity (groundwater-surface water connections), and recharge area;
- *Coastal margin and nearshore processes* – Processes associated with wave and storm-generated currents and flows, except where influenced by fluvial processes and flows near river mouths. These processes and flows are highly dynamic, spatially and temporally variable and episodic, may be oscillatory (bidirectional) or unidirectional, are water-depth dependent; and generally act parallel to the shore with a seasonal onshore-offshore component. Coastal margin and nearshore processes are highly dependent on shore-parallel hydraulic connectivity (littoral processes) and shore-normal hydraulic connectivity (deltaic, estuarine, wetland, barrier-dune hydraulic connectivity); and
- *Open-lake processes* – Processes associated with wave and storm-generated currents and flows, superimposed over broad-scale hydraulic (riverine) or thermally driven (seasonal) flows. These processes and flows are dynamic, spatially and temporally variable and episodic, may be oscillatory (bidirectional) or broad-scale unidirectional flows, and act within and between lake sub-basins and major connecting and tributary channel inflow and outflow points. Broad-scale regional unidirectional flows act within and between lake sub-basins and major connecting and tributary channel inflow and outflow points. Open-lake processes are highly dependent on the lateral hydraulic connectivity between adjacent water masses and the major connecting and tributary channel inflows and outflows.

Ecological benefits of water are related to the spatial and temporal pathways within the landscape and the type and severity of impairments. The pathways that water takes across or through the landscape allows the biological communities to utilize energy and materials as water moves through the system. For example, there is a time-distance relationship between water and the benefits that water provides to the ecosystem. The time that water stays within the system is a function of flow velocity, direction, distance traveled, and pathways and connections within, or on the landscape. Constrained by existing impairments, the ecological value of a gallon of water varies as a function of its location and residence time on, or within the landscape. This time-distance dependency is clearly demonstrated by the work by Poff *et al.* (1997) and subsequent work by Richter *et al.* (1998; 2000), Baron *et al.* (2002), and others.

Note that within the Great Lakes, all the natural processes listed in Table 3 act along pathways or within hydrogeomorphic areas that have been impaired by anthropogenic activity. These impairments affect not only the ability of natural processes to convey energy, water, materials, and biota, but alter the benefits that water provides to the ecosystem. Clearly, there is a direct linkage between natural processes, pathways, landscapes, ecosystem function, and ecological integrity.

Ecological Concept Of "Integrity"

The Agreement identifies the fundamental system components necessary to achieve ecological integrity – chemical, physical, and biological integrity – and yet curiously, does not offer conceptual definitions of these components. This may be, in part, due to the difficulty in separating the ethical *principle* of integrity from the ecological *concept* of integrity. A discussion of the ethical principle of integrity is beyond the scope of this work. Suffice it to say that a separate body of literature exists that explores the philosophical implications of why the "ideal" ecosystem paradigm is a good model to guide environmental policy and why it is imperative that an ethical principle of integrity be compatible with an ecological concept of integrity (e.g., Westra 1994; 1998). This linkage between the concept and principle is also clearly demonstrated in the Webster's Dictionary definition of "integrity":

> *Integrity* **1 a** : an unimpaired or unmarred condition : entire correspondence with an original condition : *soundness*… **b** : an uncompromising adherence to a code of moral, artistic, or other values : utter sincerity, honesty, and candor : avoidance of deception, expediency, artificiality, or shallowness of any kind… **2** : the quality or state of being complete or undivided : material, spiritual, or aesthetic wholeness : organic unity : *entireness, completeness*...

Even though there are those who make the case that "integrity" only applies to undisturbed pristine systems, one can logically make the case that a disturbed system will retain its integrity if the fundamental system components and functional relationships (i.e. natural processes) are preserved and are mutually supportive and sustainable (De Leo and Levin 1997). In other words, from an ecological perspective, integrity can still be achieved when the essential components that define an ecosystem – existing structural components and the functional and natural processes that bind them – provide the same structural and functional benefits as undisturbed natural conditions and are mutually supportive and sustainable.

> ***"…integrity is achieved when the two essential components that define an ecosystem – ecosystem structure and the functions and natural processes that bind them – provide the same structural and functional benefits as undisturbed natural conditions and are mutually supportive and sustainable."***

For the purpose of this discussion, restoration does not imply that undisturbed or pre-settlement conditions are a prerequisite to achieve integrity, as long as the existing components and processes mimic natural conditions in ways that maintain ecosystem health, promote ecosystem resiliency and regeneration, and allow the system to change and evolve irrespective of natural and anthropogenic perturbations (following Karr and Dudley 1981; Westra 1994). For example, U.S. EPA has developed a working definition of biological integrity that refers to the degree to which "an ecosystem demonstrates a balanced, resilient community of organisms with biological diversity, species composition, structural redundancy, and functional processes *comparable* to that of natural habitats in the same region" (U.S. EPA 2005). This holistic and practical view can also be applied to the essential structural components and functional processes of a system, where natural processes acting along flow paths that the water takes across, or through a landscape provide sustainable and mutually-supportive functional benefits that *correspond* to those provided by undisturbed natural conditions.

CONCEPT OF PHYSICAL INTEGRITY

Within the Great Lakes, the <u>*concept*</u> of physical integrity is not well understood, nor has it been adequately defined. Until recently, policies and regulatory programs within the Great Lakes basin have been focused almost exclusively on the chemical and biological aspects of the system with an emphasis on the ecosystem structure and assessment of system status, trends, and indicators. For example, in 2004, the SOLEC meeting focused on the physical integrity of the Great Lakes (SOLEC 2004). A definition of physical integrity was proposed that included concepts of "self-organization" and the ability to adapt to changing conditions – concepts that are integral to the traditional ecosystem paradigm. However, physical systems are regulated and controlled by the laws of physics and driven primarily by abiotic internal and external forcing functions. Physical characteristics, systems, and associated functional processes are not "adaptive" in a biological sense (it's not a matter of choice, adaptation, or extirpation – physical laws don't evolve or become extinct), and one could logically argue that biocentric elements of the traditional ecosystem paradigm are not directly applicable to physical systems.

Moreover, the SOLEC indicator suites (and most other indicator suites as well) that have been developed are not explicitly designed to tell us anything useful about the natural processes or pathways that structure, organize, and define the physical aspects of the system or the factors that influence the distribution and abundance of energy and materials that flow through that system. In essence, the current indicator suites are measuring variables that represent changes to system components without adequately considering the functional processes or pathways along which those processes act – processes that ultimately control the spatial and temporal distribution of the variables and changes being measured.

In 2002, the U.S. Policy Committee established a goal to "Protect and restore the physical integrity of the Great Lakes, supporting habitats of healthy and diverse communities of plants, fish and other aquatic life, and wildlife in the Great Lakes Basin Ecosystem" and recommended a suite of actions and outcomes that are focused in three major areas of emphasis: habitat protection and restoration, protection of the Great Lakes waters, and sustainable land use practices (U.S. Policy Committee 2002).

> ***Physical Integrity*** *- Protect and restore the physical integrity of the Great Lakes, supporting habitats of healthy and diverse communities of plants, fish and other aquatic life, and wildlife in the Great Lakes Basin Ecosystem. Protect Great Lakes water as a regional natural resource from non-sustainable diversions and exports. Promote improved land use practices and the enhancement of the Great Lakes Basin as a source of recreation and economic prosperity.* U.S. Policy Committee 2002.

Most of the recommended actions and desired outcomes are focused on protecting or restoring the structural components of the ecosystem and are based on existing traditional approaches that, for the most part, do not explicitly consider the natural processes and pathways that convey energy, water, and materials through the system. The U.S. Policy Committee document and most other policy documents (including the Agreement) refer to physical integrity indirectly by describing associated actions and desired outcomes, but do not provide a definition of physical integrity.

Clearly, an operational definition of physical integrity is needed, that addresses not only the fundamental physical components of the ecosystem, but the interactions and functional processes that maintain them. As defined earlier, the concept of landscape incorporates the integrated components of land and water area (i.e. geology, geomorphology, and land cover) and therefore encompasses the fundamental physical components of the system. Natural processes and pathways are defined as the mechanisms and paths by which energy and materials are transferred or conveyed through a system and therefore encompass the interactions and functional processes that structure, organize, and define the system. Moreover, sustainable processes, pathways, and landscapes are a necessary and essential requirement to maintain sustainable supplies of clean water and protect and restore the ecosystem functions and ecological integrity. A concept of physical integrity that incorporates all of these elements will meet the test of an operational definition that offers comprehension and a framework for action. The following operational definition of physical integrity is proposed:

Operational Definition of Physical Integrity

Sustainable natural processes, pathways, and landscapes that maintain and improve the Great Lakes water quality and quantity, and support natural biodiversity and ecosystem function.

This operational definition states that sustainable processes, pathways, and landscapes are necessary and essential requirements to maintain sustainable supplies of clean water and protect and restore the ecosystem function and ecological integrity within the Great Lakes. The definition is based on the fundamental principle that *sustainable processes build sustainable ecosystems*. Consideration of physical integrity and related concepts and principles in the Agreement will require us to explore the fundamental physical characteristics that structure, organize, and define the system; the natural processes and pathways that influence the distribution and abundance of energy and materials that flow across and through Great Lakes' landscapes; and to examine the abiotic and biotic linkages between the chemical, physical, and biological integrity, ecosystem function, and ultimately - ecological integrity. How do we know when we have achieved physical integrity?

Achieving Physical Integrity

"Physical integrity is achieved when the physical components of a system and the natural processes and pathways that structure, organize, define, and regulate them correspond to undisturbed natural conditions and are mutually supportive and sustainable."

This does not imply that undisturbed or pre-settlement conditions are a prerequisite for physical integrity, just that existing components and processes mimic natural conditions in ways that maintain ecosystem health, promote ecosystem resiliency and regeneration, and allow the ecosystem to change and evolve irrespective of natural and anthropogenic perturbations. Ultimately, the focus of the Agreement is to protect, restore, and enhance the ecological integrity of the Great Lakes. The question is how do we protect, restore, and enhance the natural processes, pathways, and landscapes to achieve physical and ecological integrity in the Great Lakes Basin?

Some Examples...

NATURAL PROCESSES AND PATHWAYS – RESTORATION OF NATURAL FLOW REGIMES

Natural Flow Regime Paradigm

Maintaining physical integrity implies that master variables - the fundamental factors that structure, organize, and define a system; influence the distribution and abundance of energy and materials; and regulate processes - are functioning in a sustainable naturalized state. Within the last decade, there has been an increasing focus on these fundamental factors as indicators of ecological health and drivers of environmental change. This is particularly true for hydrology, where considerable research has led to the recognition that hydrology, water levels, and the dynamics of flow are critical elements that influence the integrity of aquatic ecosystems.

> *"...fundamental scientific principle that the integrity of flowing water systems depends largely on their natural dynamic character; ... Streamflow quantity and timing are critical components of water supply, water quality, and the ecological integrity of river systems. Indeed, streamflow, which is strongly correlated with many critical physicochemical characteristics of rivers, such as water temperature, channel geomorphology, and habitat diversity, can be considered a "master variable" that limits the distribution and abundance of riverine species and regulates the ecological integrity of flowing water systems."* Poff *et al.* (1997)

The term "natural flow regime" is used to describe characteristics of flow that would be present without anthropogenic influences and to which individual species, biological communities, and the ecosystem as a whole have co-evolved and adapted. Flow regimes can be described by five major characteristics of flow - magnitude, frequency, duration, timing, and rate of change - that interact to determine the ecological characteristics of freshwater ecosystems (Poff et al. 1997; Richter et al. 1996, 1997, 1998).

- *Magnitude* of flow is the amount of water passing a point per unit of time.
- *Frequency* describes the flow periodicity and how often a particular flow condition occurs
- *Duration* refers to the length of time a particular flow condition lasts.
- *Timing* describes the time of year at which particular flow events occur, such as seasonal timing of flood or low flow events.
- *Rate of change* indicates how quickly flows change over time.

Magnitude of flow (or discharge) is the primary factor that regulates channel width and depth and load carrying capacity of a tributary. All moving water carries materials and the amount of material that can be carried varies with the discharge and water-surface slope, which are related to stream power - a measure of the ability of a stream or river to do work. Generally when discharge increases, so does the ability do to work. During high flows, stream banks and channels are eroded, and the water and materials are transported downstream. As discharge decreases, the entrained materials begin to settle out and sedimentation occurs as the ability to do work decreases.

The frequency, duration, and timing of flows describe the ecologically important temporal components of flow regime. Anthropogenically altered flow regimes generally exhibit higher flood frequencies and shorter flood durations than natural flow regimes. The rate of change in flow events is a measure of how quickly flow magnitude changes per unit time. A system with rapid rates of change is considered flashy, meaning that flows are highly variable over short periods of time. Flashy streams may also exhibit high peak discharges and short flood durations. Such systems are unstable and subject to scouring, flooding, and other extreme disturbances (e.g., Baker *et al.* 2004).

Natural Flow Regime

Characteristics of flow that would be present without anthropogenic influence and to which individual species, biological communities, and the ecosystem as a whole have co-evolved and adapted.

The overall flow regime measured at any particular point along a river's course is the combined result of upstream influences including the integrated effects of climate, geology, hydrology, geomorphology (topography and slope), vegetative cover, drainage area, and dominant water source within the receiving watershed. In the Great Lakes basin, these fundamental components have been altered by anthropogenic modifications to the watersheds they drain. Examples of such modifications include: dams and levies, channelization (smoothing and straightening) and deepening of channels; water withdrawals, water discharge, and flow regulation; and change in land use and land cover – all of which effect the timing, rate, and amount of water, energy, and materials conveyed through the basin's waterways (e.g. GLPF 1998; Poff et al. 1997; Richter et al. 1996, 1997, 1998; Baron et al. 2002; Bain and Travnichek 1996). The results are altered flow regimes, degraded water quality, loss of natural biodiversity, impaired ecosystem function, and reduced ecological integrity.

> *"The structure and function of freshwater ecosystems are tightly linked to the watershed, or catchment, of which they are a part (Hynes 1970, Likens 1984). As water flows on its way to the sea, it moves through freshwater systems in three spatial dimensions: longitudinal (upstream–downstream), lateral (channel–floodplain, or wetland–lake margin), and vertical (surface water–groundwater). These dimensions represent functional linkages among ecosystem compartments over time (Ward 1989). Bodies of freshwater are ultimately the recipients of materials generated from the landscape; hence they are greatly influenced by terrestrial processes, including human modifications of land (Moyle and Leidy 1992)."* Baron *et al.* (2002)

Landscapes and watersheds are linked to the Great Lakes via hydrology, i.e. surface and groundwater flows, hydraulic connectivity and continuity, and pathways (i.e. flow paths, connectivity, and patterns of flow). Landscape stressors create hydrologic impairments – by altering flow characteristics and/or the pathways that water takes to enter, or flow through the

Great Lakes. These impairments alter natural flow regimes, degrade water quality, and affect the benefits that water provides to the ecosystem.

Pathways – Flow Paths and Connectivity

A fundamental component of the natural flow regime paradigm is the recognition that rivers and lakes are hydrologically connected to the surrounding watershed by surface runoff, to aquifers and other groundwater resources by groundwater, and to each other by drainage pattern and flow paths that extend from the upper reaches of the watershed down to, and including, the Great Lakes. Implicit within the natural flow regime paradigm are the following principles:

- Flow regimes are inextricably linked to the flow paths that water takes across, or through the landscape.
- The path that water takes across, or through the landscape allows the biological communities to utilize energy and materials as water moves through the system.
- The ecological benefits and services provided by a liter (or gallon) of water are, in part a function of water quality; residence time on the landscape; flow path complexity; and energy of the system.

Landscape modifications (change in land use or land cover) that alter flow paths of water moving through the system will affect flow regime. For example, impervious surfaces associated with expanding urbanization will increase stormwater discharges after major precipitation events. Channeling runoff from impervious surfaces into ditches or stormwater drains effectively speeds up the flow of water off the land surface (i.e. alters the timing) and "short circuits" natural flow paths, thereby altering flow regime. Associated with this increase in discharge is an increase in energy (i.e. stream power) that causes channel instability and results in increased bank and bed erosion and a corresponding increase in non-point sediment loads (and corresponding reduction in water quality).

Many local restoration projects in the basin focus on stabilizing eroding stream banks and modifying instream flows in order to stabilize stream channels and reduce non-point sediment loads. Unfortunately, these projects do not address the root cause of the problem – altered flow regimes – where there is an increase in the frequency of high-discharge events due to landscape and flow path modifications that affect flows upstream from the restoration site.

> *"Increases in sediment load due to alteration of the flow regime are not due to the simple addition of man-made substances into the system but rather are due to fundamental changes in the energy of the system. Certain forms of non-point source pollution such as sedimentation may be better understood as an artifact of altered flow regime. Solutions to some non-point source pollution problems may actually be simple plumbing fixes, not expensive or intrusive pollution control programs."* (GLPF 1998).

In addition to degradation of water quality, there are biological and ecological impacts when natural flow paths and hydrologic connectivity are modified by anthropogenic actions. Water is used, processed, and recycled over and over again by a host of biological organisms and communities. Examples include biological communities and species that rely on seasonal flood pulses that inundate low-lying floodplain areas and recharge adjacent riparian wetlands. Sediments and nutrients entrained by floodwaters are deposited and processed within the floodplain complex. Biological organisms use water and nutrients within the floodplain complex to maintain biogeochemical processes and perform life-maintaining functions. Waters may be retained in vernal pools, riparian wetlands, or floodplain ponds - then may gradually drain back to the river via surface or shallow groundwater flow paths, or infiltrate through soils to recharge deeper groundwater aquifers (e.g. Shedlock *et al.* 1993). These natural processes are cyclic and renew waters that remain on the landscape. Water that leaves the landscape is also recycled and renewed by direct evaporation and/or evapotranspiration.

The spatial and temporal scales over which these natural processes operate are complex and highly variable. The time that water stays within the system is a function of flow velocity, direction and distance traveled, and pathways and connections within, or on the landscape. In general, the ecological value of water increases with residence time, flow path complexity (i.e. connectivity and patterns of flow), and the frequency and duration of flow events. These factors combine to increase the probability of exposure of water to diverse biological systems and biogeochemical processes that process and remove contaminants and improve water quality. The idea is that the longer water stays on the landscape and is cycled (and recycled) through these processes, the greater the benefits to the ecosystem (Figure 2.). This is not to say that water must be retained permanently on the landscape – we seek a set of conditions where residence time, flow paths, connectivity, patterns of flow, and the rate at which the flow of water conveys energy and materials through a system are balanced to maximize physical and ecological integrity – the natural flow regime. These time-distance-value dependencies are clearly demonstrated by the work by Poff *et al.* (1997) and subsequent work by Richter *et al.* (1998; 2000), Baron *et al.* (2002), and others.

> ***"We seek a set of conditions where residence time, flow paths, connectivity, patterns of flow, and the rate at which the flow of water conveys energy and materials through a system are balanced to maximize physical and ecological integrity – the natural flow regime."***

Anthropogenic modifications generally result in moving water off the land surface as quickly as possible thereby "short circuiting" natural hydrologic processes and pathways. This replumbing of the system not only alters fundamental characteristics of flow, but degrades water quality by reducing residence time on the landscape and bypassing the natural recycling systems that maintain, cleanse, and renew the basin's waters as it moves across, and through the landscape.

Restoration of Natural Flow Regimes – A Powerful Restoration Tool

Many organizations and agencies in the Great Lakes, when asked to identify potential restoration opportunities, focus on restoring wildlife, waterfowl, or endangered species habitat; rare or endangered plant communities; fish populations and fish community structure; and/or remediating polluted waters and contaminated sediments. These efforts are typically designed to restore specific components of the ecosystem structure and ignore the underlying functional relationships and natural processes that bind the ecosystem together. Moreover, current regulatory and monitoring programs are either watershed or open-lake based and are focused primarily on assessing, monitoring, and/or limiting pollutants that enter the system (e.g. summary by Charlton and Milne 2004). Current regulatory and monitoring programs within the Great Lakes basin are not designed to explicitly consider functional relationships and natural processes within the system.

Within systems with altered hydrology, results of ongoing research and monitoring suggest that the restoration of natural flow regimes will result in sustainable water resources and long-term improvements in habitat, biodiversity, and ecological function. Conceptually, this is not a surprise due to the fact that within the Great Lakes basin, individual species, biological communities, and the ecosystem as a whole have co-evolved and adapted to a natural range of hydrologic conditions – the natural flow regime. Altered flow regimes degrade and adversely impact the physical and ecological integrity of a system. Actions taken to restore natural flow regime will result in a positive response by the ecosystem and over time, will yield long-term benefits including sustainable water resources and improvements in habitat, biodiversity, and ecological function. More importantly, by restoring natural flow regimes, inherent natural structuring processes are allowed to act, eliminating the need to rely on long-term, continuing investments in direct anthropogenic actions to maintain physical integrity.

LANDSCAPES AND WATERSHEDS

For the purpose of this discussion, landscapes include the integrated components of land and water area (i.e. geology, geomorphology, and land cover) upon which natural processes act within the Great Lakes Basin. Watersheds are a subset of landscapes and are defined by the area of drainage that supplies surface water that feeds a river and associated tributaries. Landscapes are composed of three major components, each essential to the maintenance of physical integrity:

- *Geology* – surface and subsurface distribution of geologic materials; soils; hydrophysical characteristics (permeability, porosity, aquifers, aquatards…);
- *Geomorphology* – shape, pattern, distribution, and physical features of the land surface; landforms and drainage pattern (topography, slope, hydrography, channel morphology and bathymetry, connectivity and pattern); and
- *Land Cover* – shape, pattern, and distribution of physical, biological, and anthropogenic features on the land surface (Land Use).

Geology and the surface expression of geology, geomorphology, are considered to be one of the three natural master variables that structure, organize, and regulate the fundamental physical characteristics of a landscape and the energy and processes that act on that landscape. Geology and geomorphology represent an integration of a subset of physical attributes, some of which are actionable, some of which are not. In the case of geology and geomorphology, examples of non-actionable attributes include: the type, distribution and pattern of bedrock; soils and surficial materials; regional hydrophysical characteristics; and regional basin geomorphology. These physical attributes form the underlying framework (and can be considered to be structural components) of the ecosystem and are integral to the physical integrity of the system. Actionable attributes can be (and have been) manipulated, and in the case of geology and geomorphology, examples include: the shape, pattern, distribution, and physical features of the land surface; drainage pattern (topography, slope, hydrography, channel morphology and bathymetry, hydraulic connectivity); and landform connectivity, pattern, and distribution. Modifications to these attributes alter the flow paths, connectivity, and patterns of flow of surface and ground waters moving through the system affecting hydrology and flow regime. Moreover, by altering these attributes, not only are we changing the underlying structural components and framework of the ecosystem, but impacting the physical integrity of the system as well.

Land cover describes the shape, pattern, and distribution of physical, biological, and anthropogenic features on the land surface – features that interact to produce a complex mosaic of landscape elements and connections that have both structural and functional significance for physical integrity and the ecosystem. An in-depth discussion of the basic concepts of Landscape Ecology and pattern analyses is beyond this work, but suffice it to say that landscapes are composed of a mosaic of elements that represent discrete areas of relatively homogeneous environmental or physical characteristics (e.g., see summary by McGarigal *et al.* 2002). To provide a contextual framework, the model commonly applied to landscape features is the *patch-corridor-matrix* model (Forman 1995), where discrete landscape elements - commonly referred to as patches – are set within a broader and more extensive landscape element called a "matrix". Corridors are linear landscape elements defined by their form (structural corridors) and/or their function (e.g., habitat, dispersal conduits, or barriers). Corridors may have similar attributes as, and be physically connected to, adjacent patches within the mosaic. Typically, application of the patch-corridor-matrix model is dependent upon the attributes under consideration. For example, from a physical integrity perspective, an analysis of geomorphic processes might require the use of drainage pattern and/or topographic slope to define the matrix, patches, and corridors; whereas, from an ecological perspective, an analysis of vertebrate populations might require the use of vegetative structure to define the matrix, patches, and corridors.

When considering landscapes and watersheds, the traditional focus has been on changing land cover and land use – the shape, pattern, and distribution of biological and anthropogenic features on the land surface – and the impacts of these changes on structural components of the ecosystem (i.e. species, communities, and habitat) and water quality. A common approach used to identify impairments is to examine land-cover change and attempt to link these changes to sediment and contaminant loadings and resulting site-specific degradation of habitat, biodiversity, and ecological function. Unfortunately, the linkages between land-cover change, sediment and contaminant loadings, site-specific habitat degradation, biodiversity, and ecological function are highly variable, non systematic, and difficult to quantify. This is in part due to the different spatial and temporal scales over which these interactions occur and the multivariate relationship between land-cover change and the fundamental functions and processes that influence water resource sustainability, biodiversity, and ecological function.

> ***"Land cover directly influences physical integrity by controlling the hydrophysical characteristics of the landscape - natural processes, pathways, hydraulic connectivity and continuity - and ultimately the flow regime."***

Traditional watershed assessment approaches ignore the fact that land cover directly influences physical integrity by controlling the hydrophysical characteristics of the landscape - natural processes, pathways, hydraulic connectivity and continuity - and ultimately, the flow regime. Moreover, most watershed assessments do not consider the fact that landscapes and watersheds are linked and connected to the Great Lakes by hydrology, i.e. via surface and groundwater flows, or that actions taken within the watershed directly impact the flow regime and the Great Lakes as a whole. In fact, our ability to effectively address water quantity and water quality issues in the Basin has been severely limited by ignoring processes and functional relationships and by relying almost exclusively on land-cover change detection and analyses programs and traditional watershed assessment techniques to identify ecological protection and restoration opportunities.

One must recognize that landscapes are spatially complex and it is the integrated impact of landscape alterations and the effects of these alterations on natural processes, flow paths, connectivity, and patterns of flow that have contributed to the loss of physical integrity within the Great Lakes. Many of the physical stressors and impairments identified in the basin are the result of altered landscapes. Even though complete restoration of natural landscape patterns, connectivity, and the natural processes that structure, maintain, and regulate those patterns is not practicable, possible or desirable, it may be possible to restore critical landscape components and processes that mimic sustainable natural conditions in ways that maintain ecosystem health, promote ecosystem resiliency and regeneration, and allow the system to change and evolve irrespective of natural and anthropogenic perturbations, i.e. achieve landscape integrity.

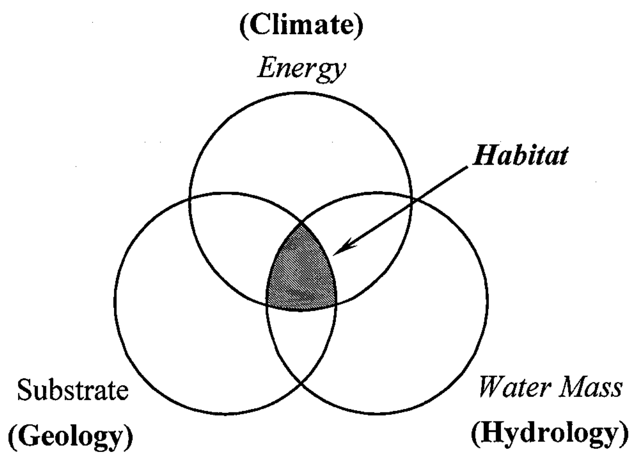
Within the Great Lakes basin, individual species, biological communities, and the ecosystem as a whole have co-evolved and adapted to a natural range of landscape conditions. Actions taken to restore natural landscape patterns and connectivity will result in a positive response by the ecosystem and over time, will yield long-term benefits including sustainable water resources and improvements in habitat, biodiversity, and ecological function. More importantly, by restoring natural landscape patterns and connectivity, the inherent natural structuring processes associated with restored hydrology and natural flow regimes will eliminate the need to rely on long-term, continuing investments in direct anthropogenic actions to maintain physical integrity.

HABITAT INTEGRITY - SUSTAINABLE HABITATS AND ECOSYSTEMS

Great Lakes habitats are inextricably linked to physical integrity. Habitat is the critical component that links the biological communities and ecosystems to natural processes, pathways, and the landscape. The pattern and distribution of habitats is controlled, in part by the underlying physical characteristics of the basin and interactions between energy, water, and the landscape (e.g., Sly and Busch 1992; Higgins *et al.* 1998). Moreover, the physical characteristics and energy conditions that define habitats are created by the interaction of master variables – climate (energy), geology (geomorphology and substrate), and hydrology (water mass characteristics and flow) – the same variables and processes that maintain physical integrity. Habitats are created when there is an intersection of a range of physical, chemical, and biological characteristics that meet the life stage requirements of an organism (Figure 1.)

"Habitat is the critical component that links biological communities and ecosystems to natural processes, pathways, and the landscape."

Figure 1. Fundamental Characteristics of Aquatic Habitat



- *Energy* – estimated from hydraulic calculations for both oscillatory and unidirectional flows.
- *Substrate* – bedrock, composition, texture, hardness, stability, porosity, permeability, roughness.
- *Water Mass* – depth, temperature, turbidity, nutrients, contaminants, and dissolved oxygen.
- *Habitat* – physical characteristics and energy conditions that meet the needs of a specific species and/or biological community for a given life stage.

From the perspective of physical integrity, *physical habitats* are defined by a range of physical characteristics and energy conditions that can be delineated geographically that meet the needs of a specific species, biological community, or ecological function for a given life stage. To be utilized as a habitat, these physical characteristics and energy conditions must exhibit an organizational pattern, be persistent, and "repeatable" – elements that are essential to maintain a sustainable and renewable resource (Peters and Cross 1992). The repeatable nature of a habitat implies that the natural processes that create a physical habitat must also be repeatable and may persist over a range of spatial and temporal scales. For example, seasonal changes in flow, thermal structure, and water mass characteristics create repeatable patterns and connections within the tributaries and lakes in the basin. Spatially, these patterns occur within the same general locations year after year. Moreover, the pattern of movement of water, energy, and materials through the system (which depends on connectivity) also exhibits an organizational pattern, persistent, and repeatable. These patterns and connections, in part control the seasonal distribution and regulate the timing, location, and use of Great Lakes habitat.

Physical Habitat

A combination of a range of physical characteristics and energy conditions that can be delineated geographically that meet the needs of a specific species, biological community, or ecological function for a given life stage.

Therefore, the quality and integrity of Great Lakes habitats are maintained by sustainable natural processes, pathways, and landscapes. Anthropogenic activities that alter natural processes, pathways, and landscapes have resulted in the loss and degradation of Great Lakes habitat. Alteration of natural processes and pathways affects how biological communities utilize energy and materials as water moves through the system. _Habitat Integrity_ is created by protecting and restoring sustainable natural processes, pathways, and landscapes that maintain a range of physical, chemical, and biological characteristics and energy conditions that can be delineated geographically that meet the needs of a specific species, biological community, or ecological function for a given life stage. The following operational concept of habitat integrity is proposed:

Habitat Integrity

Sustainable natural processes, pathways, and landscapes that maintain a range of physical, chemical, and biological characteristics and energy conditions that can be delineated geographically that meet the needs of a specific species, biological community, or ecological function for a given life stage.

Within the Great Lakes basin, individual species, biological communities, and the ecosystem as a whole have co-evolved and adapted to utilize a natural range of habitat conditions (e.g. Busch and Lary 1996; Jones et al. 1996). Actions taken to restore natural processes, pathways, and landscapes will result in a positive response by the ecosystem and over time, will yield long-term benefits including sustainable water resources and improvements in habitat, biodiversity, and ecological function. More importantly, by restoring natural processes, pathways, and landscapes, the inherent natural structuring processes will eliminate the need to rely on long-term, continuing investments in direct anthropogenic actions to maintain habitat integrity.

WATER LEVELS AND CLIMATE CHANGE

Water Levels

Within the Great Lakes coastal margin and open water systems, the equivalent of natural flow regime is the natural water-level regime. The Great Lakes water-level regimes are controlled primarily by the interaction of two master variables, climate and hydrology. The Great Lakes water levels represent the integrated sum of water inputs and losses from the system – typically expressed by a hydrologic water balance equation – that are driven by climate (long-term and seasonal weather patterns), hydrology and flow regime (surface water, ground water, and connecting channel flows), and the utilization of water resources within the basin (water withdrawals, diversions, and connecting channel flows) (IJC 2000; Quinn 2002). Primary controls of the Great Lakes water levels and flow regimes are precipitation, evapotranspiration, and the frequency, duration, and distribution of major storm events – which are driven by seasonal and longer-term climatic cycles (Quinn 2002; Baedke and Thompson 2000). Long-term and seasonal changes in precipitation and evaporation result in the inter-annual and seasonal variability of water levels and the associated connecting channel flows within, and between all the Great Lakes (Derecki 1985; Lenters 2001; Quinn 2002).

The term "water-level regime" encompasses the range and variability of water levels in response to changes in the overall water balance of the system under consideration. The "natural water-level regime" refers to the range and variability of water levels that would be present without any anthropogenic influence and to which individual species, biological communities, and the ecosystem as a whole have co-evolved and adapted. Change in the lake water levels can be characterized in ways similar to flow regimes, where the fundamental characteristics of flow – magnitude, frequency, timing, duration, and rate of change - can also be applied to Great Lakes water levels and connecting channel flows. Also influencing the water-level regimes are short-term fluctuations in the water level that are caused, in part, by local wind or storm events that perturb the water surface, such as a storm surge or seiche events, that may not necessarily reflect a change in the overall water balance of the lake or basin under consideration. These short-term fluctuations in the water level may also have important structuring effects on coastal margin and open-lake ecosystems.

Water levels of two Great Lakes - Lakes Superior and Ontario - are currently regulated. The long-term ecological impacts of regulation on Lake Superior and Lake Ontario are only just beginning to be understood. Ongoing research suggests that a reduced range of variability of lake water levels (in particular, clipping of the lows) has directly impacted coastal wetland plant communities and biodiversity in Lake Ontario (USGS 2004). These changes in wetland plant communities have also affected the productivity and structure of the fish community in Lake Ontario. Ongoing work by the GLC-supported Wetlands Consortium and the IJC Lake Ontario Reference are continuing to document the importance of water-level regime and the natural range of variability to coastal margin biodiversity and ecological integrity.

The *physical* and *hydrologic* integrity of the coastal margin and open-lake systems are defined by the interaction of water-level regimes, open-lake circulation processes and patterns, natural coastal processes, and the pathways and connections along which these processes act. Natural coastal processes include oscillatory and unidirectional flows generated by waves and currents, with the resulting conveyance of material and energy along the shore, between, and within the coastal margin areas and the open lake. These processes control the distribution of materials and substrates in the nearshore zone (area encompassed by water depths generally less than 10 m). Moreover, seasonal changes in flow, thermal structure, and water mass characteristics create regional-scale patterns and connections within and between the coastal margin and open-lake areas within the basin (e.g. Tyson *et al.* 2001). The natural coastal processes that structure, organize, and regulate the coastal margin systems act along flow paths that depend on the natural connectivity between river mouths (estuaries), embayments, open and protected shorelines, and the landscapes that drain into them.

Irrespective of cause, the altered water level regimes affect these coastal and open-lake processes, pathways, and connections. For example, lower water levels alter open-lake circulation patterns and connectivity; alter thermal structure and patterns; affect nearshore coastal processes by reducing water depth and changing wave-energy distributions in the nearshore areas; and reduce hydraulic connectivity between, and within the coastal margin and wetland/barrier systems within the Great Lakes. Anthropogenic alterations to river mouths and the "hardening" of shorelines modify flow paths and the natural coastal processes that convey energy and materials along and through the coastal land-margin systems. Moreover, altered flow regimes on the landscape may adversely impact not only the ecological integrity but also the physical and hydrologic integrity of the Great Lakes themselves. Currently, the cumulative impacts of altered flow regimes on the Great Lakes are unknown, primarily because we have only started to consider the question. Existing data sets are inadequate to perform the assessment in a meaningful way (GLC 2003).

> **"Ecological integrity is achieved by protecting and restoring water level regimes, natural coastal processes, and flow paths and connections that structure, organize, and regulate coastal margin systems and create regional-scale patterns that link coastal margin and open-lake areas within the Basin."**

From the perspective of ecological integrity, altered water level regimes, natural coastal processes and associated pathways, will affect how biological communities utilize energy, materials, and water as it is conveyed through the coastal margin and open-lake systems. Individual species, biological communities, and the ecosystem as a whole respond to changes in physical integrity as they have co-evolved and adapted to a natural range of water levels, flows, and water-mass characteristics in order to maximize benefits to themselves and the ecosystem. Ecological integrity is achieved by protecting and restoring water level regimes, natural coastal processes, and flow paths and connections that structure, organize, and regulate coastal margin systems and create regional-scale patterns that link the coastal margin and open-lake areas within the Basin.

Superimposed on these daily, seasonal, and longer-term climatic cycles and natural processes, is the potential for long-term climate change. Master variables such as climate which cannot be anthropogenically manipulated (at least over the short term) are considered to be "non-actionable". However, being "non-actionable" does not mean that these master variables are fixed or inviolate through space or time. Anthropogenic or natural changes to the physical integrity of the system may, over the long term, alter patterns and trends from historic or long-term "natural" norms.

Climate Change

Recent research and modelling results suggest that anticipated long-term changes in climate have the potential to significantly alter the physical integrity of the Great Lakes basin (summary in Kling *et al.* 2003). Changes in climate may be gradual and will be affected by interactions between natural long-term climatic cycles and potential long-term impacts due to anthropogenic changes to the earth's atmosphere. Because climate and hydrology are master variables, these changes are likely to have a significant impact not only on physical integrity, but the chemical, biological, and ecological integrity of the Great Lakes as well.

Details of the potential impacts of climate change are described elsewhere and are beyond the scope of this work (e.g., Mortsch and Quinn 1996; Lee *et al.* 1996; Magnuson 1997; Mortsch 1998; Atkinson 1999; Casselman *et al.* 2002; Lofgren *et al.* 2002; Brandt *et al.* 2002; Wuebbles and Hayhoe 2003; Kling *et al.* 2003). However, climate-change induced alterations to weather, i.e. precipitation, evapotranspiration, and storm frequency, severity, and patterns will likely alter the physical and habitat integrity of the Basin, including:

- *Tributary and groundwater flows, base flows* – seasonal alterations of flow regime; spatial and temporal shifts in seasonal timing;

- *Great Lakes water levels* – a general lowering of water levels; spatial and temporal shifts in seasonal timing;
- *Thermal effects* - thermal stratification; altered open-lake and nearshore surface water temperatures, circulation patterns, and processes; reduced ice cover; spatial and temporal shifts in seasonal timing; and
- *Latitudinal shifts in ecoregions* – regional changes in land and vegetative cover and associated terrestrial and aquatic communities and habitats.

Water Level Impacts on Ecological Integrity

For example, regional climate change models (Canadian Centre for Climate Modeling CCGM1 and UKMO/Hadley Centre HADCM2) project a 1 to 2 m decline in long-term annual water levels over the next 70 years for the Great Lakes (e.g. Lofgren et al. 2002; Sousounis and Grover 2002; Mortsch and Quinn 1996; Lee et al. 1996). Recent work by Wuebbles and Hayhoe (2003) using the HADCM3 model projects higher temperature changes for the Midwestern U.S. than those predicted by the CCGM1 and HADCM2 models. Lee et al. (1996) predicted that a reduction in long-term annual water levels in Lake Erie and Lake St. Clair by 1.5 m or more would significantly reduce the lakes' surface area and move the shoreline by less than 1 km to as much as 6 km lakeward of the current shoreline location.

Climate-induced reductions in water levels will hydrologically isolate many high-quality wetland and estuarine areas that are currently protected or maintained by government agencies and/or non-governmental conservation organizations (Mortsch 1998). Moreover, reduced water levels will alter nearshore littoral and sub-littoral habitats, permanently affecting benthic and fish community structure throughout the Great Lakes. The effects of lower water levels will also fundamentally affect seasonal timing and connectivity, food-web dynamics, and the distribution and diversity of biological communities in the basin (e.g., Kling *et al.* 2003, Casselman *et al.* 2002; Brandt *et al.* 2002).

Under natural conditions, any loss of biodiversity (and physical integrity) would be short-term because new wetlands and coastal/nearshore habitats will be created and the ecosystem would adapt to a new water-level regime as physical integrity is restored. However, continuing development pressures threaten newly exposed areas, resulting in degradation and the risk of permanent loss of these critical habitats and associated biodiversity. The combination of climate change and anthropogenic activities will potentially result in an irreversible loss of physical integrity and coastal/nearshore habitats because the system will not be able to adapt naturally to climate-induced water level change. Irrespective of cause, the permanent loss/change in the distribution of wetland, riverine, deltaic, and nearshore habitats due to lower water levels and/or climate change will result in a substantial loss of biodiversity, affecting the overall ecological integrity of the Basin.

Conservation and resource management agencies have long recognized the potential consequences of altered thermal and water-level regimes due to climate change, but have not sufficiently incorporated the effects of climate change into long-term conservation or management plans (e.g., TNC 2000; Rodriguez and Reid 2001). As a result, these plans do not provide for the future conservation of the coastal and submerged nearshore areas where new wetlands, coastal embayments, and high-quality fish habitats will form (e.g., Saxon 2003). Nor do current planning efforts incorporate the potential effects of altered climate, flow, and thermal regimes on watersheds, tributaries, nearshore and coastal margin areas, or the Great Lakes themselves.

This discussion highlights the need to incorporate into the Agreement, programmatic strategies designed to respond to potential long-term stressors, such as climate change or water diversions, which have the potential to impair the physical integrity of the Great Lakes. One recommended strategy would be to develop and implement proactive anticipatory management approaches (commonly referred to as adaptive management strategies) that identify the long-term planning, protection, and restoration needs in the Basin in response to long-term stressors and impairments. Application of adaptive management strategies will help to ensure the physical and ecological integrity of the Great Lakes in the face of major environmental changes.

DISCUSSION

Ecological Integrity and the Great Lakes Water Quality Agreement

The Great Lakes Water Quality Agreement as currently written and implemented does not provide the necessary vision, conceptual guidance, or tools to restore the ecological integrity of the Great Lakes. Under the Agreement, water quality management is focused primarily on chemical pollution and programs that are designed to reduce, regulate, and control what enters the system or manage and remove "legacy" contaminants that have already entered and reside within the system. Currently there are few, if any, programs under the Agreement that are designed to monitor or protect the natural processes, pathways, or landscapes that are essential to maintain a sustainable ecosystem.

Earlier in the discussion, we recognized that a lack of a common vision for physical and/or ecological integrity has impacted our ability to develop and implement a comprehensive restoration agenda for the Great Lakes and that there is a need to establish a shared vision or goal that captures what is meant by "Restoring the Great Lakes". Fortunately, the Great Lakes Water Quality Agreement *already* identifies the fundamental system components necessary to achieve ecological integrity – *chemical*, *physical*, and *biological* integrity - which are summarized in the following hypothesis:

Hypothesis

If chemical, physical, and biological integrity are necessary and fundamental components of ecological integrity; then protecting, restoring, and enhancing the chemical, physical, and biological integrity of the Great Lakes will protect, restore, and enhance the ecological integrity of the Great Lakes.

Through revisions to the Agreement, this hypothesis can be tested and if validated and found to be true, then one can conclude that "Restoring the Great Lakes" means protecting, restoring, and enhancing the chemical, physical, and biological integrity of the Great Lakes - and the natural processes, pathways, connections, and landscapes that maintain them. The logic behind this assertion is based on the following concepts:

1. Ecological integrity is derived from, and dependent upon, physical, chemical, and biological integrity.
2. Chemical, physical, and biological integrity are achieved by protecting and restoring fundamental ecosystem components, the natural processes that maintain them, and the functional pathways and connections along and through which those processes work.
3. Sustainable processes build sustainable ecosystems. Protection and restoration of sustainable natural processes, pathways, and landscapes will yield sustainable waters, support sustainable ecosystem functions, and achieve long-term chemical, physical, biological, and ecological integrity.

A revised Agreement has the potential to provide a binational framework for the development of a comprehensive protection and restoration strategy for the Great Lakes. What is needed is an overall *vision* of ecological integrity for the Great Lakes - along with a set of *guiding principles* and *standards* designed to protect, restore, and enhance Great Lakes water quality and quantity, and support natural biodiversity and ecosystem function, and achieve ecological integrity. Developing an overall vision of ecological integrity for the Great Lakes basin is beyond the scope of this work, even though it may be worthwhile to explore some of the fundamental principles, concepts, and potential implementation strategies that may be common to concepts of both physical and ecological integrity.

> ***"What is needed is an overall vision for the concept of Ecological Integrity of the Great Lakes - along with a set of Guiding Principles and Standards designed to protect, restore, and enhance Great Lakes water quality and quantity, and support natural biodiversity and ecosystem function."***

The concept of ecological integrity has been defined in other venues outside of the Great Lakes, and also has been considered within a philosophical context (e.g. U.S. EPA 2005; De Leo and Levin 1997; Soskolne and Bertollini 1999; Karr *et al.* 1991; Karr and Dudley 1981). It is clear that there are fundamental conceptual elements that must be included within an operational concept of ecological integrity, including ecological health and well being; ecosystem resiliency and regeneration (especially in response to internal and external stressors); capacity and options for ecosystem development and growth; and the ability of the ecosystem to change, adapt, and maintain essential ecosystem functions irrespective of long-term natural and anthropogenic stressors and impairments (Westra 1994).

"Ecological integrity (EI) is an umbrella concept that includes in various proportions and which cannot be specified precisely, the following:

1) *Ecosystem health and its present well being. This condition may apply to even non-pristine or somewhat degraded ecosystems, provided they function successfully as they presently are. Ecosystems that are merely healthy may encompass both desirable and undesirable possibilities, and may be more or less limited in the capacities they possess. It is for this reason that health alone is not sufficient.*
2) *The ecosystem must retain the ability to deal with outside interference, and, if necessary, regenerate itself following upon it. This clause refers to the capacity to withstand stress. This definition makes the distinction between non-anthropogenic stress, as part of billions of years of development, and anthropogenic stress, which may be severely disruptive.*
3) *The systems' integrity reaches a peak when the optimum capacity for the greatest number of possible ongoing development options, within its time/location, is reached. The greatest potentiality for options is fostered, for example, by biodiversity (within contextual natural constraints).*
4) *The system will possess integrity, if it retains the ability to continue its ongoing change and development, unconstrained by human interruptions, past or present. (Westra 1994)."*

Presentation by L. Westra, 1998. Ecology & Health: from a discussion document. WHO ECEH, Rome Division – July 1999.

Considering ecological integrity within a master variable context and setting aside philosophical (i.e. moral and ethical) values, there are considerable economic and societal benefits that are derived from a freshwater ecosystem that has ecological integrity. Resource utilization, i.e. the use of the basin's resources to produce economically valuable goods and services, provide abundant supplies of clean water, and provide desirable recreational and aesthetic qualities commonly associated with a natural ecosystem, forms the basis for our interest in achieving ecological integrity (e.g., Baron *et al.* 2003). More importantly, by restoring ecological integrity, inherent natural structuring processes will eliminate the need to rely on long-term, continuing investments in direct anthropogenic actions to maintain sustainable ecological functions, benefits, and services, which will ultimately result in both economic and environmental efficiencies (e.g. Karr *et al.* 1986).

Physical Integrity and Natural Processes - A New Paradigm for Great Lakes Protection and Restoration

The logical conclusion that follows from the discussion of physical and ecological integrity is that a new paradigm is emerging that is based not only on an ongoing assessment of the system components and status, but on protecting, restoring, and enhancing natural processes, pathways, and the functional relationships that create and maintain chemical, physical, and biological integrity in the Great Lakes Basin. At the core of this physical integrity paradigm is the fundamental principle that *sustainable processes build sustainable ecosystems*, and the fact that the interaction of master variables – climate, geology, and hydrology, i.e. the same variables and processes that maintain and regulate physical and habitat integrity - establishes the framework that links and integrates all the structural components of the ecosystem together into a whole.

Within the context of physical integrity, sustainable natural processes are created when master variables interact to convey energy, water, and materials through a system in ways that correspond to undisturbed natural conditions, maintain system integrity, and promote system resiliency and regeneration - irrespective of the natural and anthropogenic perturbations. The importance of physical integrity to the protection and restoration efforts cannot be overemphasized. The overarching nature of physical integrity is such, that it is possible to achieve physical integrity without achieving chemical or biological integrity, but it is much more difficult to achieve chemical or biological integrity without achieving physical integrity. This new process-based physical integrity paradigm represents an integrated, balanced approach to restoration that links the essential structural components of the ecosystem to the natural processes and pathways that maintain them, and builds on much of the work that has already been done in the Basin.

"At the core of this new paradigm is the fundamental principle that sustainable processes build sustainable systems, ..."

It is likely that in a revised Agreement, there will be a requirement to develop methods to quantify, predict, evaluate, and value the outcomes of potential ecological protection or restoration projects in response to the incorporation of a new physical integrity paradigm into the Agreement. Assessment methods would include the ability to quantify potential restoration outcomes; develop monitoring plans that measure hydrologic and ecological benefits of restoration projects; establish links between hydrologic parameters and measures of habitat, biodiversity, and ecological function; and measure the degree to which specific restoration or improvement actions contribute to physical integrity.

Traditional monitoring, assessment, and regulatory programs are not explicitly designed to identify impairments to natural processes, the pathways along which they act, or to assess the hydrologic impairments resulting from altered flow regimes. Fortunately, ongoing research has led to the development of a suite of tools designed to quantify and assess the degree and type of hydrologic alteration in impaired systems (Richter *et al.* 1996, 1998). Some of these tools are designed to generate synthetic natural flow regimes for undisturbed conditions that can be used to establish targets or endpoints (i.e. reference conditions) to achieve specific environmental outcomes. Activities that restore the natural hydrologic function by shifting flow regimes towards more natural or undisturbed conditions are to be encouraged. Moreover, progress towards environmental outcomes can be measured by comparing the current state with idealized reference conditions. Reference conditions are also required to establish thresholds that define measures of "success" for restoration projects designed to restore physical integrity.

The operational definition of physical integrity states that sustainable processes, pathways, and landscapes are the necessary and essential *requirements* to maintain sustainable supplies of clean water and protect and restore ecosystem function and ecological integrity within the Great Lakes. Achieving physical integrity is *accomplished* by protecting and restoring fundamental ecosystem components, the sustainable natural processes that maintain them, and the connections and pathways through which those processes work. Physical integrity is *achieved* when the physical components of a system and the natural processes and pathways that structure, organize, define, and regulate them, correspond to undisturbed natural conditions and are mutually supportive and sustainable.

> ***"...sustainable natural processes are created when master variables interact to convey energy, water, and materials through a system in ways that correspond to undisturbed natural conditions, maintain system integrity, and promote system resiliency and regeneration..."***

Sustainable natural processes, pathways, and associated functional relationships within the system are fundamental to *all* aspects of physical integrity. Natural processes are mechanisms that transfer energy, water, and materials across and through landscapes into the Great Lakes. The pathways that water takes as it moves across the landscape are also important. Pathways are the paths along which natural processes act to convey energy, water, and materials through a system. Alteration of natural hydrologic processes and pathways affects how biological communities utilize energy, materials, and water as it is conveyed through the system. Individual species, biological communities, and the ecosystem as a whole respond to changes in physical integrity as they have co-evolved and adapted to the natural physical and hydrologic conditions in order to maximize benefits to themselves and the ecosystem.

"Restoring the Great Lakes" means protecting, restoring, and enhancing the chemical, physical, and biological integrity of the Great Lakes - and the natural processes, pathways, connections, and landscapes that maintain them. Incorporating the concept of physical integrity into the Agreement will force a long-overdue re-examination of our approach to Great Lakes restoration and will potentially reframe many of the questions that we have been asking about the Great Lakes. The concept of physical integrity forces us to refocus our efforts toward protecting and restoring not only structural components of interest (i.e. specific species, habitat, or landscape), but also the natural processes and pathways that create and maintain them.

Moreover, in combination with the adoption of adaptive management strategies, protection and restoration of natural processes, pathways, and landscapes will improve the resiliency and regenerative capacity of the physical and biological systems to potential long-term natural and anthropogenic stressors such as altered flow regimes and lake-level changes resulting from increased water withdrawals, potential diversions, and/or effects of climate change. Incorporation of physical integrity into the Agreement will result in a "balanced" approach to Great Lakes protection and restoration by adding the consideration of sustainable natural processes, pathways, and landscapes as part of a comprehensive protection and restoration strategy for the Great Lakes.

SUMMARY

A new paradigm is emerging that is based on protecting, restoring, and enhancing natural processes, pathways, and the functional relationships that create and maintain the chemical, physical, and biological integrity in the Great Lakes Basin. At the core of this paradigm are two fundamental principles: 1) *sustainable processes build sustainable ecosystems*; and 2) *chemical, physical, and biological integrity are necessary to achieve ecological integrity*; and the fact that the interaction of master variables – climate, geology, and hydrology, and associated processes and pathways that convey energy, water, and materials through a system - establishes the framework that links and integrates all of the structural components of the ecosystem together into a whole.

A new operational definition of *physical integrity* is proposed – one that requires sustainable natural processes, pathways, and landscapes that maintain and improve the Great Lakes water quality and quantity, and support natural biodiversity and the ecosystem function. Within the context of physical integrity, sustainable natural processes are created when master variables interact to convey energy, water, and materials through a system in ways that correspond to undisturbed natural conditions, maintain system integrity, and promote system resiliency and regeneration - irrespective of the natural and anthropogenic perturbations. Physical integrity is achieved when the physical components of a system and the natural processes and pathways that structure, organize, define, and regulate them correspond to undisturbed natural conditions and are mutually supportive and sustainable.

Adoption of this operational definition and related concepts and principles will require us to explore the fundamental physical characteristics that structure, organize, and define the ecosystem; the natural processes and pathways that influence the distribution and abundance of energy and materials that flow across and through Great Lakes' landscapes; and to examine the abiotic and biotic linkages between chemical, physical, and biological integrity, ecosystem function, and ultimately - ecological integrity. Individual species, biological communities, and the ecosystem as a whole respond to changes in physical integrity as they have co-evolved and adapted to natural physical and hydrologic conditions in order to maximize benefits to themselves and the ecosystem.

"Restoring the Great Lakes" means protecting, restoring, and enhancing the chemical, physical, and biological integrity of the Great Lakes - and the natural processes, pathways, connections, and landscapes that maintain them. The importance of physical integrity to the protection and restoration efforts cannot be overemphasized. The overarching nature of physical integrity is such that it is possible to achieve physical integrity without achieving chemical or biological integrity, but it is much more difficult to achieve chemical or biological integrity without achieving physical integrity. This new process-based paradigm represents an integrated and balanced approach to restoration that links essential structural components of the ecosystem to the natural processes and pathways that maintain them, and builds on much of the work that has already been done in the Basin.

How do we incorporate this new paradigm and associated concepts of physical and ecological integrity into the Great Lakes Water Quality Agreement?

Incorporating the concept of physical integrity into the Agreement will force a long-overdue re-examination of our approach to Great Lakes restoration and will potentially reframe many of the questions that we have been asking about the Great Lakes. Consideration of physical integrity compels us to refocus our efforts towards protecting and restoring not only the structural components of interest (i.e. specific species, habitat, or landscapes), but also the natural processes and pathways that create and maintain them.

Moreover, in combination with the adoption of adaptive management strategies, protection and restoration of natural processes, pathways, and landscapes will improve the resiliency and regenerative capacity of the physical and biological systems to resist potential long-term natural and anthropogenic stressors such as altered flow regimes and lake-level changes resulting from continued growth and development, increased water withdrawals, potential diversions, and/or effects of climate change. Achieving ecological integrity requires a "balanced" approach to ecosystem protection and restoration – an approach that includes consideration of sustainable natural processes, pathways, and landscapes as part of a comprehensive protection and restoration strategy for the Great Lakes.

RECOMMENDATIONS

It is recommended that within the Agreement, we acknowledge the need for:

- Chemical, Physical, and Biological Integrity in order to achieve Ecological Integrity
- Physical and Ecological resiliency and sustainability
- Long-term planning and adaptive management

It is recommended that an overall *vision* of ecological integrity; definitions for chemical, physical, biological, and ecological integrity; and a set of *guiding principles* designed to protect, restore, and enhance the Basin's chemical, physical, and biological integrity be incorporated into the Agreement. In addition to guiding principles, a *binational strategy* needs to be implemented to develop new protection and restoration *standards* that are based on a balanced approach between assessing the status of fundamental structural components of the ecosystem and protecting and restoring the *functional processes* that maintain them - standards that are designed to protect, restore, and enhance the Great Lakes water quality and quantity, support natural biodiversity and ecosystem function, and achieve ecological integrity.

Specific Recommendations

1. Define and incorporate definitions of chemical, physical, biological, and ecological integrity into the Agreement.
2. Develop and incorporate a vision and set of guiding principles for the Great Lakes protection and restoration into the Agreement.
    a. Codify the principle that Chemical, Physical, and Biological integrity are essential to the attainment of Ecological Integrity.
    b. Codify the Master Variable concept and acknowledge the importance of both fundamental structural components and *functional processes* within the ecosystem.
    c. Codify the principle that sustainable waters and a sustainable ecosystem require sustainable natural processes, pathways, and landscapes – *sustainable processes build sustainable ecosystems*.

3. Develop and incorporate strategies to develop and implement new process-based standards for protection and restoration of chemical, physical, biological, and ecological integrity of the Great Lakes based on guiding principles.
4. Develop and incorporate strategies to develop and implement new process-based measurement, assessment, and monitoring protocols and tools.
5. Develop and incorporate strategies to implement a conceptual framework to identify opportunities for the ecosystem restoration and sustainability under the Agreement.
6. Develop and incorporate strategies to implement restoration strategies that utilize the power of natural processes to create, maintain, and restore the chemical, physical, biological, and ecological integrity of the Great Lakes.
7. Develop and incorporate strategies to implement adaptive management policies in anticipation of long-term potential natural and anthropogenic stressors and impairments.

Achieving ecological integrity requires a "balanced" approach to ecosystem protection and restoration – an approach that includes the consideration of sustainable natural processes, pathways, and landscapes as part of a comprehensive protection and restoration strategy for the Great Lakes.

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Attachment M2

DOI: 10.1007/s00267-004-0141-7

Habitat Assessment of Non-Wadeable Rivers in Michigan

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ABSTRACT / Habitat evaluation of wadeable streams based on accepted protocols provides a rapid and widely used adjunct to biological assessment. However, little effort has been devoted to habitat evaluation in non-wadeable rivers, where it is likely that protocols will differ and field logistics will be more challenging. We developed and tested a non-wadeable habitat index (NWHI) for rivers of Michigan, where non-wadeable rivers were defined as those of order ≥5, drainage area ≥1600 km^2, mainstem lengths ≥100 km, and mean annual discharge ≥15 m^3/s. This identified 22 candidate rivers that ranged in length from 103 to 825 km and in drainage area from 1620 to 16,860 km^2. We measured 171 individual habitat variables over 2-km reaches at 35 locations on 14 rivers during 2000–2002, where mean wetted width was found to range from 32 to 185 m and mean thalweg depth from 0.8 to 8.3 m. We used correlation and principal components analysis to reduce the number of variables, and examined the spatial pattern of retained variables to exclude any that appeared to reflect spatial location rather than reach condition, resulting in 12 variables to be considered in the habitat index. The proposed NWHI included seven variables: riparian width, large woody debris, aquatic vegetation, bottom deposition, bank stability, thalweg substrate, and off-channel habitat. These variables were included because of their statistical association with independently derived measures of human disturbance in the riparian zone and the catchment, and because they are considered important in other habitat protocols or to the ecology of large rivers. Five variables were excluded because they were primarily related to river size rather than anthropogenic disturbance. This index correlated strongly with indices of disturbance based on the riparian (adjusted R^2 = 0.62) and the catchment (adjusted R^2 = 0.50), and distinguished the 35 river reaches into the categories of poor (2), fair (19), good (13), and excellent (1). Habitat variables retained in the NWHI differ from several used in wadeable streams, and place greater emphasis on known characteristic features of larger rivers.

Large rivers include some of the most pristine lotic systems in the world, as well as some of the most altered. Although some large tropical and boreal rivers have remained largely intact, the large rivers of developed regions have paid a heavy toll for their utility to humankind (Hynes 1989, Arthington and Welcomme 1995). Large rivers are susceptible to cumulative impacts from all upstream land-use activities, in addition to direct impacts from dams, channelization, overharvest, invasive species, and chemical and organic pollution. Although the latter three factors can affect the biota without damage to physical habitat, many human activities associated with agricultural and urban development and that change existing land-use patterns have been linked to instream habitat degradation (Richards and others 1996, Roth and others 1996, Wang and others 1997).

KEY WORDS: Riparian; Watershed; Habitat quality; Stream health

Published online August 17, 2005.

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Habitat assessment has become an important part of the evaluation of ecological integrity (Muhar and Jungwirth 1998) and is incorporated into many stream evaluation protocols (e.g., Wright 1995, Barbour and others 1999). These protocols help to detect human influences and assess the potential of aquatic habitats to support life and maintain ecological integrity (Karr and Dudley 1981, Muhar and Jungwirth 1998). In essence, poor physical habitat conditions lead to expectations

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for degraded biological quality, whereas good habitat conditions should be reflected in high biodiversity, barring other degradation (Plafkin and others 1989).

Existing methods and protocols for assessing physical habitat quality are numerous (for reviews and generalizations of existing protocols see Barbour and others 1999, Fajen and Wehnes 1981, Rankin 1995, Simonson and others 1994, MDNR 1991). However, these efforts have been directed almost exclusively at wadeable streams, and primarily at streams of medium to high gradient (Wang and others 1998). Thus, they prioritize habitats that are uncommon in low gradient streams (Wang and others 1998) and consist of metrics that are either ineffective in non-wadeable environments or infeasible to apply (Edsall and others 1997).

In general, large river ecology has been under-studied because of sampling difficulties related to river size, power, and complexity (Johnson and others 1995). However, the applicability of fundamental stream theories such as the River Continuum Concept (Vannote and others 1980) and the flood-pulse concept (Junk and others 1989) to large rivers has received attention (Minshall and others 1983, Sedell and others 1989, Bayley 1995), and the relative importance of various sources of allochthonous and autochthonous carbon is becoming better understood (Thorp and Delong 1994). Habitats that are unique to large rivers or are of increased importance, such as backwaters (Sheaffer and Nickum 1986, Scott and Nielsen 1989), islands (Thorp 1992), woody snags (Lehtinen and others 1997), and floodplains are increasingly being studied (Petts 1996, Benke 2001). Thus, our understanding of large rivers as ecosystems is advancing steadily.

The development of appropriate indicators to assess the status of, and threats to, large river ecosystems is an important priority (Schiemer 2000). Several indices of biotic integrity have been developed in the past decade for large river fishes (e.g., Simon and Emery 1995, Simon and Sanders 1999, Lyons and others 2001). However, habitat evaluation usually is limited or absent from studies of non-wadeable reaches (e.g., Goldstein and others 2000).

Recent attempts to develop methods for field sampling of large rivers have taken several approaches. Edsall and others (1997) introduced remote sensing techniques to survey the physical habitat of large rivers to be used in conjunction with other National Water-Quality and Assessment (NAWQA) methods, and Gergel and others (2002) proposed relying on landscape indicators for larger systems. Recently, the U.S. Environmental Protection Agency (EPA) (e.g., Flotemersch and others 2000) and the Environmental Monitoring and Assessment Program (e.g., Lazorchak and others 2000) have begun to address issues related to large river sampling logistics and methodologies. Kaufmann (2000) describes a physical habitat assessment protocol for large rivers developed in the western United States. However, these methods have not been sufficiently tested for their applicability in different regions.

Our primary objective was to develop a habitat assessment protocol based on variables that best described physical habitat variability of non-wadeable rivers throughout the State of Michigan, discriminating anthropogenic disturbance from natural variation. Because the quantification of physical habitat potentially must consider a large number of disparate variables, we sought to develop a systematic approach to variable selection in which we first reduced the number of redundant measures, then determined the habitat variables that best described habitat variation among study reaches, and finally selected and weighted metrics for inclusion based on their responsiveness to independently measured gradients of disturbance in the surrounding landscape. However, we also found it necessary to include variables based on their perceived importance to large river ecosystems. This non-wadeable habitat index (NWHI) provides a concise evaluation of the large rivers of Michigan that accords well with independent assessments of disturbance in the landscape surrounding a reach and, used in conjunction with biological protocols (Wessell 2004), shows promise for monitoring and assessment of non-wadeable rivers.

Methods

Defining Non-Wadeable Rivers

A non-wadeable or large river can be defined as a reach where the investigator cannot wade along its length (Meador and others 1993) or from bank to bank (Edsall and others 1997). However, the progression from small to large river is continuous, and even the demarcation between wadeable and non-wadeable is an indistinct boundary, because the status of a single location can change between wet and dry months or years. It is desirable to establish guidelines that can be applied prior to visiting a site and used to define the sampling universe of large rivers for a region. Large rivers have been defined as those that exceed a drainage area of 1600 km^2 (Ohio EPA 1989); an average depth of 1 m (Stalnaker and others 1989); a width of 50 m (Simonson and others 1994); or a river order of six or greater (Vannote and others 1980, Sheehan and Rasmussen 1999). In contrast, Reash (1999) set a much higher threshold by defining a large river as one with a drainage area greater than 20,000 km^2.

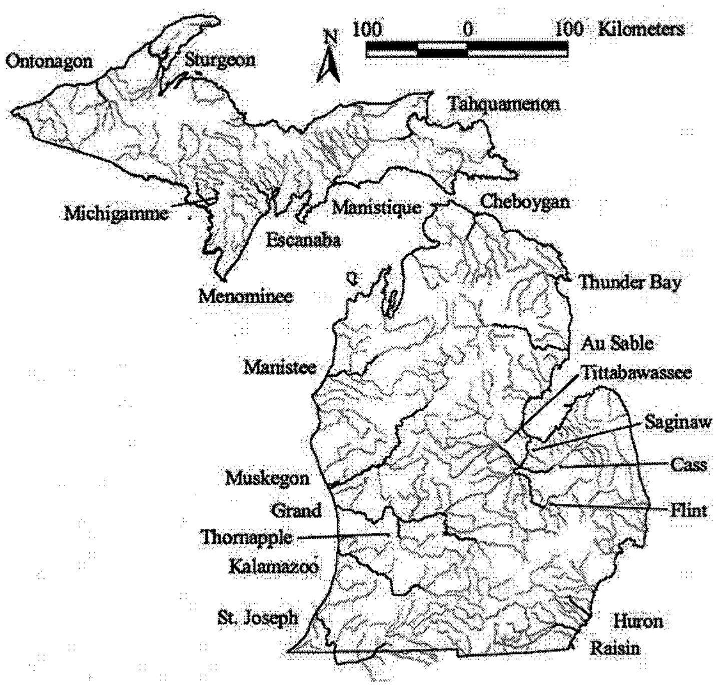

Figure 1. Location of rivers that met criteria for non-wadeable designation (see Table 1). Non-wadeable river segments are bolded.

Most approximations of river size are highly correlated with one another (Leopold and others 1964); however, each measure varies in ease of measurement and accessibility of data. Identification of the non-wadeable rivers of a region requires the selection of one or more criteria, and also of a boundary that, on average, defines a river reach that is non-wadeable during the low flows when most sampling occurs. River systems tend to be small in Michigan because of the short distances from headwaters to river mouths at the Great Lakes (Brown 1944). We define the non-wadeable rivers of Michigan as those that equal or exceed a river order of five, drainage area of 1600 km^2, mainstem length of 100 km, and mean annual discharge of 15 m^3/s. We omitted the Detroit and St. Clair Rivers from consideration because they are part of the chain of Great Lakes and experience significant ship traffic, and the Portage River and Canal because it is a ship canal traversing Michigan's Keewenaw Peninsula. Using these initial criteria, we conservatively identified 22 rivers throughout Michigan that had non-wadeable reaches (Figure 1, Table 1). A few additional rivers might have been included had more complete data been available.

Study Systems

We sampled reaches on 14 Michigan rivers within 11 major watersheds (we sampled three tributaries of the Saginaw as well as its mainstem, accounting for the number discrepancy), ranging in size from the Saginaw River (mainstem 825 km in length, drainage area 16,856 km^2) to the Tahquamenon (mainstem length 151 km, drainage area 2124 km^2) and Huron Rivers (mainstem length 116 km, drainage area 2388 km^2). Six watersheds were in the Southern Lower Peninsula (SLP), three in the Northern Lower Peninsula (NLP), and two in the Upper Peninsula (UP) (Table 1), thereby encompassing considerable range in climate, vegetation, geology, and anthropogenic disturbances (Albert 1995). According to the classification of Omernik (1976), the UP falls within the Northern Lakes and Forest Ecoregion. The NLP includes the Northern Lakes and Forest, North Central Hardwood Forests, and the northern limit of the Southern Michigan/Northern Indian Clay Plains. The SLP consists mainly of the Southern Michigan/Northern Indian Clay Plains and the Huron/Erie Lake Plain, with a small section of the Eastern Corn Belt Plains. Strong natural gradients in temperature (Wehrly and others 1998), surface vs. groundwater runoff (Wiley and Seelbach 1997), and biological communities (Zorn and others 2002) have been documented for Michigan's rivers.

Current and historic land use also vary markedly across the landscape of Michigan, with a noticeable gradient of increasing anthropogenic influence from north to south as reflected in the 11 major watersheds (Table 2). Natural areas dominate the UP, with nearly

Table 1. River size can be assessed using several measures including basin area, river length, discharge, and order

River	Drainage area (km^2)	Length (km)	MAD (m^3/s)	Order	Region	Study reaches
Saginaw	**16,856**	**825**	**190**	**7**	SLP	2
Grand	**14,359**	**769**	**107**	**6**	SLP	7
Menominee	**10,537**	**774**	**89**	—	UP	2
St. Joseph	**8112**	**492**	**103**	—	SLP	2
Tittabawassee	**6853**	**343**	**49**	**6**	SLP	1
Muskegon	**6762**	**335**	**58**	**5**	NLP	4
Au Sable	**5506**	**267**	**42**	**6**	NLP	2
Manistee	**5304**	**359**	**58**	**5**	NLP	4
Kalamazoo	**5084**	**257**	**42**	**5**	SLP	4
Manistique	**4250**	**314**	**40**	—	UP	0
Cheboygan	**3919**	**196**	**23**	**6**	NLP	0
Flint	**3737**	**161**	**21**	**5**	SLP	0
Ontonagon	**3434**	**248**	**39**	—	UP	0
Thunder Bay	**3297**	**201**	**26**	**6**	NLP	0
Raisin	**3090**	**190**	**21**	**5**	SLP	2
Cass	**2637**	**106**	**15**	**5**	SLP	1
Shiawassee	**2577**	**151**	13	**6**	SLP	1
Maple	**2461**	80	8	**5**	SLP	0
Escanaba	**2391**	**183**	**23**	—	UP	0
Huron	**2388**	**116**	**18**	**5**	SLP	1
Tahquamenon	**2124**	**151**	**26**	—	UP	2
Sturgeon (Houghton Co.)	**2093**	**174**	**23**	—	UP	0
Pere Marquette	**2051**	**191**	**20**	<5	NLP	0
Clinton	**2046**	**106**	**16**	<5	SLP	0
Thornapple	**1961**	**103**	**19**	**5**	SLP	0
Black	**1686**	**100**	9	**5**	SLP	0
Michigamme	**1621**	**154**	**20**	—	UP	0
Ford	1225	**179**	11	—	UP	0
Paint–Brule	1191	92	**17**	—	UP	0
Rifle	1134	80	9	<5	NLP	0
Sturgeon (Dickinson Co.)	1041	**137**	5	—	UP	0
Big Cedar	1036	97	—	—	UP	0
Presque Isle	808	**122**	8	—	UP	0

Bolded values meet a minimum size requirement: basin area ≥1600 km^2; length ≥ 100 km; mean annual discharge (MAD) ≥15 m^3/s; order ≥5. Italicized rivers satisfy all definitions of 'large'. A dash refers to missing data. River length and drainage area are from Brown (1944); MAD is calculated from USGS gauge data; order is from Folsom and Winters (1970). SLP, Southern Lower Peninsula, NLP, Northern Lower Peninsula, UP, Upper Peninsula.

90% of the land forested or covered by wetlands (Albert 1995). Despite extensive logging in the late 19th century, most of the NLP today (76%) is forested with a mix of coniferous and deciduous trees, with less than 4% of the land urbanized and less than 11% agricultural. The SLP is the most heavily influenced by human activity, with less than 25% remaining as natural land, more than 8% urban, and nearly 57% agriculture.

Differing geology throughout Michigan (Farrand and Bell 1982) influences the contribution of surface runoff or groundwater to rivers (Richards 1990). The porous sand and gravel substrates of the sampled NLP watersheds (61% outwash and ice contact, Table 3) result in high rates of groundwater input to stream channels. In contrast, the clays and silts of the lake plain region near Michigan's thumb area produce high rates of surface runoff. The Western UP is underlain by resistant bedrock, also resulting in high surface runoff.

Reach Selection

We selected reaches that fell within river sections that satisfied the non-wadeable criteria (Table 1), provided access via a boat launch, and were not influenced by a nearby dam. We included all geographic regions of the state and attempted to identify reaches encompassing a range of human disturbance within each river sampled to ensure that the finished protocol could detect differences attributed to degradation rather than to individual river characteristics or location within the state. Because of the limited number of non-wadeable rivers and the scarcity of river reaches meet-

Table 2. Land use within 11 study watersheds grouped by region within Michigan

	SLP (n = 6)	NLP (n = 3)	UP (n = 2)
Urban	8.2	3.7	1.3
	3.6–21.0	2.2–4.1	0.7–1.9
Agriculture	56.9	10.7	3.2
	27.0–72.7	3.7–23.0	0.8–5.6
Rangeland	10.2	9.8	3.9
	2.6–20.4	7.6–10.0	3.8–4.0
Forest	12.2	65.0	54.2
	5.5–31.0	43.0–70.5	45.1–63.2
Wetland	12.7	12.4	35.4
	8.2–22.7	10.9–16.2	22.5–48.4

Values are median and range of percent area. Data are from 1978 MIRIS land use/cover from the Michigan Rivers Inventory database (Seelbach and Wiley 1997). SLP, Southern Lower Peninsula, NLP, Northern Lower Peninsula, UP, Upper Peninsula.

Table 3. Surficial geology within 11 study watersheds grouped by region within Michigan

	SLP (n = 6)	NLP (n = 3)	UP (n = 2)
Moraines	47.4	32.8	43.9
	33.0–69.8	18.3–44.4	26.8–61.0
Outwash and ice contact	19.2	60.8	12.5
	11.1–64.1	46.2–72.1	7.5–17.5
Glacial lake deposits	29.3	5.6	13.4
	1.9–39.6	4.7–9.0	2.1–24.8
Organic deposits	0.0	0.0	20.6
	0–1.6	0–1.6	1.6–39.6
Lakes	0.4	0.4	0.5
	0–1.3	0.4–2.2	0.4–0.6
Other	0.8	0.4	9.0
	0–4.7	0.2–0.9	0.9–17.1

Values are median and range of percent area. Surficial geology data were acquired from the MRI database (Seelbach and Wiley 1997, also Farrand and Bell 1982). SLP, Southern Lower Peninsula, NLP, Northern Lower Peninsula, UP, Upper Peninsula.

ing these criteria, particularly in the southern LP, our sampling includes representative reaches on more than half of the rivers. Thirty-five reaches were visited during summer low flow conditions in 2000, 2001, and 2002, with nine reaches visited multiple times and one that was sampled all 3 years. Thus, our data included 45 sampled reaches but only 35 unique reaches. The repeat visits were primarily used to determine consistency of metrics in year-to-year comparisons (Wilhelm 2002).

A reach length of 2 km was chosen as a compromise among suggestions found in the literature. Lazorchak and others (2000) recommend a reach length equal to 100 times the wetted width. Because we recorded an average width of 86 m for the 35 reaches sampled, this criterion would specify a reach length of nearly 9 km, which would require excessive effort. More importantly, it is rarely possible to find reaches of this length that are relatively homogeneous and not disrupted by hydrologic control structures. NAWQA recommends a minimum reach length of 500 m and a maximum of 1000 m for non-wadeable sections (Meador and others 1993), which may be insufficient to assess habitat diversity. A reach of 2 km was logistically feasible to sample in 1 day and, based on preliminary surveys, appeared to capture much of the natural variation in habitat variables within the reach.

Habitat Measurements

Each 2-km reach included 11 transects at 200-m intervals. Distance between transects was measured using a laser rangefinder. Along both banks at each transect, we established a littoral plot within the river that was 20 m long × 10 m laterally, and an adjacent riparian plot that also was 20 × 10 m. A total of 171 habitat variables were measured, estimated, or calculated (Wilhelm 2002), and subsequently grouped within four major categories: a) geomorphology and hydrology, b) substrate, c) instream cover, and d) bank and riparian condition (Table 4). Methods were adapted from non-wadeable river pilot studies in Oregon and the Mid-Atlantic Region (Kaufmann 2000), and from other habitat protocols primarily designed for streams and wadeable rivers (e.g., Simonson and others 1994, Fitzpatrick and others 1998, Barbour and others 1999, Kaufmann and others 1999). We calculated a sum, mean, frequency, or coefficient of variation value for each habitat variable for each reach.

At each transect, wetted width and bankfull channel dimensions were measured using a laser rangefinder accurate to 1 m. Within 20×10 m riparian plots, extent of riparian vegetation was estimated on both banks for canopy and understory layers, including percent cover of trees with diameter at breast height > 0.3 m, small trees, woody shrubs, and grasses. In addition, riparian width was measured using a laser range finder and converted to a proportion of 25 m, the maximum distance that reliable estimates could be made into dense forest. On each bank we measured, noted, or estimated the angle, dominant vegetation, erosion extent, undercut distance if present, and bankfull height.

Human influence included any built surface, riprap, pipes, trash, lawns, and agriculture and was considered within a 20 m band centered on each transect. Influence was scored based on whether it occurred on the bank, within 10 m, or beyond 10 m. We summed the individual scores for a total visual disturbance metric.

Instream cover for fish was recorded for macrophytes, large woody debris (LWD), overhanging vegetation, boulders, filamentous algae, artificial structures, and undercut banks by estimating percent cover within 20×10 m littoral plots. For data analysis, we grouped macrophytes and filamentous algae together into a category called aquatic vegetation and everything but artificial structures into a category called natural fish cover.

Velocity, depth, and substrate were measured from an anchored boat at a minimum of 7 points across each transect. Velocity was measured at 0.6 m depth and to a maximum depth of approximately 1.3 m from the surface, limited by the length of the flow staff. Because of boat movement, equipment limitations, and water depth, the calculated discharge measures are approximate. Substrate was classified at each anchored point by "feel" with a sounding pole (Kaufmann 2000) as bedrock, boulder, cobble, coarse gravel, fine gravel, sand or fines. The reliability of this method was confirmed by applying it to shallow areas where substrate could be directly observed, and by using a fiber-optic viewer in deeper water. We grouped gravel and larger into coarse substrate and sands and smaller into fine substrate. Secchi depth was measured at mid-channel and expressed as a proportion of 1.5 m depth, which was the maximum depth of several of the smaller rivers included.

In addition to transect measurements, longitudinal sampling of depth and substrate using a sounding pole was conducted at 40 m intervals along the thalweg of the entire reach. Off-channel habitat, LWD, and drain pipes entering the channel were tallied. LWD was tallied in several size and length categories, but the final analysis used only number of pieces more than 0.1 m in diameter and 3 m in length.

Two composite indices based on visual habitat assessment of wadeable streams, the Michigan Department of Environmental Quality Procedure 51 (MDEQ) (MDNR 1991) and the EPA's rapid bioassessment protocol for low-gradient streams (Barbour and others 1999), also were evaluated for each reach. The MDEQ protocol includes nine metrics: substrate, embeddedness, velocity-to-depth variation, flow stability, bottom deposition, the variety of pools-riffles-runs, bank stability, bank vegetation, and streamside cover. The EPA protocol is similar. Slope and sinuosity were determined from USGS 1:24,000 topographic maps.

Catchment and Riparian Condition

To identify habitat variables that responded strongly to human disturbance, we evaluated a total of 66 landscape-scale variables in order to assess the extent of human disturbance associated with study reaches independently of the habitat assessment. We obtained 1978 land use/cover data, including roads, from MDNR, and dam and National Pollution Discharge Elimination System (NPDES) permit data from the Surface Water Quality Division of MDEQ. From this information we derived two indices, a Catchment Disturbance Gradient (CDG) and a Riparian Disturbance Gradient (RDG).

The CDG incorporated seven variables, including agricultural land use within the buffer and the upstream catchment; urban land use within the buffer and upstream catchment; and the density of dams, NPDES permits, and roads for the upstream catchment for each reach.

We first examined the proportional land use in urban, agricultural, and forested categories for the area less than 100 m from the river, 100 to 500 m, and greater than 500 m; for the 2-km reach length, a 10-km segment, and the entire upstream corridor of all tributaries. In addition, we determined land use for the catchment upstream of the study reach, excluding the 500-m buffer (Wilhelm 2002). We retained measures at the smallest buffer scale (100-m buffers for a 10-km river segment) and largest scale (entire upstream catchment) because these were weakly correlated (agriculture) or uncorrelated (urban). Within a single scale of measurement, urban, agricultural, and forested land were generally highly correlated, and we retained urban and agricultural measures because they are different anthropogenic disturbances. NPDES permit density and road density both were highly correlated with each other and with catchment urban land. Dam density was uncorrelated with any of the above measures. Although some redundancy remains in the CDG, we elected to retain all variables because they represent different types of anthropogenic disturbance and have the potential to capture important differences in human impact on individual river reaches. Each metric was rated on a five-point scale from 0 to 4 following Ladson and others (1999), by identifying natural breaks using Jenks' optimization (Jenks and Caspall 1971), and metrics were summed to give a total score for the CDG. A low score indicates low disturbance, whereas a high score is indicative of a highly modified reach.

The RDG incorporated only two measures obtained from aerial photographs: riparian width and number of gaps in the riparian for a 2-km river reach. Georectified Digital Orthophoto Quadrangles from 1992 (black and white) and 1998 (color) were imported into ArcView GIS(ESRI), and a centerline was digitized along each reach. Using the Route Hatch ArcView extension, nodes were systematically inserted at 100-m intervals (21 total), and distance to the boundary of forest or wetland vegetation was determined. Gaps including road crossings and any break in the riparian vegetation adjacent to the stream channel were counted and measured, as well as the number of side channels, tributaries, bridges, and islands.

Statistical Analyses

We reduced the initial 171 habitat measures to a more manageable number of variables using correlation analysis (Spearman's rho) to identify redundant variables within each of the four categories (geomorphology and hydrology, substrate, instream cover, and bank and riparian condition). Highly correlated measures ($r > 0.55$ or $r < -0.55$, $P < 0.05$ in all cases, the exact cutoff for each grouping differed) were considered similar or redundant and only one variable was retained. We discarded variables with highly skewed distributions (Goldstein and others 2002) and retained those that were simplest to measure and most consistent in year-to-year comparisons.

Remaining variables were tested for normality using a Shapiro-Wilk test and transformed as needed. We used principal components analysis (PCA) on each habitat grouping to further reduce the number of variables and to identify those that best described the main axes of habitat variation across reaches. We retained axes with eigenvalues >1 and selected one variable from each axis for subsequent analysis, typically the variable with the highest absolute loading unless other variables with similar loadings were easier to measure, were known to have higher accuracy or precision, or appeared conceptually preferable versus other selected variables.

To aid in the selection and weighting of variables for inclusion in the NWHI, we used multiple linear regression (MLR) analysis and inspected scatterplots relating the CDG and RDG to habitat variables that were retained subsequent to the PCA. Reaches were split into two groups designated as 'model' (18 reaches) and 'test' (17 reaches). Care was taken that variation in geographic location and reach condition was represented in each group. We then used MLR to determine which habitat variables from the model data responded to these two disturbance measures, and evaluated regression models with the remaining 'test' dataset by comparing the observed vs. estimated disturbance scores. The final NWHI included variables identified by this approach and also variables that were included based on their perceived importance to large river ecosystems. We applied Jenks' optimization (Jenks and Caspall 1971) to cumulative frequency diagrams of each variable to define scoring cutoffs for the final NWHI.

Results

Size Criteria for Non-Wadeable Rivers

Of the 35 reaches presumed to be non-wadeable, based on the criteria of Table 1, the majority met size criteria proposed in the literature (Stalnaker and others 1989, Simonson and others 1994, Ohio EPA 1989). For all reaches, average depth ranged from 0.6 to 5.6 m, mean thalweg depth from 0.8 to 8.3 m, wetted width from 32 to 183 m, and drainage area from 532 to 15,583 km^2.

Identification of Key Habitat Variables

Elimination of variables on the basis of skewed distributions and redundancy as determined by correlation analysis reduced the habitat data set from 171 to 31 variables (Table 4). Geomorphology and hydrology variables were reduced from 38 to 13, substrate measures from 55 to 4, instream cover variables from 29 to 6, and bank and riparian condition metrics from 49 to 8. For details of the correlation analysis see Wilhelm (2002).

Table 4. Summary statistics for 31 habitat variables retained of 171 initial habitat variables

Variable	Transformation	Median	Minimum	Maximum	n
Geomorphology and hydrology					
Discharge (m^3/s)	sqrt (x)	28.8	2.0	83.3	35
Velocity (m/s)	None	0.29	0.02	0.56	35
Location maximum velocity	None	0.16	0.06	0.34	35
Drainage area (km^2)	ln (x)	5048	532	15,583	35
Thalweg depth (m)	ln (x)	2.0	0.8	8.3	35
Standard deviation thalweg depth (m)	ln (x)	0.53	0.18	3.92	35
Maximum depth (m)	ln (x)	2.4	1.0	8.1	35
Location maximum depth	None	0.21	0.07	0.35	35
Wetted width (m)	ln (x)	76	32	183	35
Wetted width to depth ratio	ln (x)	56	16	147	35
Bankfull height (m)	ln (x)	0.6	0.1	2.3	35
Sinuosity	1/(x)	1.22	1.01	2.97	35
Slope (m/m)	ln (x)	3.6E-04	7.2E-05	1.3E-03	35
Substrate					
Coarse thalweg substrate (%)	None	35	0	100	33[a]
Fine substrate in shallows (%)	None	83	13	100	34[a]
Coarse substrate in shallows (%)	asin(sqrt (x))	13	0	78	34[a]
Bottom deposition (MDEQ-5)	None	11	2	15	35
Instream cover					
LWD quantity (no. of pieces)	None	72	3	306	35
LWD volume (m^3/piece)	None	0.25	0.03	0.65	35
Quantity of off-channel habitat (no.)	ln (x+1)	2	0	10	35
Secchi depth (% of 1.5 m)	ln (x+1)	25	3	65	35
Aquatic vegetation (% cover)	ln (x+1)	10	0	59	35
Natural fish cover (% cover)	None	41	0	122	35
Bank and riparian condition					
Riparian width (m)	asin(sqrt (x))	19	4	>25	35
Woody shrubs (% cover)	None	21	7	58	35
Bank angle (degrees)	None	51	16	78	35
Undercut distance (m)	None	0.4	0.0	0.9	33[b]
Riparian cover (% cover)	None	125	48	185	35
Human disturbance (score)	ln (x+1)	3.9	0.0	11.7	35
Bank stability (MDEQ-7)	None	8.4	6.8	10.0	35
Bank vegetative stability (MDEQ-8)	asin(sqrt (x))	8.1	2.8	10.0	35

[a]No data taken from dredged river channels.
[b]Data missing for two reaches.
Median, minimum, and maximum values are for untransformed values across all reaches. The transformation used in subsequent analyses is shown.
MDEQ, Michigan Department of Environmental Quality procedure 51; LWD, large woody debris.

PCA applied to each habitat subgrouping identified 12 core habitat variables that best explained habitat variability among the 35 study reaches (Table 5). The first four axes from the PCA of the geomorphology and hydrology group explained 75% of the variation among reaches. Thalweg depth, wetted width-to-depth ratio, discharge, and slope were selected for further analysis based on high variable loadings on axes one, two, three, and four respectively, as well as their ease of measurement and interpretation. Axis five did not have any highly loaded variables and explained less than 9% of the remaining variation; therefore, no variable was retained despite an eigenvalue of 1.12.

For substrate, the first two axes of the PCA explained 79% of the variation among reaches (Table 5). Visually assessed bottom deposition (MDEQ metric 5) was selected over percent fine substrate on the first axis, and coarse thalweg substrate was retained over coarse shallow substrate on axis two, despite slightly lower loadings, because of their ease of measurement.

The first three axes of the instream cover PCA explained more than 73% of the variation among reaches (Table 5). Aquatic vegetation, quantity of LWD, and off-channel habitat were selected due to their high loadings on the first three axes.

The first three axes of the bank and riparian condition PCA explained more than 77% of the variation among reaches (Table 5). Three measures were heavily loaded on axis one, including the composite visual disturbance metric, riparian width, and bank vegetative

Table 5. Twelve variables were retained from principal components (PC) analysis of the model data for each habitat variable grouping

Variable grouping	PC1	PC2	PC3	PC4	Cumulative variance explained (%)
Geomorphology and hydrology					
Variable selected	Thalweg depth	Wetted width-to-depth ratio	Discharge	Slope	
Variance explained by axis	28.6	21.8	15.3	9.3	74.9
Substrate					
Variable selected	Bottom deposition	Coarse thalweg substrate			
Variance explained by axis	46.8	32.6			79.4
Instream cover					
Variable selected	Aquatic vegetation	Quantity LWD	Off-channel habitat		
Variance explained by axis	29.5	25.7	17.4		72.6
Bank and riparian condition					
Variable selected	Riparian width	Bank stability	Bank angle		
Variance explained by axis	34.2	26.8	16.3		77.4

One high-loading variable was selected to represent each component based on an eigenvalue >1.
LWD, large woody debris.

stability (MDEQ metric 8). Riparian width was selected since it is easily obtained on-site compared to the calculations required to obtain the visual human impact metric, and is more quantitative than the MDEQ metric. In addition, riparian width yields a measurement that is easily understood, whereas the visual disturbance value is only useful relative to other reaches. Visually assessed bank stability (MDEQ metric 7) was selected for its high loading on axis two over other measures of riparian composition that seemed conceptually redundant with riparian width. Bank angle had high loadings on axis three and was therefore selected.

Habitat variables could have high PCA loadings because they distinguish reaches based on location (e.g., within a region or a particular river) rather than on habitat quality and human disturbance. Because inspection of scatterplots of PCA 1 vs. PCA 2 for each of the four habitat groups revealed minimal spatial pattern for the identified variables (Figure 2), the habitat variation within our data set appears to reflect site quality rather than spatial location. Although instream cover exhibited some tendency towards spatial separation between NLP and SLP reaches, reaches within rivers did not cluster, and the latitudinal gradient was judged to be influenced more by human disturbance than by a natural gradient. Thus, all 12 variables were retained for evaluation against the disturbance gradients.

Anthropogenic Disturbance Gradients

The extent of anthropogenic disturbance associated with reaches differed markedly based on the two indices, with the CDG ranging from 0 to 14 out of a possible 28 points and the RDG ranging from 0 to 8 out of a possible 8 points. The CDG and RDG were significantly correlated (r = 0.66, $P < 0.001$), despite being derived at different spatial scales and from different data sources.

The CDG ($F_{2,32} = 46.8$, $P < 0.0001$) and the RDG ($F_{2,32} = 5.77$, $P = 0.007$) both differed significantly by location (Figure 3). Using Tukey's method for paired comparisons, significant differences were found in the CDG between the SLP and the NLP ($P < 0.0001$) and the SLP and UP ($P < 0.0001$), and in the RDG between the SLP and the UP ($P = 0.0007$). UP reaches were scored as markedly less disturbed by both indices, and differences between the NLP and SLP were more pronounced using the CDG vs. the RDG. In addition, 3 of the 11 rivers had study reaches that encompassed the full range of RDG scores, which was not the case with the CDG. For these reasons, it appears that the RDG may be a more appropriate indicator of anthropogenic disturbance to rivers than the CDG, because it is less strongly location dependent.

Selection of NWHI Variables

To evaluate the responsiveness of habitat variables to anthropogenic disturbance, we examined the strength of statistical associations of the 12 remaining habitat variables with the independently derived CDG and RDG for the 18 model reaches using MLR (Table 6). For the CDG, stepwise backward regression resulted in a significant model ($P < 0.001$) with an adjusted R^2 of 0.78. Retained variables included

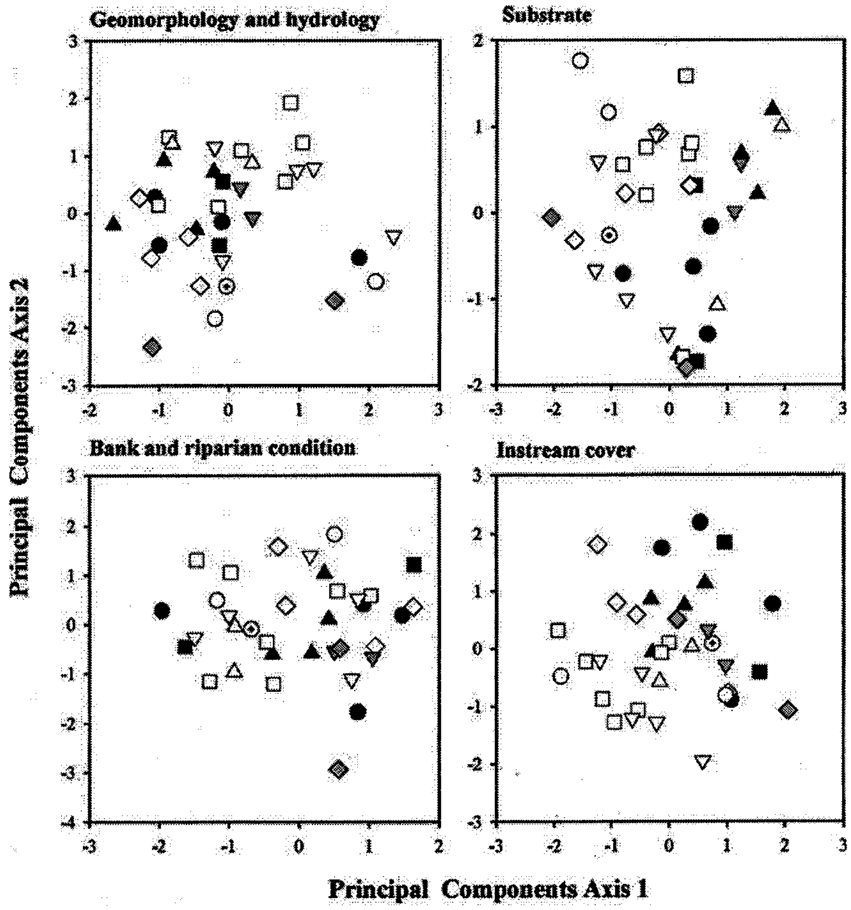

Figure 2. Spatial relationships among river reaches for each of the four groups of habitat variables. SLP, open symbols; NLP, closed symbols; UP, gray-tone symbols. Au Sable (■), Manistee (●), Muskegon (▲), Grand (□), Huron (⊙), Kalamazoo (◇), Raisin (○), Saginaw (▽), St. Joseph (△), Menominee (▼), Tahquamenon (◈). Some spatial dependency is evident for instream cover variables. Reaches within rivers show little tendency to cluster, suggesting that habitat metrics reflect reach quality rather than river or region.

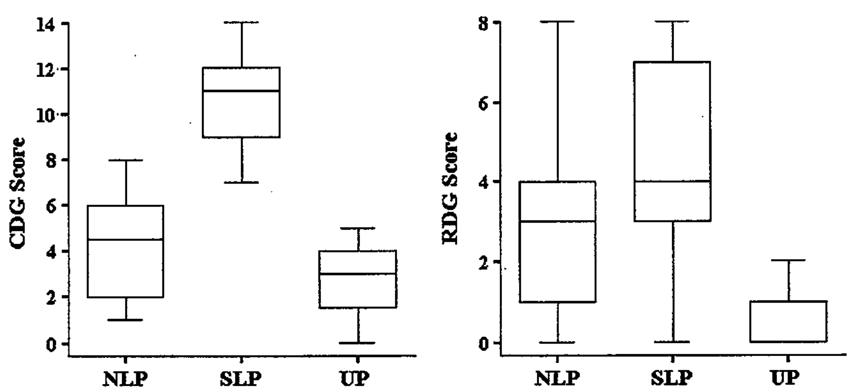

Figure 3. Catchment (left) and riparian (right) disturbance gradients depicted for three regions of Michigan to investigate north–south anthropogenic gradient. SLP, southern Lower Peninsula; NLP, northern Lower Peninsula; UP, Upper Peninsula. Median, quartiles, maximum and minimum values are displayed.

quantity of LWD, aquatic vegetation, and riparian width. However, the model's predictive power was found to be modest when used to estimate the CDG from habitat data at test sites, resulting in an adjusted R^2 of 0.34 between predicted and observed CDG. This model consistently overpredicted the disturbance gradient, especially at the least disturbed reaches. The estimated disturbance scores ranged from 5.6 to 12.4 compared to the observed disturbance scores from 0 to 13.

For the RDG, backward stepwise regression retained only one variable, riparian width, with an adjusted R^2 of 0.75 (Table 6). Using this model with the test data resulted in a relatively good fit of observed versus pre-

Table 6. Backward stepwise multiple linear regression using the model data identified habitat variables that were the best predictors of the disturbance gradients

Dependent variable	Adj. R^2	*P*-value	X_1	X_2	X_3	O/E Adj. R^2	O/E *P*-value
CDG	0.78	<0.001	Quantity LWD	Aquatic Vegetation	Riparian Width	0.34	<0.008
RDG	0.75	<0.001	Riparian Width			0.73	<0.001

Expected values (E) for both disturbance gradients were estimated using habitat information from test reaches, and compared to observed values (O) of the two disturbance gradients. Three habitat variables selected by stepwise models appear to be the strongest indicators of human disturbance.

CDG, catchment disturbance gradient; RDG, riparian disturbance gradient; LWD, large woody debris.

dicted RDG values, explaining 73% of the variation. This model also tended to consistently overpredict disturbance for the most natural reaches, although not as markedly as the CDG model. The estimated disturbance scores ranged from 1.4 to 6.8, compared to the observed score range from 0 to 8.

A strong relationship between aerial photo measures of riparian width (included in the RDG) and the river habitat riparian metric is expected, and could 'mask' other river habitat variables that might otherwise be implicated. Repeating the regression with riparian width excluded resulted in a model that retained off-channel habitat, bottom deposition, quantity of LWD, and thalweg substrate (adjusted $R^2 = 0.35$). Although this analysis suggests additional variables for inclusion in the habitat index, the predictive ability of this model when applied to the test data was poor (adjusted $R^2 = 0.02$).

Constructing the NWHI

Based on the two disturbance gradients, riparian width, LWD, and aquatic vegetation are particularly important components of habitat quality in these non-wadeable rivers. Bivariate scatter plots further illustrate their relationships with the disturbance gradients ($P < 0.05$; Figure 4), and suggest that bottom deposition also should be included. These four variables are useful in developing an index that can distinguish reaches with poor vs. good habitat, using the disturbance gradients as the measure of 'poor' and 'good.'

Although the remaining eight variables were not selected in the CDG and RDG models, three can be justified for inclusion in the final index based on perceived importance. Bank stability and substrate size are important measures of habitat frequently included in assessment protocols. Substrate composition provides microhabitat for fishes (Mebane 2001) and influences macroinvertebrate (Beisel and others 2000) and freshwater mussel (Lewis and Riebel 1984) distribution and abundance. Large, stable substrate is generally considered more favorable for epifaunal colonization and fish cover (Barbour and others 1999). Stable banks provide cover and reduce nutrient and sediment inputs to the stream, which can be detrimental to the biota (Stevenson and Mills 1999). In large rivers, off-channel habitat may play a role of increased importance as biological hotspots (Reash 1999), places of refugia during disturbance events, regions of nutrient enrichment, and spawning or nursery areas (Sheaffer and Nickum 1986, Scott and Nielsen 1989). Therefore, despite the lack of strong relationships with the disturbance gradients, off-channel habitat, bank stability, and thalweg substrate were included in the final habitat index. This decision receives further support from the finding that off-channel habitat and thalweg substrate (as well as bottom deposition) were included in the RDG regression that excluded the field riparian metric.

The five remaining variables identified as important in describing habitat variability (discharge, thalweg depth, slope, width-to-depth ratio, and bank angle) are not easily associated with a scale of anthropogenic disturbance, and several are strongly associated with river size. Discharge, thalweg depth, width-to-depth ratio, and slope may be helpful in determining biological or habitat expectations for a given reach, but not in determining reach quality. We recommend measuring thalweg depth, as opposed to discharge, as a surrogate for river size; slope to define expectations for habitat features; and width-to-depth ratio to characterize the general channel shape. However, we do not assign a corresponding quality scale nor include these in the NWHI.

Bank angle was the final variable that was not correlated with the disturbance indices and appeared to provide little information about habitat quality. Because of difficulties in measuring bank angle, and its conceptual redundancy with the selected MDEQ bank stability metric, no bank angle measurement was included in the final habitat index.

In summary, riparian width, LWD, aquatic vegetation, thalweg substrate, bottom deposition, off-channel

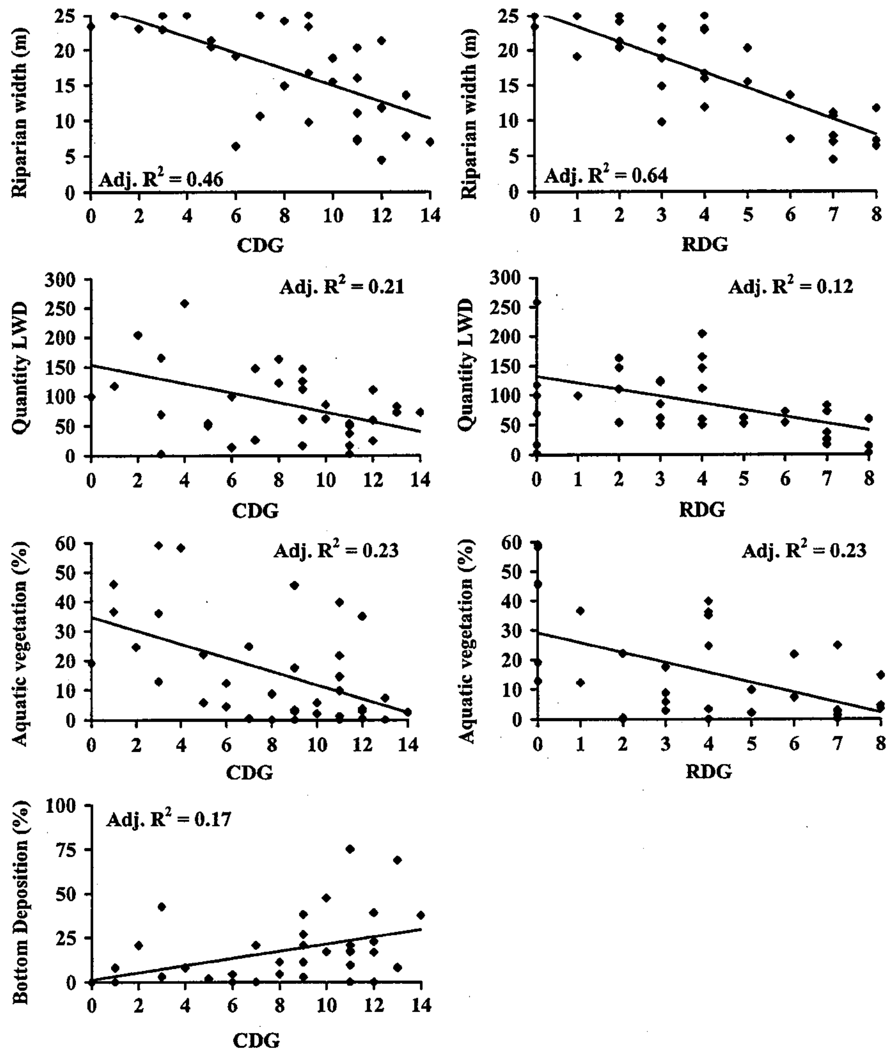

Figure 4. Several variables considered for inclusion in the non-wadeable habitat index were significantly correlated with either the Catchment Disturbance Gradient (CDG) or the Riparian Disturbance Gradient (RDG) ($P < 0.05$). Appropriate transformations to meet the normality assumption were performed (see Table 4), however, untransformed data are displayed here. Trend lines represent linear regressions.

habitat, and bank stability are the seven habitat variables evaluated in the habitat index to determine habitat quality at a given reach (Table 7). Due to their selection in regression models, woody debris, aquatic vegetation, and riparian width were given the highest weight. Riparian width was scored on a 25-point scale due to its relation with both disturbance gradients, whereas LWD and aquatic vegetation were scored on a 20-point scale. This weighting also agreed with field observations: reaches with abundant wood, established macrophytes, and an intact, natural riparian buffer consistently appeared to have extensive high-quality river habitat compared to other reaches. Bottom deposition, thalweg substrate, and bank stability were given an intermediate weight and were scored on a 10-point scale. Off-channel habitat was given the lowest weight and was scored on a 5-point scale. This variable was the weakest measure in the instream cover grouping based on the PCA.

Habitat Quality of Michigan Rivers

The 35 non-wadeable river reaches sampled during 2000–2002 ranged in NWHI scores from 25 points for an urban reach of the Grand River to 85 points for a forested reach on the Manistee River, out of a possible 100 points (Figure 5). By summing across the seven metrics, we established criteria for reaches that are excellent (84–100), good (56–84), fair (28–56), and poor (0–28). Of the 35 evaluated reaches, 1 was ranked excellent, 13 were good, 19 were fair, and 3 ranked as poor. The mean score was just under 52 and the median score was 50, both of which fell in the fair category for overall habitat quality.

Table 7. Summary of scoring criteria for the non-wadeable river habitat index

Habitat variable	Poor	Fair	Good	Excellent
Riparian width	Mean riparian width <10 m 0–5	Mean riparian width 10–17.5 m 6–12	Mean riparian width 17.5–24 m 13–19	Mean riparian width >24 m 20–25
LWD	Fewer than 50 pieces of LWD 0–5	Between 50 and 100 pieces of LWD 6–10	Between 100 and 200 pieces of LWD 11–15	Greater than 200 pieces of LWD 16–20
Aquatic vegetation	<5% coverage of aquatic vegetation 0–5	5–15% coverage of aquatic vegetation 6–10	15–25% coverage of aquatic vegetation 11–15	>25% aquatic vegetation 16–20
Bottom deposition	>50% of the bottom affected by deposition and sedimentation 0–2	25–50% of the bottom affected by deposition and sedimentation 3–5	5–25% of the bottom affected by deposition and sedimentation 6–8	0–5% of the bottom affected by deposition and sedimentation 9–10
Bank stability	Unstable banks, >60% of reach shows erosion scars 0–2	Moderately unstable, 30–60% of reach with erosion 3–5	Moderately stable, 5–30% of reach has areas of erosion 6–8	Banks stable, <5% of banks show evidence of erosion 9–10
Thalweg substrate	<15% gravel or larger substrate 0–2	15–35% gravel or larger substrate 3–5	35–60% gravel or larger substrate 6–8	>60% gravel or larger substrate 9–10
Off-channel habitat	<2 off-channel habitats 0	2–3 off-channel habitats 1–2	4–5 off-channel habitats 3–4	>5 off-channel habitats 5

Each variable was scored on a 25-, 20-, 10-, or 5-point scale. Individual categories were further subdivided so that each point corresponded with a range of values obtained from field sampling. LWD, large woody debris.

NWHI scores were highly correlated with both the EPA and MDEQ visual assessment scores ($P < 0.001$), despite the inclusion of several different measures of habitat quality in the latter indices. NWHI scores were also significantly correlated with disturbance gradient scores ($P < 0.001$; Figure 6). The spatial distribution of NWHI scores suggests that they were not strongly location dependent (Figure 5). The Manistee and Grand Rivers both had reaches covering at least three of the four categories of poor to excellent.

NWHI scores were calculated for the three regional groupings and were significantly different ($F_{2,32}$, $P = 0.003$). In general, reaches in the SLP had the lowest mean score (44), UP reaches had intermediate scores (61), and the NLP reaches had the highest scores (63).

Discussion

Habitat lies at the interface between the forces structuring rivers and the organisms that inhabit them (Harper and Everard 1998), thereby providing a link between the physical environment and its residents (Maddock 1999). Habitat condition has been shown to influence species composition, diversity, abundance, and productivity within a river segment (Gorman and Karr 1978, Harper and Everard 1998). Habitat degradation has resulted in extinctions, local extirpations, reduced populations, and other modifications of aquatic fauna throughout the United States (Karr 1991) and is recognized as one of the most important causes of the decline of biodiversity in fluvial ecosystems (Allan and Flecker 1993). However, habitat evaluation of large rivers is hampered by the absence of a standard protocol that addresses their logistical challenges and specific habitat features.

Because large rivers are the ultimate sinks of pollution and cumulative landscape effects, it may be appropriate to use large rivers to monitor the ecological health of the whole drainage basin (Hynes 1989). Indeed, it is becoming accepted that, if a stream is assessed as unhealthy, then the catchment also is unhealthy (Norris and Thoms 1999).

The weighting of metrics included in the NWHI reflects the strength of statistical association of each with independent measures of anthropogenic disturbance, as well as knowledge of the ecological role of the variables represented. A high weighting for natural riparian areas is expected because of their dynamic interaction with lowland, floodplain rivers (Vannote and others 1980) and their essential roles in nutrient and sediment retention, as sources of wood and leaf

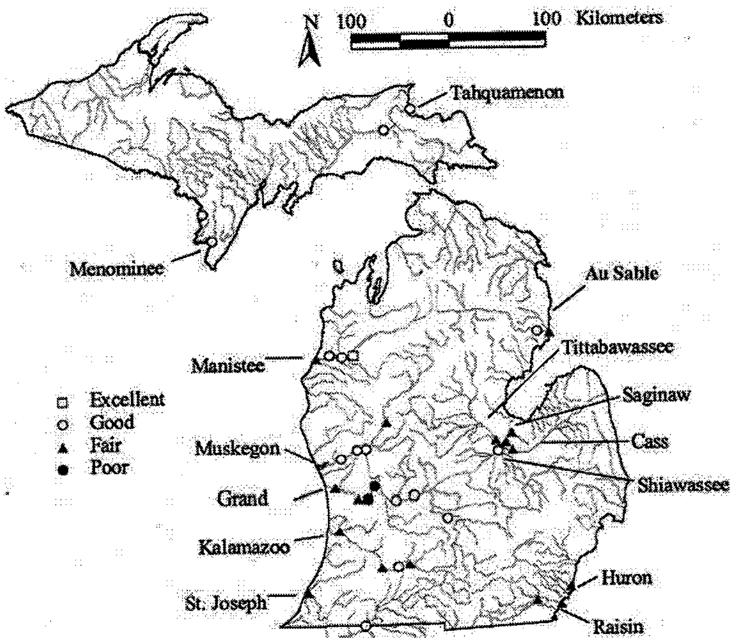

Figure 5. Spatial distribution of assessed habitat quality for 35 non-wadeable reaches on rivers of Michigan. Reaches ranked "good" occurred throughout the state, and reaches on a single river received as many as three different rankings, suggesting that the non-wadeable habitat index evaluates reach quality regardless of location.

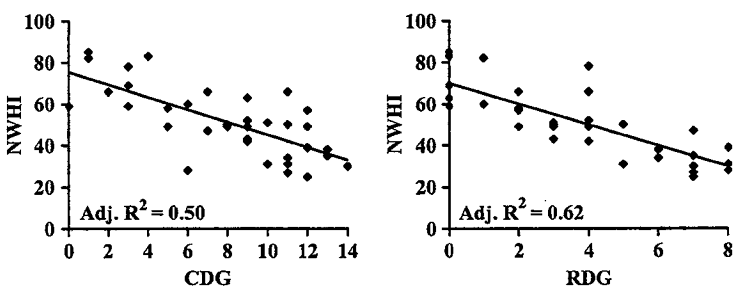

Figure 6. Correlations between non-wadeable habitat index (NWHI) and disturbance gradient scores were highly significant ($r < -0.75$, $P < 0.001$). CDG, Catchment Disturbance Gradient; RDG, Riparian Disturbance Gradient.

debris, and in bank stabilization and providing overhanging cover (Gregory and others 1991).

It is not surprising that riparian width recorded from the river channel was strongly implicated in regressions with both the CDG and RDG, because the disturbance metrics also included information on the riparian zone. Although the RDG evaluated riparian vegetation at a larger scale (10 km in length, to the lateral extent of forest or wetland) than the field riparian metric, their high correlation suggests that these are in fact two measures of local-scale riparian condition, perhaps most useful in establishing that riparian condition varies more on the local scale than does catchment condition. The fact that unique reaches along the same river differed in total habitat quality is a strong indicator that the local riparian area is an important influencing force and that natural buffers do protect the river from larger-scale human impacts. These findings support the view that variation in local, reach-scale riparian conditions influences habitat quality of non-wadeable rivers, and presumably the biota as well.

The NWHI also gives significant weight to aquatic vegetation and woody debris. Macrophytes and LWD are important components of instream habitat structure, loss of which may significantly reduce fish populations and biodiversity. In the rivers sampled, they were frequently the primary stable substrates and were important in contributing to localized areas of hydraulic diversity.

Inclusion of bottom deposition, bank stability, thalweg substrate, and off-channel habitat is justified based on ecological understanding of their importance, and to some extent by statistical findings, although these variables were less strongly implicated. Thus, their inclusion with lower weighting appears appropriate.

The two wadeable habitat protocols (MDEQ and EPA) were highly correlated with the NWHI. Although this might suggest that existing, wadeable stream indices can be used in larger rivers, we believe that the NWHI is an improvement over these. First, the NWHI includes some metrics and excludes others in accordance with basic knowledge of small streams versus larger rivers. Several variables commonly used in wadeable indices are notably absent, including pool variability, channel flow status, and sinuosity, either because they were not applicable to large river systems or showed little variation in rivers throughout Michigan. Although the relative change in width and habitat with flow can be considerable in small rivers, where extreme low flows can be especially damaging (Jowett 1997), larger rivers in Michigan usually have ample flows and the appearance of adequate wetted habitat. Similarly, wadeable protocols tend to estimate habitat representation of deep and shallow pools, runs, and riffles. The primary geomorphic units in large rivers are bends and crossover regions instead of pools, riffles, and runs (Leopold and others 1964, Fitzpatrick and others 1998). Run or glide was the overwhelmingly dominant habitat type in the rivers sampled and therefore always scored in the poor or fair categories. In addition, our NWHI included off-channel habitats, which are recognized as biologically rich locations within large rivers (Stalnaker and others 1989, Reash 1999), and are not normally considered in traditional wadeable habitat protocols. It may be desirable to expand this metric to assess various forms of channel and hydraulic complexity by considering backwater, off-channel, tributary and island habitats, which exhibit extensive variation in large floodplain rivers (Kellerhals and Church 1989).

Second, the wadeable protocols grouped all the reaches together in the fair and good categories. The EPA method scored no reaches as 'poor,' whereas the MDEQ protocol scored no reaches in the 'excellent' or 'poor' range. In contrast, the distribution of scores for the NWHI (Figure 5) included all categories from poor to excellent with the majority of reaches scored as fair, compared to the good rating received by most reaches using the visual methods for wadeable streams.

Finally, the NWHI involved many quantitative metrics rather than visually estimated measures and was developed using statistical procedures and objective criteria as much as possible to avoid personal bias, subjectivity, and constraints of knowledge (Boulton 1999).

We used the CDG and RDG as criteria to identify habitat variables that were sensitive to anthropogenic impacts based on the view that catchment and/or riparian character influences the river (Allan and Johnson 1997). An alternative approach would be to use biological data to select habitat variables that predict, for example, best conditions for fish (Wang and others 1998). Such data were unavailable for this study, although a comparison between the NWHI and macroinvertebrate indices is forthcoming (Wessell 2004). We believe our approach is warranted as a test of the hypothesis that altered land use directly impacts habitat, which in turn influences the biota; and because it allows the subsequent comparisons of habitat and biological metrics to use independently derived metrics.

Ideally, the final index would be calibrated against existing reference reaches to define best attainable habitat conditions. However, because of extensive logging throughout the state in the late 1800s, in addition to current agricultural practices, urban development, pollution, and hydrological modification due to dams and channelization, few river reaches can truly be considered natural or unmodified. Therefore, there are relatively few large rivers in Michigan from which to derive comparisons, a general concern in referencing large rivers (Norris and Thoms 1999). Without a sufficient number of unimpacted reaches from which to draw baseline comparisons, the cumulative dataset was used to derive variations in attainable conditions (Simon 1991). This resulted in a relative scale of habitat quality ranging from poor to excellent, whereas comparison to presettlement conditions might indicate that few of Southern Michigan's larger rivers can be regarded as healthy. Although the final habitat index has not yet been tested extensively for its relevance to the biological potential of a river, it provides an adequate index of overall reach quality, which accords well with riparian conditions derived from aerial photographs and reach-based professional judgment.

The NWHI developed in this study appears to be a valid tool for assessing habitat quality in Michigan rivers. It likely would be applicable to adjacent states and provinces, especially within the Upper Midwest where rivers are of similar size and gradient. However, its applicability to rivers of other regions, and/or larger size, is unknown. There are approximately 5000 rivers of fifth through seventh order in North America, and only 50 of eighth through tenth order (Leopold and others 1964). Thus, the vast majority of non-wadeable rivers are similar in size to those included in this study, and the largest rivers are a class to themselves. Future efforts to improve habitat assessment of non-wadeable rivers should address several issues: the extent of regional modification that is needed for the index to be effective, how metric inclusion and weighting may require modification for much larger rivers, and the ability of the NWHI to predict biological condition. Regardless, we believe that the transparent and rigorous process of metric selection and index development described here can be applied widely.

Acknowledgments

We thank Michael Alexander for assistance with project logistics, and the Michigan Department of Environmental Quality for funding. Faith Fitzpatrick, David Galat, Phil Kaufman, Lizhu Wang, and Troy Zorn provided constructive comments on the manuscript. Field and computer assistance was provided by James Roberts, Ron Dolen, Sarah McRae, Dana Infante, Todd White, Janelle Francis, Mike Mueller, Ben Opdyke, and Liza Liversedge.

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Attachment M3

Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

RESEARCH AND DEVELOPMENT DEPARTMENT

REPORT NO. 98-10

A STUDY OF THE FISHERIES RESOURCES AND WATER QUALITY IN THE CHICAGO WATERWAY SYSTEM 1974 THROUGH 1996

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June 1998

Metropolitan Water Reclamation District of Greater Chicago

A STUDY OF THE FISHERIES RESOURCES AND WATER QUALITY IN THE CHICAGO WATERWAY SYSTEM 1974 THROUGH 1996

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ACKNOWLEDGMENTS

The authors wish to thank the laboratory personnel, past and present, who assisted with the collection and analyses of samples and with the subsequent data analyses during the period 1974 through 1996, including Carl Athas, Mary Pat Buckley, Luke Butler, Carl R. Carlson, Jr., Margaret Donahue, John L. Dorkin, Jr., Joseph Ferencak, Geraldine Guarte, Richard Gore, Terri Hair, Anthony Halaska, Mary Lynn Hartford, Reda Kelada, Loretto Kennedy, Jacqueline A. Krzyzak, Herbert G. Lopatka, Monika Rydzinski, Damrong Mangkorn, Richard Marcinkiewicz, Zoe Mather, James Papanikolaou, Donald S. Ridolfi, Joseph Salerno, Waheeda Shaikh, Michael Shepard, Catherine Sopcak, Michael Sopcak, Charles E. Spielman, Gregory Stamish, Sheril Sullivan, Shirley A. Tobias, Amit Trivedi, Janice Wagner, William Wagner, Gary D. Whyte, and Michael Yore.

The authors also wish to thank the personnel of the Industrial Waste Division, past and present, who aided in the collection of samples during the period 1974 through 1996, including Joseph Bojanowski, Robert Chmela, Lawrence Conroy, Robert Day, John Dakuras, James Figlewicz, Brian Gembara, Harold Martinek, Carl Kurucar, Thomas Pastiak, Javier Salazar, Daniel Seasock, and Alexander Wilczak.

DISCLAIMER

Mention of proprietary equipment and chemicals in this report does not constitute endorsement by the Metropolitan Water Reclamation District of Greater Chicago.

SUMMARY AND CONCLUSIONS

The Metropolitan Water Reclamation District of Greater Chicago (District) monitored the fish populations within the 81 mile long Chicago Waterway System from 1974 through 1996. A considerable improvement in the numbers of fish species, in the relative abundance of fish, and in the quality of the water occurred downstream from the District's three major water reclamation plant (WRP) effluent outfalls.

Six months after cessation of effluent chlorination on April 1, 1984, a five-fold increase in fish species and a 10-fold increase in numbers of fish occurred from one to two miles downstream of the North Side WRP effluent outfall.

A 150 percent increase in the abundance of fish and a 50 percent increase in the number of fish species occurred throughout the waterway system after the Tunnel and Reservoir Plan (TARP) went online in 1985.

The five Sidestream Elevated Pool Aeration (SEPA) Stations increased the dissolved oxygen (DO) in the Calumet River System by pumping canal water to elevated pools and allowing it to cascade back into the waterway. This attracted game fish species, such as smallmouth and largemouth bass and channel catfish, to these locations.

Water quality is now generally good downstream of the WRP effluents. Stream quality for fish improved, but is limited by the practical considerations of providing for navigation and water reclamation in an urban environment.

The improvements in the quality of the fishery and in the water quality and stream quality of the Chicago Waterway System, are due to the effectiveness of the discontinuation of effluent chlorination at the major WRPs, TARP's prevention of waterway pollution, and increased dissolved oxygen provided by the SEPA stations.

Major measures of improvements in the fisheries resources and water quality within the waterways of the Chicago Waterway System that occurred between the 1970s and the 1990s were as follows:

1. North Shore Channel: Water quality improved from poor to good. Stream quality improved from poor to fair. Total fish species increased from 21 to 34. Game fish species increased from 11 to 15. Total weight of fish catch increased from 15 to 22 pounds per 30 minutes. Total number of fish increased from 39 to 246 per 30 minutes.
2. North Branch of the Chicago River: Water quality improved from poor to good. Stream quality improved from poor to fair. Total fish species increased from 10 to 22. Game fish species increased from 3 to 9. Total weight of fish catch increased from less than 1 pound to 36 pounds

per 30 minutes. Total number of fish increased from 1 to 53 per 30 minutes.

3. Chicago River: Water quality remained good. Stream quality remained fair. Total fish species increased from 21 to 32. Game fish species increased from 11 to 15. Total weight of fish catch increased from 16 pounds to 65 pounds per 30 minutes. Total number of fish increased from 23 to 71 per 30 minutes.

4. Chicago Sanitary and Ship Canal: Water quality improved from poor to good. Stream quality improved from poor to fair. Total fish species increased from 5 to 25. Game fish species increased from 2 to 10. Total weight of fish catch increased from 1 to 79 pounds per 30 minutes. Total number of fish increased from 2 to 88 per 30 minutes.

5. Calumet River: Water quality remained good. Stream quality remained fair. Total fish species increased from 15 to 33. Game fish species increased from 7 to 15. Total weight of fish catch increased from 21 pounds to 53 pounds per 30 minutes. Total number of fish increased from 86 to 119 per 30 minutes.

6. Little Calumet River: Water quality improved from poor to fair. Stream quality remained

fair. Total fish species increased from 14 to 20. Game fish species increased from 4 to 9. Total weight of fish catch increased from 14 to 49 pounds per 30 minutes. Total number of fish increased from 33 to 82 per 30 minutes.

7. Cal-Sag Channel: Water quality improved from very poor to fair. Stream quality improved from poor to fair. Total fish species increased from 12 to 24. Game fish species increased from 3 to 9. Total weight of fish catch increased from less than 1 pound to 20 pounds per 30 minutes. Total number of fish increased from 4 to 32 per 30 minutes.

The following conclusions were drawn from this study:

1. The discontinuation of effluent chlorination at the District's major WRPs, TARP's prevention of waterway pollution, and the increased dissolved oxygen provided by the SEPA stations, have directly benefited the fisheries by improving the water and stream quality of the Chicago Waterway System.
2. The abundance and species richness of the fish populations have increased in every one of the seven waterway segments of the Chicago Waterway System from 1974 through 1996.

3. Numbers of game fish species have increased in all waterway segments of the Chicago Waterway System from 1974 through 1996. Harvestable size game fish in the waterways now include northern pike, white bass, white perch, rock bass, green sunfish, pumpkinseed sunfish, bluegill, smallmouth and largemouth bass, white and black crappie, and yellow perch, as well as the rainbow, brook, brown and lake trout and coho and chinook salmon that enter the waterway system from Lake Michigan.
4. The cessation of WRP final effluent chlorination removed toxic chlorine and chloramines from the waterways downstream of the three major WRP outfalls which resulted in considerable improvement in the fish populations because of the absence of these toxicants.
5. TARP similarly removed the mixture of raw sewage and storm water that flowed into the waterways during every storm event (an average of once every four days), thus removing a significant quantity of materials that exert biochemical oxygen demand and toxicity. This also caused a dramatic improvement in conditions for maintaining healthy fish populations.

6. The SEPA stations increased the dissolved oxygen levels in the waterways and attracted desirable species of fish to areas where they were not previously collected.

7. Because of improvements in the collection and treatment of wastewater by the District, the water quality for fish in the Chicago Waterway System is now, theoretically, of a quality good enough to support balanced fish populations. This is of itself a major accomplishment and indicates commendable environmental stewardship by the District. Such water quality improvement helps to protect the fisheries resources downstream, especially those of the Illinois River.

8. Even though the water quality is generally good, the fish populations of the Chicago Waterway System are still dominated by omnivores, tolerant forms, and habitat generalists. This is primarily because water quality alone does not take into concern the condition of habitat, flow, or other outside factors. The waterways of the Chicago Waterway System were not constructed to be fishable streams with diverse habitat types. They were built for navigation and water reclamation. It is unlikely that these waterways can achieve the same stream

quality for fish as a natural habitat-rich waterway unless desirable fish habitat is created, such as the unique habitat that the SEPA waterfall tailraces provide.

INTRODUCTION

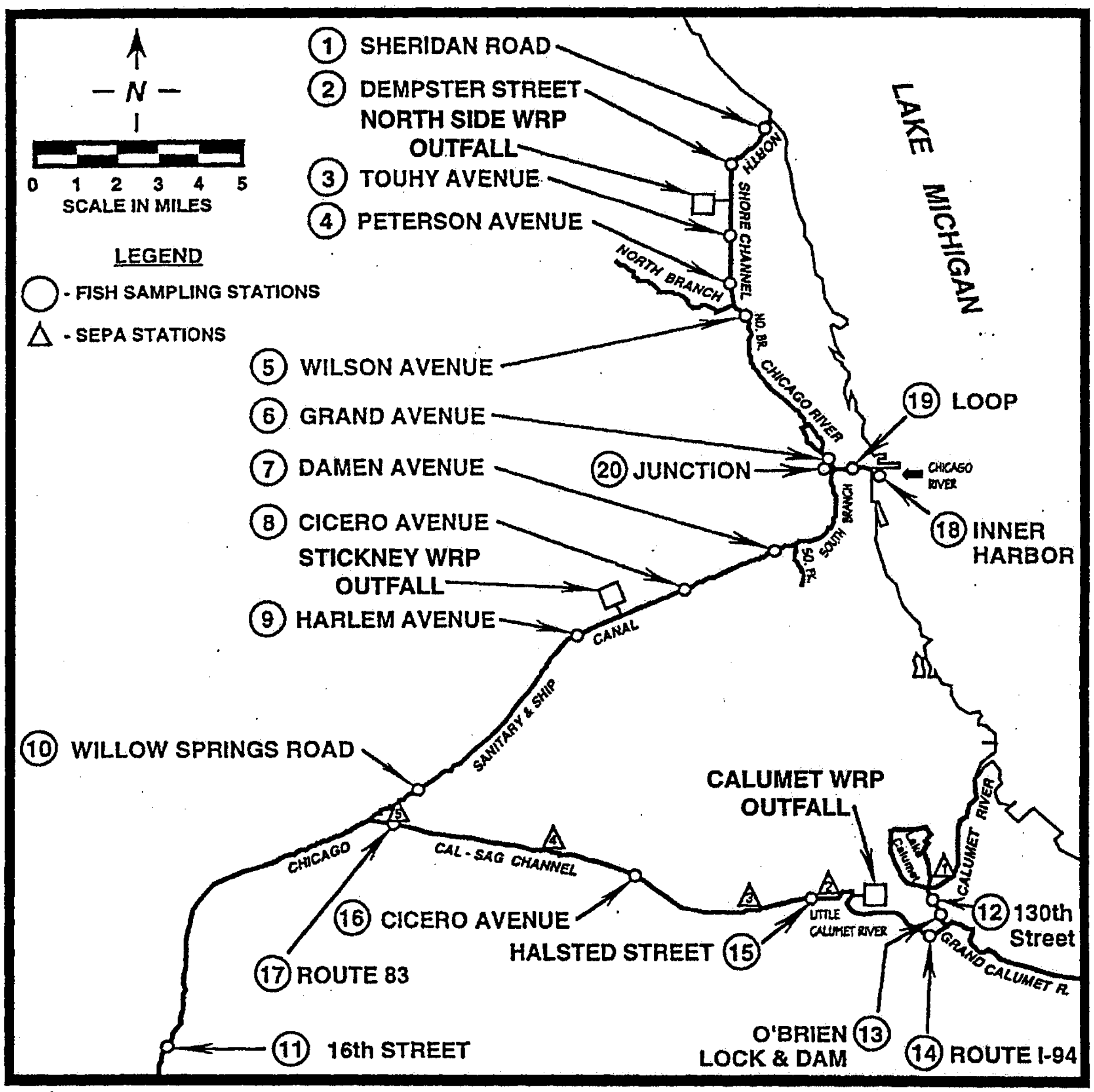
The Metropolitan Water Reclamation District of Greater Chicago (District) serves an area of 872 square miles. The area is highly urbanized and industrialized. The District treats a total domestic and nondomestic wastewater load that is equivalent to a population of 9.5 million people. Approximately 375 square miles of the District's area is served by combined sewers, with the remainder served by storm sewers or is unsewered. The District presently owns and operates seven water reclamation plants (WRPs) which all utilize the biological activated sludge process, and approximately 537 miles of intercepting sewers. The North Side, Stickney, Calumet and Lemont WRPs together have 1889 MGD of secondary capacity. The Hanover, Egan and Kirie WRPs have a combined tertiary capacity of 114 MGD (1).

In order to protect the area's primary water supply, Lake Michigan, the flow of the Chicago River System was reversed in 1900 and the Calumet River System was reversed in 1922. Fifty-four miles of navigable canals were constructed and connected to existing river systems to form the 81 mile long Chicago Waterway System (Figure 1). The District's Research and Development Department has conducted electrofishing surveys to monitor the species composition, distribution and relative abundance of fish populations in the Chicago Waterway System from 1974 through 1996.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 1

LOCATION OF SAMPLING STATIONS FOR FISH IN THE METROPOLITAN CHICAGO WATERWAY SYSTEM



The Chicago Waterway System (Figure 1) includes the Chicago River System with five segments: North Shore Channel, North Branch Chicago River, Chicago River, South Branch Chicago River and Chicago Sanitary and Ship Canal and the Calumet River System with three segments: Calumet River, Little Calumet River, and Cal-Sag Channel.

The North Shore Channel is 7.63 miles long and 5.2 to 7.3 feet deep (1). The Channel was completed in 1907 to divert more lake water to the North Branch of the Chicago River for dilution of sewage, in order to protect Lake Michigan. The lock at Sheridan Road was installed in 1910. The North Shore Channel receives final effluent from the District's North Side WRP (Figure 1) which began operation on October 3, 1928 (2).

The deep draft portion of the North Branch of the Chicago River extends from its junction with the North Shore Channel to its junction with the Chicago River in downtown Chicago. This portion of the river is 7.85 miles long and 6.1 to 18.5 feet deep (1).

The 1.31 mile long Chicago River extends from the locks at Chicago Harbor through downtown Chicago to the river's junction with its North and South Branches.

The South Branch of the Chicago River is 4.83 miles long and 18.5 to 20.2 feet deep (1). It extends from the Chicago River junction to the beginning of the Chicago Sanitary and Ship Canal near Damen Avenue.

The Chicago Sanitary and Ship Canal is 30.06 miles long and 10.7 to 27.1 feet deep (1). This canal was completed in 1900 to divert Lake Michigan water for dilution of sewage. The Stickney WRP began operation on June 2, 1930, (West Side Plant) and on May 23, 1939, (Southwest Plant) (2). The final effluent from the Stickney WRP flows into the Chicago Sanitary and Ship Canal (Figure 1).

The Calumet River is 7.73 miles long and 8.5 to 11.5 feet deep (1). The river flows from Calumet Harbor to the junction with the Grand Calumet River, just downstream of the O'Brien Lock and Dam.

The deep draft portion of the Little Calumet River is 6.55 miles long and 14 feet deep (1). The original Calumet WRP began operation on September 11, 1922. It was replaced by a conventional activated sludge plant in 1935 (2). The final effluent from the Calumet WRP flows into the Little Calumet River (Figure 1).

The Cal-Sag Channel is 15.98 miles long and 8.8 to 11.7 feet deep (1). The Channel extends from its junction with the Little Calumet River to its junction with the Chicago Sanitary and Ship Canal.

The fish monitoring program has served to document the effectiveness of the District's wastewater treatment program, especially as to the effects of the discontinuation of effluent chlorination at the major WRPs, TARP, and the SEPA stations.

Cessation of Effluent Chlorination

In 1983, the Appellate Court of Illinois allowed cessation of chlorination for District WRPs which discharge into secondary contact and indigenous aquatic life waters. Also in 1983, the District filed a petition for variance before the Illinois Pollution Control Board (IPCB) requesting a variance from the water quality effluent standards for the Calumet WRP, which discharges final effluent into the designated secondary contact waters of the Little Calumet River (Figure 1). This variance was granted for the period of August 1, 1983 through March 31, 1984. On March 21, 1984, the IPCB granted a variance beginning April 1, 1984, for the District's major WRPs, including the Calumet, North Side, and Stickney WRPs (3). The North Side WRP discharges final effluent into the designated secondary contact waters of the North Shore Channel (Figure 1). The Stickney WRP discharges final effluent into the designated secondary contact waters of the Chicago Sanitary and Ship Canal (Figure 1).

Tunnel and Reservoir Plan (TARP)

The District's TARP was designed to capture wastewater being washed into streams with runoff from the 375 square miles of combined sewer area within the District. TARP Phase I is for pollution control and consists of 109 miles of tunnels. This phase of TARP prevents backflows into Lake Michigan and intercepts combined sewer overflows (CSOs). TARP

Phase II is for flood control in the combined sewer area and is planned to consist of 21.5 miles of additional conveyance tunnels and three storage reservoirs totaling 125,630 acre-foot. As of December 1996, 75.4 miles of tunnels have been constructed and 18 miles are under construction. The 31-mile long Mainstream TARP became operational in May 1985. The 9.2-mile long Calumet TARP system commenced intercepting CSOs in October 1985, but full utilization was not achieved until July 1988 (1).

Sidestream Elevated Pool Aeration Stations (SEPA)

The SEPA system was designed to provide artificial aeration to the Calumet Waterway System in order to maintain a minimum dissolved oxygen concentration of 3.0 mg/L. With this system of five SEPA stations, low dissolved oxygen water is withdrawn from the waterways by means of screw pumps, passed through a shallow elevated pool, and cascaded over a number of steps back to the waterway. The primary aeration mechanism is the waterfall cascade (1).

MATERIALS AND METHODS

Fish populations were monitored in the Chicago Waterway System from the three waterway controlling works near Lake Michigan (on the North Shore Channel, the Chicago River and the Calumet River) to Lockport, Illinois. These collections occurred primarily at each of 20 locations which were sampled once or twice per year from 1974 through 1977, three or four times per year from 1985 through 1991, and twice per year from 1992 through 1996. Fishing gear used was primarily a 230-volt alternating current boat-mounted electrofisher. Generally, both sides of a 400-meter section of channel were included in the electrofishing sample at each location.

The parameters used to estimate improvements in the fishery were the number of fish species, the species composition, and the relative abundance of fish, as measured by the catch of fish per 30 minutes electrofishing or catch per unit of effort (CPUE), by both numbers and weight. Indices used to estimate water and stream quality for fish were the Bluegill Toxicity Index (BTI) devised by Lubinski and Sparks (4) and the Index of Biotic Integrity (IBI), devised by Karr *et al.* (5), respectively. The IBI was modified for use in Illinois by Bertrand *et al.* (6).

Water quality, as measured by the BTI, is based on the acute toxicity level effects on the bluegill sunfish of up to 20 toxicants. If the mixture of chemicals in the water is toxic enough to cause death to 50 percent of the bluegills exposed to it for a period of four days (LC_{50}), then the water quality was defined, in this study, as being very poor. If the toxicity of the mixture is less than 20 percent of the LC_{50}, then the water quality was defined as being good.

Stream quality, as measured by the IBI, is based on the estimation of the biotic, or biological, integrity of a stream. Biological integrity is the ability to support a balanced, integrated, adaptive community of organisms having a species composition, diversity and functional organization comparable to that of the natural habitat of the region. Stream quality is collectively, the combination of chemical, biological and physical features that characterize stream systems. Chemical attributes include nutrients and toxics in both the water and sediments; biological attributes include the fauna and flora of streams; and physical features include stream hydrology variables (e.g., flow regime, discharge, and velocity), and habitat factors such as substrate type and instream cover (7). Stream quality could range from poor quality, or a restricted aquatic resource, to good quality, or a unique aquatic resource (8).

RESULTS

From 1974 through 1996, 113,376 fish, representing 61 species and 8 hybrids, were collected during 809 quantitative collections from the Metropolitan Chicago Waterway System, as shown in Table 1. The total weight of the catch was 15,079 kg (33,244 pounds). Bluntnose minnows, gizzard shad, goldfish, fathead minnows, and carp were collected in the greatest numbers. Together these five species made up 67 percent of the total catch, by number. Carp alone made up 76 percent of the total catch, by weight. Harvestable size game fish have included northern pike, white bass, white perch, rock bass, green sunfish, pumpkinseed sunfish, bluegill, smallmouth and largemouth bass, white and black crappie, and yellow perch, as well as the rainbow, brook, brown and lake trout and coho and chinook salmon that enter the waterway system from Lake Michigan.

Following the cessation of WRP effluent chlorination on April 1, 1984, both the relative abundance and the number of fish species increased by the end of October of that year, at sample stations located one and two miles downstream of the North Side WRP (Figure 2). One hundred fifteen fish (44 CPUE) composed of nine species were collected one mile downstream and 366 fish (141 CPUE) composed of 11 species were collected two miles downstream. Previously, not more than three species and seven individual fish had been collected from either

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE 1

FISH COLLECTED FROM THE DEEP DRAFT CANALS OF THE CHICAGO WATERWAY SYSTEM 1974 THROUGH 1996

Family and Species	North Shore Channel	North Branch Chicago River	Chicago River	Chicago Sanitary and Ship Canal	Calumet River	Little Calumet River	Cal-Sag Channel	Grand Total
<u>Bowfins</u>								
Bowfin	0	1	0	1	1	0	0	3
<u>Freshwater eels</u>								
American eel	0	0	0	0	1	0	0	1
<u>Herrings</u>								
Alewife	2,661	39	528	98	721	49	8	4,104
Gizzard shad	2,216	735	920	1,422	3,567	3,734	1,047	13,641
<u>Salmon and Trouts</u>								
Rainbow trout	16	4	10	2	3	0	1	36
Brown trout	28	0	33	1	0	0	0	62
Brook trout	2	1	1	0	0	0	0	4
Lake trout	1	0	3	0	0	0	0	4
Coho salmon	5	0	10	0	1	0	0	16
Chinook salmon	6	0	11	1	7	1	0	26
<u>Smelts</u>								
Rainbow smelt	2,024	2	34	71	5	1	0	2,137
<u>Mudminnows</u>								
Central mudminnow	5	1	0	15	0	2	9	32

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE 1 (Continued)

FISH COLLECTED FROM THE DEEP DRAFT CANALS OF THE CHICAGO WATERWAY SYSTEM 1974 THROUGH 1996

Family and Species	North Shore Channel	North Branch Chicago River	Chicago River	Chicago Sanitary and Ship Canal	Calumet River	Little Calumet River	Cal-Sag Channel	Grand Total
<u>Pikes</u>								
Grass pickerel	2	0	0	2	2	2	0	8
Northern pike	1	0	0	0	0	0	0	1
<u>Minnows and Carps</u>								
Goldfish	3,289	708	402	5,623	99	1,255	290	11,666
Grass carp	0	0	1	0	1	0	0	2
Carp	854	568	1,022	3,675	900	940	667	8,626
Carp x Goldfish hybrid	596	169	116	183	32	118	39	1,253
Brassy minnow	1	0	0	0	0	0	0	1
Hornyhead chub	1	0	0	0	0	0	0	1
Golden shiner	2,494	112	63	163	83	121	9	3,045
Emerald shiner	25	20	116	346	873	1,242	241	2,863
Bigmouth shiner	1	0	0	0	0	0	0	1
Spottail shiner	1,160	34	105	82	54	34	1	1,470
Spotfin shiner	1	0	0	0	0	0	0	1
Sand shiner	3	0	1	0	5	0	0	9
Bluntnose minnow	19,270	376	1,278	2,746	6,934	520	56	31,180
Fathead minnow	9,765	49	12	437	127	47	26	10,463
Longnose dace	16	0	0	0	0	0	0	16
Creek chub	1	0	0	2	0	0	5	8
Central stoneroller	0	0	2	0	1	0	0	3

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE 1 (Continued)

FISH COLLECTED FROM THE DEEP DRAFT CANALS OF THE CHICAGO WATERWAY SYSTEM 1974 THROUGH 1996

Family and Species	North Shore Channel	North Branch Chicago River	Chicago River	Chicago Sanitary and Ship Canal	Calumet River	Little Calumet River	Cal-Sag Channel	Grand Total
Suckers								
Quillback	0	0	0	0	4	0	0	4
White sucker	123	13	1	2	53	12	24	228
Black buffalo	0	0	1	0	1	0	0	2
Loaches								
Oriental weatherfish	11	1	0	0	0	0	0	12
Freshwater catfishes								
Black bullhead	380	40	39	248	5	20	34	766
Yellow bullhead	5	1	0	3	0	0	1	10
Channel catfish	0	0	0	0	7	1	15	23
Trout-perches								
Trout-perch	0	0	2	0	0	0	0	2
Livebearers								
Mosquitofish	0	0	0	2	0	4	0	6
Silversides								
Brook silverside	0	0	1	0	0	0	0	1
Sticklebacks								
Brook stickleback	1,252	29	2	2	0	0	0	1,285
Threespine stickleback	25	63	19	9	0	1	2	119
Ninespine stickleback	27	0	2	0	0	0	0	29

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE 1 (Continued)

FISH COLLECTED FROM THE DEEP DRAFT CANALS OF THE CHICAGO WATERWAY SYSTEM 1974 THROUGH 1996

Family and Species	North Shore Channel	North Branch Chicago River	Chicago River	Chicago Sanitary and Ship Canal	Calumet River	Little Calumet River	Cal-Sag Channel	Grand Total
Temperate basses								
White bass	0	0	2	0	2	0	0	4
White perch	0	3	11	1	430	406	1	852
Yellow bass	0	0	0	7	0	11	15	33
White x Striped bass hybrid	0	0	0	0	1	0	0	1
Sunfishes								
Rock bass	70	1	556	1	20	0	0	648
Green sunfish	1,524	243	580	113	744	116	520	3,840
Pumpkinseed	174	15	70	36	455	272	15	1,037
Warmouth	0	0	0	0	1	0	1	2
Orangespotted sunfish	81	9	12	3	142	17	1	265
Bluegill	691	284	663	123	467	105	243	2,576
Smallmouth bass	0	0	61	1	77	0	3	142
Largemouth bass	473	198	454	293	1,108	135	190	2,851
White crappie	1	0	0	0	1	0	1	3
Black crappie	83	12	13	13	29	2	7	159
Hybrid sunfish								
Green x Orangespotted	0	1	0	0	1	0	0	2
Green x Pumpkinseed	14	5	2	1	14	3	3	42
Green x Bluegill	14	6	6	1	13	0	1	41
Pumpkinseed x Orangespotted	0	0	0	0	8	1	0	9
Pumpkinseed x Bluegill	7	2	4	0	5	0	0	18
Bluegill x Orangespotted	0	0	0	0	3	0	0	3

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE 1 (Continued)

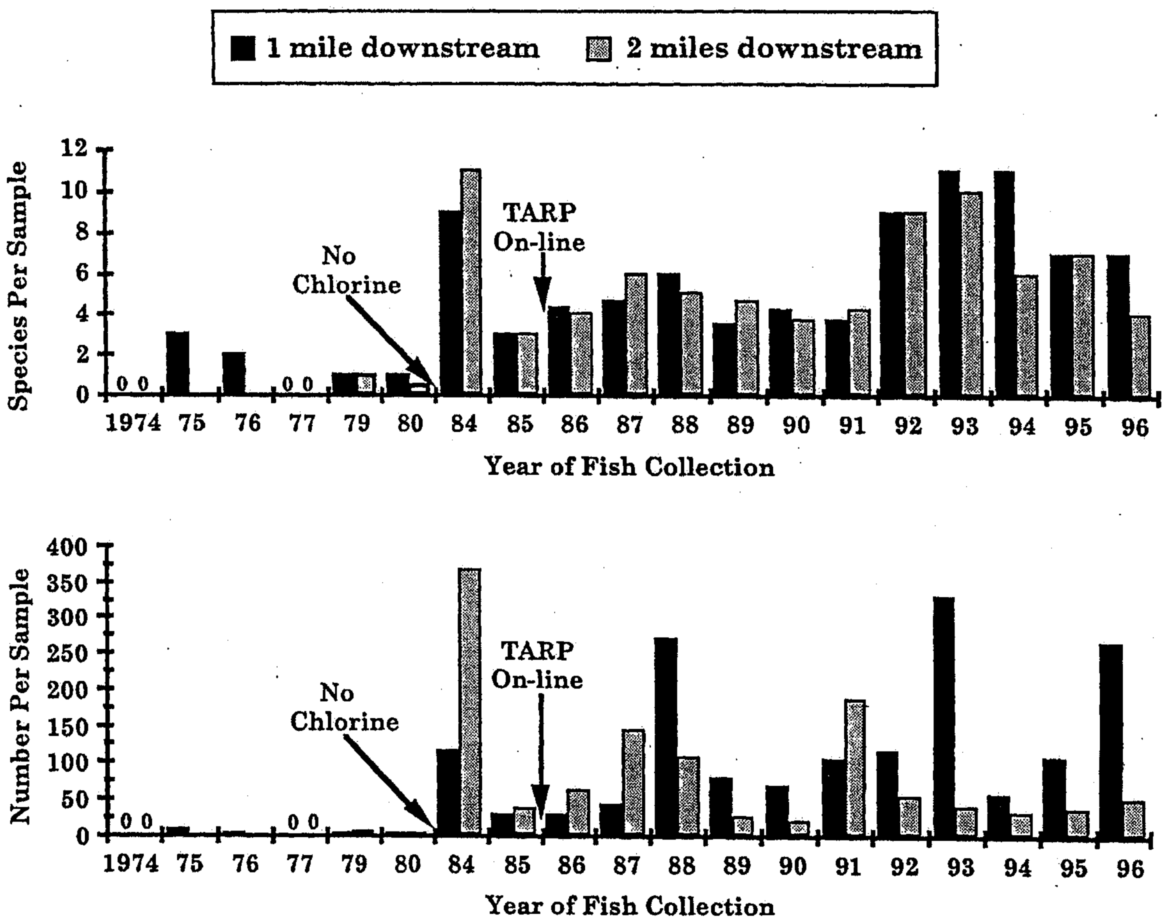
FISH COLLECTED FROM THE DEEP DRAFT CANALS OF THE CHICAGO WATERWAY SYSTEM 1974 THROUGH 1996

Family and Species	North Shore Channel	North Branch Chicago River	Chicago River	Chicago Sanitary and Ship Canal	Calumet River	Little Calumet River	Cal-Sag Channel	Grand Total
<u>Perches</u>								
Johnny darter	1	0	15	0	1	0	0	17
Yellow perch	3,827	300	1,387	909	1,064	118	11	7,616
<u>Drums</u>								
Freshwater drum	0	0	1	0	14	1	1	17
<u>Sculpins</u>								
Mottled sculpin	4	0	2	0	0	0	0	6
<u>Gobies</u>								
Round goby	0	0	0	0	22	0	0	22
Total Fish	53,231	4,045	8,574	16,638	18,109	9,291	3,488	113,376
Number of Species	44	29	41	34	40	28	30	61
Number of Hybrids	4	5	4	3	8	4	3	8

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 2

NUMBER OF FISH SPECIES AND NUMBER OF FISH PER SAMPLE DOWNSTREAM FROM THE NORTH SIDE WATER RECLAMATION PLANT EFFLUENT OUTFALL 1974 THROUGH 1996



location during any one sampling event from 1974 through 1980. The discontinuance of chlorination at the North Side WRP also apparently led to a reduction in the nuisance midge population in the North Shore Channel because of predation by these increased fish populations (9).

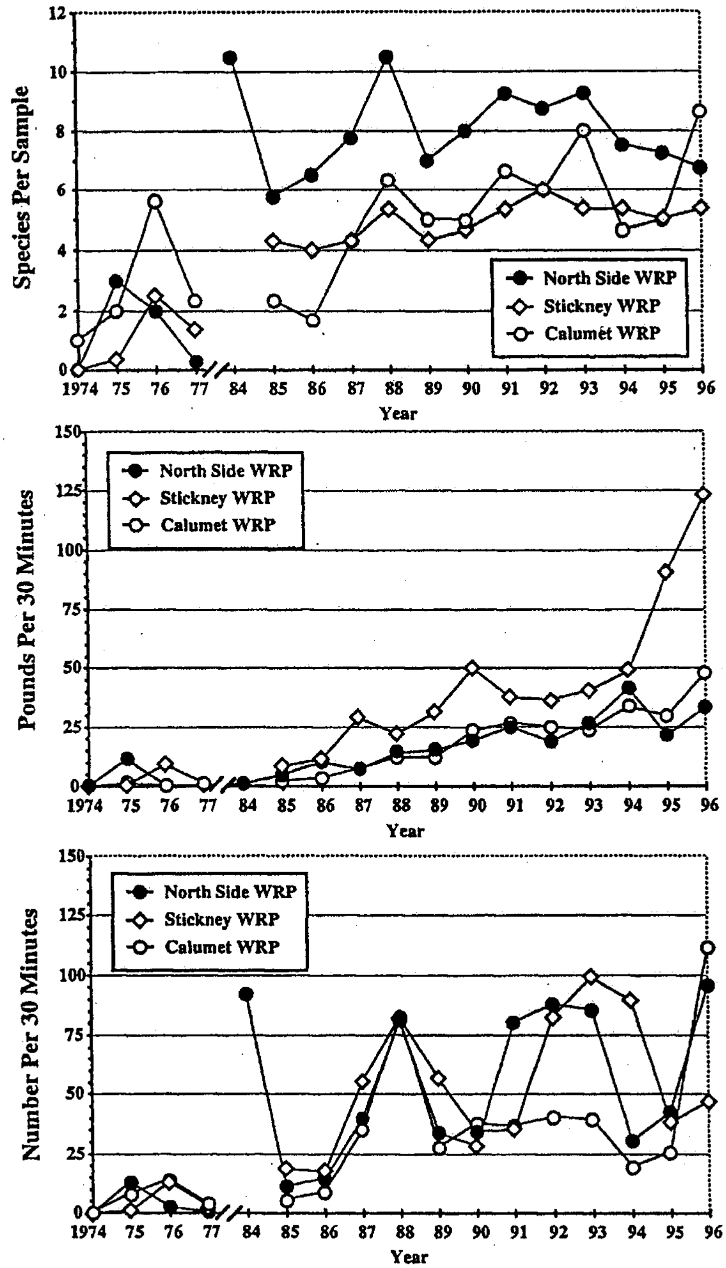
Comparing the years 1974 through 1977 plus 1985 (before TARP) versus 1986 through 1996 (after TARP) for all 20 locations sampled routinely for fish in the Chicago and Calumet River Systems, there has been a 150 percent increase in the abundance of fish, from an average of 43 fish CPUE to an average of 111 fish CPUE and a 50 percent increase in the number of fish species, from 41 species to 61 species. The number of fish species and CPUE, by both number and weight, increased downstream of the three WRPs after TARP went on-line in 1985 (Figure 3).

Thirty-two species of fish were collected from the Chicago and Calumet River Systems both at the start of this study during the period 1974 through 1977 and also in 1995. However, the proportion of game fish in the total collection had increased from 16 percent in the 1970's to 36 percent in 1995, primarily due to the 18 percent increase in the number of largemouth bass and the 4 percent increase in the number of bluegill sunfish. Maximum weight of individual largemouth bass collected from the Chicago and Calumet River Systems had also increased from 0.01 kg (0.02 pounds) in 1974 to 2.2 kg (4.8 pounds) in 1995.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 3

AVERAGE NUMBER OF FISH SPECIES COLLECTED PER SAMPLE AND WEIGHT AND NUMBER OF FISH IN TOTAL CATCH PER 30 MINUTES ELECTROFISHING DOWNSTREAM FROM THE NORTH SIDE, STICKNEY AND CALUMET WRP EFFLUENT OUTFALLS

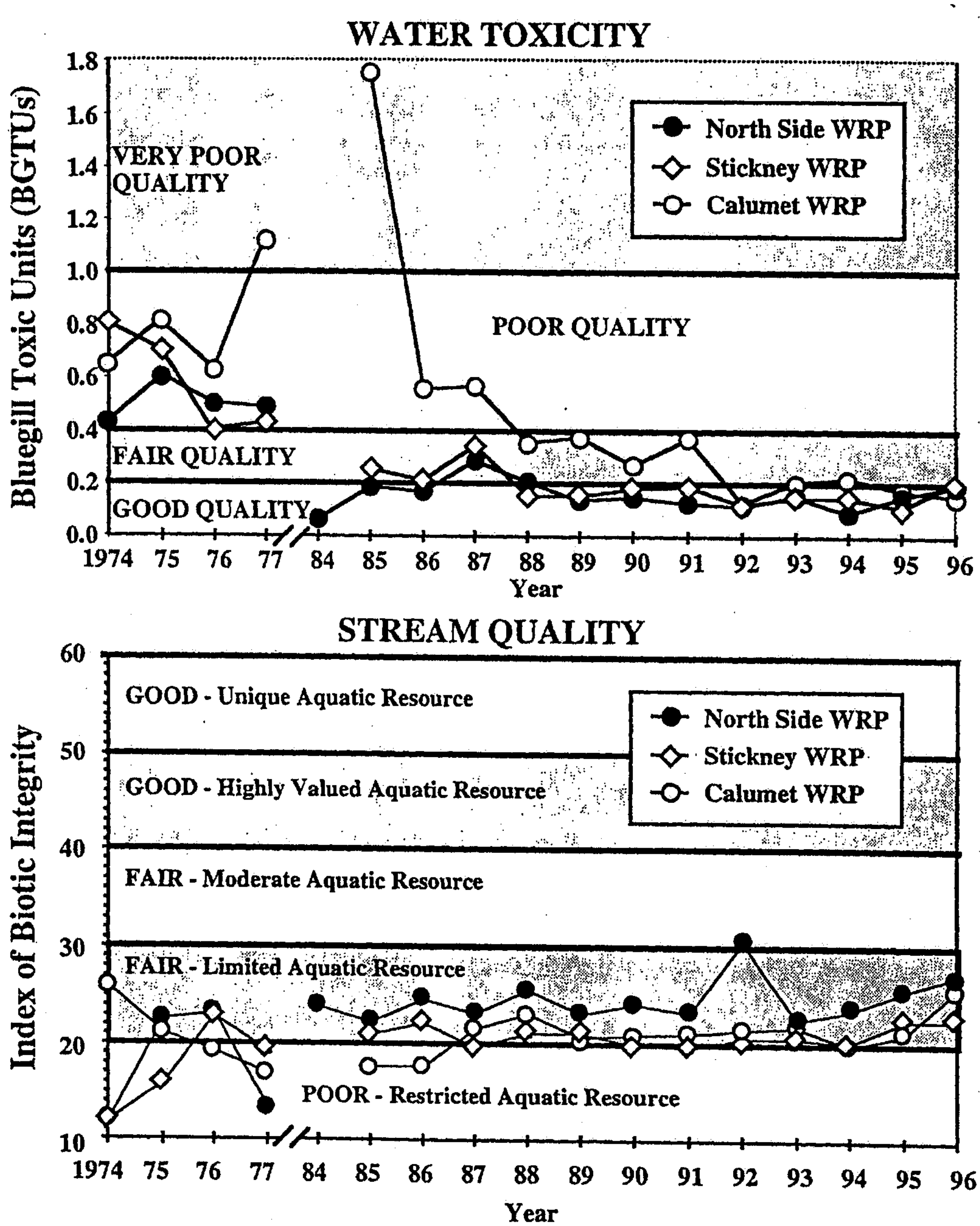


The water quality has improved with the cessation of effluent chlorination and the operation of TARP. Improvements occurred from 1974 to 1996 from poor to good water quality below the North Side and Stickney WRPs and from poor and very poor to fair water quality below the Calumet WRP (Figure 4). Depending on location in the waterway, effluent chlorination would have added a component toxicity of from 3 to 270 percent of the LC_{50} for bluegills to the existing toxic fraction in the water within five miles of a WRP outfall. Stream quality, as measured by the IBI, has improved from poor to fair from 1974 to 1996 downstream of the North Side, Stickney, and Calumet WRPs.

The SEPA stations have also shown an immediate benefit for the quality of the fish populations in the Calumet River System. Twenty-five fish species have been collected from the waterways at the five SEPA station locations during 1995 and 1996. Smallmouth bass and channel catfish were collected at SEPA stations on the Cal-Sag Channel. This was the first occurrence of these desirable game fish species in the Cal-Sag Channel collections. These game fish were evidently attracted by the elevated dissolved oxygen (DO) concentrations downstream of the waterfalls. At the time of fish collection during 1995, at SEPA Station 3 the DO was 7.8 mg/L, at SEPA Station 4 the DO was 7.6 mg/L, and at SEPA Station 5 the DO was 6.9 mg/L, while the DO in the main channel was 5.5, 4.6, and 4.2 mg/L, respectively.

FIGURE 4

WATER QUALITY AS DETERMINED BY THE BLUEGILL TOXICITY INDEX AND STREAM QUALITY AS DETERMINED BY THE INDEX OF BIOTIC INTEGRITY DOWNSTREAM FROM THE NORTH SIDE, STICKNEY AND CALUMET WRP EFFLUENT OUTFALLS



North Shore Channel

Forty-four fish species were collected from four locations on the North Shore Channel from 1974 through 1996, as shown in Figure 5. Twenty-one species were collected during the 1970s, 36 species during the 1980s and 34 species during the 1990s. The average catch of fish per 30 minutes electrofishing from the North Shore Channel was 39 fish with a total catch weight of 15 pounds during the 1970s, 237 fish weighing 19 pounds during the 1980s, and 246 fish weighing 22 pounds during the 1990s.

Water quality, as measured by the BTI, was poor during the 1970s and good during both the 1980s and 1990s. Stream quality for fish, as measured by the IBI, was poor during the 1970s and fair during the 1980s and 1990s.

North Branch Chicago River

Twenty-nine fish species were collected from two locations on the North Branch of the Chicago River from 1975 through 1996, as shown in Figure 6. Ten species were collected during the 1970s, 21 species during the 1980s and 22 species during the 1990s. The average catch of fish per 30 minutes electrofishing from the North Branch of the Chicago River was 1 fish with a total catch weight of less than one pound during the 1970s, 29 fish weighing 12 pounds during the 1980s, and 53 fish weighing 36 pounds during the 1990s.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 5

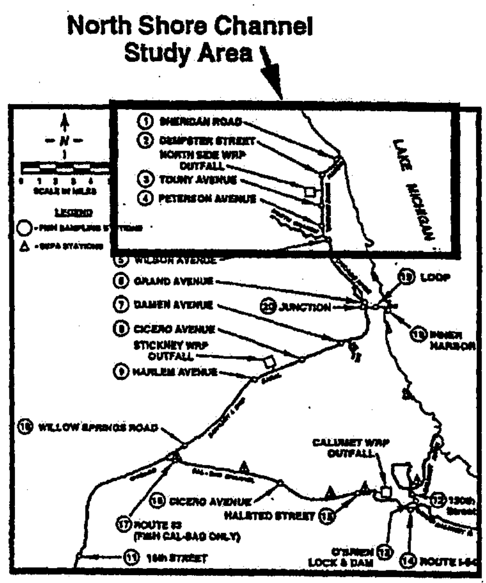
ABUNDANCE AND SPECIES COMPOSITION OF NORTH SHORE CHANNEL FISH WITH CHANGES IN WATER AND STREAM QUALITY 1974 THROUGH 1996

Forty-four fish species have been collected by the Research and Development Department from the North Shore Channel, primarily at four routine sample locations:

(1) Sheridan Road.
(2) Dempster Street
(3) Touhy Avenue
(4) Peterson Avenue

	1970s	1980s	1990s
Water Quality	Poor	Good	Good
Stream Quality	Poor	Fair	Fair
Species	21	36	34
Pounds[1]	15	19	22
Number[1]	39	237	246

[1]Per 30 Minutes Electrofishing



Chicago Waterway System

FISH SPECIES COLLECTED 1974 THROUGH 1996*

Herrings
Alewife 1,2,3,4
Gizzard shad 1,2,3,4

Salmon and Trouts
Rainbow trout 1,2,3
Brown trout 1
Brook trout 1
Lake trout 1
Coho salmon 1,3
Chinook salmon 1,2

Smelts
Rainbow smelt 1,2

Mudminnows
Central mudminnow 1,3,4

Pikes
Grass pickerel 1
Northern pike 1

Loaches
Oriental weatherfish 2,3,4

Minnows and Carps
Goldfish 1,2,3,4
Carp 1,2,3,4
Carp x Goldfish hybrid 1,2,3,4
Brassy minnow 2
Hornyhead chub 1
Golden shiner 1,2,3,4
Emerald shiner 1,4
Bigmouth shiner 4
Spottail shiner 1,2,3,4
Spotfin shiner 3
Sand shiner 1,4
Bluntnose minnow 1,2,3,4
Fathead minnow 1,2,3,4
Longnose dace 1,3,4
Creek chub 4

Suckers
White sucker 1,2,3,4

Freshwater catfishes
Black bullhead 1,2,3,4
Yellow bullhead 1,2

Sticklebacks
Brook stickleback 1,2,3,4
Threespine stickleback 1,2,3,4
Ninespine stickleback 1

Sunfishes
Rock bass 1,2,3
Green sunfish 1,2,3,4
Pumpkinseed 1,2,3,4
Orangespotted sunfish 1,2,3,4
Bluegill 1,2,3,4
Largemouth bass 1,2,3,4
White crappie 1
Black crappie 1,2,3,4
Hybrid sunfish 1,2,3,4

Perches
Johnny darter 1
Yellow perch 1,2,3,4

Sculpins
Mottled sculpin 1

*Numbers indicate North Shore Channel Station where species was collected.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 6

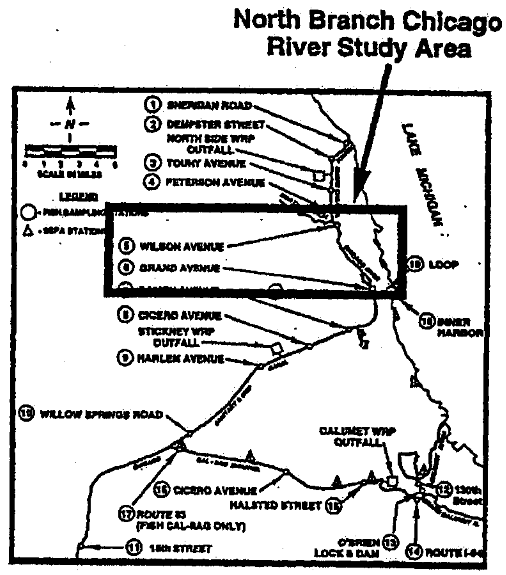
ABUNDANCE AND SPECIES COMPOSITION OF NORTH BRANCH CHICAGO RIVER FISH WITH CHANGES IN WATER AND STREAM QUALITY 1975 THROUGH 1996

Twenty-nine fish species have been collected by the Research and Development Department from the North Branch of the Chicago River, primarily at two routine sample locations:

(5) Wilson Avenue
(6) Grand Avenue

	1970s	1980s	1990s
Water Quality	Poor	Fair	Good
Stream Quality	Poor	Fair	Fair
Species	10	21	22
Pounds[1]	0	12	36
Number[1]	1	29	53

[1]Per 30 Minutes Electrofishing



Chicago Waterway System

FISH SPECIES COLLECTED 1975 THROUGH 1996*

Bowfins
Bowfin 5

Herrings
Alewife 5,6
Gizzard shad 5,6

Salmon and Trouts
Rainbow trout 6
Brook trout 6

Smelts
Rainbow smelt 6

Mudminnows
Central mudminnow 5

Minnows and Carps
Goldfish 5,6
Carp 5,6
Carp x Goldfish hybrid 5,6
Golden shiner 5,6
Emerald shiner 5,6
Spottail shiner 5,6
Bluntnose minnow 5,6
Fathead minnow 5,6

Suckers
White sucker 5

Loaches
Oriental weatherfish 5

Freshwater catfishes
Black bullhead 5,6
Yellow bullhead 6

Sticklebacks
Brook stickleback 5
Threespine stickleback 5,6

Temperate basses
White perch 6

Sunfishes
Rock bass 6
Green sunfish 5,6
Pumpkinseed 5,6
Orangespotted sunfish 5,6
Bluegill 5,6
Largemouth bass 5,6
Black crappie 5,6
Hybrid sunfish 5,6

Perches
Yellow perch 5,6

*Numbers indicate North Branch Station where species was collected.

Water quality, as measured by the BTI, was poor during the 1970s, fair during the 1980s, and good during the 1990s. Stream quality for fish, as measured by the IBI, was poor during the 1970s and fair during the 1980s and 1990s.

Chicago River

Forty-one fish species were collected from three locations on the Chicago River from 1975 through 1996, as shown in Figure 7. Twenty-one species were collected during the 1970s, 31 species during the 1980s and 32 species during the 1990s. The average catch of fish per 30 minutes electrofishing from the Chicago River was 23 fish with a total catch weight of 16 pounds during the 1970s, 56 fish weighing 35 pounds during the 1980s, and 71 fish weighing 65 pounds during the 1990s.

Water quality, as measured by the BTI, was good during all three decades. Stream quality for fish, as measured by the IBI, was fair during all three decades.

Chicago Sanitary and Ship Canal

Thirty-four fish species were collected from five locations on the Chicago Sanitary and Ship Canal from 1974 through 1996, as shown in Figure 8. Five species were collected during the 1970s, 29 species during the 1980s and 25 species during the 1990s. The average catch of fish per 30 minutes electrofishing from the Chicago Sanitary and Ship Canal was 2 fish with a total catch weight of one pound during the 1970s,

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 7

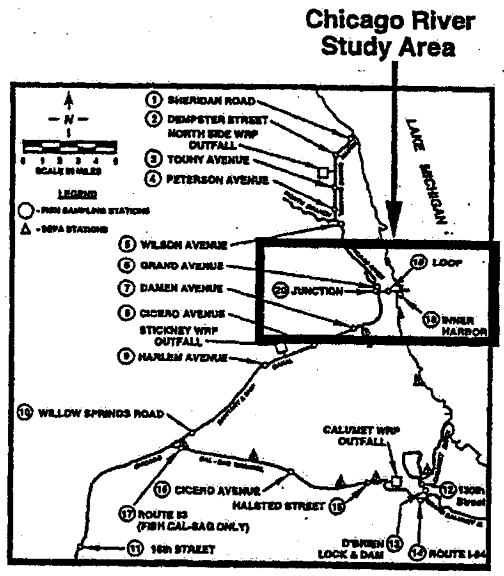
ABUNDANCE AND SPECIES COMPOSITION OF CHICAGO RIVER FISH WITH CHANGES IN WATER AND STREAM QUALITY 1975 THROUGH 1996

Forty-one fish species have been collected by the Research and Development Department from the Chicago River at three locations:

(18) Inner Harbor
(19) Loop (Franklin Street to Wabash Avenue)
(20) Junction of the North and South Branches of the Chicago River

	1970s	1980s	1990s
Water Quality	Good	Good	Good
Stream Quality	Fair	Fair	Fair
Species	21	31	32
Pounds[1]	16	35	65
Number[1]	28	56	71

[1]Per 30 Minutes Electrofishing



Chicago Waterway System

FISH SPECIES COLLECTED 1975 THROUGH 1996*

Herrings
Alewife 18,19,20
Gizzard shad 18,19,20

Salmon and Trouts
Rainbow trout 18,19
Brown trout 18,19,20
Brook trout 18
Lake trout 18
Coho salmon 18,19,20
Chinook salmon 18,19,20

Smelts
Rainbow smelt 18,19,20

Suckers
White sucker 20
Black buffalo 20

Freshwater catfishes
Black bullhead 18,20

Trout-perches
Trout-perch 18

Minnows and Carps
Goldfish 18,19,20
Grass carp 18
Carp 18,19,20
Carp x Goldfish hybrid 18,19,20
Golden shiner 18,19,20
Emerald shiner 18,19,20
Spottail shiner 18,19,20
Sand shiner 18
Bluntnose minnow 18,19,20
Fathead minnow 18,20
Central stoneroller 18

Silversides
Brook silversides 19

Sticklebacks
Brook stickleback 19,20
Threespine stickleback 18,19,20
Ninespine stickleback 18

Temperate basses
White perch 20
White bass 18,20

Sunfishes
Rock bass 18,19,20
Green sunfish 18,19,20
Pumpkinseed 18,19,20
Orangespotted sunfish 18,20
Bluegill 18,19,20
Smallmouth bass 18,19,20
Largemouth bass18,19,20
Black crappie 18,20
Hybrid sunfish 18,19,20

Perches
Johnny darter 18
Yellow perch 18,19,20

Drums
Freshwater drum 20

Sculpins
Mottled sculpin 18

*Numbers indicate Chicago River Station where species was collected.

FIGURE 8

ABUNDANCE AND SPECIES COMPOSITION OF CHICAGO SANITARY AND SHIP CANAL FISH WITH CHANGES IN WATER AND STREAM QUALITY 1974 THROUGH 1996

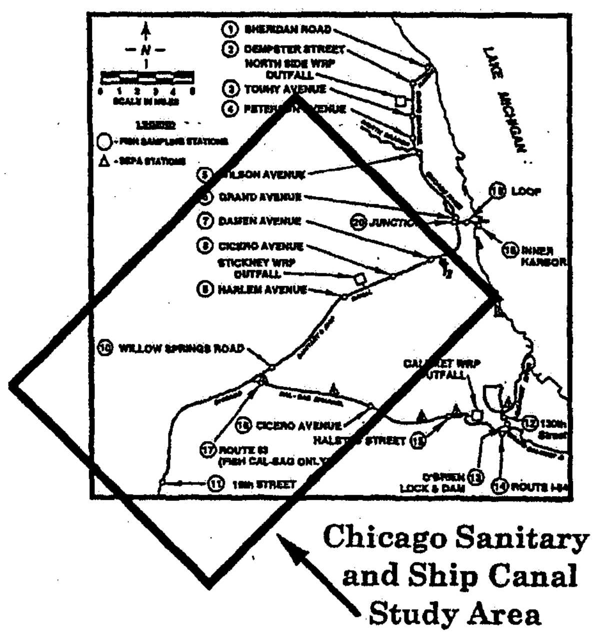
Thirty-four fish species have been collected by the Research and Development Department from the Chicago Sanitary and Ship Canal, primarily at five routine sample locations:

- **(7) Damen Avenue**
- **(8) Cicero Avenue**
- **(9) Harlem Avenue**
- **(10) Willow Springs Road**
- **(11) 16th Street, Lockport**

	1970s	1980s	1990s
Water Quality	Poor	Fair	Good
Stream Quality	Poor	Fair	Fair
Species	5	29	25
Pounds[1]	1	24	79
Number[1]	2	55	88

[1]Per 30 Minutes Electrofishing

Chicago Waterway System



FISH SPECIES COLLECTED 1974 THROUGH 1996*

Bowfins
Bowfin 11

Herrings
Alewife 7,8,9,11
Gizzard shad 7,8,9,10,11

Salmon and Trouts
Rainbow trout 7
Brown trout 9
Chinook salmon 9

Smelts
Rainbow smelt 7,8,9,10

Mudminnows
Central mudminnow 7,9,10,11

Pikes
Grass pickerel 9,11

Minnows and Carp
Goldfish 7,8,9,10,11
Carp 7,8,9,10,11
Carp x Goldfish hybrid 7,8,9,10,11
Golden shiner 7,8,9,11
Emerald shiner 7,8,9,10,11
Spottail shiner 7,8,9,10,11
Bluntnose minnow 7,8,9,10,11
Fathead minnow 7,8,9,10,11
Creek chub 8.11

Suckers
White sucker 7,11

Freshwater catfishes
Black bullhead 7,8,9,10,11
Yellow bullhead 8,9,10

Livebearers
Western mosquitofish 8,10

Sticklebacks
Brook stickleback 8
Threespine stickleback 7,8,9

Temperate basses
White perch 7
Yellow bass 11

Sunfishes
Rock bass 9
Green sunfish 7,8,9,10,11
Pumpkinseed 7,8,9,10,11
Orangespotted sunfish 7,11
Bluegill 7,8,9,10,11
Smallmouth bass (SEPA 5)
Largemouth bass 7,8,9,10,11
Black crappie 7,8,10,11
Hybrid sunfish 7,10

Perches
Yellow perch 7,8,9,10,11

*Numbers indicate Chicago Sanitary and Ship Canal Station where species was collected.

55 fish weighing 24 pounds during the 1980s, and 88 fish weighing 79 pounds during the 1990s.

Water quality, as measured by the BTI, was poor during the 1970s, fair during the 1980s, and good during the 1990s. Stream quality for fish, as measured by the IBI, was poor during the 1970s and fair during the 1980s and 1990s.

Calumet River

Forty fish species were collected from two locations on the Calumet River from 1974 through 1996, as shown in Figure 9. Fifteen species were collected during the 1970s, 34 species during the 1980s, and 33 species during the 1990s. The average catch of fish per 30 minutes electrofishing from the Calumet River was 86 fish with a total catch weight of 21 pounds during the 1970s, 253 fish weighing 79 pounds during the 1980s, and 119 fish weighing 53 pounds during the 1990s.

Water quality, as measured by the BTI, was good during all three decades. Stream quality for fish, as measured by the IBI, was fair during all three decades.

Little Calumet River

Twenty-eight fish species were collected from two locations on the Little Calumet River from 1974 through 1996, as shown in Figure 10. Fourteen species were collected during the 1970s, 22 species during the 1980s, and 20 species during

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 9

ABUNDANCE AND SPECIES COMPOSITION OF CALUMET RIVER FISH WITH CHANGES IN WATER AND STREAM QUALITY 1974 THROUGH 1996

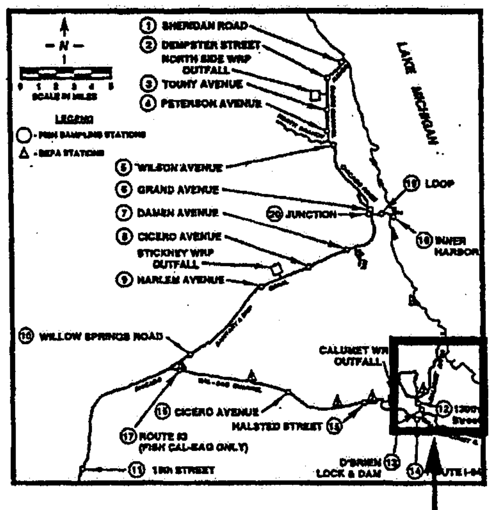
Forty fish species have been collected by the Research and Development Department from the Calumet River at two locations:

(12) 180th Street
(13) O'Brien Lock and Dam

	1970s	1980s	1990s
Water Quality	Good	Good	Good
Stream Quality	Fair	Fair	Fair
Species	15	34	33
Pounds[1]	21	79	53
Number[1]	86	253	119

[1]Per 30 Minutes Electrofishing

Chicago Waterway System



Calumet River Study Area

FISH SPECIES COLLECTED 1974 THROUGH 1996*

Bowfins
Bowfin 13

Freshwater eels
American eel 13

Herrings
Alewife 12,13
Gizzard shad 12,13

Salmon and Trouts
Rainbow trout 12,13
Coho salmon 13
Chinook salmon 12,13

Smelts
Rainbow smelt 12,13

Pikes
Grass pickerel 12

Suckers
Quillback 12
White sucker 12,13
Black buffalo 12

Minnows and Carps
Goldfish 12,13
Grass carp 12
Carp 12,13
Carp x Goldfish hybrid 12,13
Golden shiner 12,13
Emerald shiner 12,13
Spottail shiner 12,13
Sand shiner 12,13
Bluntnose minnow 12,13
Fathead minnow 12,13
Central stoneroller 13

Freshwater catfishes
Black bullhead 12,13
Channel catfish 12,13

Temperate basses
White perch 12,13
White bass 12
Striped bass x White bass hybrid (SEPA 1)

Sunfishes
Rock bass 12,13
Green sunfish 12,13
Pumpkinseed 12,13
Warmouth 13
Orangespotted sunfish 12,13
Bluegill 12,13
Smallmouth bass 12,13
Largemouth bass 12,13
White crappie 12,13
Black crappie 12,13
Hybrid sunfish 12,13

Perches
Johnny darter 12
Yellow perch 12,13

Drums
Freshwater drum 12,13

Gobies
Round goby 12,13

*Numbers indicate Calumet River Station where species was collected.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 10

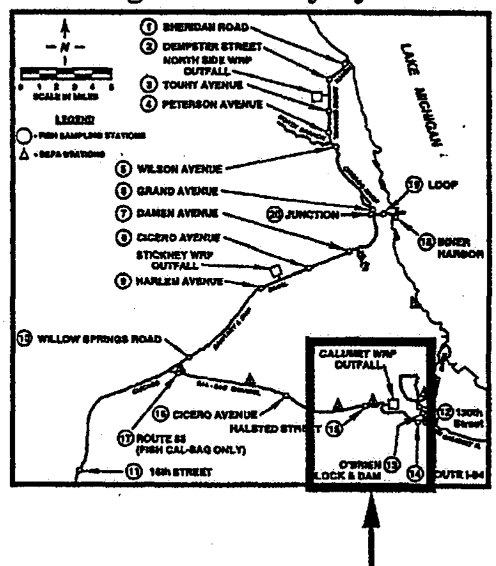
ABUNDANCE AND SPECIES COMPOSITION OF LITTLE CALUMET RIVER FISH WITH CHANGES IN WATER AND STREAM QUALITY 1974 THROUGH 1996

Twenty-eight fish species have been collected by the Research and Development Department from the Little Calumet River, primarily at two routine sample locations:
(14) Route I-94 and
(15) Halsted Street

	1970s	1980s	1990s
Water Quality	Poor	Poor	Fair
Stream Quality	Fair	Fair	Fair
Species	14	22	20
Pounds[1]	14	19	49
Number[1]	88	78	82

[1]Per 30 Minutes Electrofishing

Chicago Waterway System



Little Calumet River Study Area

FISH SPECIES COLLECTED 1974 THROUGH 1996*

Herrings
Alewife 14,15
Gizzard shad 14,15

Salmon and Trouts
Chinook salmon 15

Smelts
Rainbow smelt 14

Mudminnows
Central mudminnow 15

Pikes
Grass pickerel 14,15

Suckers
White sucker 14,15

Minnows and Carps
Goldfish 14,15
Carp 14,15
Carp x Goldfish hybrid 14,15
Golden shiner 14,15
Emerald shiner 14,15
Spottail shiner 14,15
Bluntnose minnow 14,15
Fathead minnow 14,15

Freshwater catfishes
Black bullhead 14,15
Channel catfish 14

Sticklebacks
Threespine stickleback (SEPA)

Livebearers
Western mosquitofish 15

Temperate basses
White perch 14,15
Yellow bass 14,15

Sunfishes
Green sunfish 14,15
Pumpkinseed 14,15
Orangespotted sunfish 14,15
Bluegill 14,15
Largemouth bass 14,15
Black crappie 14,15
Hybrid sunfish 14,15

Perches
Yellow perch 14,15

Drums
Freshwater drum 14

*Numbers indicate Little Calumet River Station where species was collected. The term SEPA means that the species was collected only near a Sidestream Elevated Pool Aeration Station.

the 1990s. The average catch of fish per 30 minutes electrofishing from the Little Calumet River was 33 fish with a total catch weight of 14 pounds during the 1970s, 78 fish weighing 19 pounds during the 1980s, and 82 fish weighing 49 pounds during the 1990s.

Water quality, as measured by the BTI, was poor during the 1970s and 1980s, and fair during the 1990s. Stream quality for fish, as measured by the IBI, was fair during all three decades.

Cal-Sag Channel

Thirty fish species were collected from two locations on the Cal-Sag Channel from 1974 through 1996, as shown in Figure 11. Twelve species were collected during the 1970s, 20 species during the 1980s, and 24 species during the 1990s. The average catch of fish per 30 minutes electrofishing from the Cal-Sag Channel was 4 fish with a total catch weight of less than one pound during the 1970s, 19 fish weighing 7 pounds during the 1980s, and 32 fish weighing 20 pounds during the 1990s.

Water quality, as measured by the BTI, was very poor during the 1970s, poor during the 1980s, and fair during the 1990s. Stream quality for fish, as measured by the IBI, was poor during the 1970s and fair during the 1980s and 1990s.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 11

ABUNDANCE AND SPECIES COMPOSITION OF CAL-SAG CHANNEL FISH WITH CHANGES IN WATER AND STREAM QUALITY 1974 THROUGH 1996

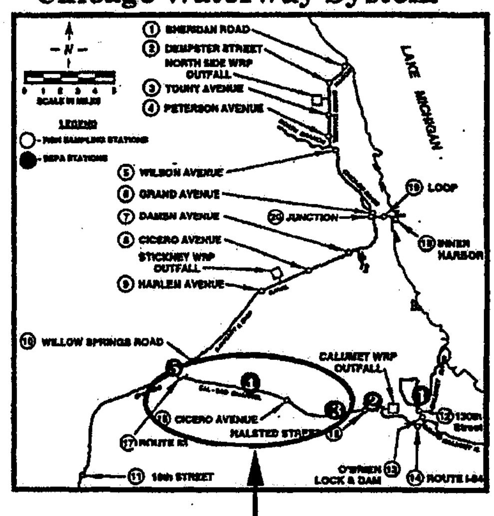
Thirty fish species have been collected by the Research and Development Department from the Cal-Sag Channel, primarily at two routine sample locations:

(16) Cicero Avenue
(17) Route 83

	1970s	1980s	1990s
Water Quality	Very Poor	Poor	Fair
Stream Quality	Poor	Fair	Fair
Species	12	20	24
Pounds[1]	0	7	20
Number[1]	4	19	32

[1]Per 30 Minutes Electrofishing

Chicago Waterway System



Cal-Sag Channel Study Area

FISH SPECIES COLLECTED 1974 THROUGH 1996*

Herrings
Alewife 16,17
Gizzard shad 16,17

Salmon and Trouts
Rainbow trout 17

Mudminnows
Central mudminnow 16,17

Minnows and Carps
Goldfish 16,17
Carp 16,17
Carp x Goldfish hybrid 16,17
Golden shiner 16,17
Emerald shiner 16,17
Spottail shiner 17
Bluntnose minnow 16,17
Fathead minnow 16,17
Creek chub 16,17

Suckers
White sucker 16

Freshwater catfishes
Black bullhead 16,17
Yellow bullhead 17
Channel catfish (SEPA)

Sticklebacks
Threespine stickleback (SEPA)

Temperate basses
White perch 17
Yellow bass 16,17

Sunfishes
Green sunfish 16,17
Pumpkinseed 16,17
Warmouth (SEPA)
Orangespotted sunfish 16
Bluegill 16,17
Smallmouth bass (SEPA)
Largemouth bass 16,17
White crappie 16
Black crappie 16,17
Hybrid sunfish 16,17

Perches
Yellow perch 17

Drums
Freshwater drum (SEPA)

*Numbers indicate Cal-Sag Channel Station where species was collected. The term SEPA means that the species was collected only near a Sidestream Elevated Pool Aeration Station.

SEPA Stations

Twenty-five fish species were collected at the locations of the five SEPA stations during 1995 and 1996 (Figure 12). Numbers of fish collected from Stations 1 through 20 during each year are listed in Appendix Tables AI-1 through AI-20.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 12

FISH IN THE WATERWAYS AT THE
SIDESTREAM ELEVATED POOL AERATION (SEPA) STATIONS
1995 THROUGH 1996

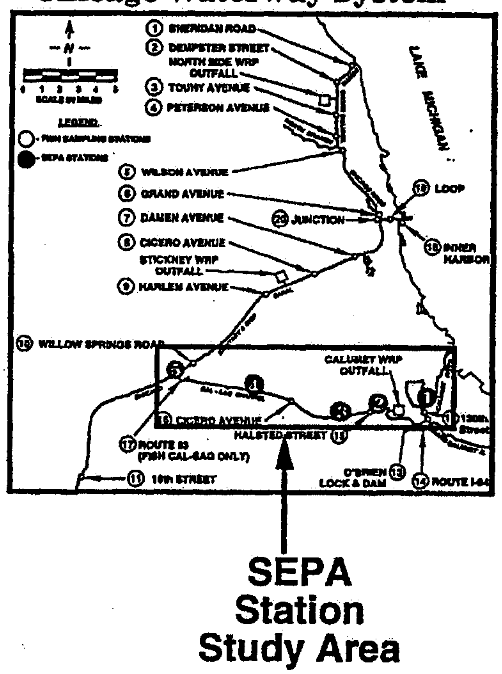
Twenty-five fish species and three hybrids have been collected by the Research and Development Department from the Calumet River, Little Calumet River and Cal-Sag Channel at the locations of the five Sidestream Elevated Pool Aeration (SEPA) Stations, during 1995 and 1996:

Calumet River
SEPA 1 - Torrence Avenue

Little Calumet River
SEPA 2 - 127th Street

Cal-Sag Channel
SEPA 3 - Western Avenue
SEPA 4 - Harlem Avenue
SEPA 5 - Junction of the Cal-Sag Channel with the Chicago Sanitary and Ship Canal

Chicago Waterway System



FISH SPECIES COLLECTED DURING 1995 AND 1996*

Herrings
Gizzard shad 1,2,3,4,5

Pikes
Grass pickerel 1

Minnows and Carps
Goldfish 1,2,3,4,5
Carp 1,2,3,4,5
Carp x goldfish hybrid 2
Golden shiner 2,3
Emerald shiner 1,2,3,4,5
Bluntnose minnow 1,2,3,4
Fathead minnow 1,2,3,4

Suckers
Quillback 1
White sucker 1,2,3,4

Freshwater catfishes
Black bullhead 3,4
Channel catfish 4,5

Sticklebacks
Threespine stickleback 2,3,4

Temperate basses
White perch 1,2
Yellow bass 3,4,5
Striped bass x white bass hybrid 1

Sunfishes
Rock bass 1
Green sunfish 1,2,3,4,5
Pumpkinseed 1,2,3,5
Warmouth 3
Bluegill 1,2,3,4,5
Hybrid sunfish 1,4
Smallmouth bass 1,3,4,5
Largemouth bass 1,2,3,4,5
Black crappie 4

Drums
Freshwater drum 1,4

Gobies
Round goby 1

*Numbers indicate the SEPA Station where the species was collected.

DISCUSSION

The increased fish populations below the North Side WRP outfall in the North Shore Channel, and North Branch of the Chicago River, and below the Stickney WRP outfall in the Chicago Sanitary and Ship Canal that occurred after the cessation of effluent chlorination on April 1, 1984, at both the North Side and Stickney WRPs were apparently responses to the absence of toxicity to fish following the removal of chlorine and chloramines from these waterways. Similarly, the improved water quality and fish populations that have occurred with the operation of TARP have resulted from the absence of the mixture of pollutants which had previously entered the Chicago Waterway System via the combined sewer system with every rainfall.

The increased numbers of the piscivorous largemouth bass may be one reason for the 16 percent decrease in the proportion of forage fish in the catch when the period 1974 through 1977 is compared with 1995. Also notable was the 12 percent decrease in the proportion of goldfish in the catch. The goldfish is a pollution tolerant and opportunistic species which does well when other species do not, but is otherwise a poor competitor.

The water quality for fish in the Chicago Waterway System is now, theoretically, of a quality good enough to support balanced fish populations. However, the waterway fish populations are still dominated by omnivores, tolerant forms and habitat generalists. This is primarily because water quality alone does not take into concern the condition of habitat, flow or other outside factors. The waterways of the Chicago Waterway System were not constructed to be fishable streams with diverse habitat types. They were built for navigation and water reclamation. It is unlikely that these waterways can achieve the same stream quality for fish as a natural habitat-rich waterway. However, these waterways can now be listed as limited aquatic resources and some segments could become moderate aquatic resources within the urban environment. For example, the game fish at the SEPA stations were evidently attracted by the elevated DO concentrations and unique habitat that the waterfall tailraces provide.

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APPENDIX AI

Number of Fish Collected from Each Station in the Chicago Waterway System from 1974 through 1996

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-1

NUMBER OF FISH COLLECTED FROM STATION 1 AT SHERIDAN ROAD (RIVER MILE 341.2) ON THE NORTH SHORE CHANNEL FROM 1974 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																			Grand Total
	1974	1975	1976	1977	1977[1]	1979	1980[2]	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	323	90	34	0	34	0	238	1	80	208	466	227	228	239	167	61	19	27	2442
Gizzard shad	0	2	0	0	0	0	0	0	1	6	80	11	15	3	29	1	1	18	4	171
Rainbow trout	0	1	0	0	0	0	0	4	4	1	1	0	0	1	1	0	0	1	0	14
Brown trout	0	0	0	8	0	2	0	0	0	4	2	2	0	5	1	2	1	1	0	28
Brook trout	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Lake trout	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Coho salmon	1	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	4
Chinook salmon	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	0	1	5
Rainbow smelt	0	0	1	0	0	47	0	1407	18	493	3	11	16	1	0	0	0	0	0	1997
Central mudminnow	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Northern pike	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Grass pickerel	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	2
Goldfish	275	180	18	20	40	7	6	62	25	40	115	106	37	95	49	13	22	32	6	1148
Carp	134	50	12	0	5	18	4	55	28	22	9	11	6	5	5	2	8	8	5	387
Carp x Goldfish	1	47	7	2	3	5	0	19	10	7	9	7	2	6	1	2	7	5	7	147
Hornyhead chub	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Golden shiner	0	0	0	2	0	0	0	37	34	49	103	124	216	378	18	3	6	5	1	976
Emerald shiner	0	0	0	0	0	0	0	14	2	0	0	5	0	0	1	0	0	0	0	22
Spottail shiner	0	27	2	1	0	20	0	85	8	40	104	231	62	29	31	29	37	4	0	710
Sand shiner	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Bluntnose minnow	0	321	166	0	0	18	0	1086	679	1443	1998	1296	3726	2379	3515	680	343	32	5	17687
Fathead minnow	0	0	22	0	0	107	0	1420	160	104	460	185	2012	484	124	29	2	0	0	5109
Longnose dace	0	0	0	0	0	0	0	0	0	0	2	0	3	0	1	0	0	0	0	6
White sucker	1	0	0	0	0	1	0	16	1	1	2	3	1	1	0	2	0	1	0	30
Black bullhead	0	0	0	0	0	0	0	61	0	10	16	6	0	2	2	8	11	6	4	126
Yellow bullhead	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	1	4
Brook stickleback	0	0	0	0	0	0	0	512	209	29	11	5	1	0	0	0	0	0	0	767
Threespine stickleback	0	0	0	0	0	0	0	0	0	0	1	0	0	1	8	8	0	0	0	18
Ninespine stickleback	0	0	1	0	0	25	0	0	0	0	0	0	0	0	0	0	0	1	0	27
Rock bass	0	1	2	0	0	0	0	1	1	6	20	9	2	9	1	4	4	2	2	64
Green sunfish	5	6	14	1	1	5	3	481	34	27	42	10	65	29	47	26	35	13	10	854
Pumpkinseed	1	0	2	0	0	3	0	38	2	3	5	6	2	6	4	0	14	0	0	86
Orangespotted sunfish	0	0	0	0	2	0	0	18	1	2	4	1	1	1	2	1	2	1	0	36
Bluegill	0	17	24	0	0	3	0	25	8	32	37	19	31	19	7	11	51	30	21	335
Largemouth bass	0	2	0	0	0	0	0	4	12	2	19	6	35	2	1	27	54	52	50	266
White crappie	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Black crappie	0	0	0	0	0	1	0	3	7	0	0	0	1	0	0	0	2	3	0	17
Green x Pumpkinseed	0	0	2	0	0	0	0	1	0	1	0	0	2	0	1	2	0	0	0	9
Green x Bluegill	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	2	1	1	0	7
Pumpkinseed x Bluegill	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	1	0	5
Johnny darter	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Yellow perch	0	117	1	0	0	5	0	919	294	343	205	23	1	2	0	9	0	1	4	1924
Mottled sculpin	0	0	0	0	0	0	0	1	0	1	0	2	0	0	0	0	0	0	0	4
Total Fish	418	1095	364	68	51	303	13	6508	1539	2748	3460	2549	6466	3687	4092	1029	666	238	149	35443
Total Species	6	13	13	6	4	16	2	23	21	24	24	25	22	22	22	19	18	20	15	39
Sample Events Per Year	3	3	1	2	2	2	1	5	3	3	3	3	4	4	2	2	2	2	2	

[1]Data for collection at Lincoln Street (River Mile 340.2).
[2]Data for collections from Bridge Street (River Mile 339.5) to Church Street (River Mile 338.7).

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-2

NUMBER OF FISH COLLECTED FROM STATION 2 AT DEMPSTER STREET (RIVER MILE 338.2) ON THE NORTH SHORE CHANNEL FROM 1975 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																	Grand Total
	1975	1976	1977	1979	1980[1]	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	0	13	0	9	0	1	0	36	17	2	30	2	1	0	4	115
Gizzard shad	0	0	0	0	0	0	0	6	4	7	18	0	116	0	2	11	24	188
Rainbow trout	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Chinook salmon	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Rainbow smelt	0	0	0	0	0	3	3	19	0	0	2	0	0	0	0	0	0	27
Goldfish	37	6	5	2	0	43	79	320	340	174	353	199	26	16	8	20	6	1634
Carp	4	3	2	17	0	12	3	15	71	7	17	23	3	3	8	10	2	200
Carp x Goldfish	20	7	0	8	0	15	15	18	41	14	59	36	3	9	12	21	4	282
Brassy minnow	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Golden shiner	0	0	0	0	0	4	29	75	117	275	171	166	20	9	8	5	5	884
Spottail shiner	0	0	0	0	0	3	10	12	9	4	29	3	17	8	25	0	3	123
Bluntnose minnow	0	0	0	0	0	4	41	38	9	51	75	404	100	20	3	2	4	751
Fathead minnow	0	1	0	25	0	424	154	194	244	1637	969	233	54	3	2	0	0	3940
White sucker	0	0	0	0	0	3	1	6	6	2	0	0	0	1	0	0	0	19
Oriental weatherfish	0	0	0	0	0	0	0	1	0	0	3	3	0	0	0	1	0	8
Black bullhead	0	0	0	0	0	23	28	43	27	34	6	12	0	2	2	0	9	186
Yellow bullhead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Brook stickleback	0	0	0	0	0	23	201	7	37	5	1	0	0	0	0	0	0	274
Threespine stickleback	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	3
Rock bass	0	0	0	0	0	0	0	0	1	0	0	3	0	0	0	0	0	4
Green sunfish	1	0	0	0	1	63	41	40	29	18	55	69	16	10	13	5	6	367
Pumpkinseed	0	0	0	0	0	4	0	15	8	1	2	14	4	10	5	7	3	73
Orangespotted sunfish	0	0	0	0	0	0	0	1	12	2	0	0	1	0	1	2	0	19
Bluegill	0	0	0	0	0	4	3	17	55	35	23	6	3	6	12	6	23	193
Largemouth bass	0	0	0	0	0	0	5	0	2	3	3	2	2	0	9	36	17	79
Black crappie	0	0	0	0	0	4	9	4	3	2	3	2	0	1	0	0	0	28
Green x Pumpkinseed	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	2
Green x Bluegill	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	1	4
Pumpkinseed x Bluegill	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	2
Yellow perch	0	0	0	0	0	473	482	292	366	10	2	0	0	0	0	0	0	1625
Total Fish	62	17	7	65	1	1115	1105	1126	1381	2318	1808	1177	399	101	111	128	113	11034
Total Species	3	3	2	4	1	16	15	20	18	18	18	15	15	13	14	13	12	26
Sample Events Per Year	1	1	2	4	2	4	3	3	3	3	4	4	2	2	2	2	2	

[1]Data for collections from Church Street (River Mile 338.7) to Oakton Street (River Mile 337.2).

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-3

NUMBER OF FISH COLLECTED FROM STATION 3 AT TOUHY AVENUE (RIVER MILE 336.1) ON THE NORTH SHORE CHANNEL FROM 1974 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																			Grand Total
	1974	1975	1976	1977	1979	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	0	0	0	0	0	12	0	0	0	0	8	2	7	58	0	0	0	87
Gizzard shad	0	0	0	0	0	0	0	0	2	21	84	23	36	83	135	524	1	130	477	1516
Rainbow trout	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Coho salmon	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Central mudminnow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Goldfish	0	1	0	0	0	0	1	21	10	41	82	26	51	44	4	3	10	15	22	331
Carp	0	0	2	0	3	0	2	22	8	8	36	17	35	8	3	9	9	2	4	168
Carp x Goldfish	0	1	0	0	0	0	0	6	4	7	23	11	25	11	4	9	8	7	2	118
Golden shiner	0	0	0	0	0	0	0	0	3	9	191	158	60	54	30	11	40	5	1	562
Spottail shiner	0	0	1	0	0	0	0	0	2	8	43	6	2	39	27	10	6	0	0	144
Spotfin shiner	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Bluntnose minnow	0	0	0	0	0	0	12	0	0	7	20	2	0	106	7	10	1	0	0	165
Fathead minnow	0	0	0	0	0	1	71	13	0	2	177	39	3	14	2	0	0	0	0	322
Longnose dace	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	3
White sucker	0	0	0	0	0	0	0	4	3	1	18	1	3	2	0	7	3	3	3	48
Oriental weatherfish	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	2
Threespine stickleback	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2
Black bullhead	0	0	0	0	0	0	1	17	5	6	1	2	4	8	0	1	1	1	0	47
Brook stickleback	0	0	0	0	0	0	18	10	8	3	11	9	1	0	0	0	0	0	0	60
Rock bass	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	2
Green sunfish	0	4	0	0	2	4	7	3	2	8	2	0	23	31	6	7	3	0	0	102
Pumpkinseed	0	0	0	0	0	0	0	1	0	0	4	0	1	0	0	1	5	0	0	12
Orangespotted sunfish	0	0	0	0	0	0	0	0	0	0	15	1	0	0	0	0	0	0	0	16
Bluegill	0	1	0	0	0	0	0	1	1	1	8	9	6	7	0	8	9	15	2	68
Largemouth bass	0	0	0	0	0	0	0	1	2	0	1	1	3	2	1	0	11	30	16	68
Black crappie	0	0	0	0	0	0	0	0	2	1	1	5	7	5	0	2	1	2	0	26
Green x Pumpkinseed	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2
Green x Bluegill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2
Yellow perch	0	0	0	0	0	0	2	1	26	3	91	0	0	0	0	0	0	0	0	123
																			0	
Total Fish	0	7	3	0	5	5	116	112	78	126	809	310	270	419	227	660	111	213	529	4000
Total Species	0	3	2	0	2	2	9	12	13	14	18	14	17	15	11	13	15	11	8	25
Sample Events Per Year	1	1	1	2	2	2	1	4	3	3	3	4	4	4	2	2	2	2	2	

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-4

NUMBER OF FISH COLLECTED FROM STATION 4 AT PETERSON AVENUE (RIVER MILE 334.6) ON THE NORTH SHORE CHANNEL FROM 1974 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																	Grand Total
	1974	1977	1979	1980[1]	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	0	0	0	5	0	1	0	1	3	2	3	1	0	1	0	17
Gizzard shad	0	0	0	0	0	0	0	2	3	9	28	158	49	4	0	13	75	341
Central mudminnow	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	3
Goldfish	0	0	0	0	7	13	10	3	64	32	8	19	3	10	8	4	1	182
Carp	0	0	2	2	6	27	22	1	18	3	2	5	0	2	3	4	0	97
Carp x Goldfish	0	0	1	1	2	7	4	0	8	4	4	6	0	3	4	1	0	45
Golden shiner	0	0	0	0	1	0	1	23	12	2	3	8	3	7	11	0	1	72
Emerald shiner	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	3
Bigmouth shiner	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Spottail shiner	0	0	0	0	1	0	3	4	31	1	1	124	14	4	0	0	0	183
Sand shiner	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2
Bluntnose minnow	0	0	0	0	100	1	8	155	49	1	0	313	17	17	6	0	0	667
Fathead minnow	0	0	0	0	171	32	1	115	34	0	1	35	4	1	0	0	0	394
Longnose dace	0	0	0	0	6	0	0	1	0	0	0	0	0	0	0	0	0	7
Creek chub	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
White sucker	0	0	0	0	0	1	0	0	7	4	1	9	0	0	1	3	0	26
Oriental weatherfish	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Black bullhead	0	0	0	0	0	2	9	4	0	0	2	4	0	0	0	0	0	21
Brook stickleback	0	0	0	0	68	3	2	53	13	11	1	0	0	0	0	0	0	151
Threespine stickleback	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	2
Green sunfish	0	0	4	0	0	46	10	35	25	4	7	38	6	12	5	8	0	200
Pumpkinseed	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	3
Orangespotted sunfish	0	0	0	0	0	0	0	0	6	0	0	2	0	0	1	1	0	10
Bluegill	0	0	0	0	2	2	2	20	7	2	3	15	2	12	15	6	7	95
Largemouth bass	0	0	0	0	0	1	0	1	0	1	4	0	3	2	3	30	15	60
Black crappie	0	0	0	0	0	0	3	1	0	0	2	1	2	3	0	0	0	12
Green x Pumpkinseed	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Green x Bluegill	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Yellow perch	0	0	0	0	2	1	106	2	43	1	0	0	0	0	0	0	0	155
Total Fish	0	0	7	3	367	141	182	426	322	77	71	744	107	78	57	71	100	2753
Total Species	0	0	2	1	11	12	12	18	15	14	15	17	12	12	9	9	6	26
Sample Events Per Year	1	2	2	1	2	4	3	3	3	3	4	4	2	2	2	2	2	

[1]Data for collections from Peterson Avenue to Foster Avenue (River Mile 333.6).

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-5

NUMBER OF FISH COLLECTED FROM STATION 5 AT WILSON AVENUE (RIVER MILE 332.7) NORTH BRANCH CHICAGO RIVER FROM 1975 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																Grand Total
	1975[1]	1976	1977	1979[1]	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Bowfin	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Alewife	0	0	0	0	4	1	0	2	1	1	1	1	0	0	0	0	11
Gizzard shad	1	0	0	0	0	0	5	94	5	8	62	20	5	0	42	18	260
Central mudminnow	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Goldfish	21	1	1	0	22	12	29	113	82	26	88	8	26	17	13	16	475
Carp	12	0	3	4	22	11	18	39	14	23	35	9	27	12	18	12	259
Carp x Goldfish	1	0	0	0	5	0	1	23	4	8	24	5	10	1	1	0	83
Golden shiner	0	0	0	0	0	0	1	9	6	8	51	2	11	1	6	8	103
Emerald shiner	0	0	0	0	0	0	0	1	0	1	2	0	1	0	0	0	5
Spottail shiner	0	0	0	0	1	0	2	5	1	0	4	3	0	0	1	0	17
Bluntnose minnow	0	0	0	0	0	0	16	2	6	1	44	185	15	1	0	0	270
Fathead minnow	0	0	0	0	18	0	1	17	4	0	4	1	0	0	0	0	45
White sucker	0	0	0	0	0	0	0	0	0	0	2	1	3	3	4	0	13
Oriental weatherfish	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Black bullhead	0	1	0	0	3	3	8	3	0	5	3	0	0	0	0	1	27
Brook stickleback	0	0	0	0	6	3	14	6	0	0	0	0	0	0	0	0	29
Threespine stickleback	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
Green sunfish	6	0	0	0	25	4	28	16	5	12	56	8	28	4	9	5	206
Pumpkinseed	0	0	0	0	0	0	0	0	2	0	8	0	1	0	0	1	12
Orangespotted sunfish	0	0	0	0	2	0	0	3	1	1	0	0	0	0	1	0	8
Bluegill	0	1	0	0	1	1	45	40	13	9	22	3	11	9	26	41	222
Largemouth bass	1	0	0	0	0	0	1	0	2	3	3	1	6	8	43	45	113
Black crappie	0	1	0	0	0	0	0	1	0	3	2	0	0	2	1	0	10
Green x Orangespotted	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Green x Pumpkinseed	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0	5
Green x Bluegill	0	0	0	0	0	0	0	0	0	2	3	0	0	0	0	0	5
Pumpkinseed x Bluegill	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Yellow perch	0	0	0	0	2	1	0	97	0	0	0	0	0	0	0	0	100
Total Fish	42	4	4	4	111	36	174	473	146	111	415	248	144	59	165	148	2283
Total Species	5	4	2	1	11	8	13	16	13	13	16	13	11	10	11	10	22
Sample Events Per Year	1	1	2	1	4	3	3	3	3	4	4	2	2	2	2	2	

[1]Data from fish collection at the junction of the North Shore Channel with the North Branch Chicago River (River Mile 333.5).

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-6

NUMBER OF FISH COLLECTED FROM STATION 6 AT GRAND AVENUE (RIVER MILE 326.0) NORTH BRANCH CHICAGO RIVER FROM 1975 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																		Grand Total
	1975[1]	1976	1977[1]	1977	1980[2]	1980[3]	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	0	0	1	0	0	1	0	1	2	3	4	1	7	8	0	13	41
Gizzard shad	0	0	0	0	0	0	5	12	16	114	12	15	15	202	25	3	43	0	462
Rainbow trout	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	4
Brook trout	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Rainbow smelt	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	2
Goldfish	6	0	1	0	0	0	5	0	2	28	34	57	18	25	7	22	15	14	234
Carp	0	0	0	0	0	0	15	24	4	22	20	35	50	24	21	51	20	23	309
Carp x Goldfish	0	0	0	0	0	0	1	0	2	12	7	15	20	7	6	8	7	1	86
Golden shiner	0	0	0	0	0	0	1	0	0	2	1	1	4	0	0	0	0	0	9
Emerald shiner	0	0	0	0	0	0	0	0	0	3	2	5	0	1	1	0	0	3	15
Spottail shiner	2	0	0	0	0	0	0	1	3	1	6	3	0	1	0	0	0	0	17
Bluntnose minnow	0	0	0	0	0	0	0	6	14	9	11	26	15	25	0	0	0	0	106
Fathead minnow	0	0	0	0	0	0	2	1	1	0	0	0	0	0	0	0	0	0	4
Black bullhead	0	0	0	0	0	0	7	1	1	1	0	1	1	0	1	0	0	0	13
Yellow bullhead	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Threespine stickleback	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	61	62
White perch	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	3
Rock bass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Green sunfish	2	0	0	0	0	1	2	4	4	1	0	5	11	1	2	1	1	2	37
Pumpkinseed	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	3
Orangespotted sunfish	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Bluegill	0	0	0	0	0	0	2	3	4	6	5	9	12	3	3	1	5	9	62
Largemouth bass	0	0	0	0	0	0	1	1	1	1	2	6	1	3	4	4	37	24	85
Black crappie	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	2
Green x Bluegill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Pumpkinseed x Bluegill	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Yellow perch	1	0	0	0	2	0	47	9	15	125	1	0	0	0	0	0	0	0	200
Total Fish	11	0	1	0	3	1	89	67	69	327	103	185	153	294	79	100	128	152	1762
Total Species	4	0	1	0	2	1	11	14	12	14	11	15	11	11	10	8	6	10	24
Sample Events Per Year	1	1	2	2	1	1	4	4	3	4	4	4	4	2	2	2	2	2	

[1]Data from fish collection at Diversey Avenue (River Mile 330).
[2]Data from fish collection at North Avenue (River Mile 327.8).
[3]Data from fish collection at Chicago Avenue (River Mile 326.5).

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-7

NUMBER OF FISH COLLECTED FROM STATION 7 AT DAMEN AVENUE (RIVER MILE 321.1) ON THE CHICAGO SANITARY AND SHIP CANAL FROM 1975 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year														Grand Total
	1975	1977	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	5	1	46	2	4	0	0	7	0	0	0	0	65
Gizzard shad	0	0	1	2	6	13	7	5	16	71	19	2	20	38	200
Rainbow trout	0	0	1	0	1	0	0	0	0	0	0	0	0	0	2
Rainbow smelt	0	0	23	2	20	0	0	0	1	0	0	0	0	0	46
Central mudminnow	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2
Goldfish	0	0	58	28	39	123	81	107	203	204	44	12	20	5	924
Carp	0	0	41	49	53	57	113	166	151	84	31	86	69	41	941
Carp x Goldfish	0	0	5	2	6	5	4	3	3	1	4	2	2	0	37
Golden shiner	0	0	1	1	4	13	11	12	31	18	13	3	3	0	110
Emerald shiner	0	0	0	0	5	47	4	0	1	2	0	0	0	0	59
Spottail shiner	0	0	1	0	2	5	3	0	0	4	0	0	0	0	15
Bluntnose minnow	0	0	5	0	2	29	7	24	71	354	12	6	1	0	511
Fathead minnow	0	0	7	0	1	4	1	0	2	6	0	0	3	0	24
White sucker	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Black bullhead	0	0	24	43	46	33	27	11	0	0	2	1	1	0	188
Threespine stickleback	0	0	0	0	0	0	0	0	1	0	0	0	0	1	2
White perch	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Green sunfish	0	0	6	3	1	0	1	3	3	2	2	1	0	1	23
Pumpkinseed	0	0	0	0	0	0	0	1	5	6	0	2	1	1	16
Orangespotted sunfish	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2
Bluegill	0	0	5	2	38	8	5	8	10	5	1	0	0	4	86
Largemouth bass	0	0	0	0	5	7	10	16	37	5	9	8	36	10	143
Black crappie	0	0	0	1	2	0	0	0	0	1	0	1	0	1	6
Green x Bluegill	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Yellow perch	0	0	22	12	17	175	82	0	0	0	0	0	0	0	308
Total Fish	0	0	205	147	297	523	361	356	535	770	137	124	156	102	3713
Total Species	0	0	14	11	19	14	15	10	12	14	9	10	9	9	23
Sample Events Per Year	1	2	4	4	4	4	4	4	4	2	2	2	2	2	

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-8

NUMBER OF FISH COLLECTED FROM STATION 8 AT CICERO AVENUE (RIVER MILE 317.3) ON THE CHICAGO SANITARY AND SHIP CANAL FROM 1974 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																Grand Total
	1974	1975	1976	1977	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	2	0	0	0	0	2	2	1	1	3	0	1	0	0	12
Gizzard shad	0	0	0	0	0	0	9	24	1	4	32	12	153	6	9	41	291
Rainbow smelt	0	0	0	0	5	1	1	2	10	1	0	0	0	0	0	0	20
Goldfish	0	0	7	0	84	81	47	704	330	382	337	41	41	36	38	19	2147
Carp	0	0	3	0	36	32	113	126	110	183	197	37	93	106	134	107	1277
Carp x Goldfish	0	0	4	0	2	8	3	16	9	5	13	3	2	6	6	6	83
Golden shiner	0	0	0	0	0	0	2	6	1	6	2	4	2	3	2	0	28
Emerald shiner	0	0	0	0	0	1	2	31	5	2	0	8	0	0	0	0	49
Spottail shiner	0	0	0	0	0	0	0	12	1	1	18	0	1	0	0	0	33
Bluntnose minnow	0	0	0	0	0	0	1	39	10	152	435	111	11	123	19	0	901
Fathead minnow	0	0	0	0	3	3	0	9	3	10	10	5	1	16	2	0	62
Creek chub	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Black bullhead	0	0	0	0	5	15	4	1	5	4	2	0	0	1	0	0	37
Yellow bullhead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Mosquitofish	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Brook stickleback	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	2
Threespine stickleback	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	2
Green sunfish	0	0	0	0	2	0	2	0	0	1	3	5	0	1	2	0	16
Pumpkinseed	0	0	0	0	0	0	0	0	0	1	3	2	0	0	1	0	7
Bluegill	0	0	0	0	0	0	2	1	1	0	2	0	0	0	2	0	8
Largemouth bass	0	0	0	0	0	0	0	0	0	1	9	7	0	13	33	16	79
Black crappie	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	3
Yellow perch	0	0	0	0	0	21	15	205	82	0	0	0	0	0	0	0	323
Total Fish	0	0	17	0	137	162	202	1180	571	754	1065	238	305	312	249	191	5383
Total Species	0	0	4	0	6	7	12	15	14	14	14	11	8	10	11	6	22
Sample Events Per Year	1	1	1	2	3	4	4	4	4	4	4	2	2	2	2	2	

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-9

NUMBER OF FISH COLLECTED FROM STATION 9 AT HARLEM AVENUE (RIVER MILE 314.0) ON THE CHICAGO SANITARY AND SHIP CANAL FROM 1974 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																Grand Total
	1974	1975	1977	1977[1]	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	0	0	0	0	11	0	0	0	0	2	0	0	0	0	13
Gizzard shad	0	0	0	0	1	0	2	62	11	1	6	30	3	0	15	41	172
Brown trout	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Chinook salmon	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Rainbow smelt	0	0	0	0	3	0	1	0	0	0	0	0	0	0	0	0	4
Central mudminnow	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2
Grass pickerel	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Goldfish	0	0	0	0	238	45	166	219	169	133	62	83	1	8	19	4	1147
Carp	0	2	1	5	103	34	63	101	76	79	70	31	14	27	67	55	728
Carp x Goldfish	0	0	0	0	12	0	5	6	0	2	1	1	0	1	2	0	30
Golden shiner	0	0	0	0	0	0	1	1	0	1	14	2	0	0	0	0	19
Emerald shiner	0	0	0	0	0	0	0	6	7	0	15	1	0	1	0	0	30
Spottail shiner	0	0	0	0	3	3	0	1	2	0	0	16	2	0	0	0	27
Bluntnose minnow	0	0	0	0	1	1	12	27	68	33	122	263	264	99	0	1	891
Fathead minnow	0	0	0	0	2	0	0	3	0	0	12	9	33	14	1	0	74
Black bullhead	0	0	0	0	2	1	0	2	0	0	0	0	0	0	0	0	5
Yellow bullhead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Threespine stickleback	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5
Rock bass	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Green sunfish	0	0	0	0	3	0	3	0	0	0	1	0	0	0	0	0	7
Pumpkinseed	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	4
Bluegill	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	4	7
Largemouth bass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	13	16
Yellow perch	0	0	0	0	41	2	132	3	54	0	0	0	0	0	0	0	232
Total Fish	0	2	1	5	412	86	396	433	388	249	308	439	318	150	107	124	3418
Total Species	0	1	1	1	12	6	9	12	8	5	10	10	7	5	5	8	23
Sample Events Per Year	1	1	2	2	4	4	4	4	4	4	4	2	2	2	2	2	

[1]Data for collections at the C & IW Railroad Bridge (River Mile 314.8).

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-10

NUMBER OF FISH COLLECTED FROM STATION 10 AT WILLOW SPRINGS ROAD (RIVER MILE 307.9) ON THE CHICAGO SANITARY AND SHIP CANAL FROM 1974 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																Grand Total
	1974	1975	1976	1977	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Gizzard shad	0	0	0	0	0	1	0	92	1	0	1	6	0	0	0	2	103
Rainbow smelt	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Central mudminnow	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	3
Goldfish	0	0	1	1	52	178	285	395	200	34	29	8	17	35	4	0	1239
Carp	0	0	1	2	5	16	16	24	22	65	23	15	5	29	25	40	288
Carp x Goldfish	0	0	0	0	0	0	1	0	1	0	3	1	0	0	0	0	6
Emerald shiner	0	0	0	0	0	0	0	1	0	8	0	0	0	0	1	0	10
Spottail shiner	0	0	0	0	0	1	0	0	1	1	1	0	0	1	0	0	5
Bluntnose minnow	0	0	0	0	0	0	1	13	2	28	29	76	119	132	33	2	435
Fathead minnow	0	0	0	0	0	0	0	2	0	1	0	2	4	262	4	0	275
Black bullhead	0	0	0	0	1	1	0	0	2	0	0	0	0	0	0	0	4
Yellow bullhead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Mosquitofish	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Green sunfish	0	0	0	0	0	0	3	0	0	2	8	0	0	2	4	0	19
Pumpkinseed	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	3	6
Bluegill	0	0	0	0	0	1	1	0	0	1	0	1	0	0	1	1	6
Largemouth bass	0	0	0	0	0	0	0	0	1	1	2	1	1	3	5	9	23
Black crappie	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Green x Pumpkinseed	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Yellow perch	0	0	0	0	1	2	5	3	10	0	0	0	0	0	0	0	21
Total Fish	0	0	2	3	60	201	312	531	240	142	100	110	146	466	78	57	2448
Total Species	0	0	2	2	5	8	6	8	8	10	9	7	5	9	9	6	18
Sample Events Per Year	1	1	1	2	3	4	3	4	4	4	4	2	2	2	2	2	

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-11

NUMBER OF FISH COLLECTED FROM STATION 11 AT 16TH STREET IN LOCKPORT (RIVER MILE 292.1) ON THE CHICAGO SANITARY AND SHIP CANAL FROM 1975 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year															Grand Total
	1975	1976	1977	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Bowfin	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Alewife	0	0	0	0	0	6	0	0	0	0	1	0	1	0	0	8
Gizzard shad	0	0	0	0	0	0	290	41	10	11	23	143	34	37	67	656
Central mudminnow	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	8
Grass pickerel	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Goldfish	0	38	1	11	14	29	9	8	8	17	2	3	23	2	1	166
Carp	0	15	20	24	30	41	19	32	41	55	14	36	19	37	60	443
Carp x Goldfish	0	6	0	4	1	2	2	5	0	2	0	2	1	0	2	27
Golden shiner	0	0	0	0	0	0	1	0	2	2	0	1	0	0	0	6
Emerald shiner	0	0	0	0	1	0	98	83	4	3	0	1	0	0	0	190
Spottail shiner	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	2
Bluntnose minnow	0	0	0	2	0	1	3	0	0	0	0	1	0	1	0	8
Fathead minnow	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2
Creek chub	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
White sucker	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Black bullhead	0	4	0	5	2	1	0	0	2	0	0	0	0	0	0	14
Yellow bass	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	6
Green sunfish	0	0	0	1	1	2	2	1	32	3	0	0	0	4	1	47
Pumpkinseed	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	3
Orangespotted sunfish	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Bluegill	0	0	0	2	5	0	1	1	0	1	0	1	1	0	2	14
Largemouth bass	0	0	0	0	0	0	0	0	1	6	0	0	5	2	11	25
Black crappie	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	3
Yellow perch	0	0	0	2	5	6	1	11	0	0	0	0	0	0	0	25
Total Fish	0	64	21	53	67	89	430	183	101	103	41	194	84	84	144	1658
Total Species	0	4	2	9	8	8	13	8	9	9	5	8	6	7	6	23
Sample Events Per Year	1	1	2	3	4	3	4	4	4	4	2	2	2	2	2	

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-12

NUMBER OF FISH COLLECTED FROM STATION 12 AT 130TH STREET (RIVER MILE 327.0) ON THE CALUMET RIVER FROM 1976 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																Grand Total
	1976	1977	1980	1983[1]	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	4	0	2	0	0	0	0	0	20	28	1	0	2	0	0	0	57
Gizzard shad	16	5	19	82	47	3	26	506	156	333	117	78	60	32	47	102	1629
Rainbow trout	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Chinook salmon	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	4
Rainbow smelt	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	2
Grass pickerel	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Goldfish	6	7	1	8	1	0	1	4	3	6	1	3	0	1	1	1	44
Grass carp	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Carp	22	15	2	18	14	32	16	45	45	37	19	9	10	5	4	20	313
Carp x Goldfish	0	1	0	0	0	0	0	0	1	3	0	1	0	0	0	0	6
Golden shiner	0	2	1	8	12	0	4	0	2	1	1	0	0	0	0	3	34
Emerald shiner	51	7	2	0	0	0	6	18	17	223	4	0	8	0	1	57	394
Spottail shiner	0	3	2	0	9	0	2	0	0	1	1	0	0	0	0	0	18
Sand shiner	0	0	2	0	3	0	0	0	0	1	0	0	0	0	0	0	6
Bluntnose minnow	784	60	452	165	1521	333	568	555	76	85	67	1	2	10	28	37	4744
Fathead minnow	0	0	8	1	15	2	1	1	1	23	2	0	0	0	0	0	54
Quillback	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	3
White sucker	0	0	0	0	1	2	0	2	1	5	1	2	0	1	0	6	21
Black buffalo	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Black bullhead	0	0	0	3	2	0	0	0	0	0	0	0	0	0	0	0	5
Channel catfish	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	3
White bass	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	2
White perch	0	0	0	0	1	0	24	20	69	114	36	18	5	4	0	7	298
Rock bass	0	0	0	0	0	0	0	0	0	0	0	0	2	2	4	6	14
Green sunfish	14	2	14	61	29	17	52	36	14	12	20	9	7	5	1	2	295
Pumpkinseed	4	0	5	70	23	17	11	27	31	4	20	24	12	4	4	3	259
Orangespotted sunfish	0	1	5	164	23	22	10	18	1	0	0	0	0	0	0	0	244
Bluegill	0	0	1	10	1	2	8	30	35	15	25	5	1	1	8	2	144
Smallmouth bass	0	0	0	0	0	0	0	0	0	0	1	0	1	3	4	18	27
Largemouth bass	41	2	5	34	20	19	34	85	42	26	45	23	13	63	16	29	497
White crappie	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	5
Black crappie	1	0	2	7	1	1	0	0	0	0	0	0	0	0	0	0	12
Green x Pumpkinseed	0	0	0	0	0	0	1	2	0	0	1	0	0	0	0	0	4
Green x Bluegill	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	2
Pumpkinseed x Bluegill	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Pumpkinseed x Orangespot.	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Johnny darter	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Yellow perch	12	4	68	5	153	323	13	62	16	0	0	0	0	0	0	0	656
Freshwater drum	0	0	0	0	0	0	0	0	2	0	1	0	2	0	2	0	7
Round goby	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	4
				0												0	
Total Fish	955	109	591	642	1878	774	779	1412	535	924	369	173	125	134	121	293	9814
Total Species	11	11	17	15	20	13	17	15	19	18	22	10	13	13	13	14	35
Sample Events Per Year	1	2	1	1	3	3	3	4	4	4	4	2	2	2	2	2	

[1]Data from a collection in Lake Calumet.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-13

NUMBER OF FISH COLLECTED FROM STATION 13 AT O'BRIEN LOCK AND DAM (RIVER MILE 326.2) ON THE CALUMET RIVER FROM 1974 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year															Grand Total
	1974	1975	1977	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Bowfin	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
American eel	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Alewife	0	0	0	6	2	0	7	638	13	0	0	0	0	0	0	666
Gizzard shad	32	177	12	25	8	113	798	136	154	101	118	153	13	4	69	1913
Rainbow trout	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	2
Coho salmon	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Chinook salmon	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	3
Rainbow smelt	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	3
Goldfish	2	9	0	2	1	2	4	18	3	6	2	3	7	4	0	63
Carp	28	42	12	92	51	30	83	61	32	38	29	3	6	14	52	573
Carp x Goldfish	1	3	5	6	0	0	0	5	1	1	2	1	1	0	0	26
Golden shiner	0	5	0	0	0	1	4	16	1	6	7	13	5	0	0	58
Emerald shiner	0	130	1	20	29	0	88	4	12	87	2	0	1	6	36	416
Spottail shiner	0	0	0	1	0	3	2	31	0	1	0	0	0	0	0	38
Sand shiner	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Bluntnose minnow	0	167	35	882	200	563	191	47	29	137	49	82	155	157	103	2797
Fathead minnow	0	0	0	13	49	9	2	0	1	6	0	1	0	0	0	81
Central stoneroller	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
White sucker	0	0	0	0	0	0	0	2	0	1	1	3	7	12	4	30
Black bullhead	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	3
Channel catfish	0	0	0	0	0	0	1	2	0	1	0	0	0	0	0	4
White perch	0	0	0	0	0	2	26	64	11	17	2	1	0	0	0	123
Rock bass	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	5
Green sunfish	0	3	29	23	39	66	44	39	103	123	7	22	9	5	6	518
Pumpkinseed	0	1	7	7	10	13	55	37	7	49	34	14	12	12	8	266
Warmouth	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Orangespotted sunfish	0	0	1	12	3	13	27	8	0	0	2	0	0	1	0	67
Bluegill	0	2	2	1	10	9	31	45	12	110	28	22	6	28	20	326
Smallmouth bass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4
Largemouth bass	1	17	7	11	15	30	23	27	14	84	35	90	87	63	66	570
White crappie	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Black crappie	0	0	0	5	7	2	1	0	2	2	2	0	1	1	3	26
Green x Orangespotted	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Green x Pumpkinseed	0	0	0	0	1	2	0	1	1	4	0	1	0	0	0	10
Green x Bluegill	0	0	0	0	0	2	0	0	2	4	1	0	0	0	1	10
Pumpkinseed x Orangespotted	0	0	0	0	2	2	0	4	0	0	0	0	0	0	0	8
Pumpkinseed x Bluegill	0	0	0	0	0	0	2	1	0	0	1	0	0	0	0	4
Bluegill x Orangespotted	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	3
Yellow perch	18	37	0	104	100	169	32	13	4	1	1	2	0	0	0	481
Freshwater drum	0	0	0	2	0	0	1	0	0	0	0	3	0	0	0	6
Round goby	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	4
Total Fish	82	593	111	1213	529	1036	1428	1201	404	781	323	415	311	313	375	9115
Total Species	5	11	9	17	16	18	22	19	16	19	15	15	13	15	12	34
Sample Events Per Year	1	3	2	3	3	3	4	4	4	4	2	2	2	2	2	

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-14

NUMBER OF FISH COLLECTED FROM STATION 14 AT ROUTE I-94 (RIVER MILE 324.7) ON THE LITTLE CALUMET RIVER FROM 1975 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																Grand Total
	1975	1976	1977	1977[1]	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	0	0	0	0	0	7	3	0	0	0	7	0	2	0	19
Gizzard shad	32	47	31	61	159	45	207	370	132	154	511	100	290	53	68	166	2426
Rainbow smelt	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Grass pickerel	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Goldfish	60	19	6	20	27	8	27	202	70	31	34	11	24	14	0	1	554
Carp	19	24	31	67	45	22	17	52	60	58	66	38	12	17	28	18	574
Carp x Goldfish	2	7	9	3	1	0	3	6	13	6	11	1	0	3	4	0	69
Golden shiner	1	0	0	0	0	0	5	2	9	13	6	2	4	2	0	1	45
Emerald shiner	30	10	32	3	0	0	3	167	20	255	22	75	6	27	7	21	678
Spottail shiner	0	0	0	0	0	0	0	8	2	7	15	1	0	0	0	0	33
Bluntnose minnow	16	5	14	4	298	14	33	8	0	1	10	57	3	15	1	29	508
Fathead minnow	1	0	0	1	9	1	1	3	0	1	0	0	0	0	0	0	17
White sucker	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Black bullhead	0	0	0	1	1	0	2	1	1	4	2	0	1	0	0	0	13
Channel catfish	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
White perch	0	0	0	0	0	0	6	71	46	92	43	50	12	29	21	10	380
Yellow bass	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	7	8
Green sunfish	0	1	0	11	0	0	1	0	1	0	2	0	0	0	0	1	17
Pumpkinseed	0	1	0	0	7	0	19	19	14	18	10	64	7	27	20	51	257
Orangespotted sunfish	0	0	0	0	1	0	1	12	2	0	0	0	0	0	0	0	16
Bluegill	3	0	0	0	1	0	5	18	7	2	3	8	2	3	0	4	56
Largemouth bass	11	0	4	2	3	7	6	7	2	1	12	5	12	15	9	12	108
Black crappie	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Green x Pumpkinseed	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	2
Yellow perch	0	0	0	0	92	6	6	10	1	0	0	0	0	0	0	0	115
Freshwater drum	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Total Fish	175	114	127	173	644	105	342	964	383	643	748	415	380	207	160	321	5901
Total Species	9	7	6	10	11	9	15	17	15	13	13	13	12	12	8	12	24
Sample Events Per Year	1	1	2	2	3	3	3	4	4	4	4	2	2	2	2	2	

[1]Data for collections at Indiana Avenue (River Mile 322.4).

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-15

NUMBER OF FISH COLLECTED FROM STATION 15 AT HALSTED STREET (RIVER MILE 320.1) ON THE LITTLE CALUMET RIVER FROM 1974 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year																	Grand Total
	1974	1975	1976	1977	1983	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	0	0	0	0	0	0	3	27	0	0	0	0	0	0	0	30
Gizzard shad	0	26	0	0	4	23	22	367	240	120	40	34	32	85	14	29	247	1283
Chinook salmon	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Central mudminnow	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2
Grass pickerel	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Goldfish	0	0	1	3	0	6	0	1	327	93	122	74	13	13	46	4	13	716
Carp	0	2	2	1	6	11	3	15	134	36	49	46	20	22	20	18	36	421
Carp x Goldfish	0	2	1	0	1	6	2	2	9	3	5	7	1	1	5	2	3	50
Golden shiner	0	0	0	0	0	0	0	0	31	5	4	3	1	12	1	6	5	68
Emerald shiner	0	0	0	0	0	0	0	0	440	3	1	6	1	0	0	5	23	479
Spottail shiner	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Bluntnose minnow	0	0	0	0	0	0	0	0	4	0	0	2	1	1	0	1	2	11
Fathead minnow	0	0	0	0	0	8	1	0	19	0	0	0	0	1	0	0	1	30
White sucker	0	0	0	0	0	0	0	0	0	0	0	1	0	4	0	1	1	7
Black bullhead	0	0	1	1	0	1	0	0	0	3	2	0	0	0	0	0	0	8
Mosquitofish	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
White perch	0	0	0	0	0	0	0	0	9	0	0	3	4	1	3	0	5	25
Yellow bass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
Green sunfish	0	0	55	7	0	0	0	2	10	0	4	19	0	1	1	3	2	104
Pumpkinseed	0	0	0	0	0	0	0	0	2	0	0	4	0	0	1	2	3	12
Orangespotted sunfish	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Bluegill	1	0	2	4	0	0	0	10	12	3	0	7	0	0	0	0	1	40
Largemouth bass	0	0	0	0	0	0	0	0	1	1	0	6	1	1	3	3	7	23
Black crappie	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Green x Pumpkinseed	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Pumpkinseed x Orangespotted	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Yellow perch	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3
Total Fish	1	30	67	16	11	56	29	397	1245	295	227	215	74	142	94	74	353	3326
Total Species	1	2	7	5	2	5	4	5	16	10	7	14	8	10	8	10	15	24
Sample Events Per Year	1	1	1	2	1	3	3	3	4	4	4	4	2	2	2	2	2	

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-16

NUMBER OF FISH COLLECTED FROM STATION 16 AT CICERO AVENUE (RIVER MILE 314.9) ON THE CAL-SAG CHANNEL FROM 1974 THROUGH 1996

Fish Species or Hybrid Cross	Year																	Grand Total
	1974[1]	1975[1]	1976	1977	1977[1]	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Gizzard shad	0	31	0	1	0	0	1	1	107	19	45	39	53	3	13	2	47	362
Central mudminnow	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	3
Goldfish	1	0	12	2	0	0	0	0	22	18	51	64	5	5	0	3	3	186
Carp	0	0	10	1	0	0	2	4	59	41	19	49	28	22	18	35	40	328
Carp x Goldfish	0	0	0	0	0	0	0	0	3	6	5	3	1	4	0	1	0	23
Golden shiner	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2
Emerald shiner	0	0	1	0	0	0	1	0	12	1	1	3	18	1	0	48	6	92
Bluntnose minnow	0	0	0	0	0	0	0	0	3	0	0	0	7	3	1	0	5	19
Fathead minnow	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	3
Creek chub	0	0	2	0	0	0	0	0	1	0	0	0	0	1	0	0	0	4
White sucker	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	3
Black bullhead	0	0	3	0	0	0	1	3	3	0	0	0	0	0	0	0	0	10
Yellow bass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Green sunfish	0	0	25	0	0	0	0	8	4	0	6	8	0	6	1	0	3	61
Pumpkinseed	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	3
Orangespotted sunfish	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Bluegill	0	0	5	0	1	0	2	10	1	2	5	12	0	6	0	1	1	46
Largemouth bass	0	0	0	0	0	0	0	0	0	2	2	1	0	3	0	6	3	17
White crappie	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Black crappie	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2
Green x Pumpkinseed	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2
Total Fish	1	31	60	5	1	0	7	27	218	92	135	184	113	54	33	98	111	1170
Total Species	1	1	8	4	1	0	5	6	11	9	8	10	6	9	4	7	11	20
Sample Events Per Year	1	1	1	2	2	3	3	3	4	4	4	4	2	2	2	2	2	

[1]Data for fish collection at Ashland Avenue (River Mile 319.0).

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-17

NUMBER OF FISH COLLECTED FROM STATION 17 AT ROUTE 83 (RIVER MILE 304.2) ON THE CAL-SAG CHANNEL FROM 1975 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year															Grand Total
	1975[1]	1976	1977	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	0	0	0	4	0	0	0	3	0	0	0	0	0	0	7
Gizzard shad	0	0	0	1	55	7	100	9	4	66	67	31	0	4	291	635
Rainbow trout	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Central mudminnow	0	1	0	1	0	3	0	0	1	0	0	0	0	0	0	6
Goldfish	16	1	2	3	1	6	18	14	12	16	0	1	2	0	0	92
Carp	1	0	0	11	8	16	76	20	23	30	5	15	13	17	26	261
Carp x Goldfish	0	0	0	2	1	1	7	2	1	0	0	1	0	1	0	16
Golden shiner	0	0	0	0	1	0	4	0	0	0	0	1	0	0	0	6
Emerald shiner	0	0	0	0	0	1	3	1	1	2	3	0	0	1	2	14
Spottail shiner	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Bluntnose minnow	0	0	0	0	0	0	1	0	1	2	1	4	1	0	3	13
Fathead minnow	0	0	0	12	0	0	3	0	3	0	0	2	1	0	0	21
Creek chub	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Black bullhead	0	0	0	10	3	7	0	0	1	1	0	0	0	0	0	22
Yellow bullhead	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
White perch	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Yellow bass	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	3
Green sunfish	0	0	1	35	5	118	19	6	153	23	5	35	6	22	22	450
Pumpkinseed	0	0	0	0	1	0	1	1	0	6	1	0	0	0	0	10
Bluegill	0	0	1	3	2	28	4	2	46	10	7	39	7	13	8	170
Largemouth bass	0	0	0	3	1	5	5	12	10	5	4	8	2	13	9	77
Black crappie	1	0	0	0	0	2	1	0	0	0	0	0	0	0	0	4
Green x Pumpkinseed	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Yellow perch	0	0	0	1	2	6	2	0	0	0	0	0	0	0	0	11
Total Fish	18	2	4	83	84	201	244	67	260	163	93	138	33	71	363	1824
Total Species	3	2	3	11	11	12	13	8	13	11	8	10	8	6	8	22
Sample Events Per Year	1	1	2	4	4	3	4	4	4	4	2	2	2	2	2	

[1]Data for fish collection at 86th Avenue (River Mile 309.7).

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-18

NUMBER OF FISH COLLECTED FROM STATION 18 AT THE INNER HARBOR (RIVER MILE 327.0) ON THE CHICAGO RIVER FROM 1975 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year														Grand Total
	1975	1976	1977	1980	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	2	36	0	12	20	109	4	35	1	70	0	0	1	0	290
Gizzard shad	15	0	0	1	0	2	85	1	0	1	371	0	3	0	479
Rainbow trout	0	0	1	0	1	0	2	0	1	1	0	0	0	2	8
Brown trout	0	0	0	0	2	8	6	7	3	0	0	1	0	0	27
Brook trout	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Lake trout	0	0	0	0	3	0	0	0	0	0	0	0	0	0	3
Coho salmon	0	0	0	0	3	0	1	4	0	0	0	0	0	0	8
Chinook salmon	0	0	1	0	1	0	0	6	0	1	0	0	0	0	9
Rainbow smelt	0	0	0	0	8	1	9	1	0	1	0	0	0	0	20
Goldfish	1	18	0	0	4	7	6	9	6	10	2	2	3	0	68
Grass carp	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Carp	3	9	8	1	6	11	20	10	21	13	21	9	6	17	155
Carp x Goldfish	0	1	0	0	1	0	4	2	7	4	0	1	1	0	21
Golden shiner	0	2	0	1	0	20	3	7	1	3	0	1	0	0	38
Emerald shiner	0	0	0	1	13	5	2	17	0	24	0	0	0	0	62
Spottail shiner	0	0	0	0	4	0	1	1	50	2	0	0	0	1	59
Sand shiner	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Bluntnose minnow	7	222	6	8	48	7	9	28	503	69	0	7	0	1	915
Fathead minnow	0	0	0	1	7	0	0	0	2	0	0	0	0	0	10
Central stoneroller	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2
Black bullhead	0	1	4	3	6	1	7	4	4	0	1	7	2	0	40
Trout-perch	0	0	0	1	0	0	0	0	2	0	0	0	0	0	3
Threespine stickleback	0	0	0	0	0	0	0	0	1	2	0	0	0	0	3
Ninespine stickleback	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2
White bass	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Rock bass	0	63	19	1	12	20	47	88	130	41	27	44	18	25	535
Green sunfish	0	3	0	3	41	23	38	196	117	22	6	7	2	0	458
Pumpkinseed	0	4	0	2	0	1	2	1	23	8	0	5	0	1	47
Orangespotted sunfish	0	0	3	0	1	0	2	4	0	0	0	0	0	0	10
Bluegill	3	3	0	0	303	29	24	35	68	11	16	46	9	6	553
Smallmouth bass	0	0	0	0	0	3	3	2	22	12	5	6	4	1	58
Largemouth bass	6	4	0	0	18	6	18	39	41	9	6	97	61	13	318
Black crappie	0	1	1	0	0	1	1	5	1	0	0	0	0	0	10
Green x Pumpkinseed	0	0	0	0	0	0	0	0	1	1	0	0	0	0	2
Green x Bluegill	0	0	0	0	0	0	0	1	0	0	2	0	1	0	4
Pumpkinseed x Bluegill	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Johnny darter	0	0	0	1	10	0	1	0	3	1	0	0	0	0	16
Yellow perch	0	0	0	17	327	335	208	3	3	1	0	1	0	1	896
Mottled sculpin	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2
Total Fish	39	371	43	53	839	592	503	507	1011	307	457	235	111	68	5136
Total Species	9	15	8	14	21	20	23	23	21	20	9	13	10	10	35
Sample Events Per Year	1	1	2	1	3	3	3	4	4	2	2	2	2	2	

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-19

NUMBER OF FISH COLLECTED FROM STATION 19 AT THE LOOP (RIVER MILE 326.0) ON THE CHICAGO RIVER FROM 1980 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year											Grand Total
	1980	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	0	1	82	0	52	3	0	0	0	0	1	139
Gizzard shad	0	0	18	3	0	47	0	0	0	0	1	69
Rainbow trout	0	0	1	1	0	0	0	0	0	0	0	2
Brown trout	0	0	2	1	2	0	0	0	0	0	0	5
Coho salmon	0	0	0	0	1	0	0	0	0	0	0	1
Chinook salmon	0	0	0	0	0	1	0	0	0	0	0	1
Rainbow smelt	0	12	0	0	0	0	0	0	0	0	0	12
Goldfish	0	0	2	15	25	9	5	2	4	1	1	64
Carp	2	27	44	57	82	78	22	15	6	27	19	379
Carp x Goldfish	0	0	0	3	1	0	1	0	0	1	1	7
Golden shiner	0	0	0	0	1	0	0	0	0	0	0	1
Emerald shiner	0	0	19	0	0	0	0	0	0	0	0	19
Spottail shiner	0	0	2	0	0	0	1	0	0	0	2	5
Bluntnose minnow	0	10	3	0	3	10	5	0	0	0	0	31
Brook silverside	0	0	0	0	0	0	0	0	0	0	1	1
Brook stickleback	0	1	0	0	0	0	0	0	0	0	0	1
Threespine stickleback	0	0	0	0	0	0	0	1	0	0	1	2
Rock bass	0	0	0	0	0	2	3	2	2	0	2	11
Green sunfish	0	10	10	2	6	9	8	1	2	0	1	49
Pumpkinseed	0	3	0	0	1	1	0	0	1	0	1	7
Bluegill	0	7	0	1	2	9	0	0	0	0	3	22
Smallmouth bass	0	0	0	0	1	1	0	0	0	0	0	2
Largemouth bass	0	0	0	0	2	7	2	0	3	26	4	44
Green sunfish x Bluegill	0	0	0	0	0	0	0	0	0	0	1	1
Yellow perch	0	196	188	75	9	8	3	0	0	0	0	479
Total Fish	2	267	371	158	188	185	50	21	18	55	39	1354
Total Species	1	9	11	9	14	13	9	5	6	4	12	24
Sample Events Per Year	1	3	3	3	4	4	2	2	2	2	2	

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-20

NUMBER OF FISH COLLECTED FROM STATION 20 AT THE NBCR/SBCR[1] JUNCTION (RIVER MILE 325.5) ON THE CHICAGO RIVER FROM 1976 THROUGH 1996

Fish Species or Hybrid Cross (x)	Year													Grand Total
	1976	1977	1980	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	
Alewife	11	0	0	18	4	27	10	26	4	8	0	3	0	111
Gizzard shad	0	0	0	22	13	74	20	210	6	0	0	1	27	373
Brown trout	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Coho salmon	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Chinook salmon	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Rainbow smelt	0	0	0	1	0	0	0	0	1	0	0	0	0	2
Goldfish	12	2	0	0	29	21	47	40	21	44	21	15	18	270
Carp	10	2	1	32	24	68	85	65	25	53	42	38	46	491
Carp x Goldfish	3	0	0	1	3	48	11	8	1	7	1	3	2	88
Golden shiner	6	0	3	0	0	2	11	1	2	0	0	0	0	25
Emerald shiner	0	0	0	12	1	2	0	2	1	0	0	0	18	36
Spottail shiner	0	0	0	0	0	24	6	11	0	0	0	0	0	41
Bluntnose minnow	0	0	0	15	17	50	84	133	22	13	6	0	0	340
Fathead minnow	1	0	1	0	0	1	0	0	0	0	0	0	0	3
White sucker	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Black buffalo	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Black bullhead	0	0	0	1	0	1	0	0	0	0	0	0	0	2
Brook stickleback	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Threespine stickleback	0	0	0	0	0	0	0	0	0	0	0	0	14	14
White bass	0	0	0	0	0	1	0	0	0	0	0	0	0	1
White perch	0	0	0	0	1	3	0	3	1	2	1	0	0	11
Rock bass	0	0	0	0	0	1	2	4	1	1	1	1	0	11
Green sunfish	0	0	2	10	12	3	17	12	7	7	5	0	1	76
Pumpkinseed	0	0	0	0	1	5	6	4	0	1	0	0	1	18
Orangespotted sunfish	0	0	0	0	0	0	0	1	0	1	0	0	0	2
Bluegill	0	0	0	5	27	9	17	19	3	4	1	1	2	88
Smallmouth bass	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Largemouth bass	0	0	0	3	3	10	9	7	1	3	6	18	32	92
Black crappie	0	0	0	0	1	0	1	1	0	0	0	0	0	3
Green x Bluegill	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Pumpkinseed x Bluegill	0	0	0	0	3	0	0	0	0	0	0	0	0	3
Yellow perch	0	0	0	14	2	9	3	1	0	0	0	0	0	29
Freshwater drum	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Total Fish	43	4	7	134	143	359	332	548	97	146	85	80	161	2139
Total Species	5	2	4	11	15	17	17	17	14	13	8	7	9	30
Sample Events Per Year	1	2	1	3	3	3	4	4	2	2	2	2	2	

[1]NBCR/SBCR denotes North Branch of the Chicago River and South Branch of the Chicago River.

Attachment M4

Table 1. Data Availability, Metrics and Methods

Assessment Factor	Applicability	Rankin (2004), CAWS UAA, Statement of Reasons	Habitat Evaluation and Improvement Study
Number of Instream Sampling Sites	Natural and artificial systems	**20 sampling sites based on availability of fish data, no consideration of physical habitat**	**30 sampling sites based on consideration of physical habitat, geospatially integrated with continuous monitoring stations and shoreline/ bank-edge inventory and assessment**
Distance between Sampling Sites	Natural and artificial systems	**Min: 0.5 miles (0.8 km) Max: 15.8 miles (25.4 km) Mean: 4.3 miles (6.9 km)**	**Min: 0.25 miles (0.4 km) Max: 9.6 miles (15.3 km) Mean: 2.9 miles (4.7 km) Continuous shoreline/bank-edge inventory and assessment**
Type and Extent of Substrates	Natural and artificial systems	Numerous sediment samples available - ***not used in Aquatic Life Use designation Analyses***	**Geospatial integration of historic and new sediment sampling data**
Substrate Quality	Natural and artificial systems	Sediment chemistry and contaminant data available – ***not used in Aquatic Life Use designation Analyses***	**Review and evaluation of sediment quality data, including organic and inorganic chemical data, as well as sediment toxicity data; geospatial referencing of historic sediment chemistry and contaminant data**
Type and Extent of Instream Habitat Cover	Natural and artificial systems	**Data at 20 sampling sites, sites located based on available fisheries data**	**Data at 30 sampling sites, sites located based on physical habitat characteristics**
Type and Extent of Shoreline and Bank-Edge Habitats	Natural and artificial systems	***Unknown, not surveyed or inventoried.* Qualitative observations only.**	**Geospatially referenced, continuous digital shoreline video for both banks of the entire CAWS, for inventory and assessment**
Type and Extent of Riparian Cover	Natural and artificial systems	***Unknown, not surveyed or inventoried.* Qualitative observations only.**	**Geospatially referenced, continuous digital shoreline video for both banks of the entire CAWS, for inventory and assessment**
Flow Regime and Water Levels	N/A to CAWS as flows and water levels are regulated for flood control, conveyance of wastewater, navigation	Flow, water level, and hydraulic modeling data available – *not used in Aquatic Life Use designation*	Flow, water level, and hydraulic modeling data available, potential for analysis of conveyance, navigation impacts of proposed restoration activities
Water Quality	Natural and artificial systems	Complete suite of water quality data available – **no evidence that proposed increase in DO will yield significant biological response**	**Rigorous evaluation of continuous DO data, supplemented with the DO profiles conducted at the 29 habitat sampling stations surveyed during 2008 season; analysis of other water quality data; integration with biotic data**
Physical Habitat Metric	Metric for natural systems, Metric for low-gradient artificial systems	**QHEI – *not designed for low-gradient, urban streams or rivers***	**Developing new physical habitat index designed specifically for the unique conditions within the CAWS and other similar low-gradient urban streams and rivers**
Habitat Pattern and Juxtaposition	Natural and artificial systems	**None – not considered**	**Geospatial integration of discrete sample data and continuous sampling data**
Fish Community Metrics	Metric for natural systems, Metric for low-gradient artificial systems	**Boatable IBI – *incorrectly calculated***	**Selection of fish metrics will be based on CAWS fish data and new CAWS-specific fish metrics will be developed if appropriate**

Assessment Factor	Applicability	Rankin (2004), CAWS UAA, Statement of Reasons	Habitat Evaluation and Improvement Study
Macroinvertebrate Community Metrics	Natural and artificial systems	**MBI – *not used in Aquatic Life Use designation***	**MBI geospatially integrated with historic and current datasets**
Science-based Integrative Methodology and Metric(s)	Natural and artificial systems	***IBI percentile scores and best professional judgment used to delineate Aquatic Life Use categories and waters***	**Apply existing and new methods to geospatially integrate environmental data and to analyze and summarize condition of the CAWS using a new suite of metrics, potentially at a much finer scale.**
Navigation Impacts on Fish	Natural and artificial systems	**None – not considered**	**Navigation effects from commercial shipping activities may play a significant role in limiting near shore habitat potential and some aspects of water quality and those impacts are currently being evaluated using a combination of literature reviews and field observations from the 2008 season**

Note: - Red text indicates components that are considered to be deficient assessment factors.
- Green text indicates components of the ongoing "Habitat Evaluation and Improvement Study" that address those deficiencies.

Attachment M5

ADDENDUM TO CONTRACT DOCUMENTS FOR

REQUEST FOR PROPOSAL 07-RFP-34
CHICAGO AREA WATERWAY SYSTEM
HABITAT EVALUATION AND IMPROVEMENT STUDY

ADDITIONAL INFORMATION CONCERNING THE SCOPE OF WORK PROVIDED AT PRE-PROPOSAL MEETING, NOVEMBER 9, 2007 10:00 AM TO 12:00 PM STICKNEY WATER RECLAMATION PLANT LABORATORY AUDITORIUM

Please address any questions regarding Affirmative Action Goals for this Request for Proposal to the Affirmative Action Section, telephone (312) 751-4038.

II SCOPE OF WORK

The following work items shall be included in the subject professional service contract along with any additional work items introduced by bidders that are deemed appropriate to the study by Metropolitan Water Reclamation District of Greater Chicago (District) personnel during interviews with the bidders. All work items must be complete by December 31, 2008.

1. Determine, for all waterways included in the Chicago Area Waterway System (CAWS) Use Attainability Analysis (UAA), current instream and riparian physical habitat metrics using existing data and data collected by the consultant. All waterways evaluated for the CAWS UAA are included in the Scope of Work. These waterways are:

    a) North Shore Channel (NSC).

    b) North Branch Chicago River from its confluence with the NSC to its confluence with the South Branch Chicago River.

    c) Chicago River.

    d) South Branch of the Chicago River and South Fork (Bubbly Creek).

    e) Chicago Sanitary and Ship Canal.

    f) Lake Calumet and its connecting channel to the Calumet River.

    g) Calumet River from Lake Michigan to the Grand Calumet River.

    h) Grand Calumet River from the Indiana state line to its confluence with the Calumet River.

    i) Little Calumet River from its junction with the Grand Calumet River to the Calumet-Sag Channel.

    j) Calumet-Sag Channel.

2. Employ a multimetric habitat index such as the Michigan Department of Environmental Quality "Non-Wadeable Habitat Index" (Wilhelm and Allan 2005), or approved equivalent, to evaluate CAWS physical habitat metrics. For example, the District has used the Qualitative Habitat Evaluation Index (QHEI), developed by the Ohio EPA. It is the contractor's responsibility to find or develop a valid index that will accurately characterize habitat in artificial and modified urban waterways like the CAWS.

3. Create a geographical information system (GIS) using all District and consultant-collected physical habitat data, sediment physical/chemical data, and biological survey data for the entire CAWS for the years 2001 to the present. The District has 59 Ambient Water Quality Monitoring (AWQM) Program sample locations on both wadeable and non-wadeable streams. Twenty-seven of these monitoring locations are on the CAWS UAA waterways listed in Item 1 of this scope of work. It would be desirable for future District use of the GIS for the consultant to include data for all 59 stations in the GIS.

   The District will make available, at the consultant's request, any specific, or all, biological, chemical, sediment and habitat data collected from the 59 stations during the AWQM Program since 2001, as well as any specific, or all, hourly dissolved oxygen (DO), water temperature, specific conductance, pH, and turbidity data collected as part of the District's Continuous Dissolved Oxygen Monitoring (CDOM) Program. The AWQM Program data are stored in Microsoft EXCEL files and the CDOM Program data are stored in a Microsoft ACCESS database. Any data collected by the consultant during this habitat evaluation study will be incorporated into the GIS.

   The consultant will provide the GIS and instructions on its use to the District upon completion of the contract. In regard to the GIS, the consultant will:

   a) Analyze existing data structure and if necessary convert it to a District approved usable format for incorporation to the GIS application.

   b) Develop required layers and databases that will be incorporated into the application using District Standard Database (Oracle 10G on Sun Solaris).

   c) Create UAA Map Documents (.MXD file) with existing base map layers along with existing and new data. The District will provide Base Map Data (orthophotos, planimetric, topo, and cadastral data) to the consultant.

   d) Develop ArcGIS Server (9.2 Advanced) web-based application for use on District's internal network that will allow required data entry, analysis, and modification.

   e) Provide general user training for 10 users and power user training for 5 users.

      i) Power Users will be individuals that perform unique analysis as well as maintain the Map Document including the application specific layer and tables.

ii) General Users are the everyday user that will be performing the day to day operations through Internet Explorer on the system.

iii) The training should be application specific. General GIS training is the responsibility of the District (e.g. ArcGIS 1 and ArcGIS 2). The consultants are only responsible for providing training for any application specific functionality that they develop.

f) Analyze District enterprise architecture (description of the architecture to be provided to the consultant by the District) and provide recommendations for implementation of public facing web application to disseminate study information to the public.

g) For all data associated with this project, the consultant shall develop Data Dictionary and Metadata, and Data Maintenance Procedures conforming to District standards.

i) Data Dictionary is a document that clearly states the relationship between all data tables in the application along with a detailed description of all fields.

ii) Metadata is part of each layer that describes the various attributes of the layer.

iii) Data Maintenance Procedures are procedures that clearly identify when and how each dataset shall be maintained to preserve the data integrity.

h) All custom source code developed for this project will become property of the District, and must be delivered to the District by the conclusion of the project. The District standard is Dot Net, and web application to be developed with Visual Basic (ASP).

i) No additional hardware or software needs to be provided to the District by the consultant under this contract.

j) Applications developed under this contract will run on thin clients for General Users and on PCs for Power Users.

k) All data developed for this project shall be in Oracle databases, however, some of the existing data currently resides in an MS Access database.

l) It is expected that the District's GIS will become functional during the duration of this contract.

4. Determine what modifications to current instream and riparian physical habitat would be required in the CAWS to achieve a sustainable fish community (all life stages) characteristic of a balanced, propagating fish community in a natural waterway of similar size and use. Include habitat requirements for non-fish biota (plankton, periphyton, and macroinvertebrates) that would function as prey species for the fish community. Prioritize areas of

the CAWS for restoration based on benefit:cost ratio. The cost estimates are planning level opinion of probable costs with a potential variation of +/- 30%. Restoration efforts shall be identified in an incremental manner proceeding from lowest to highest cost. Improvements in current water quality required to sustain improved biota shall be identified at each habitat improvement step.

5. Determine what other existing habitat improvement projects are planned or being implemented by other agencies, municipalities, or organizations, for those Chicago area waterways included in the UAA, and, if possible and appropriate, mesh these projects into any restoration recommendations of Item 4.

6. Determine what fish species would be expected to have self-sustaining populations in the CAWS after the recommended instream and riparian habitat improvement steps were implemented.

7. Examine the District's water quality monitoring data for the CAWS and determine whether, in the last six years, any of the measured parameters exceeded the tolerance limits of the fish species identified in Item 6. The District has monthly information on water quality within the CAWS. Hourly DO, temperature, and conductivity readings are available in selected reaches. IEPA 303d listed reaches in the CAWS were used to select monitoring locations for the District's AWQM Program. All reaches within the CAWS are listed as impaired by IEPA. It is expected that impacts of current and projected levels of pollutants responsible for IEPA 303d listing will be analyzed.

8. Provide the opinion of probable cost per unit of waterway distance for the habitat restoration work identified in Item 4. The cost estimates are planning level opinion of probable costs with a potential variation of +/- 30%.

9. Provide a report to the District summarizing:

    a) current instream and riparian physical habitat conditions in the CAWS,

    b) instream and riparian physical habitat conditions expected in the CAWS after each habitat restoration step suggested in Item 4 was completed,

    c) fish species present in the CAWS after each restoration step is implemented,

    d) based on assessment of current habitat, evaluation of changes in fish species or populations expected to occur as a result of achievement of proposed IEPA UAA standards,

    e) any impacts that current or future IEPA-proposed water quality standards would have on the post-restoration fish population, and probable cost per unit of waterway distance for the proposed habitat restoration work,

    f) the GIS which includes all map documents, layers and training provided for in this contract.

BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
	)	
WATER QUALITY STANDARDS AND	)	
EFFLUENT LIMITATIONS FOR THE	)	R08-9
CHICAGO AREA WATERWAY SYSTEM	)	(Rulemaking - Water)
AND THE LOWER DES PLAINES RIVER:	)	
PROPOSED AMENDMENTS TO 35 Ill.	)	
Adm. Code Parts 301, 302, 303 and 304	)	

PRE-FILED TESTIMONY OF MARCELO H. GARCIA, PhD

Introduction

My name is Marcelo H. Garcia and I am a Professor of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign (UIUC). In this testimony I will provide my professional opinion regarding the water quality standards proposed by the Illinois Environmental Protection Agency (IEPA) for dissolved oxygen in the Chicago Area Waterways (CAWS). In particular, the focus of my presentation will be on the standards being proposed for the South Fork of the South Branch of the Chicago River popularly known as Bubbly Creek. I believe that there is a need to set a water quality standard for Bubbly Creek that is different from the rest of the waterways and that takes into account the unique nature of this historical waterway.

A biographical sketch including my education and experience in water resources and river engineering as they relate to this testimony follows. My full CV is included as Attachment 1. I hold an Ing. Dipl. (Universidad Nacional del Litoral, Argentina, 1982) in water resources engineering, and M.S. (University of Minnesota 1985), and Ph.D. (University of Minnesota 1989), both in civil engineering. I have been on the faculty of the Department of Civil and Environmental Engineering at UIUC since 1990, and have served as Director of the Ven Te Chow Hydrosystems Laboratory since 1997.

I have written a book on Environmental Hydrodynamics (in Spanish) and have worked also as Editor-in-Chief and co-author of the new "Manual of Practice 110 Sedimentation Engineering: processes, measurements, modeling and practice," published by the American Society of Civil Engineers, or ASCE, in May 2008. My research has been supported by the National Science Foundation, the Office of Naval Research, the U.S. Environmental Protection Agency, the U.S. Department of Agriculture, the U.S. Army Corps of Engineers, and several State agencies. My work on river engineering has been recognized with several honors and awards from professional societies (ASCE, IAHR).. In 2001, I became the first Chester and Helen Siess Endowed Professor of Civil Engineering at UIUC. More detailed information on my experience and research can be found in Attachment 1.

Experience with Chicago Area Waterways (CAWS) and other Illinois Streams

Since joining the faculty at UIUC in January 1990, I have had the opportunity to work on several projects involving the Chicago Area Waterways as well as other streams in Illinois and around the world. In the Chicago River, my research group was the first to recognize the phenomenon of density currents after the observations of bi-directional flows made by the US Geological Survey in 1998 (Bombardelli and Garcia 2001). After proving their existence with the help of numerical simulations, we built a physical model of the main stem of the Chicago River to be able to determine the conditions that lead to the development of density currents (Manriquez et al. 2005). More recent analysis of field observations has indicated that salt, which is commonly used for deicing and snow melting in the streets of Chicago during the winter months (approximately 300,000 metric tons), is the main culprit for the density differences leading to the development of density currents in the Chicago River (Garcia et al 2007; Jackson et al. 2008). Density currents could affect water quality and transport low-oxygen, sediment-laden water and contaminants for long distances (Garcia 1992).

I have also worked with the U.S. Army Corps of Engineers Chicago District on the design of a bubble-plume aeration system to prevent anaerobic conditions in McCook Reservoir to be built as part of the Tunnel and Reservoir Plan (TARP) in Chicago (Bombardelli et al. 2007). These studies included a set laboratory experiments on sediment oxygen demand by resuspended CSO sediments taken from the O'Hare CUP reservoir (Briskin and Garcia 2002). Since 2003, we have been working on the development of a real-time hydrologic-hydraulic model of the Tunnel and Reservoir Plan (TARP) to be used by the District to optimize the operation of the system to prevent hydraulic transients, maximize storage and minimize the discharge of combined sewer overflows into the CAWS (Leon et al. 2006).

For the West Fork of the North Branch of the Chicago River and with support from the U.S. EPA, we have designed together with my colleagues and students at UIUC a set of pools and riffles to improve water quality conditions along the West Fork of the North Branch at Northbrook (Rhoads et al 2008). Post construction monitoring has shown an increase in dissolved oxygen during low-flow conditions.

Along the Calumet-Sag Canal, we have modeled the District's SEPA Station No 3 to prevent sedimentation and allow for the best performance in terms of water-quality enhancement. Our recommendations have been implemented and sedimentation has been curtailed and the air entraining capabilities have been enhanced at the SEPA stations. Our field measurement also indicated that there are large amounts of fine-grained sediments carried in suspension along the Calumet-Sag Canal. After large storms the concentration of organic-rich sediments in suspension could curtail the efficiency of the SEPA station in terms of maintaining the DO levels that are now proposed by the UAA analysis.

About a decade ago, I led a multi-year study on the environmental impact of increasing navigation after enlarging the navigation locks on the Upper Mississippi and Illinois Rivers for the Waterways Experiment Station of the US Army Corps of Engineers (Garcia et al 1999). We found that for low draft conditions substantial amounts of sediments could be entrained into suspension by barges. Barge traffic can also be expected to have an impact on sediment entrainment and turbidity levels along the Calumet-Sag Canal as well as the rest of the waterways. However, navigation-induced resuspension has received practically no attention at all in the UAA analysis. How much of the oxygen that is introduced by the SEPA stations will be captured by organic-rich sediments and then mixed and kept in suspension along the Cal-Sag Canal remains an open question. The same can be said about the role of both suspended and deposited sediments in Bubbly Creek, as I will discuss next.

History and Physical Description of Bubbly Creek, Chicago, Illinois

Bubbly Creek, located southwest of downtown Chicago (Exhibit 1), is the South Fork of the South Branch of the Chicago River, having a length of approximately 1.3 miles, a mean width of about 150 feet and a fairly straight channel alignment. Flow depths vary from 3 to 13 feet. Most of the stream bank consists of steeply sloped earth or rock materials. However, there are several sections with vertical dock walls. The mean channel bottom slope is about 0.001, but this is misleading because the channel bottom elevation varies significantly along the creek. The upstream 60% is shallow due to the lack of navigation. The downstream 40% is scoured by periodic barge traffic associated with a gravel-sand operation. The location of the barge dock is the narrowest width in the channel length. From 1865 to 1940, Bubbly Creek was used as a drainage channel for the direct discharge of wastes from Chicago's Union Stockyards and other industries. Chapter 8 in Upton Sinclair's novel *The Jungle* gives a vivid description of the creek. It is important to consider the history of Bubbly Creek in order to understand the origin of its name, its past and current conditions as well as the factors that make it so different from the rest of the waterways.

In the early 1900s, wastewater from the south area of Chicago was discharged via a pumping station located at the intersection of 39th Street and Lake Michigan into a 20 feet diameter interceptor, the 39th Street Conduit, which flowed into Bubbly Creek. The 39th Street Pumping Station, built in 1904 by the City of Chicago as a cooperative venture with the Sanitary District of Greater Chicago, pumped the sewage, wastewater, and drainage from the Lake Michigan front interceptor which served an area of approximately 12,000 acres, or about 20 square miles. Another function of the 39th Street Pumping Station was to pump <u>flushing water from Lake Michigan to Bubbly Creek and purge the bottom deposits</u> toward the main stem of the Chicago Sanitary and Ship Canal. In addition to the discharge form the pumping station the 39th Street Conduit also collected flows from combined sewer mains that served a total collection area of about 28 square miles on the south side of the City. As years passed, this system became overloaded, motivating an agreement between the Sanitary District and the City of Chicago in 1928, whereby the District would construct a large pumping station at 39th Street and Racine Avenue as well as large sewer lines (South Side Interceptors) to serve the near South Side of Chicago. Construction of the Racine Avenue Pumping Station (RAPS) started ten years later and finally the new pumping station went into operation on December 1939. The historical 39th Street Pumping Station was removed from service right after RAPS went into operation. At the time of its construction, RAPS was the largest pumping station in the world. It was sized to pump the entire flow of the 39th Street Conduit as well as the contents of the Southwest and South Side interceptors into Bubbly Creek. The South Branch of the Chicago River continued to receive the entire discharge from RAPS via Bubbly Creek until March 1940, when the Southwest Interceptor No. 4 was completed and connected to RAPS to convey wastewater to the Stickney Water Reclamation Plant (WRP).

Today, this historically industrial area, characterized by the presence of industrial plants, trucking terminals, rail and construction material yards, is being transformed into a residential development. Efforts are under way to completely redefine the Bridgeport area around the Bubbly Creek (Gallun 2003). However, the hydraulic behavior of the creek including its flow regime and sedimentation patterns, need to be well understood in order to set water quality standards and aquatic life use for Bubbly Creek.

A striking flow pattern change is a significant part of the uniqueness of Bubbly Creek. During dry periods, the water in Bubbly Creek is stagnant and susceptible to large gas ebullition events, or sudden bursts of gas bubbling to the surface, caused by degradation of organic matter under anaerobic conditions in the bed sediments. Sediment oxygen demand from bottom deposits can be expected to be at a maximum during dry-weather periods. During light rainfall events there are no noticeable changes, because the combined sewer flows from the 36 square miles serviced by the Racine Avenue Pumping Station (463,400 people and 169,900 households served), are conveyed to the District's Stickney WRP and not discharged to the creek. During heavy storms, when the Stickney WRP's capacity is surpassed, the Racine Avenue Pumping Station discharges into both the Mainstream Tunnel of TARP and to the creek, so that the water flows northward into the South Branch of Chicago River (**Exhibit 1**). During very heavy storms, several combined sewer outfalls located along the channel may discharge to Bubbly Creek depending on the intensity of the rainfall events. There are 9 such outfalls along the banks of the creek (Exhibit 1). More than six decades after first going into operation, RAPS continues to be one of the largest sewage pumping stations in the world, with a maximum discharge capacity of 6000 ft^3/s (3890 MGD).

Characteristics of Observed Flows in Bubbly Creek (CSO events)

Because Bubbly Creek experiences flow only during wet-weather periods, it is important to briefly consider the CSO discharge from the Racine Avenue Pumping Station (RAPS). RAPS has a total of 14 pumps and the District records the volume discharged by each single pump as well as the discharge duration during extreme hydrologic events. With this information, the total volume of water discharged into Bubbly Creek during large storms can be estimated and used for calculating the loads in to the Creek and for modeling purposes as described later.

From 1992 to 2001, discharges from RAPS have occurred between 17 and 27 times per year, lasting between 3 and 30 hours, with volumes ranging between 71 and 1172 million gallons and flows between 777 and 2452 cubic feet per second. These flows are strong enough to cause erosion and entrainment into suspension of bottom sediments in Bubbly Creek (Garcia and Parker 1991; Lopez and Garcia 2001). Once bottom deposits are resuspended, both turbidity levels and biochemical oxygen demand (BOD) are known to increase proportionally with the concentration of suspended solids (Briskin and Garcia 2002). Obviously, high turbidity and low oxygen levels in the water column will have a detrimental effect on fish and other life forms. It is precisely the poorly understood characteristics of the sediments as well as their complex impact on water quality during both dry-weather (i.e. SOD) and wet-weather (i.e. BOD, turbidity) conditions that render water-quality management a challenging endeavor in Bubbly Creek.

We are currently conducting research to learn more about the settling characteristics and erosion rates of the sediments in Bubbly Creek. Previous studies have concentrated mainly on the quality of the sediments, clearly indicating that physical characteristics and behavior of the bottom deposits can be expected to vary over a wide range depending on the location along the creek (CDM 2005). Of particular interest for any attempt at setting water quality standards, is the quantification of sediment oxygen demand (SOD) for different flow velocities, including the critical case of nearly stagnant water when oxygen levels can be expected to be very low and the only mechanism for air entrainment (i.e. re-aeration) may be wind action. Our goal is to eventually incorporate the knowledge gained from these studies into a three-dimensional (3D) Hydrodynamic-Sedimentation-Water Quality model that is currently being developed for Bubbly Creek. Some of the progress made to date with the modeling is summarized next.

Hydrodynamic, Sedimentation and Water Quality Modeling of Bubbly Creek

Both steady and unsteady 2D depth-averaged hydrodynamic models, of which the detailed development and implementation are presented in Attachment 2, and a 2D depth-averaged sediment transport and water quality model, which is detailed in Attachment **3**, were developed by our research group. The main objectives of these studies were to understand the hydraulic behavior of Bubbly Creek by performing flow simulations when CSO discharges from the RAPS take place following heavy rainfall events, and the impact on water quality in Bubbly Creek, particularly on dissolved oxygen (DO) and Biochemical Oxygen demand (BOD), by performing water quality simulations when the water in Bubbly Creek is nearly stagnant after a CSO discharge from the RAPS stops. The simulation with the unsteady 2D hydrodynamic model indicated that there was approximately a 2-feet difference in water surface elevation from the beginning to the end of a CSO event on September 13, 2006 at the headwaters of Bubbly Creek, as shown in Figure 4 of Attachment 2, whereas the surface water elevation near the end of the creek rarely changed. It is important to mention that these simulations did not account for backwater effects from the South Branch of the Chicago River. A steady 2D hydrodynamic model (Abad et al 2008), which allows for characterizing the water velocity, shear stress and turbulence fields in Bubbly Creek during CSO discharges from the RAPS, was used to examine whether sediment re-suspension could occur in Bubbly Creek during a discharge from RAPS. Figure 5 in Attachment 2 and Figure 26 in Attachment 3 show shear velocity fields in Bubbly Creek for three different discharge flows from 1240 to 6000 ft^3/s (35 to 170 m^3/s). Even at the lowest flow studied, the sediments in most areas of the creek would be resuspended, which was indicated by the shear velocities greater than the critical Shield shear velocity of 0.012 m/s (0.039 ft/s). For the purpose of numerical modeling, the critical Shield shear velocity needed for sediment entrainment, considering a median grain size of 0.112 mm (0.0044 inch) for the bed sediments, was estimated by assuming that the sediments behave as non-cohesive, granular material (Garcia 1999). The resuspension of sediments was also indicated in the model simulations by an increase in concentrations of suspended solids in the downstream direction on Bubbly Creek, as shown in Figure 3 of Attachment 3. It is important to mention that the actual critical shear stresses needed to erode and suspend bottom sediments in Bubbly Creek need to be determined with the help of both in-situ and laboratory experiments. This observation stems for the fact that sediments samples and cores taken along Bubbly Creek and analyzed by CDM (2005) for the US Army Corps of Engineers indicate that:

"Sediment typically consisted of clay that was wet, soft, had little fine sand and silt, and contained organics. Sandy material was present in some cores ....while gravel was present in others. Most sediment had an organic odor, with some locations exhibiting a hydrocarbon odor. The sediment color was typically black.... An oily sheen was observed in some cores and grab samples. Hair and foil were present in many cores, while trash, wood, glass, and bone fragments were present in a small number of cores."

This account of the heterogeneous nature of the bottom deposits clearly points to the need for conducting in-situ experiments to determine the critical flow velocity and shear stress needed to erode and suspend sediments at different locations in Bubbly Creek so that this information can be incorporated into our predictive models and be used to assess water quality dynamics and the impact of using different improvement technologies.

The 2D depth-averaged hydrodynamic, sedimentation and water quality model was implemented on a 1.3 mile stretch from the headwaters to downstream for 4 days (96 hours) after the CSO discharge on September 13, 2006 stopped. The simulation results indicate that the BOD concentrations in the water column for both upstream and downstream locations decrease temporally because of BOD settling and oxidation. The model is also able to capture qualitatively the evolution of DO levels. The DO concentrations in the downstream location (I-55 water quality sampling station) recover slowly after a sharp initial drop to below 4 mg/L for about 24 hours, as shown in Figure 34 in Attachment 3. However, the DO concentrations in the upstream location (35^{th} Street water quality sampling station) remain below 2 mg/L for 96 hours after a slower initial decline.

Although the results reported are considered preliminary, the conceptual framework seems to be sound and potentially applicable to a three-dimensional model to be described next. It is also necessary to estimate an in situ relationship for the resuspension of solids from the bed in the form that correlates the erosion rate to the bed shear stress and to the bulk density of the bed (Admiraal et al. 2000). This, along with better information on the sediment settling flux would help address the importance of sediment and BOD resuspension during CSO events in a 3D hydrodynamic model for Bubbly Creek.

Current On-going Studies of Bubbly Creek and the CAWS

The Chicago Area Waterway System (CAWS) is very complex and the tools currently available cannot provide a complete understanding of certain local flow and water quality phenomena. The unsteady, one-dimensional flow and water quality model developed by Marquette University (Marquette University Model) has been used in many studies related to the evaluation of alternative technologies for the Use Attainability Analysis (UAA) Study conducted by the Illinois Environmental Protection Agency (IEPA). While the Marquette University Model has been beneficial in understanding dynamic conditions in the CAWS, it has also raised more questions regarding the influence of site-specific effects, such as density currents, sediment oxygen demand, mixing of heated-water discharges and water quality effects of off-channel slips and wide areas. How and why the CAWS behave in certain ways at some locations is still unknown. For instance, the 1D Marquette University Model does not account for the potential effect of sediment erosion and resuspension on proposed water quality improvements nor does it capture stratified flow conditions (i.e. vertical variation of flow velocity, temperature, dissolved oxygen, etc). The extent to which these uncertainties will impact the UAA Study is yet to be determined. Thus there is a clear need to better understand these phenomena so that credible scientific explanations can be presented and sound recommendations can be made for water quality improvements and appropriate technologies to achieve them. As explained next, the need to gain more insight has provided the motivation to develop a state-of-the-art, three-dimensional hydrodynamic, sediment transport and water quality computer model of the CAWS.

The main objective of this work is the development, implementation and calibration of a three-dimensional environmental fluid dynamics model (EFDC) for the CAWS that can be used to explore and analyze the water quality management strategies proposed in the UAA. There are several codes in the literature that could be used for this work. The one we selected for the CAWS is known as the Environmental Fluid Dynamics Code (EFDC). This code is in the public domain and is also supported by the U.S. EPA. It has been used in several rivers for TMDL studies (http://www.epa.gov/athens/wwqtsc/EFDC.pdf). The Environmental Fluid Dynamics Code (EFDC) is a state-of-the-art hydrodynamic model that can be used to simulate aquatic systems in one, two, and three dimensions. It has evolved over the past two decades to become one of the most widely used and technically defensible hydrodynamic models.

About a year and one-half ago, we started with the development of the EFDC Model for the CAWS. This first phase of this 36-month-long effort currently in progress includes the modeling of the following reaches:

Main Stem Chicago River
CRCW to Wolf Point

North Branch Chicago River
Wolf Point to Grand Avenue

South Branch Chicago River-Sanitary and Ship Canal
Wolf Point to Cicero Avenue

South Fork of the South Branch Chicago River (Bubbly Creek)
From its mouth to the end-of-channel near Pershing Road.

Bubbly Creek was initially modeled with STREMRHySed (Abad et al 2008); a 2D hydrodynamic and sediment transport code developed at UIUC as described in Attachments 2 and 3. At the outset of our studies, it became apparent that Bubbly Creek is a rather peculiar "stream" with characteristics, which I just described, that are quite unique and very different from the rest of the CAWS and, as such, it became clear that its water quality issues cannot be addressed in the same manner as the rest of the streams and canals that make the CAWS. It seems, however, that the uniqueness of Bubbly Creek has been overlooked during the development of proposed aquatic life use and dissolved oxygen standards for the CAWS. In fact, IEPA proposed the same aquatic life use and dissolved oxygen requirements for Bubbly Creek as those proposed for the South Branch of the Chicago River, which has none of the unique characteristics of Bubbly Creek.

Before any technology can be implemented to improve the water quality conditions in Bubbly Creek, it is necessary to have a better understanding of the stream dynamics during wet-weather events. To this end, we are currently implementing a 3D EFDC model for Bubbly Creek described above. In particular, the transport and fate of the sediments that enter the creek during extreme rainfall events, the risk of bottom sediment erosion and resuspension, and the amount of sediment oxygen demand (SOD) during dry-weather periods with and without windy conditions, need to be assessed before implementing any water-quality improvement measures such as flow augmentation and/or re-aeration in Bubbly Creek. One-dimensional (1D) and two-dimensional (2D) models do not provide any information about the vertical structure of the flow (e.g. flow velocity and sediment concentration profiles) which in some cases, like in Bubbly Creek, becomes essential in order to understand all the processes that affect water quality. This indicates the need for having a fully calibrated and validated three-dimensional model. Furthermore, there is anecdotal evidence that under certain conditions, the South Branch of the Chicago River acts as a barrier to the flow coming out of Bubbly Creek. This could determine how much of the BOD and sediment load stays in the Creek and what fraction is transported into the South Branch. The only way to know the answer to this important question is by studying different scenarios with the help of the 3D EFDC model currently being developed.

My opinion is that in order to determine which technology might be most effective, or even feasible, for water-quality management in Bubbly Creek, it is imperative to first complete the 3D computational modeling studies, laboratory experiments and field observations currently being conducted with the support of the District. Completion of these research projects will result in scientific knowledge and insight about different processes in Bubbly Creek that will affect efforts to improve water quality and that will enable attainable uses to be determined, thereby potentially saving millions in tax-payer dollars that would otherwise be spent on ineffective solutions to the current water quality problems. If this study is not completed and supplemental aeration systems are nevertheless constructed on Bubbly Creek, they may not work to increase DO levels enough to meet the proposed standards. They may simply re-suspend the very fine, organic-rich sediment and further exacerbate the depletion of DO in this isolated water body, potentially causing more harm than good.

IEPA has acknowledged the unusual conditions in Bubbly Creek, but unfortunately they have not accounted for them in their UAA proposal for the CAWS.

Conclusions and Recommendations

Based on what has been described above, my conclusions are as follows:

- Bubbly Creek is very different than the other stretches of the CAWS: flows, sediment loads and isolation make Bubbly Creek unique.
- Proposed water quality improvements may not result in attainment of the proposed standards. Flow augmentation, and even supplemental aeration, may scour sediment and prove ineffective in increasing DO levels. This cannot be determined accurately using the 1D Marquette University Model that was deployed to assess water quality improvements along

some stretches of the CAWS, but rather requires 3D hydrodynamic modeling, which is being developed now, but is not yet complete.

- Additional study of the system and behavior and fate of sediments is essential before attainable uses can be properly evaluated and resources to improve water quality are implemented, rather than imposing measures now that may prove to be ineffective or even lead to further degradation of the system.
- Until this additional study is complete, Bubbly Creek should be regulated for fish passage with additional consideration for extreme temperature conditions (hot weather causing DO to plummet) and wet-weather events that increase BOD through combined-sewer-overflows and the scour and suspension of organic-rich, bottom sediments.

Respectfully submitted,

Marcelo Garcia

By: Marcelo H. Garcia, PhD
University of Illinois at Urbana-Champaign

Testimony Attachments

1. CV Marcelo Garcia
2. Paper by Motta et al (2007)
3. Progress Report on Bubbly Creek Modeling by UIUC
4. Cited References

Exhibit 1 Aerial view of Bubbly Creek with the locations of the CSO outfalls (circles) and the Racine Avenue Pumping Station (RAPS)

Attachment 1

Curriculum Vitae
Marcelo H. García, PhD.
Chester and Helen Siess Endowed Professor of Civil Engineering
Professor of Civil and Environmental Engineering & Geology
Director, Ven Te Chow Hydrosystems Laboratory
Editor-in-Chief, International Journal of Hydraulic Research (IAHR) (2001-2006)
Editor-in-Chief, ASCE Manual of Practice 110 "Sedimentation Engineering" (2007)
Corresponding Member, National Academy of Engineering of Argentina
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Education

PhD in Civil Engineering (Fluid Mechanics & Hydraulics) Dec. 1989
University of Minnesota - St. Anthony Falls Hydraulics Laboratory
Thesis Title: Depositing and Eroding Sediment-Laden Flows: turbidity currents
Thesis Advisor: Professor Gary Parker

Master of Science in Civil Engineering Oct. 1985
University of Minnesota – St. Anthony Falls Hydraulics Laboratory
Thesis Title: Experimental Study of Turbidity Currents
Thesis Advisor: Professor Gary Parker

Dipl. Ing. Water Resources Engineering March 1982
Universidad Nacional del Litoral – Argentina
Undergraduate Research: Experimental Study of Clay Erosion in the Parana River
Research Advisor: Dr. Gertrud Onipchenko, Hydroproject, Moscow, Russia.

Administrative Experience

Director, Ven Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering, University of Illinois, Feb. 1997–present.

Director, Centro Internacional de Estudios de Grandes Rios (CIEGRi), Universidad Nacional del Litoral, Argentina, Dec. 2001-present (*ad honorem*)

Academic Experience

Chester and Helen Siess Professor of Civil Engineering, Department of Civil and Environmental Engineering, University of Illinois, April 2001-present

Professor of Geology (by invitation), Department of Geology, University of Illinois at Urbana-Champaign, April 2006-

Honorary Professor, Universidad Nacional del Litoral, Argentina, October 2001-present

Professor, Department of Civil and Environmental Engineering, University of Illinois, August 2000-present

Associate Professor (tenured), Department of Civil and Environmental Engineering, University of Illinois, August 1996–July 2000

Visiting Associate Professor, Ecole Polytechnique Federale de Lausanne, Switzerland, July, 1999

Visiting Associate Professor, Civil Engineering and Environmental Engineering Science, California Institute of Technology, April 1997–July 1997

Assistant Professor, Department of Civil Engineering, University of Illinois, Jan. 1990–May 1996

Visiting Professor, Facultad de Ingenieria y Ciencias Hidricas, Universidad Nacional del Litoral, Argentina, Sept. 1993–present

Contract Professor, Istituto di Idraulica, University of Genoa, Italy, May 1993 - August 1993

Research Fellow, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Jan. 1988 - Dec. 1989

Research Assistant, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Sep. 1983 - Dec. 1987

Teaching Assistant, Fluid Mechanics Lab., Dept. of Civil and Mineral Engineering, University of Minnesota, Jan. 1984 - Jan. 1986

Research Docent, Apr. 1982 - Dec. 1987, and Teaching Assistant, Apr. 1979 - Mar. 1981, Department of Hydrology, Universidad Nacional del Litoral, Argentina

<u>Other Professional Experience</u>

Visiting Research Engineer, National Applied Hydraulics Laboratory, INCyTH, Ezeiza, Buenos Aires, Argentina, February-August 1983 (on leave from A.y.E.E.)

Assistant Engineer, Parana Medio Project, A.y.E.E., Santa Fe, Argentina, Mar. 1982–Aug. 1983.

Technical Assistant, Parana Medio Project, A.y.E.E., Santa Fe, Argentina, Nov. 1979 – Feb. 1982

Teaching Experience

Hydraulic Engineering, Water Resources Engineering, Field Methods in Hydrology and Environmental Sciences, Sediment Transport, River Mechanics, Environmental Hydrodynamics, Open-Channel Hydraulics, Turbulence.

Areas of Research Interest and Expertise

River Mechanics and Sediment Transport: particle-turbulence interaction, sediment erosion and resuspension by unsteady flows, saltation and suspension mechanics, turbidity currents, meandering streams, bank erosion, bedform dynamics, river mixing, coherent turbulent structures, particle/pollutant transport and transformation; movable-bed hydraulic modeling; impact of navigation on biota and sedimentation, mudflows and debris flows, sediment transport in vegetated channels, wave-sediment-structure interaction, and large-scale computational river mechanics.

Environmental Hydraulics: hydraulics of bubble plumes, boundary-layer flows involving turbulence-driven mass transfer at sediment-water interfaces; density currents; stratified flows; fluid mechanics of wastewater disposal, ocean outfalls, fluid turbulence; turbulence measurements and modeling; turbulence effects on aquatic life; vegetation-flow interaction; bubble-plume-sediment interaction and hydrodynamics of UV disinfection units, hydrodynamics in settling tanks and impact of air entrainment in stream-reservoir water quality.

Water Resources Engineering: river hydraulics and sedimentation, floodplain management, flood and sedimentation hazard analysis, hydraulic engineering, drown-proofing of low-head dams, hydraulic design of canoe chutes, reservoir sedimentation, environmental impact assessment of dam and reservoir operation, sedimentation upon dam removal, storm-water management, modeling of unsteady, closed and open-channel flows, flow measurements, risk and uncertainty analysis.

Honors and Recognitions

Teaching

Recognized for Excellence in Advising, College of Engineering, UIUC, 1997, 2001
Included in Incomplete List of Teachers Ranked as Excellent by Their Students at UIUC:
- Spring 1992, 1993, 1995, 1997, 2001, 2004 for CEE459 "Sediment Transport"
- Spring 1994, 1996, 1998, 2003 for CEE498EH "Environmental Hydrodynamics"
- Fall 1995, 1996, 1998 for CEE255 "Introduction to Hydrosystems Engineering"
- Spring 1999 and 2004 for CEE353 "Analysis and Design of Hydraulic Systems"
- Campus Award for Excellence in Graduate and Professional Teaching, Honorable Mention," 2003.
- Honorary Member Chi Epsilon National Civil Engineering Honor Society, April 2004.

Research

Alvin G. Anderson Award, University of Minnesota, 1989
Hokkaido River Disaster Prevention Institute Fellowship, Japan, 1990
National Science Foundation Research Initiation Award, 1992
Invited Professorship, University of Genoa, Italy, 1993
Listed in American Men and Women of Science, 1994-present
Invited Lecturer, University of Essen, Germany, 1995

Invited Jury Member, Institut de Mecanique des Fluides, Toulouse, France, 1996
Karl Emil Hilgard Hydraulic Prize, ASCE, 1996. (Best Paper in J. of Hydr. Eng., ASCE)
Invited Professorship, California Institute of Technology, 1997
Listed in Who's Who in Engineering, 1997-present
Walter Huber Civil Engineering Research Prize, ASCE, 1998
International L.G. Straub Award for Best Ph.D. Thesis in Hydraulic Engineering presented to Dr. Yarko Nino (advisee), 1998
Arthur and Virginia Nauman Faculty Scholar, Civil and Environmental Eng., UIUC, 1998
Illinois River Science Advisory Committee, 1998 (appointed by Lt. Governor of Illinois)
Karl Emil Hilgard Hydraulic Prize, ASCE, 1999. (Best Paper in J. of Hydr. Eng., ASCE)
Invited Professorship, Ecole Polytechnique Federal de Lausanne, Switzerland, 1999
Invited Professorship, Universidad de Castilla-La Mancha, Spain, 2000
University Scholar Award, University of Illinois at Urbana-Champaign, 2000-2003
International L.G. Straub Award for Best Ph.D. Thesis in Hydraulic Engineering presented to Dr. Jeffrey Parsons (advisee), 2001
12th Arthur Thomas Ippen International Award, IAHR, Beijing, China, 2001
Honorary Professorship, Universidad Nacional del Litoral, Argentina, 2001
Listed in Who's Who in the World, 2003
Corresponding Member, National Academy of Engineering of Argentina, 2005 (elected)
Hans Albert Einstein Award for contributions to the field of river engineering and sediment transport, ASCE/EWRI/COPRI, 2006.

Editorships of Journals

International Journal of Hydraulic Research, IAHR, Editor-in-Chief, 2001-2006
Water Resources Research (American Geophysical Union), Associate Editor, 1999-2000
Hydraulic Eng. in Mexico (Mexican Institute of Water Technology), Assoc. Editor, 1999-present
International Journal of Infrastructure and Natural Disasters, Assoc. Editor, 2000-2005 (Puerto Rico)
Ingenieria del Agua, Madrid, Spain, International Associate Editor, 2005-present

Graduate Students Supervised

PhD: Yarko Nino (1995), Sung-Uk Choi (1996), Fabian Lopez (1997), Jeffrey Parsons (1997), Martha Cardona (1997-Coadvisor with Doug Shaw) David Admiraal (1999), Xin Huang (1999), Juan Fedele (2003), Arthur Schmidt (2002-Coadvisor with Ben Chie Yen), Jose Rodriguez (2003), Robert Holmes (2003), Fabian Bombardelli (2004), Carlos Marcelo Garcia (2005), Yovanni Catano (2005), Mariano Cantero (2006), Michael Yang (2006), Jorge Abad (2007), Arturo Leon (2007), Xiaofeng Liu (2008), Octavio Sequeiros (2008-Co advisor with Gary Parker), Juan Ezequiel Martin (2008), Francisco Pedocchi (2009), Albert Dai (2009), Blake Landry (2010), Ruye Wang (2011), Jose Maria Mier Lopez (2011).
M.S. (with thesis): Yarko Nino (1992), Anthony Dill (1994), Laura Bittner (1994), Fabian Lopez (1994), Chad Dunn (1996), Jeffrey Parsons (1996), Bernardo Echavarria (1996), Jose Rodriguez (1998), Juan Fedele (1998), Jonathan Armbruster (1998), Andrew Waratuke (1999), Andrew Peabody (2000), Marjorie Caisley (2000), Josephine Schuster (2000), Jacob Spenn (with Chris Rehmann), Jose Guzman (2001), Jorge Abad (2002), Brigid Briskin (2002), Mariano Cantero (2002), Felix Lopez (2005), Lucas Rincon (2003), Rodrigo Musalem (2003), Claudia Manriquez (2005), Octavio Sequeiros (2005), Francisco Pedocchi (2005), Salih Demir (2005), Felix Lopez (2006) Javier Ancalle (2007), Davide Motta (2008).

<u>Invited Lectures and Conference Presentations</u>

<u>Keynote Lectures</u>

"Trends in Environmental Hydrodynamics"
XVI Latin American Congress of Hydraulics
International Association for Hydraulic Research, IAHR,
Santiago, Chile, November, 1994.

"Flood Hazards in Pilar, Paraguay: The Human Side of Engineering"
Straub Award Lecture, University of Minnesota, Minneapolis, Minnesota, April 1998.

"Sediment Entrainment by Unsteady Turbulent Flows"
Fall Meeting American Geophysical Union, San Francisco, California, December 1998

"Near-Bed momentum Fluxes, Turbulent Bursting, and Bagnold's Hypothesis for Sediment Suspension," IAHR Symposium on River, Coastal and Estuarine Morphodynamics, Genoa, Italy, September 1999.

"Nuevas Tendencias en la Hidraulica Fluvial y el Manejo de Rios"
XIX Latin American Congress of Hydraulics
International Association for Hydraulic Research, IAHR,
Cordoba, Argentina, October 2000.

"The Parana River: a Natural Laboratory-*the tale of the tunnel under the river*"
12th Arthur Thomas Ippen Award Lecture.
Cardiff, United Kingdom, June 2002.

"Holistic Stream Restoration" US-Chinese Joint Workshop on Sediment Transport and Environmental Studies, Marquette University, Wisconsin, July 2002.

"Water Management in the USA: Role of Water Transfers in California"
100th Aniversario Asociacion de Ingenieros de Caminos Canales y Puertos, Spain
150th Anniversary American Society of Civil Engineers (ASCE)
Madrid, Spain, September 2002.

"Turbulence in Open Channel Flows with Simulated Vegetation: implications for sediment transport"
Keynote Lecture at Riparian Forest Vegetation Workshop, University of Trento, Italy, Feb. 2003.

"Holistic Stream Restoration: Challenges and Opportunties"
Symposium on "River, Coastal and Estuarine Morphodynamics (RCEM), Barcelona, Spain, 2003.

"Naturalizacion de Rios"
Primer Simposio Regional sobre Hidraulica de Rios, INA, Buenos Aires, Argentina, 2003.

"Sediment Science-New directions and evolving issues"
National Surface Water Meeting, US Geological Survey, San Antonio, Texas, Nov. 2003.

"Naturalizacion de Rios en Zona Urbanas: desafios y oportunidades para la hidraulica fluvial"
XXI Congreso Latinoamericano de Hidraulica, Sao Pedro, Brasil, Oct. 2004

"Hydraulic in the Times of Cholera: the Chicago River, Lake Michigan and Urban Growth," International Hydraulic Engineering and Research Association Congress (IAHR), Seoul, South Korea, November 2005.

"La Hidraulica en los tiempos de Colera: Chicago y el desarrollo sustentable," 20 Aniversario Instituto Mexicano de Tecnologia del Agua," Curnavaca, Mexico, August 2006

"El Universo de las corrientes de densidad," Congreso Latinoamericano de Hidraulica, IAHR, Ciudad Guayana, Venezuela, October 2006.

Invited Seminars

Hokkaido University, Japan, 1990
Tokyo Institute of Technology, Japan, 1990
Kyoto University, Japan, 1990
University of Genoa, Italy, 1993
Universidad Autonoma del Estado de Mexico, Mexico, 1993
Cornell University,1994
Universidad Nacional del Litoral, Argentina, 1995
University of Essen, Germany, 1995
University of Karlsruhe, Germany, 1995
California Institute of Technology, 1996
Cornell University, 1997
IMTA, Mexico, 1997
University of Iowa, 1997
SUNY (Buffalo), 1998
University of Minnesota, 1998, 1999, 2003
Ecole Polytechnique Federale de Lausanne, Switzerland, 1999, 2002, and 2003
Arizona State University, 2000
Northwestern University, 2001
University of Iowa, 2002
University of Illinois, Theoretical and Applied Mechanics Department (TAM) 2002
University of Trento, Italy, 2003
University of Illinois, Geology Department, 2003
Universidad de Castilla-La Mancha, Spain, 2003
University of Minnesota, 2003
University of Zaragoza, 2006

Professional Societies

American Society of Civil Engineers (ASCE); International Association for Hydraulic Research (IAHR); American Geophysical Union (AGU); American Society for Engineering Education (ASEE).

Activities in Professional Societies

American Society of Civil Engineers (ASCE)

Member- Alfred Noble Prize Committee 1998-2002
Hydraulics Division
Discussion and Technical Note Awards Committee, Member,1991 - 1994, Chairman, 1992 - 1994
Environmental and Water Resources Institute (EWRI)
Sedimentation Committee
Control Group Member, 1994 – 1998, chair 1998-2004
Member Einstein Award Committee 1999-2003
Editor-in-Chief, Sedimentation Engineering Manual 54 (vol. 2), 2000-2006
Engineering Mechanics Division

Turbulence Committee, Member, 1992–1996; Control Group Member 1997-2000

International Association for Hydraulic Research (IAHR)

Fluid Mechanics Committee, Member, 1994 – 2004

Editor-in-Chief, Journal of Hydraulic Research, 2001-2006

American Geophysical Union (AGU)

Associate Editor, Water Resources Research 1998-2000.

Major Consulting Activities

Movable-bed hydraulic modeling, Northern States Power Company, Minnesota (1989)

Reservoir Sedimentation, Water Resources Planning Commission, Taiwan (1992)

River Sedimentation, Parana-Santa Fe Sub-Fluvial Tunnel Commission, Argentina (1993)

Environmental Impact of Navigation, U.S. Army Corps of Engineers, St. Louis Distr. (1996)

Flood Management, Government of Paraguay, USAID Office (1998)

Evaluation of Dam Removal Alternatives in the Pacific Northwest, Stillwater Science, Berkeley, CA (2000)

Sedimentation Analysis for Stabilization of Rio Cuarto, Cordoba, Argentina, 2000

Hydrodynamic and Sedimentation Modeling of Housatonic River, MA, General Electric and EPA, 2001-present

Hydrodynamic and Sedimentation Modeling in San Antonio River Tunnel (SART), Halff Associates, Inc., 2002

Sediment Erosion and Washout at Howard Street Tunnel, Baltimore, Maryland, CFX Transportation, 2002.

Evaluation of Stormwater Management Manual for Puerto Rico, FEMA and University of Puerto Rico, 2003.

Evaluation of Flood Control Project for City of Buenos Aires, Argentina, The World Bank, 2004.

Evaluation of Bermejo River Project, Argentina-Bolivia, United Nations Environmental Program (UNEP), 2004-2005.

Evaluation of Rio Piedras Project for Flood Control and Stream Naturalization, Puerto Rico, Applied Ecological Services, 2005.

Analysis of Reservoir Sedimentation and Water Supply, St Lucia, West Indies, Sir Halcrow and Partners (2005).

Evaluation of Alternatives and Technology for Retention of Mining Tailings, West Papua, Indonesia, MWH, 2006.

Analysis of Reservoir Sedimentation for Valenciano Reservoir, Puerto Rico, CSA & Associates, 2007.

Review Panels and Scientific Committees

U.S. Environmental Protection Agency Review Panel on "The Role of Sediments on the Transport and Fate of Pollutants in Freshwater and Estuaries", Newport, Rhode Island, 1990.

U.S.-Taiwan Bilateral Panel on "Understanding Sedimentation and Model Evaluation", National Research Council and Federal Energy Regulatory Commission, Washington, DC, 1991.

U.S.-Taiwan Bilateral Panel on "Understanding Sedimentation and Model Evaluation", National Research Council and Federal Energy Regulatory Commission, San Francisco, California, 1993.

Office of Naval Research Workshop on "Continental Terrace Sediment Process", New York University at Stony Brook, New York, 1993.

National Science Foundation Review Panel for Research Initiation Awards in Fluid, Hydraulic, and Particulate Systems Program, Arlington, VA 1994.

Sino-German Workshop on "Unsteady Sediment Transport Modelling", Berlin, Germany, 1995. (only representative from USA).

Sino-USA Workshop on "Sediment-Related Disasters", Beijing, China. (Supported by NSF), March 1999.

Office of Naval Research Workshop on "Mine Burial Prediction in Coastal Environments," New Orleans, Louisiana, 2000.

Workshop on "Modeling and Management of Environmental Issues," Invited Panelist on Modeling of Contaminated Sediment Processes, Organized by Du Pont de Nemours and Company, July 2000.

Steering Committee for Workshop on Environmental Windows for Dredging Projects, National Research Council, July 2000-June 2001.

Expert Panel for "Development of a TMDL Model for PCBs in the Delaware River Basin," Delaware River Basin Commission, West Trenton, New Jersey, 2000-2001.

Expert Panel for "Housatonic River Hydrodynamic Modeling," Commonwealth of Massachusetts, US Environmental Protection Agency, State of Connecticut, Department of the Interior, NOAA, March- 2001.

Expert Panel for "River Science at the US Geological Survey," National Research Council, The National Academies, Washington, D.C., 2004-2006

Expert Panel for "Water Resources at the US Geological Survey." National Research Council, The National Academies, Washington, D.C., 2004-2006.

Science Advisory Committee, University of Trento, Italy, 2007-2010.

International Great Lakes Commission (Canada-USA)
Co-Leader Sedimentation Studies Task Working Group for St. Clair River, 2007-2010

Journal Referee

Journal of Hydraulic Engineering, ASCE
Journal of Engineering Mechanics, ASCE

Journal of Irrigation and Drainage, ASCE
Journal of Geotechnical and Geoenvironmental Engineering, ASCE.
Water International, IWRA
Water Resources Research, AGU
Experiments in Fluids
International Journal of Multiphase Flows
Journal of Geophysical Research, Oceans, AGU
Journal of Great Lakes Research
Journal of Sedimentary Research
Limnology and Oceanography
Marine Geology
Sedimentology
Oceanography
Journal of Fluid Mechanics
Physics of Fluids

Reviewer of Research Proposals:

National Science Foundation
U.S. Environmental Protection Agency
American Chemical Society
Great Lakes Research Foundation
Illinois Water Resources Center
Purdue Water Resources Center
Wisconsin Sea Grant Program
Research Board, UIUC
Natural Environment Research Council, United Kingdom
Hong Kong Research Grants Council
The Leverhulme Trust, United Kingdom
Marsden Fund, The Royal Society of New Zealand
SDSU Foundation, California Energy Commission

Publications

Books

Garcia, M.H. (Editor-in-Chief), Manual of Practice 110 "Sedimentation Engineering: Processes, Measurements, Modeling, and Practice," American Society of Civil Engineers, to appear December 2007.

Garcia, M.H., "Hydrodynamics of Sediment Transport" to be published by John Wiley & Sons (under preparation)

García, M.H. "Hidrodinamica Ambiental" Centro de Publicaciones, Universidad Nacional del Litoral, Argentina, 1996 (in Spanish).

Encyclopedia Articles

Garcia, M.H., "Turbidity Currents" in Encyclopedia of Earth System Science, Vol. 4, edited by W.A. Nieremberg, Academic Press Inc., pp. 399-408, 1992 (invited).

Garcia, M.H., "Turbidity Current" in McGraw-Hill Encyclopedia of Science and Technology, 8th Edition, 18:680, 1997 (invited)

Admiraal, D.M. and García, M.H. (2002) "Impacts of Navigation and Navigation Structures on Rivers," Article 2.7.5.1 in Rivers and Streams, in Encyclopedia of Life Support Systems (EOLSS), Oxford, UK. (invited)

Chapters in Books

Garcia, M.H., Nino, Y., and Lopez, F., "Laboratory Observations of Particle Entrainment Into Suspension by Turbulent Bursting" In Coherent Flow Structures In Open Channels: Origins Scales, and Interaction with Sediment Transport and Bed Morphology, Edited by Ashworth, P., Bennetts, S., Best, T., and McLelland, S., John Wiley & Sons, Ltd., Chapter 3, 63-86, 1996.

Garcia, M.H., "Sedimentation and Erosion Hydraulics," Chapter 6 in Hydraulic Design Handbook, edited by Larry Mays, McGraw-Hill, Inc., 6.1-6.113, June 1999.

Fedele, J., and M.H. Garcia, "Hydraulic Roughness in Alluvial Streams: A Boundary Layer Approach," Chapter in Riverine, Coastal, and Estuarine Morphodynamics, G. Seminara (Editor) to be published by Springer-Verlag, Italy, 2001.

Garcia, M.H., "Modeling Sediment Entrainment into Suspension, Transport, and Deposition in Rivers," Chapter in "Model Validation in Hydrologic Science," Paul Bates and Malcolm Anderson (Editors), Wiley and Sons, United Kingdom, February 2001.

Garcia, M.H., "Sediment Transport Mechanics," Chapter 2 in Sedimentation Engineering Manual 110, ASCE, to appear in 2007.

Garcia, M.H., Mac Arthur, R., Bradley, J., and R. French, "Sedimentation Hazards," Chapter 19 in Sedimentation Engineering Manual 110, ASCE, to appear in 2007.

Garcia, M.H., Lopez, F., Dunn, C. and C. Alonso, "Flow, Turbulence and Resistance in a Flume with Simulated Vegetation," in Riparian Vegetation and Fluvial Geomorphology: Hydraulic, Hydrologic and Geotechnical Interactions," Edited by Sean Bennett and Andrew Simon, American Geophysical Union, Washington DC, 2004.

Monographs

Garcia, M.H., "Environmental Hydrodynamics", Latin American Division, International Association for Hydraulic Research, Santiago, Chile, 189 p., 1994. (in Spanish).

Articles in Journals

Parker, G., Garcia, M.H., Fukushima, Y., and W. Yu, "Experiments on Turbidity Currents over an Erodible Bed", Journal of Hydraulic Research, IAHR, vol. 25, N1, pp. 123-147, 1987.

Garcia, M.H., and Parker, G., "Experiments on Hydraulic Jumps in Turbidity Currents Near a Canyon-Fan Transition", Science, vol. 117, N4, pp. 393–396, July 1989.

Garcia, M.H., and Parker, G., "Entrainment of Bed Sediment into Suspension", Journal of Hydraulic Engineering, ASCE, vol. 117, N4, pp. 414-435, April 1991.

Garcia, M.H., and Parker, G., "Experiments on the Entrainment of Sediment into Suspension by a Dense Bottom Current", Journal of Geophysical Research (oceans), AGU, vol. 98, C3, pp. 4793-4807, March 1993.

Garcia, M.H., "Hydraulic Jumps in Sediment-laden Bottom Currents", Journal of Hydraulic Engineering, ASCE, vol. 199, N6, pp. 1094-1117, October 1993.

Garcia, M.H., and Nino, Y., "Dynamics of Sediment Bars in Straight and meandering Channels: Experiments on the Resonance Phenomenon", Journal of Hydraulic Research, IAHR, vol. 31, N6, pp. 739-761, 1993.

Nino, Y., Garcia, M.H., and Ayala, L., "Gravel Saltation I: Experiments", Water Resources Research, AGU, vol. 30, N6, pp. 1907-1914, June 1994.

Nino, Y., and Garcia, M.H., "Gravel Saltation II: Modeling", Water Resources Research, AGU, vol. 30, N6, pp. 1915-1924, June 1994.

Garcia, M.H., "Depositional Turbidity Currents Laden with Poorly-Sorted Sediment," Journal of Hydraulic Engineering, ASCE, vol. 120, N11, pp. 1240–1263, Nov. 1994. *(received Hilgard Hydraulic Prize from ASCE for this paper)*

Garcia, M.H., Lopez, F., and Nino, Y., "Characterization of Near-Bed Coherent Structures in Turbulent Open Channel Flow Using Synchronized High-Speed Video and Hot-Film Measurement", Experiments in Fluids, vol. 19, pp. 16-28, 1995.

Choi, S.U., and Garcia, M.H., "Modelling of One-Dimensional Turbidity Currents with a Dissipative-Galerkin Finite Element Method," Journal of Hydraulic Research, IAHR, vol. 33, N5, pp.1-26, 1995.

Garcia, M.H., and Parsons, J.D., "Mixing at the Front of Gravity Currents," Dynamics of Atmospheres and Oceans, vol. 24, 197-205, 1996.

Lopez, F., Nino, Y., and Garcia, M.H., "Turbulent Coherent Structures in Open-Channel Flows with Smooth Beds," Hydraulic Engineering in Mexico, vol. XI, 1, pp. 5-13, IMTA, Mexico, 1996 (in Spanish).

Nino, Y., and Garcia, M.H., "Experiments on Particle-Turbulence Interactions in the Near Wall Region of an Open Channel Flow: Implications For Sediment Transport", Journal of Fluid Mechanics, 326, 285-319, 1996.

Pratson, L.F., H.J. Lee, G. Parker, M.H. García, B.J. Coakley, D. Mohrig, J. Locat, U. Mello, J.D. Parsons, S. Choi and K. Israel, "Studies of Mass-Movement Processes on Submarine Slopes," Oceanography, 9:3, 168-172, 1996.

Choi, S.U., and Garcia, M.H., "Arbitrary Lagrangian-Eulerian Approach for Finite Element Modeling of Two-Dimensional Turbidity Currents," Water International, 21, 175-182, 1996.

Huang, X. and M.H. García, "A Perturbation Solution for Bingham Plastic Mud Flows," ASCE, Journal of Hydraulic Engineering, 123:11, 984-996, 1997. (Received the 1999 Karl Emil Hilgard Hydraulic Prize from ASCE for this paper)

Nino, Y., and Garcia, M.H., "Using Lagrangian Particle Saltation Observations for Bedload Sediment Transport Modeling, " Hydrological Processes, 12, 1197-1218, 1998.

Niño, Y. and M.H. García, "On Engelund's Analysis of Turbulent Energy and Suspended Load," ASCE, Journal of Hydraulic Engineering, 124:4, 480-483 (technical note), 1998.

Niño, Y. and M.H. García, "Experiments on Saltation of Fine Sand," ASCE, Journal of Hydraulic Engineering, 124:10, 1014-1025, 1998.

López, F. and M.H. García, "Open-Channel Flow Through Simulated Vegetation: Suspended Sediment Transport Modeling," Water Resources Research, 34:9, 2341-2352, 1998.

Huang, X. and M.H. García, "A Herschel-Bulkley Model for Mud Flows Down a Slope, Journal of Fluid Mechanics, 374, 305-333, 1998.

Parsons, J.D. and M.H. García, "Similarity of Gravity Current Fronts," Physics of Fluids, 10:12, 3209-3213, 1998.

Huang, X. and M.H. García, "Modeling of Non-Hydroplaning Mudflows on Continental Slopes," Marine Geology, 154:131-142, 1999.

López, F. and M.H. García, "Wall Similarity in Open Channels: Universal value of the Normalized Vertical Flux of Turbulent Kinetic Energy, "ASCE Journal of Engineering Mechanics, "Special Issue on Turbulence," 125:7,789-796, July 1999.

García, M.H., Admiraal, D.M., and J.F. Rodriguez," Laboratory Experiments on Navigation-Induced Bed Shear Stresses and Sediment Resuspension," vol. 14(2), 303-317, International Journal of Sediment Research, 1999.

Niño, Y., F. López, I. Hillmer, C. Pirard, and M.H. García, "Numerical Modeling of Wind-Induced Turbulent Mixing Processes in Stratified Water Bodies. Hydraulic Engineering in Mexico, vol. XV, 1, 13-25, 2000 (in Spanish).

Admiraal, D. and M.H. García, "Laboratory Measurements of Suspended Sediment Concentration Using an Acoustic Concentration Profiler (ACP)," Experiments in Fluids, Vol. 28, 116-127, 2000.

Parsons, J.D. and M.H. García, "Enhanced Sediment Scavenging Due to Double-Diffusive Convection," Journal of Sedimentary Research, Vol. 70, N1, 47-52, January 2000.

Admiraal, D., M.H. García and Rodriguez, J.F., "Entrainment Response of Bed Sediment to Time-Varying Flows," Water Resources Research, 36: 1, 335-348, January 2000.

Huang, X. and M.H. García, "Pollution of Gravel Spawning Grounds by Deposition of Suspended Sediment," Journal of Environmental Engineering, ASCE, vol. 126, N10, 963-967, October 2000.

López, F. and M.H. García, "Risk of Sediment Erosion and Suspension in Turbulent Flows," Journal of Hydraulic Engineering, vol. 127, N3, 231-235, March 2001.

López, F. and M.H. García, "Open-Channel Flow Through Simulated Vegetation: Mean Flow and Turbulence Modeling," Journal of Hydraulic Engineering, ASCE, vol. 127, No5, 392-402, May 2001.

Rodriguez, J.F., Garcia, M.H. and Admiraal, D.M. "Computation of entrainment of sediment into suspension in unsteady turbulent flows using an stochastic approach." *Ingenieria Hidraulica en Mexico*, 16(2), 5-16 (2001) (in Spanish).

Choi, S-U. and Garcia, M.H. "Spreading of gravity plumes on an incline," Coastal Engineering, v. 43, p. 221-237, 2001

Teeter, A.M., Johnson, B.H., Berger, C., Stelling, G., Scheffner, N.W., Garcia, M.H. and Parchure, T.M., "Hydrodynamic and sediment transport modeling with emphasis on shallow-water, vegetated areas (lakes, reservoirs, estuaries and lagoons)," Hydrobiologia 444: 1-23, 2001.

Choi, S-U. and Garcia, M.H. "*k-e* turbulence modeling of density currents developing two dimensional on a slope," Journal of Hydraulic Engineering, v. 128, p. 55-62, 2002.

Rodríguez, J. F., Admiraal, D.M., García, M.H. and López, F. (2002) "Unsteady bed shear stresses induced by navigation: laboratory observations," *J. Hydr. Eng.*, ASCE, 128(5).

Wade, R. J., Rhoads, B. L., Rodríguez, J. F., Daniels, M., Wilson, D., Herricks, E. E., Bombardelli, F. A., García, M. H., and Schwartz, J. (2002). "Integrating Science and Technology to Support Stream Naturalization near Chicago, Illinois." *J. American Water Resources Association*, AWRA, 38, 931-944.

Buscaglia, G. C., Bombardelli, F. A., and García, M. H. (2002). "Numerical modeling of large-scale bubble plumes accounting for mass transfer effects." *Int. J. of Multiphase Flow*, vol. 28, 1763-1785.

Niño, Y., F. López, and M.H. García, "Threshold for Particle Entrainmnet into Suspension," *Sedimentology*, International Association of Sedimentologists, vol. 50, 247-263, 2003.

Rodríguez, J. F., Bombardelli, F. A., García, M. H., Frothingham, K., Rhoads, B. L., Abad, J. D., and Guzmán, J. M. (2004). "High-resolution numerical simulation of flow through a highly sinuous river reach." *Water Resources Management*, Kluwer.

Bombardelli, F.A. and Garcia, M.H. "Hydraulic design of large-diameter pipes," *Journal of Hydraulic Engineering*, ASCE, vol. 129, N011, November, 2003.

Coleman, S.E., Fedele, J.J., and Garcia, M.H. "Closed-conduit bed-form initiation and development. *Journal of Hydr. Eng.*, ASCE, vol. 129, No12, December 2003.

Rodríguez, J. F., Bombardelli, F. A., García, M. H., Frothingham, K., Rhoads, B. L., Abad, J. D., and Guzmán, J. M. "High-resolution numerical simulation of flow through a highly sinuous river reach." *Water Resources Management*, Kluwer, vol. 18, pp. 177-199, 2004..

Garcia, C.M., Cantero, M, Nino, Y. and Garcia, M.H. "Turbulence Measurements Using Acoustic Doppler Velocimeters," *Journal of Hydraulic Engineering*, ASCE, 131: 1062-1073, 2005.

Abad J. D. and García, M. H., "*RVR* Meander: A toolbox for re-meandering of channelized streams," *Computers & Geosciences*, 32: 92-101, 2006.

Cataño-Lopera, Y., Demir, S.T., and García, M.H., "Self-Burial of Free Cylinders under Oscillatory Flows and Waves plus Currents." Accepted with revisions in IEEE *J. of Oceanic Engineering*, 2005.C

Cataño-Lopera, Y. and García, M.H., "Burial of Short Cylinders Induced by Scour under Combined Waves and Currents." *J. Wtrwy., Port, Coast., and Oc. Engrg.*, ASCE, 132(6), 439-449, 2005.

Cataño-Lopera, Y. and García, M.H., "Geometry and Migration Characteristics of Bedforms under Waves and Currents: Part 1, Ripples Superimposed on Sandwaves." *Coastal Engineering*, 53, 763-780, 2006.

Cataño-Lopera, Y. and García, M.H., "Geometry and Migration Characteristics of Bedforms under Waves and Currents: Part 2, Sandwaves and flow structure." *Coastal Engineering*, 53, 781-793, 2006.

Cantero, M.; Balachandar, S.; García, M. and Ferry, J., " Direct numerical simulation of planar and cylindrical density currents," *Journal of Applied Mechanics*, ASME, 73, 923-930, 2006.

León A. S., Ghidaoui, M. S., Schmidt, A. R., and García M. H.. ``Godunov-type solutions for transient flows in sewers." *J. Hydraul. Eng.*, ASCE, in press, 2006.

Demir, S.T. and García, M.H., "Experimental studies on burial of finite-length cylinders under oscillatory flow." *J. Wtrwy., Port, Coast., and Oc. Engrg.*, ASCE, 2006..

García C; Jackson P; and García M.. "Confidence intervals in the determination of turbulence parameters". *Experimenst in Fluids*, in press, 2006.

Admiraal, D., Musalem, R., Garcia, M.H., and Nino, Y, "Vortex trajectory hysteresis above self-formed vortex ripples," *Journal of Hydraulic Research.*, IAHR, in press, 2006.

García C.M. and García M.H., "Characterization of flow turbulence in large-scale bubble-plume experiments," *Experimenst in Fluids*, 2006.

Sequeiros, O., Nino, Y, and Garcia, M.H., "Erosion of finite thickness sediment beds by single and multiple circular jets," IAHR, *J. Hydraul. Eng.*, ASCE, in press, 2006.

Pedocchi, F., and García M.H., "Evaluation of the LISST-ST instrument for suspended particle size distribution and settling velocities," *Continental Shelf Research*, 26, 943-958, 2006.

Pedocchi, F., and García M.H., "Noise-resolution trade-off in projection algorithms for laser diffraction particle sizing,"*Applied Optics*, 45(15), 2006.

Abad J. D. and García, M. H. RVR Meander: A toolbox for re-meandering of channelized streams. Computers & Geosciences, 32: 92-101, 2006.

Abad, J. D., Buscaglia, G. and Garcia, M. H. *2D Stream Hydrodynamic, sediment transport and bed morphology model for engineering applications*. In press, Hydrological Processes. 2007.

Cantero, M.I., Lee, J.R., Balachandar, S., and Garcia, MH., "On the front velocity of gravity currents,' Journal of Fluid Mechanics, in press, 2007.

Discussions

Amsler, M.L. and M.H. García, Discussion of "Sand-Dune Geometry of Large Rivers During Floods," by P.Y. Julien and G.J. Klaasen, Journal of Hydraulic Engineering, 123:6, 582-584, 1997.

Garcia, M.H., Discussion on "The Legend of A.F. Shields," by John M. Buffington, *Journal of Hydraulic Engineering*, ASCE, Vol. 126, 718-720, Sept. 2000.

Bombardelli, F. A., Hirt, C. W., and García, M. H. (2001). "Discussion on 'Computations of curved free surface water flow on spiral concentrators,' by B. W. Matthews, C. A. J. Fletcher, A. C. Partridge, and S. Vasquez." J. Hyd. Engrg., ASCE, 122(7), 629-630.

Abad, J. D. and García, M. H. Discussion of "Efficient algorithm for Computing Einstein Integrals by Junke Guo and Pierre Y. Julien" (Journal of Hydraulic Engineering, Vol. 130, No. 12, pp. 1198-1201, 2004). *Journal of Hydraulic Engineering*, ASCE, 132 (3): 332-334, 2006.

Technical Reports and Conference Proceedings

Reports

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Rodriguez, J.F., García, M.H., Lopez, F.M. and García C.M. "Effects of bed topography and vegetation on 3D flow patterns in low-gradient rivers. ICHE 2004, Sixth International Conference on Hydro-Science and Engineering, Brisbane, Australia.

Rodriguez, J.F., García, M.H., Lopez, F.M. and García C.M.. "Three dimensional hydrodynamics of pool-riffle sequences for urban stream restoration." River Flow 2004, Second International Conference on Fluvial Hydraulics, IAHR, Naples, Italy.

20 more conference proceeding papers need to be added

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Garcia, M.H., and Parker, G., "Hydraulic and Depositional Mechanics of Turbidity Currents", Geophysical Grain Flows Conference, Sponsored by Office of Naval Research and National Science Foundation, Scripps Institution of Oceanography, San Diego, California, July 1989. (invited)

Parker, G. and Garcia, M.H., "Experiments on Turbidity Currents Near a Canyon-Fan Transition", Transactions International Geology Congress, August 1989. (invited)

Garcia, M.H., "Hydraulic Model Study of Sedimentation Near a Power Plant in the Minnesota River", International Exchange Seminar, River Disaster Prevention Research Center, Hokkaido, Japan, July 1990. (invited)

Nino, Y., and Garcia, M.H., "Experiments on the Resonance Phenomenon in Meandering Rivers", EOS, Transactions American Geophysical Union, vol. 72, No. 44, October 1991.

Garcia, M.H., Chincholle, L., and Lopez, F., "A New Sensor for Measuring Sediment Transport", Proceedings of Euromech 310, Le Havre, France, September 1993.

University/Campus Service

Civil Engineering Department

Member, Graduate Admissions, Fellowships, and Assistantships Committees, 1994–1996
Member, Civil Engineering Advisory Committee 1993–1996
Member, Safety Committee, April 1990–1995

Member, Building Equipment and Nonrecurring Expenses Committee,
August 1990–1995
Member, Student Awards Committee, August 1990–1995
Member, Fellowships Committee, 1994–1999
Member, Promotion and Tenure Committee, 2002-2004
Member, Administrative Committee, 2002-2004.

College of Engineering

Member, Fluid Dynamics Coordinating Committee, October 1992–present
Judge, Engineering Open House, March 1995
Member, Search Committee for Civil Engineering Department Head,
December 1995–May 1996 and December 2001-May 2002, August 2004-present
Honors Council, 1999-2000
University Host, resident's Award Program for Minorities, 1992-present
University Senate, 1999-2003.
Dean's Committee on Appointments, 2002-present.
College of Engineering Executive Committee, 2004-2006.

Grants Received

Source	Project Title	Time Period	Personnel
Research Board UIUC	Stability of Alluvial Channels	8/90–5/91	García (PI)
American Chemical Society–Petroleum Research Fund	Particle Entrainment into Suspension by Turbulent Flows	9/91–9/93	García (PI)
Research Board UIUC	High-Speed Particle Motion Analysis	1/92–6/92	García (PI)
Illinois Water Resource Center	Using PIV to Study Transport in Porous Media	7/92–6/93	Valocchi (PI) García (Co-PI)
Illinois Water Resource Center	Math. Modelling of Meandering Streams in Illinois	7/92–6/93	García (PI)
National Science Foundation (RIA)	Lagrangian Model for Bedload Transport	6/92–11/95	García (PI)
Office of Naval Research, ONR	Sediment Transport and Mixing at Turbidity Current Fronts	10/92–9/94	García (PI)
Illinois-Indiana Sea Gra Program	Novel Instrument for Measuring Erosion in Coastal Environments	12/92–5/93	García (PI) L. Chincholle, France(Co-PI)
Illinois-Indiana Sea Gra Program	Assessment of Sediment Resuspension in the Great Lakes	8/93–12/93	García (PI)
U.S. Army Corps of Engineers, WES	Sediment-Laden Flows Through Vegetation	1/94–12/95	García (PI)
Office of Naval Research, ONR	Sediment Transport and Mixing at Density Currents Fronts	10/94–9/96	García (PI)
Office of Naval Research, ONR	Sediment Transport by Gravity Currents	7/94–6/97	García (PI)

Source	Project Title	Time Period	Personnel
(AASERT)			
Illinois Department of Natural Resources	Drown Proofing of Yorkville Dam Il.	5/95–12/95	García (PI)
Illinois Transport. Research Center	Stream Channel Migration Effects on Bridges	8/95–12/96	Yen (PI) Garcia (Co-PI)
U.S. Army Corps of Engineers, WES	Sediment Entrainment Induced by Navigation	11/95–10/97	García (PI)
U.S. Army Corps of Engineers, WES	Navigation-Induced Flow and Bed Shear Stresses	2/96–9/96	García (PI)
Office of Naval Research, ONR	Sediment Transport by Turbidity Currents	1996-1998	García (PI)
U.S. Army Research Office (AASERT)	Sediment Resuspension by Unstea Turbulent Flows	5/1/96–4/30/9	García (PI)
Environmental Council (UIUC)	Field Methods Course in Hydrolog	1997	Valocchi(PI) García (CoPI)
U.S. Army Corps of Engineers, WES	Sediment Entrainment	1998	García (PI)
Illinois DNR	Canoe Chutes and Fishways	1998	García (PI)
Du Pont Co.	Contaminated Sediments Modelin in the Water Environment	1998	Minsker (PI), García, Herricks Rehmann, Werth(CoPI's)
College of Engineering (UIUC)	Boneyard Creek Model Study	1998-2000	García (PI)
Illinois DNR	Drown Proofing of Batavia Dam, Illinois	1998-1999	García (PI)
Illinois DNR	Canoe Chute Model Study	1998-1999	García (PI)
Office of Naval Resear	Mudflows and Submarine Channe Formation	1998-2000	García (PI)
Environmental Protecti Agency Water and Watersheds program	Development of Technology for Stream Naturalization	1998-2001	Rhoads (PI) García, Herricks Wilson/CoPIs)
Illinois Department of Natural Resources	Modeling Dam Removal in the Fo River, Illinois	2000	García (PI)
Office of Naval Resear	Submarine Bedforms Generated b Gullies	2000-2001	García (PI)
U.S. Army Corps of Engineers, WES	Settling and Resuspension of CSO Solids	2000	García (PI)
U.S. Army Corps of Engineers, WES	Interaction of Bubbles and Biosoli in CSOs	2000	García (PI) Rehmann
Metropolitan Water Reclamation District of Greater Chicago	Hydrodynamic Modeling of the Chicago River	$25,000	García (PI)
U.S. Army Corps of Engineers, CERL	Large Scale Experiments on Bubb Columns for Combined-Sewer-Overflows Management	2000-2002	García (PI) Rehmann (CoPI

Source	Project Title	Time Period	Personnel
Battelle National Lab a Environmental Protecti Agency	Simulation of Transient, Low-Pressure-Induced Contaminant Intrusion into Water Distribution Systems	2000	García (PI)
Department of Defense DURIP Program	Large Scale Oscillating Water-Sediment Tunnel	2001-2002	García (PI)
Office of Naval Resear	Wave-Current-Induced Mine Buri due to Sediment Fluidization	2001-2002	García (PI)
Greeley and Hansen, Chicago	Sedimentation in Side Elevated Re aeration Pools (SEPA)	2001-2002	García (PI)
US Army Corps of Engineers, WES	Settling and Oxygen Demand of Suspended Combined-Sewer-Overflow Solids	2002	García (PI)
US Army Corps of Engineers, WES	Interaction of Coarse-Bubble Plumes and Water Jets with Suspended Solids	2002	García (PI) Rehmann (CoPI
Metcalf & Eddy, Chica Office	Hydraulic Model Study of Calume Pumping Station	2002-2003	García (PI)
National Science Foundation	Stage-Discharge Ratings for Open Channel Flows	2001-2002	García (Co-PI) Yen (PI)
Sanitary District of Decatur Illinois	Hydraulic Analysis of UV Disinfection Units	2002	García (PI)
Metropolitan Water Reclamation District of Greater Chicago and Illinois Department of Natural Resources	Modeling of Density Currents in Chicago River	2002-2004	García (PI)
Office of Naval Resear	Dynamics of Turbidity Currents a Mud Flows	2002-2003	García (PI)
Illinois Water Resource Center	Integrated Engineering and Geomorphological Analysis for Assessing the Performance of Bendway Weirs in Illinois Stream	2001-2003	Rhoads (PI) García (CoPI)
National Science Foundation(Internation Collaboration with University of Leeds, U	Integration of Mathematical Modeling, Physical Modeling and Field Research for Advanced Understanding of River Dynamics	2001-2004	Rhoads (PI) García (CoPI)
U.S. Dept. of Agricultu	Management of Vegetative Ripari Stream Corridors	2001-2006	García (PI)
Office of Naval Resear	Experiments with Oscillating Wat Tunnel	2002-2004	Garcia (PI)
Metropolitan Water Reclamation District of Greater Chicago	Design of Jet System for Solids Management	2003-2004	Garcia (PI)

Source	Project Title	Time Period	Personnel
Metropolitan Water Reclamation District of Greater Chicago	TARP (Deep Tunnel and Reservoirs) Modeling Phase I-Calumet System	2003-2006	Garcia (PI)
Office of Naval Resear	Burial of Objects by local Scour ar Sand Waves	2003-2005	Garcia(PI)
Office of Naval Resear	Morphodynamics of Ripples in Benthic Boundary-Layer Flows	2004-2006	Garcia(PI)
Metropolitan Water Reclamation District of Greater Chicago	TARP (Deep Tunnel and Reservoirs) Modeling Phase I-Main Stem & Des Plaines River	2005-2007	Garcia (PI) Schmidt (Co-PI)

Attachment 2

HYDRODYNAMIC MODELLING OF BUBBLY CREEK, CHICAGO, ILLINOIS: FLOW PATTERNS DURING COMBINED-SEWER-OVERFLOW EVENTS

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ABSTRACT

The objective of this preliminary analysis is to understand the hydraulic behavior of Bubbly Creek, the South Fork of the South Branch of the Chicago River, where water is nearly stagnant during dry periods and where, during heavy storms, the Racine Avenue Pumping Station (RAPS) discharges combined-sewer-overflow (CSO) at the upstream end of the creek. During dry-weather periods, the RAPS has been operated in a reverse mode with the goal of increasing dissolved-oxygen levels. The analysis was conducted with two different 2D hydrodynamic finite-volume models, one for steady flow conditions and a second one for fast-transient flows, which were used to model the whole length of Bubbly Creek, from RAPS to the turning basin at the confluence with the South Branch of the Chicago River.
The flow analyses were validated through a comparison between the predictions made with both models and the results of previous studies conducted for the restoration of Bubbly Creek. Observations of a CSO event in 2006 allowed for the evaluation of the hydrodynamic behavior in the creek due to a sudden CSO discharge. Of particular interest were the influence of the flow resistance coefficient, the variation of water levels and the characteristics of the mean flow velocity and turbulence fields. These results provide a starting point for the implementation of a water quality model for Bubbly Creek to be used for the evaluation of potential flow augmentation and supplemental aeration technologies.

INTRODUCTION

Description of Bubbly Creek

Bubbly Creek, located S-W of Chicago (Figure 1), is the South Fork of the South Branch of the Chicago River, having a length of approximately 2000 meters, a mean width of about 46 meters and a fairly straight channel alignment. The mean channel bottom slope is about 0.001, but this is misleading because the channel bottom varies so much. The upstream 60% is shallow due to the lack of navigation. The downstream 40% is scoured by periodic barge traffic. The location of the barge dock is the narrowest width in the channel length, as can be observed on Figure 1. From 1865 to 1939, Bubbly Creek was used as a drainage channel for the waste resulting from Chicago's stockyards. Today, this historically industrial area, characterized by the presence of industrial plants, trucking terminals, rail and construction material yards, is being transformed into a residential development, with strip malls and residences. As a consequence, water quality in the creek has become a very important issue, particularly during the summer months, when dissolved-oxygen levels are very low. During dry periods, the water in Bubbly Creek is stagnant. With light rainfall events there are no noticeable changes, since the combined-sewer-overflow (CSO) coming from the 36 square miles service area (463400 people and 169900 households served) is conveyed to the Metropolitan Water Reclamation District's (MWRDGC) Stickney Water Reclamation Plant (WRP) and not discharged to the creek. During heavy storms, the Racine Avenue Pumping Station (RAPS, see Figure 1) discharges CSO to the creek, so that the water flows northward into the South Branch of Chicago River. For excessively heavy storms, several CSO outfalls located along the channel may discharge to the creek depending on the intensity of the rainfall event. There are 9 such outfalls along the banks of the creek (shown in Figure 1). At the time it was commissioned by the Chicago Sanitary District in the 1940's, the RAPS was one of the largest pumping stations in the world.

Characteristics of observed CSO events

Herein the CSO discharge to the creek from the Racine Avenue Pumping Station (RAPS) is analyzed. In the period 1992-2001, pumping from RAPS into Bubbly Creek occurred 17 times per year on average (maximum 27 times in 1993, lowest 10 times in 1997, *MWRDGC, 2003*). In the period 2005-2007, the information made available by MWRDGC (*htpp://www.mwrd.org/*) shows that the average overflow volume was about 300 MG (maximum value 1172.40 MG on 10/02-03/2006, minimum value 70.87 MG on 02/25/2007), the average overflow duration was about 8.6 hours (maximum value 29.81 hours on 01/12-13-14/2005, minimum value 3.02 hours on 02/25/2007) and the average mean discharge was about 35.1 m^3/s (maximum value 69.4 m^3/s on 09/13/2006, minimum value 22.0 m^3/s on 01/12/2005).

The Racine Avenue Pumping Station has two sets of pumps, one set given even numbers and the other set given odd numbers. For small CSO events, only the 9 even-numbered pumps work, discharging along the RAPS side called "Inflow 1" (see Figure 1 and later in the report) through 9 pipes. The 5 odd-numbered pumps can pump either to Bubbly Creek (along the RAPS side herein called "Inflow 2" through 3 gates) or to the Stickney Wastewater Treatment Plant. For each CSO event, MWRDGC records the volume discharged by each single pump as well as the discharge duration.

Figure 1. Aerial view of Bubbly Creek with the location of the CSO outfalls along the creek (circles) and detail of the Racine Avenue Pumping Station (RAPS) with the location of "Inflow 1" and "Inflow 2".

HYDRODYNAMIC ANALYSES OF BUBBLY CREEK

Main objectives

The main goal of the present study is to perform flow simulations for Bubbly Creek when CSO discharges from the Racine Avenue Pumping Station (RAPS) take place following heavy rainfall events. Indeed, due to the operations of the gates and pumps at RAPS, an unsteady flow occurs in the creek, inducing changes in the free-surface elevation.

The unsteady flow simulations were done with the SV2D code (*Soares Frazão, 2002*), a 2D finite-volume model which was primarily designed for dam-break flows, i.e. fast transients where the free-surface position can vary rapidly, but where turbulence and secondary flows play a minor role. The results of the unsteady flow simulations were then used to refine the analysis of the flow patterns during the pumping operations using the STREMR code (*Bernard, 1993*; *Abad et al., 2007*), a 2D finite-volume model that uses the rigid lid assumption for the free-surface. With a rigid lid, only steady flow simulations are possible or simulations of flows where the free surface can be assumed to vary uniformly in the flow direction. In this work, the feasibility of using a rigid lid model for Bubbly Creek was investigated, comparing the results provided by SV2D and STREMR for a steady flow simulation with a discharge value equal to the maximum capacity of the RAPS pumps. STREMR accounts for turbulent shear stresses using a refined k-ε model, as well as corrective terms to account for the presence of secondary flows. It is thus able to provide a detailed and accurate velocity distribution under steady flow conditions. This kind of analysis represents a starting point for the future implementation of a water quality model for Bubbly Creek.

Bathymetric data

Bathymetric data are available for Bubbly Creek, from Racine Avenue Pumping Station (South end of the creek) to the turning basin at the confluence with the Chicago River (North end of the Creek). The bathymetric data were provided by the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC).

Comparison between the SV2D and STREMR models

First, steady-flow simulations were run using both the SV2D code and the STREMR code, in order to compare them in the same framework. All computations were run considering a discharge of 170 m^3/s, equal to the maximum capacity of the pumps at RAPS, and assuming a Manning's roughness coefficient of 0.024. This value was found by trial and error, starting from a value of 0.03 and running the STREMR model for different Manning's coefficients until the flow was close to uniform. The water level downstream (turning basin) was assumed equal to 175.93 m a.s.l. (from *MWRDGC, 2003*).

The structured computational mesh used for the comparison is an irregular mesh made up of rectangles. There are 337 rectangles in the flow direction and 15 rectangles in the direction normal to flow. The mesh was built using the meshing capabilities of the SMS program (*http://www.ems-i.com/*). The zone just downstream the Racine Avenue Pumping Station was not considered in the mesh, but was included in the unsteady flow analysis presented later below. Moreover, since the water level in the reach is higher than the higher limit of each surveyed cross-section, vertical banks were assumed to complete the cross-sections. The validity of this assumption was checked as shown below.

The STREMR model was run with a two-equation turbulence model (k-ε) and a correction due to secondary flow was included. The water level upstream (southern end of the creek) was assumed equal to 176.84 m a.s.l. and the rigid lid representing the water surface was a plane having a slope of 0.00038 (those values were obtained through the trial and error procedure mentioned above). A constant numerical time step was adopted, equal to 0.005 s. The time to reach equilibrium flow conditions was about 3000 s.

For the steady-flow simulation with SV2D the same mesh, discharge, Manning's roughness coefficient and water level at the downstream end considered for the simulation with STREMR were used. The initial water level was set equal to 175.93 m all over the creek, water being at rest. The time step was defined according to the CFL condition (CFL number equal to 0.9), and the time to equilibrium was about 3000 s.

The results obtained with the two codes were analyzed considering the differences, cell by cell or along the creek thalweg, in terms of water depths and flow velocities. The STREMR model matches well the water depth values calculated by the free-surface flow model (see Figure 2) with some discrepancies however, due to the assumption made for the free-surface plane (rigid lid with constant slope). In general, the water depths calculated by SV2D are slightly greater in the upstream reach of the creek and smaller in the central reach. The matching in the downstream part is good. The mean value of the water depth STREMR – SV2D difference is -0.04 m.

Regarding flow velocities, the results of the two models are generally similar, with a mean difference of 0.10 m/s (see Figure 2). The main discrepancies are located at the upstream end of the creek, where the combined-sewer-overflow is discharged and at the downstream end, where the differences are due to the way the boundary conditions are set in the two models: in STREMR, the Sommerfeld radiation condition is used, in SV2D, the downstream water level is imposed and the discharge is calculated according to the characteristics. In general, the flow velocity values calculated by STREMR along the thalweg are greater than the values calculated by SV2D because of the absence of a free surface (the flow is constricted by the rigid lid).

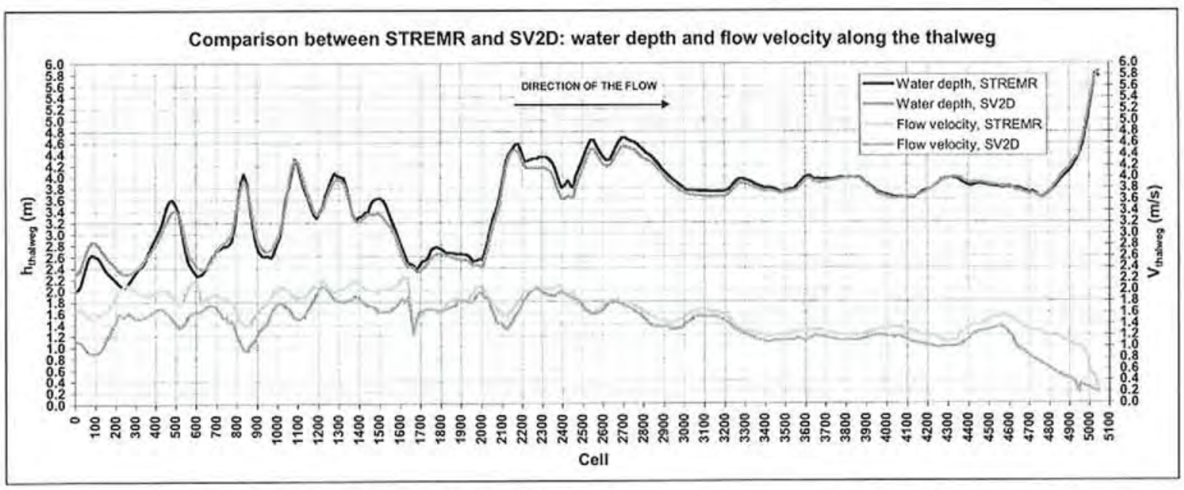

Figure 2. Comparison between the water depths and the flow velocities calculated along the thalweg of the creek by STREMR and SV2D.

Steady flow simulations with the SV2D code

An unstructured triangular mesh made of 16942 elements was built, extending the domain up to include the area right downstream the Racine Avenue Pumping Station. The bathymetric information was completed in that area with data from a recent survey performed by USGS. The upstream boundary condition was set along the two profiles called "Inflow 1" and "Inflow 2", where respectively the even and the odd pumps are (see Figure 1).

A sensitivity analysis on the Manning's roughness coefficient of Bubbly Creek was done for a discharge of 170 m^3/s, considering the values $n = 0.024$ (value adopted in the analysis presented above) and $n = 0.030$, following a previous analysis by *MWH* (2006). A value 0.030 results in an increase of the water level at RAPS of 0.20 m. In general, the variation of the Manning's coefficient does not produce noticeable changes in the water levels. In the following analyses, the value 0.024, computed by trial and error, will be used. Future water level measurements along the creek could allow for a more accurate calibration of the roughness coefficient.

A sensitivity analysis on the influence of the location of the combined-sewer-overflow discharge input to Bubbly Creek was done. In particular, the CSO can be discharged by the 9 even-numbered pumps along the Racine Avenue Pumping Station "Inflow 1" side or by the 5 odd-numbered pumps along the "Inflow 2" side (see Figure 1). The study was done using the unstructured triangular mesh described above.

The simulations were run for the maximum capacity of the odd-numbered pumps, which is 54.5 m^3/s. Three cases were considered: CSO discharge from the 9 pumps along "Inflow 1", CSO discharge from the 5 pumps along the "Inflow 2" and CSO discharge from both the sides. For each case the discharge was uniformly distributed across the input points (an input point for each of the even-numbered pumps and for each of the three gates for the odd-numbered pumps).

Four reference sections of Bubbly Creek were considered for the analysis of the water level and of the flow velocity (see Figure 3a). The equilibrium flow velocity field in each of the three cases is indicated in Figure3b,c,d.

The velocity fields for the cases when the combined-sewer-overflow is discharged from the "Inflow 1" side and from both the RAPS sides are similar, whereas, when the flow is discharged through the "Inflow 2" side, the velocity values are higher at the entrance, on the left side of Section 1 and on the right side of Section 3 (up to 1.8 m/s, the red color in Figure 3 indicates velocity values equal or greater than 1.2 m/s). At Section 4, located about 200 m downstream from Section 1, the influence of the inflow location is already negligible. The differences in the water surface levels between the different scenarios are negligible too, being their maximum value equal to 4-5 cm at Section 1.

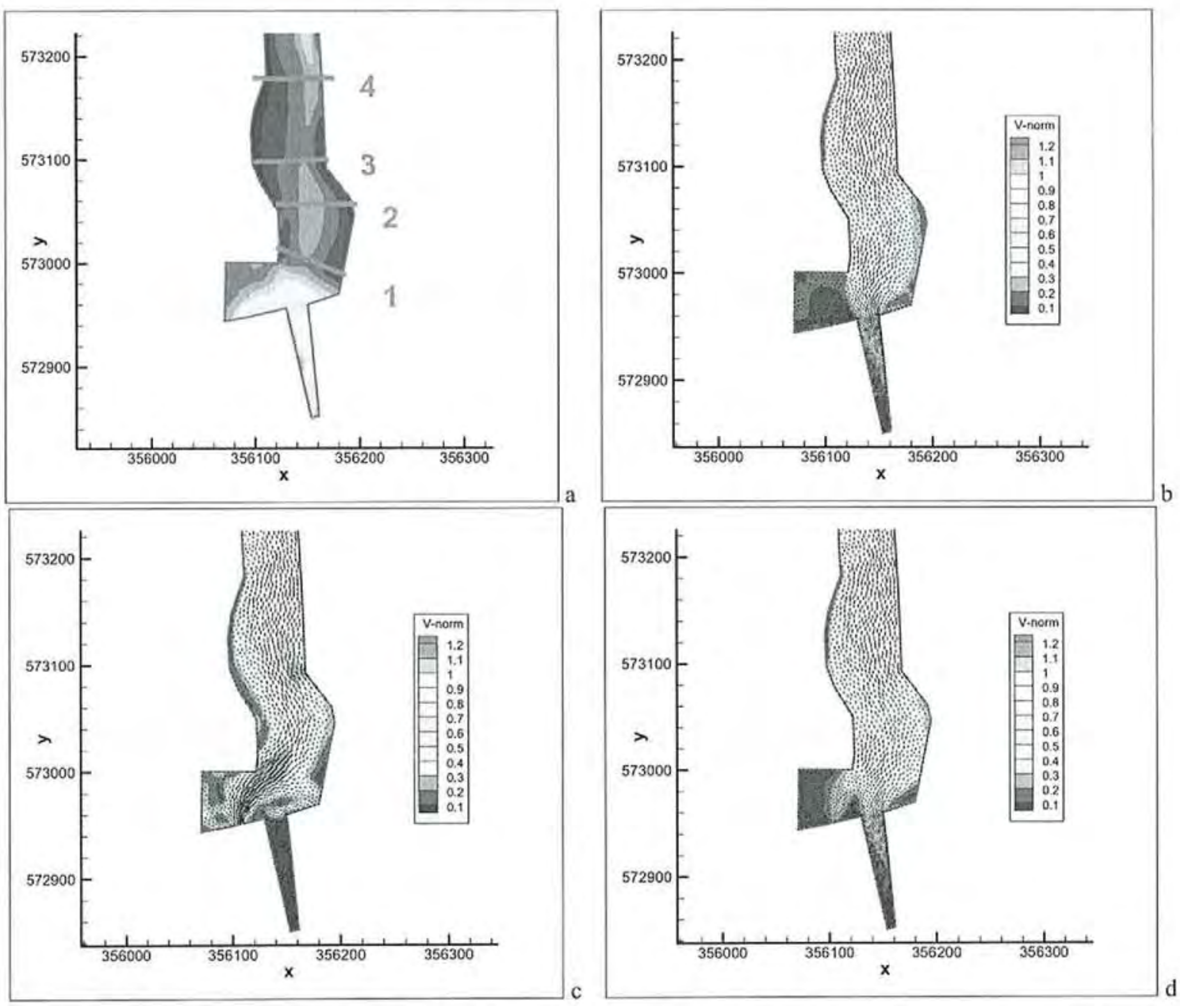

Figure 3. Results of the sensitivity analysis on the influence of the location of the combined-sewer-overflow discharge input in terms of flow velocity. (a) Sections considered for the analysis, (b) CSO from the 9 pumps along "Inflow 1", (c) CSO from the 5 pumps along "Inflow 2", and (d) CSO distributed over "Inflow 1" and "Inflow 2".

The SV2D unsteady flow analyses for real events and the data for STREMR

Given that the CSO volume and discharge duration are known for each pump at RAPS for all the events in the period 2005-2007, the hydrodynamics of those events can be simulated with the SV2D code. In particular, an unsteady flow simulation was run for the CSO event of September 13, 2006 (the largest one observed in the period 2005-2007), characterized by an overflow volume of 505.84 MG, a duration of 7.66 hr and a mean discharge of 69.4 m^3/s. The simulation shows the scarce influence of the operations of each single pump on the overall flow field in Bubbly Creek (see Figure 4 for the evolution of discharge at RAPS and water levels at the Bubbly Creek entrance and at the turning basin, where that influence is negligible). In other words, accounting for the different CSO volumes and duration of each single pump at RAPS does not add much information regarding the hydrodynamics in Bubbly Creek. Moreover, the temporal variation of the hydraulic variables in the creek is really limited. This supports the approach of using a steady flow code like STREMR for the further analyses.

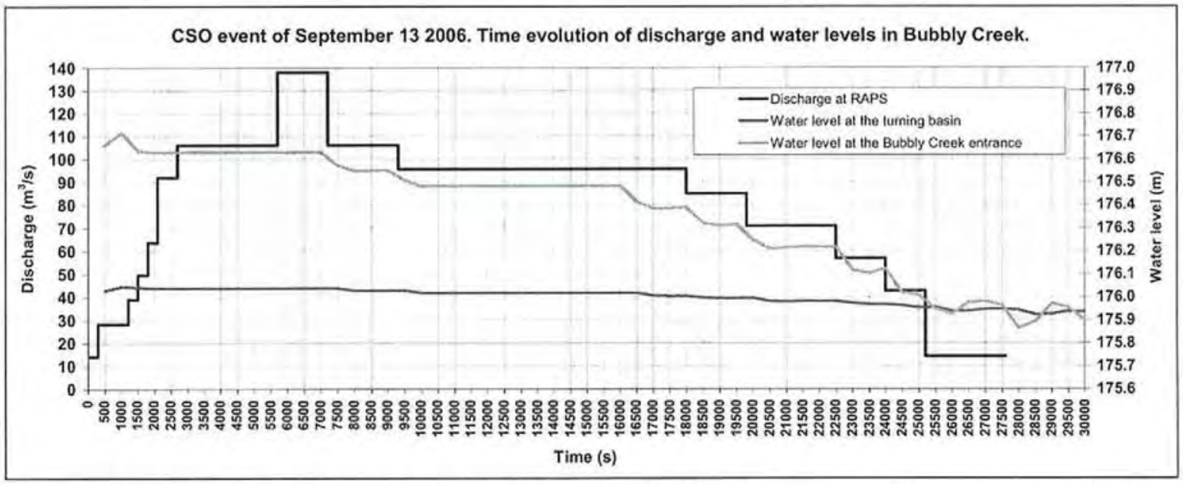

Figure 4. Evolution of discharge and water levels at the Bubbly Creek upstream and downstream ends for the CSO event of September 13 2006.

Unsteady flow simulations were run with the SV2D code to generate three curves: (i) water surface elevation as a function of time, (ii) water surface elevation as a function of the discharge, and (iii) mean water surface slope as a function of the discharge. In particular, this latter curve allows for setting the slope of the rigid lid in STREMR for different discharge values. The rating curve obtained in this way is in good agreement with the previous assumptions made for the comparison STREMR – SV2D and with the results of some additional SV2D steady flow simulations. It therefore can be used to determine the slope of the rigid lid used in STREMR for different discharge values.

Preliminary steady flow analyses for different CSO discharges in STREMR

Some preliminary steady flow analyses with STREMR allowed for characterizing the velocity, shear stress and turbulence fields for different CSO discharge values. In particular, Figure 5 shows the comparison between the velocity and shear velocity fields for a discharge of 35 m^3/s (mean discharge for the CSO events occurred in the period 2005-2007) and 170 m^3/s (maximum capacity of the pumps). For both the scenarios, the free surface slope was set in STREMR according to the curves generated in the unsteady flow analysis.

In Bubbly Creek, sediment oxygen demand (SOD) plays an important role for the water quality since the dissolved oxygen (DO) is lowered by that oxygen demand. It is known that part of the SOD is due to the CSO loads. On the other hand, the sediment deposited on the creek bottom is another factor affecting oxygen demand. The entrainment into suspension of these sediments depends on the flow rate. Considering a median grain size of 0.112 mm for the bed sediments (source *USGS*), the critical Shields shear velocity needed for erosion is about 0.012 m/s (*García, 1999*). The shear velocities corresponding to a discharge of 170 m^3/s are much greater than the critical value needed for erosion in almost all the creek, whereas, for a discharge of 35 m^3/s, the sediments are hardly entrained, especially downstream.

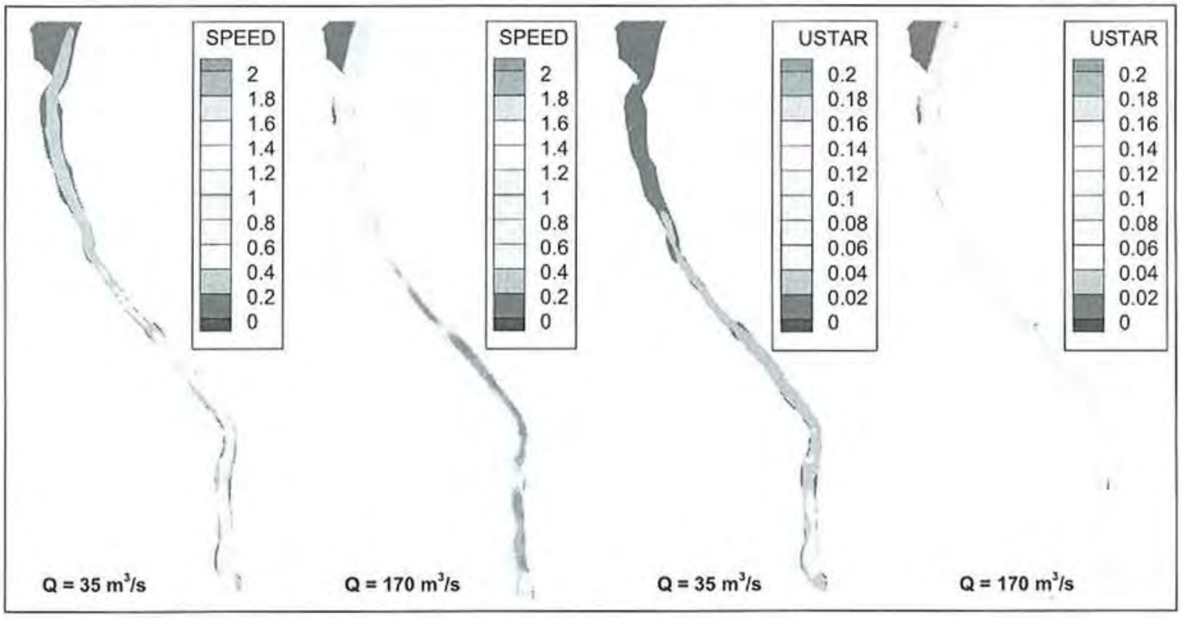

Figure 5. Comparison between the velocity ("SPEED" in m/s) and shear velocity ("USTAR" in m/s) fields in the creek for discharges of 35 m^3/s and 170 m^3/s, respectively.

FUTURE DEVELOPMENTS

The analyses presented in this paper will provide a base for the implementation of a STREMR water quality module for dissolved oxygen (DO) and biochemical oxygen demand (BOD). The module will be used to investigate the variations in dissolved oxygen concentration observed after each historical CSO event, clarifying the roles played by the CSO loads, the waste layer on the bottom of the creek and the DO variability within the event. Regarding potential technologies for the creek purification, in 2002 and 2003, during dry-weather periods, the RAPS was used in a reverse mode in order to increase the dissolved-oxygen levels (*MWRDGC, 2003, 2004*) and other analogous scenarios have been suggested and analyzed more recently (*MWRDGC, 2006*). The water quality model will facilitate the evaluation of different technologies for flow augmentation and supplemental aeration in Bubbly Creek.

ACKNOWLEDGMENTS

The financial support of the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) through a research grant to the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign, is gratefully acknowledged. Comments by Mr. Richard Lanyon were very helpful for the completion of the manuscript. Sandra Soares Frazão also thanks the support of Université Catholique de Louvain, Belgium.

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Attachment 3

Progress Report
ENVIRONMENTAL CHICAGO AREA WATERWAY SYSTEM MODELING (Phase I)
Modeling of the South Fork of the South Branch of the Chicago River, Bubbly Creek

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INTRODUCTION

The present progress report is a part of a more comprehensive study regarding the water quality of the Chicago Area Waterway System (CAWS), which is currently being made by the University of Illinois under the supervision of Prof. Marcelo H. Garcia and is funded by the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC).

For this study, a model for the evaluation of the effect of sediment resuspension from a river bed on the BOD-DO (biochemical oxygen demand - dissolved oxygen) dynamics, especially in presence of organic-rich beds, was implemented in the two-dimensional depth-averaged hydrodynamic, sediment transport and water quality model STREMRySedWq. Notice that, in this document, the words "sediments" and "solids" are considered as interchangeable.

The bed-water interaction was modeled through the incorporation of a dynamic description of the process of BOD transport across the bed-water interface. Only one layer of sediments was considered in the implementation of the model in STREMRHySedWq, written in FORTRAN language.

The main advancements represented by the implementation of a bed-water sediment and BOD exchange model in STREMRHySedWq are the following:

- since STREMRHySedWq is two-dimensional, it can provide information on the horizontal gradients of all the variables of interest. As regards in particular the bed-water interaction, a 2-D approach can model the cross-sectional variation of the bottom shear stress, which affects the resuspension fluxes of sediments and BOD;
- the sediment entrainment from the bottom, instead of being entered as external data by the user (as made in the most popular available codes),

is related to the flow characteristics, by coupling the water quality module with the hydrodynamics and sediment entrainment/deposition modules. The sediment module, implemented by Abad *et al.* (2007), considers two entrainment formulae for the solids on the bottom: Smith-McLean (1977) and Garcia-Parker (1991). In this study the Smith-McLean formula was used.

The sediment entrainment and deposition fluxes are associated to corresponding BOD entrainment and deposition fluxes, since a fraction of the total BOD is attached to the solids and since erosion and deposition can respectively release or include pore water which contains dissolved BOD.

The BOD entrainment and settling fluxes are additional source/sink terms in the BOD conservation equation. Those terms affect the BOD levels and consequently the DO levels in the water column: in fact, the oxidation term, which appears in both the BOD and DO conservation equations, is proportional to the BOD concentration.

Once the model was implemented, two analyses were done. The first one is an analysis of the sensitivity of the BOD bed-water exchange model to its parameters. The second is an application to Bubbly Creek in Chicago, in particular to the so called combined-sewer-overflow (CSO) events. To perform this second analysis, besides using the 2-D model STREMRHySedWq (to model the CSO discharge period), a 1-D model was implemented to describe the dispersion-reaction processes occurring once the CSO discharge is over.

The results reported in this progress report have to be considered as preliminary, essentially because of the assumptions on the value of some of the parameters for Bubbly Creek, which is currently under further investigation. On the other hand, a sound conceptual framework for modeling beds characterized by high organic matter content, as well as qualitatively encouraging preliminary results are presented.

A further model improvement is currently being made (but not presented in this document) in order to better characterize the sediment erosion and settling rates, which, for cohesive and organic-rich sediments, need to be described with different expressions than the ones commonly used for non cohesive sediments. The goal is better understanding the impact of sediment and BOD resuspension during CSO events, which for some historic events appears to be high (as in the case of the CSO event analyzed in this study) and for others less important.

THE MODEL STREMRHYSEDWQ

The two-dimensional depth-averaged hydrodynamic model STREMR includes a k-ϵ two-equation turbulence model and a correction for the mean flow due to secondary flow. The model was developed by Robert S. Bernard at the Waterways Experiment Station (WES) of the U.S. Army Corps of Engineers (Bernard, 1993). It is a numerical model that generates discrete solutions of the incompressible Navier-Stokes equations for depth-averaged 2-D flow. The discretization of the equations is based on the Finite Volume (FV) method, in which a stair-stepped (piecewise constant) discretization of the flow depth is adopted. A limitation of STREMR is that it imposes a rigid-lid approximation for the free surface which requires the specification of the water surface elevation. However, STREMR accounts for the free surface influence by means of a correction to the pressure equation. The assumption of rigid lid implies that only steady flow and subcritical flow conditions can be modeled. Anyway, the assumption of rigid lid was proved to work fairly well for the kind of events analyzed later in this analysis for Bubbly Creek (Motta *et al.*, 2007). A detailed description for the hydrodynamic model is not reported in this document. For more information, see Bernard (1993) and Abad *et al.* (2007).

Modules based on the depth-averaged hydrodynamic model were incorporated into STREMR for suspended and bed-load transport in the new version STREMRHySed (Abad *et al.*, 2007). The depth-averaged sediment transport equations for the suspended sediment, incorporated into the hydrodynamic model, consider different size classes. The suspended and bed-load sediment transport model was validated against experimental measurements and analytical solutions, finding an acceptable agreement. As regards the suspended transport module, which was interesting in the view to modeling an analogous module for water quality, the original assumption of fixed bottom elevation was relaxed according to the Exner formulation, while maintaining the water surface elevation constant.

The two-dimensional depth-averaged numerical model STREMRHySedWq contains a water quality module, developed by Motta *et al.* (2008), based on the depth-averaged advection-diffusion transport model for non conservative scalars, whose concentration is modified by physical, biological and chemical processes, described by kinetics equation. The advection-diffusion-reaction equation is therefore solved. As regards the suspended sediments (or solids), the eddy diffusivity is calculated as ratio of the eddy viscosity (calculated by the model of turbulence) and the Schmidt number, assumed constant.

Hydrodynamics and the transport of scalars, treated as dissolved, were not coupled originally. Anyway a recent modification to the code, implemented for this analysis, allows for coupling the hydrodynamics, the transport of solids and the BOD resuspension and settling.

Since the model is two-dimensional, the stratification in the vertical direction is not modeled.

The water quality module models the oxygen cycle which considers the biochemical oxygen demand (BOD) and the dissolved oxygen (DO). The model is able to account for the time variation of temperature (on which many parameters depend), which is entered by the user. The oxygen cycle is affected by processes which involve other substances (specifically ammonia, nitrate and phytoplankton). The model considers these processes, even though, as it currently is, the concentrations of ammonia, nitrate and phytoplankton are constant during the simulation. The same is valid for salinity.

The depth-averaged mass balance equation for non-conservative substances

Water quality is modeled by solving the depth-averaged mass balance equation for non-conservative substances.

The equation is obtained from the conservation equation, which can be derived for example using the control volume approach, that is

$$\frac{\partial C}{\partial t} + \nabla \cdot J_c - S = 0 \tag{1}$$

where C is the concentration of a generic substance, t is time, S is the net rate of production by sources and sinks and J_c is the flux defined as the sum of an advective and a diffusive flux

$$J_c = UC - D\nabla C \tag{2}$$

where U is the bulk velocity and D is the turbulent (eddy) diffusivity, that is here calculated as

$$D = \frac{\nu_t}{Sc} \tag{3}$$

where ν_t is the eddy viscosity, calculated in STREMRHySedWq with a k-ϵ two-equation turbulence model, and Sc is the turbulent dimensionless Schmidt number. Several authors presented formulae or values for the Schmidt number Sc for different substances.

The equation (1) is integrated in the vertical to obtain the depth-averaged conservation equation:

$$\frac{\partial}{\partial t}(HC) + \nabla_h \cdot (HJ_c) = S' \tag{4}$$

where "h" denotes "horizontal" gradient (in the directions x and y), H is the water depth and S' is the depth-integrated net rate of production by sources and sinks. The bulk velocity U for the advective flux has two components u and v, which are the depth-averaged velocity components in the horizontal x and y directions.

Different water quality models consider different substances and a typical model would include dissolved oxygen, ammonia, organic nitrogen, nitrite, nitrate, organic phosphorous, inorganic phosphorous, biochemical oxygen demand, algal biomass and temperature (Chapra, 1997). All these substances interact through kinetic processes.

STREMRHySedWq solves the first two terms on the right-hand side of the depth-averaged mass balance equation for BOD (C_{BOD}, mgO_2/l) and DO (C_{DO}, mgO_2/l), i.e. the transport terms. In addition, kinetic processes for BOD and DO are incorporated as source/sink terms S'. The kinetic equations implemented in the water quality module (Colonna Rosman, 2006) contain the following variables:

- ammonia nitrogen concentration C_{NH_3}(mgN/l);
- nitrate nitrogen concentration NO_3^- (mgN/l);
- phytoplankton carbon biomass concentration C_{ph}(mgC/l). Notice that in this model the phytoplankton is expressed as mass of carbon;
- temperature T(°C);
- salinity S(mg/l).

The time variation of the temperature can be entered by the user, while the concentrations of ammonia, nitrate and phytoplankton, as well as salinity, are assumed constant by STREMRHySedWq.

Biochemical oxygen demand (BOD) kinetics equation

The following equation describes the kinetic processes (terms S in (1)), having dimensions of concentration over time) involving the biochemical oxygen demand concentration C_{BOD} (mgO$_2$/l):

$$\begin{aligned}\frac{dC_{BOD}}{dt} = {} & a_{oc}K_{1D}C_{ph} - K_D\Theta_D^{(T-20)}\left(\frac{C_{DO}}{K_{BOD}+C_{DO}}\right)C_{BOD}+ \\ & -\frac{5}{4}\frac{32}{14}K_{2D}\Theta_{2D}^{(T-20)}\left(\frac{K_{NO3}}{K_{NO3}+C_{DO}}\right)C_{NO_3^-} + W_{BOD}\end{aligned} \tag{5}$$

The positive terms in the right-hand side of the equation produce an increase of the BOD, the negative terms produce a decrease of BOD.

Other terms can be added on the RHS of the equation, in particular the terms relative to the BOD resuspension and settling, which are introduced and investigated in detail later in this document.

Let's briefly analyze the kinetic terms one by one.

Decaying of phytoplankton biomass (positive term)

$$a_{oc}K_{1D}C_{ph} \tag{6}$$

where:

- a_{oc} is the decaying coefficient for phytoplankton biomass (-);
- K_{1D} is the phytoplankton biomass decaying coefficient (day^{-1});
- C_{ph} is the phytoplankton carbon biomass concentration (mgC/l).

Oxidation (negative term)

$$K_D\Theta_D^{(T-20)}\left(\frac{C_{DO}}{K_{BOD}+C_{DO}}\right)C_{BOD} \tag{7}$$

where:

- K_D is the deoxygenation (oxidation) coefficient at 20 °C (day^{-1});

- Θ_D is the temperature coefficient for deoxygenation (-);
- T is the water temperature (°C);
- C_{DO} is the dissolved oxygen concentration (mgO_2/l);
- K_{BOD} is the half saturation constant for the BOD oxidation (mgO_2/l);
- C_{BOD} is the biochemical oxygen demand concentration (mgO_2/l).

De-nitrification (negative term)

$$\frac{5}{4}\frac{32}{14}K_{2D}\Theta_{2D}^{(T-20)}\left(\frac{K_{NO3}}{K_{NO3}+C_{DO}}\right)C_{NO_3^-} \tag{8}$$

where:

- K_{2D} is the de-nitrification coefficient at 20 °C (day^{-1});
- Θ_{2D} is the temperature coefficient for de-nitrification (-);
- K_{NO_3} is a half saturation constant (mgO_2/l);
- C_{DO} is the dissolved oxygen concentration (mgO_2/l);
- $C_{NO_3^-}$ is the nitrate nitrogen concentration (mgN/l).

BOD input (positive term)

Localized inputs of BOD not associated to inflow boundaries are represented by the term

$$W_{BOD} \tag{9}$$

which has dimensions of concentration over time ($mgO_2/l/s$). If the BOD input is known in terms of mass over time M_{BOD} (mgO_2/s) and the input is "applied", considering a numerical domain, to a certain number i of cells having area A and depth H, W_{BOD} is calculated as follows

$$W_{BOD} = \frac{M_{BOD}}{\sum_i A_i H_i} \tag{10}$$

Dissolved oxygen (DO) kinetics equation

The following equation describes the kinetic processes (terms S in (1), having dimensions of concentration over time) involving the dissolved oxygen concentration C_{DO} (mgO_2/l):

$$\begin{aligned}\frac{dC_{DO}}{dt} &= K_a\Theta_a^{(T-20)}\left(C_s - C_{DO}\right) + G_{PI}\left(\frac{32}{12}+\frac{48}{14}\frac{14}{12}\left(1-P_{NH3}\right)\right)C_{ph} + \\ -K_D\Theta_D^{(T-20)}&\left(\frac{C_{DO}}{K_{BOD}+C_{DO}}\right)C_{BOD} - \frac{64}{14}K_{12}\Theta_{12}^{(T-20)}\left(\frac{C_{DO}}{K_{NIT}+C_{DO}}\right)C_{NH_3} + \\ &-\frac{32}{12}K_{1R}\Theta_{1R}^{(T-20)}C_{ph} - \frac{SOD}{H}\Theta_s^{(T-20)} + W_{DO}\end{aligned} \tag{11}$$

The positive terms in the right-hand side of the equation produce an increase of the DO, the negative terms produce a decrease of DO.

As done for BOD kinetic terms, let's briefly analyze the kinetic terms for DO one by one.

Reaeration (positive term)

$$K_a \Theta_a^{(T-20)} \left(C_s - C_{DO}\right) \tag{12}$$

where:

- K_a is the reaeration coefficient (day^{-1});
- Θ_a is the temperature coefficient for reaeration (-);
- C_s is the dissolved oxygen concentration at saturation (mgO_2/l) and it is function of the temperature T and salinity S according to different expressions from literature.

Schladow and Hamilton (1997) suggest to use Mortimer formula (named here as "Formula 1"), where the temperature T is measured in °C:

$$C_s = \exp\left[7.71 - 1.31 \ln\left(T + 45.93\right)\right] \tag{13}$$

Colonna Rosman (2006) reports the following equation (named here as "Formula 2"), where the temperature T is measured in K and salinity in PSU (Practical Salinity Units):

$$\begin{aligned} \ln\left(C_s\right) = -139.34 + \frac{1.5757\ 10^5}{T} - \frac{6.6423\ 10^7}{T^2} + \frac{1.2438\ 10^{10}}{T^3} - \frac{8.6219\ 10^{11}}{T^4} + \\ -S\left(1.7674\ 10^{-2} - \frac{1.0754\ 10^1}{T} + \frac{2.1407\ 10^3}{T^2}\right) \end{aligned} \tag{14}$$

A document by the Marquette University in Milwaukee (Alp and Melching, 2004) reports a formula by the Committee on Sanitary Engineering Research (1960), named here as "Formula 3". In this case C_s is the dissolved oxygen concentration at saturation at sea level (mgO_2/l), T is the water temperature (°C), f is the correction factor above sea level (-), E is the site elevation (ft) and s is the air temperature (°C):

$$C_s = 14.652 - 0.41022T + 0.00799T^2 - 0.000077774T^3 \tag{15}$$

$$f = \frac{\left(2116.8 - \left(0.08 - 0.000115s\right)E\right)}{2116.8} \tag{16}$$

Figure 1 shows a comparison between the three formulae reported above for the calculation of the dissolved oxygen concentration at saturation. The "Formula 2" is plotted for two values of salinity (15 PSU and 25 PSU).

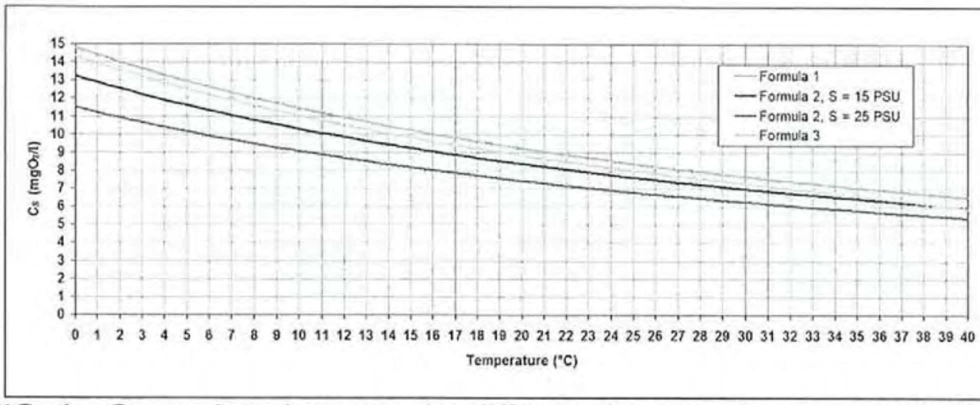

FIG. 1. Comparison between the different formulae for the calculation of the dissolved oxygen concentration at saturation C_S.

As regards the reaeration coefficient K_a, several formulae are available from literature. Thomann (1972) and Chapra (1997) present a review of the main studies and investigations on the parameter K_a, based on theoretical investigations and empirical field studies. The most common formulae presented are by O'Connor and Dobbins, Churchill and Owens and Gibbs. The widely used O'Connor and Dobbins formulation is here reported:

$$K_a = \frac{3.93U^{1/2}}{H^{3/2}} \tag{17}$$

K_a is the reaeration coefficient in day^{-1}, U is the flow velocity in m/s and H is the flow depth in m.

Photosynthesis (positive term)

$$G_{PI}\left(\frac{32}{12} + \frac{48}{14}\frac{14}{12}\left(1 - P_{NH3}\right)\right)C_{ph} \tag{18}$$

where:

- G_{PI} is the phytoplankton growth rate (day^{-1});
- C_{ph} is the phytoplankton carbon biomass concentration (mgC/l).

In STREMRHySedWq the following formula for the calculation of the dimensionless P_{NH3} is used:

$$\begin{aligned} P_{NH3} = {} & NH_3 \frac{NO_3^-}{\left(K_{mN} + NH_3\right)\left(K_{mN} + NO_3^-\right)} + \\ & + NH_3 \frac{K_{mN}}{\left(NH_3 + NO_3^-\right)\left(K_{mN} + NO_3^-\right)} \end{aligned} \tag{19}$$

Both ammonia NH_3 and nitrate NO_3^- are expressed in μgN/l and K_{mN} is the Michaelis half saturation constant for nitrogen (a typical value is $K_{mN} = 25$ μgN/l). If the concentration of both ammonia NH_3 and nitrate NO_3^- is equal to zero, P_{NH3} is set to 1.

Oxidation (negative term)

$$K_D \Theta_D^{(T-20)} \left(\frac{C_{DO}}{K_{BOD} + C_{DO}} \right) C_{BOD} \tag{20}$$

where:

- K_D is the deoxygenation (oxidation) coefficient at 20 °C (day^{-1});
- Θ_D is the temperature coefficient for deoxygenation (-);
- T is the water temperature (°C);
- C_{DO} is the dissolved oxygen concentration (mgO$_2$/l);
- K_{BOD} is the half saturation constant for the BOD oxidation (mgO$_2$/l);
- C_{BOD} is the biochemical oxygen demand concentration (mgO$_2$/l);

Nitrification (negative term)

$$\frac{64}{14} K_{12} \Theta_{12}^{(T-20)} \left(\frac{C_{DO}}{K_{NIT} + C_{DO}} \right) C_{NH_3} \tag{21}$$

where:

- K_{12} is the nitrification coefficient at 20 °C (day^{-1});
- Θ_{12} is the temperature coefficient for nitrification (-);
- K_{NIT} is a half saturation constant (mgO$_2$/l);
- C_{NH_3} is the ammonia concentration (mgN/l).

Respiration (negative term)

$$\frac{32}{12} K_{1R} \Theta_{1R}^{(T-20)} C_{ph} \tag{22}$$

where:

- K_{1R} is the biomass respiration coefficient at 20°C (day^{-1});
- Θ_{1R} is the temperature coefficient for respiration (-);
- C_{ph} is the phytoplankton carbon biomass concentration (mgC/l).

Sediment oxygen demand (negative term)

$$\frac{SOD}{H} \Theta_s^{(T-20)} \tag{23}$$

where:

- SOD is the sediment oxygen demand ($g/m^2/day$);
- H is the flow depth (m);
- Θ_s is the temperature coefficient for the sediment oxygen demand (-).

SOD is due to the oxidation of organic matter in bottom sediments. The benthic deposits ("sludge beds") derive from several sources: wastewater particulates, allochthonous particulates (leaf litter and eroded organic-reach soils), photosynthetically produced plant matter (especially in eutrophic lakes, estuaries and rivers) (Chapra, 1997).

DO input (positive term)

Localized inputs of DO not associated to inflow boundaries are represented by the term

$$W_{DO} \tag{24}$$

which has dimensions of concentration over time ($mgO_2/l/s$). Analogously to BOD, if the DO input is known in terms of mass over time M_{DO} (mgO_2/s) and the input is "applied" to i cells having area A and depth H, W_{DO} is calculated as follows

$$W_{DO} = \frac{M_{DO}}{\sum_i A_i H_i} \tag{25}$$

DYNAMIC DESCRIPTION OF THE BED-WATER INTERACTION AND COUPLING WITH THE BOD-DO MODEL

The bed-water interaction was modeled in STREMRHySedWq through a dynamic description of the transport across the bed-water interface. The following sections describe:

- the sediment entrainment/sedimentation module;
- the BOD transport across the bed-water interface;
- the incorporation of the BOD fluxes from and to the bed into the BOD conservation equation solved for the water column.

Sediment entrainment/sedimentation module

The entrainment and sedimentation of sediments (solids) are modeled is the following way:

- sedimentation is considered to be a first order process;
- resuspension is related to the bottom shear stress;
- sedimentation and resuspension are assumed to occur simultaneously and in the vertical direction.

The following equation expresses the variation in time t of the suspended sediment depth-averaged concentration in the water column $C_{ss,w}$ (expressed here as volume concentration, that is m^3_{ss}/m^3, where m^3_{ss} denotes the volume of suspended sediment):

$$\frac{dC_{ss,w}}{dt} = \frac{-F_{sed,ss} + F_{res,ss}}{H} = \frac{-v_{ss}C_{ss,w} + F_{res,ss}}{H} \tag{26}$$

where $F_{sed,ss}$ is the sedimentation flux $((m^3_{ss}/m^3)(m/s))$, $F_{res,ss}$ is the resuspension flux $((m^3_{ss}/m^3)(m/s))$, v_{ss} is the sediment settling velocity (m/s) and H is the water depth (m).

Because of sedimentation and resuspension, the sediment-water interface is moving with respect to the fixed coordinate system. The velocities v_s and v_r (m/s) by which the sediment surface is displaced can be expressed in terms of $F_{sed,ss}$ and $F_{res,ss}$:

$$v_s = \frac{F_{sed,ss}}{(1-n)} = \frac{v_{ss}C_{ss,w}}{C_{ss,b}} \tag{27}$$

$$v_r = \frac{F_{res,ss}}{(1-n)} = \frac{F_{res,ss}}{C_{ss,b}} \tag{28}$$

where $C_{ss,b}$ is the sediment concentration in the bed (m^3_{ss}/m^3, here assumed as constant) and n is the bed porosity (dimensionless).

The net displacement v_{sr} (m/s) of the interface is given by the so called Exner equation:

$$v_{sr} = v_s - v_r \tag{29}$$

v_{sr} is positive if deposition is greater than resuspension, otherwise it is negative.

The expressions for the velocities v_s and v_r are here re-expressed as as follows:

$$v_s = \frac{v_{ss}D_s}{1-n} \tag{30}$$

$$v_r = \frac{v_{ss}E_s}{1-n} \tag{31}$$

D_s is the volume sediment concentration at the bed-water interface. Considering this concentration, rather than the suspended solids depth-averaged concentration (as previously done, for the sake of simplicity of explanation in the equation (26) for $F_{sed,ss}$), allows for accounting for a more realistic shape of the the concentration vertical profile, which presents lower concentrations closer to the water surface and higher concentrations close to the bottom. E_s is the dimensionless entrainment into suspension, which can be calculated using several formulae presented in literature according to the characteristics of the flow and the sediments (here the Smith and McLean formula is adopted). Later in this document, an alternative expression for v_r is presented and discussed.

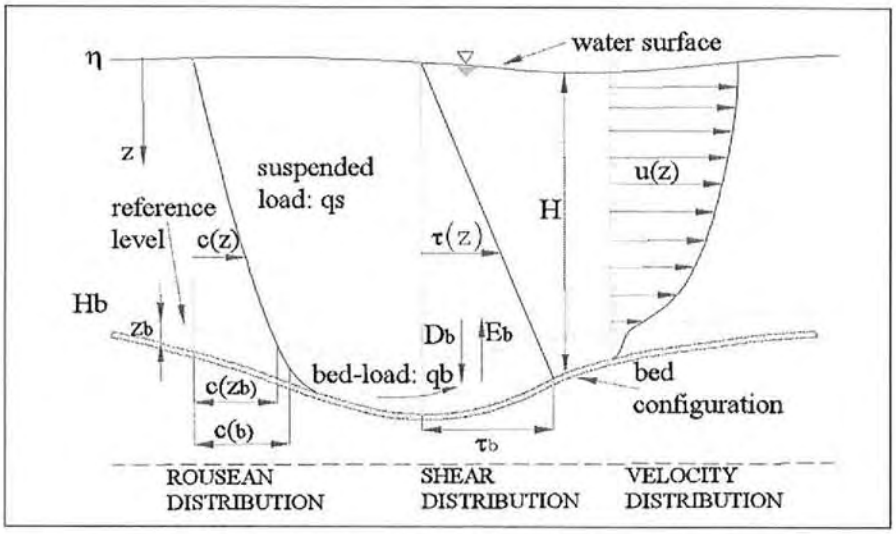

FIG. 2. Sediment model configuration.

The dimensionless sediment concentration at the bed-water interface

As regards the dimensionless sediment concentration at the bed-water interface D_s, the vertical distribution of suspended sediment for equilibrium conditions can be derived invoking the eddy-diffusivity concept (Garcia, 2001) and the Rousean distribution profile (Rouse, 1937). The results presented here are discussed in detail in Abad *et al.* (2007).

With reference to the Figure 2, shifting the datum for the vertical coordinate z to the bed-water interface, D_s is properly defined as the concentration at $z = z_b$, where the reference level that separates the bed-load (neglected in this analysis) and suspended transport is.

The Rousean distribution profile (Rouse, 1937) is expressed as:

$$\begin{aligned} C'_{ss}(z) = C'_{ss}(z_b)\left(\frac{(H-z)/z}{(H-z_b)/z_b}\right)^{Z_R} &= \\ = D_s\left(\frac{(H-z)/z}{(H-z_b)/z_b}\right)^{Z_R} \end{aligned} \tag{32}$$

The superscript " $'$ " denotes local values of suspended sediment concentration in the vertical. Z_R is the Rouse number, defined as

$$Z_R = \frac{v_{ss}}{\kappa u_*} \tag{33}$$

where κ is the dimensionless Von Karman's constant (equal to 0.4) and u_* is the shear velocity (m/s). After few passages, reported by Abad *et al.* (2007), the depth-averaged suspended sediment concentration in the water column C_{ss} can be expressed as

$$C_{ss} = D_s INT(Z_R) \tag{34}$$

Abad and Garcia (2006) presented a practical expression for INT ("INT" stands for "integral", since the expression comes from the numerical solution of an integral):

$$INT(Z_R) = \frac{1}{c_0^I + c_1^I Z_R + c_2^I Z_R^2 + c_3^I Z_R^3 + c_4^I Z_R^4 + c_5^I Z_R^5 + c_6^I Z_R^6} \tag{35}$$

where the coefficients c are reported by Abad and Garcia (2006): $c_0^I = 1.1038$, $c_1^I = 2.6626$, $c_2^I =5.6497$, $c_3^I = 0.3822$, $c_4^I =$ -0.6174, $c_5^I = 0.1315$ and $c_6^I =$ -0.0091.

The expression for the dimensionless sediment concentration at the sediment-water interface D_s is therefore

$$D_s = \frac{C_{ss}}{INT(Z_R)} \tag{36}$$

The dimensionless entrainment into suspension

Several relations are available for estimating the dimensionless rate of entrainment E_s. The formula here considered, suitable for fine grain size sediments, is the one by Smith and McLean (1977). Their formula is expressed as follows

$$E_s = \frac{0.65\gamma_0 \left(\frac{\tau_s^*}{\tau_c^*} - 1\right)}{1 + \gamma_0 \left(\frac{\tau_s^*}{\tau_c^*} - 1\right)} \tag{37}$$

where τ_s^* is the dimensionless bottom shear stress, τ_c^* is the dimensionless critical shear stress and $\gamma_0 = 2.4 \cdot 10^{-3}$.

The dimensionless bottom shear stress τ_s^* is given by

$$\tau_s^* = \frac{u_*^2}{RgD} \tag{38}$$

The shear velocity u_* (m/s) is calculated as follows

$$u_* = \sqrt{u^2 + v^2}\sqrt{C_f}$$

where u and v are the depth-averaged velocity components in the x and y direction and C_f is the friction coefficient, given by Manning's equation

$$C_f = \frac{gn^2}{H^{1/3}} \tag{39}$$

where n is Manning's roughness coefficient, g is the acceleration of gravity (9.81 m^2/s) and H is the water depth. Notice that the lower is the water depth, the higher is the friction coefficient and, as a consequence, the shear velocity and stress.

In (38) D is the grain size (m) while the dimensionless sediment submerged specific gravity R is defined as follows:

$$R = \frac{\rho_{ss} - \rho_w}{\rho_w} \tag{40}$$

ρ_{ss} and ρ_w are respectively the mass density of sediment and water.

As regards the value of the critical shear stress τ_c^*, it can be be calculated using Brownlie's formula modified by Parker (2003)

$$\tau_c^* = 0.5(0.22 Re_p^{-0.6} + 0.06 \cdot 10^{(-7.7 Re_p^{-0.6})}) \tag{41}$$

where Re_p is the dimensionless sediment Reynolds number, defined as

$$Re_p = \frac{\sqrt{RgD}D}{\nu} \tag{42}$$

where ν is the kinematic viscosity (here assumed equal to 10^{-6} m^2/s).

As mentioned above, the expression (31) for the evaluation of the erosion rate v_r (m/s) has to be replaced, for cohesive sediment, by another expression, having the following general form (see Lick, 2005):

$$v_r = A\tau^n \rho^m \tag{43}$$

where τ is the bed shear stress, ρ is the bulk density of the sediment bed and A, n and m are constants depending on the grain size and other properties of the sediments (mineralogy, organic content, time after deposition, gas, presence of bacteria and benthic organisms). In general, the erosion rate v_r increases when the bed shear stress increases (since n is positive) and/or the bulk density decreases (since m is negative). In particular the effect of the bulk density (in other words, the compaction) on the erosion rate is strong for very fine particles, for which the cohesion contribution is strong, especially for high compaction.

The parameters A, m and n can be measured in laboratory or in field and depend on the site. Straight or annular flumes or devices such as Shaker or Sedflume (see Lick, 2005) can be used to estimate a relation for v_r. In reality, the process of erosion is even more complicated. Usually the grain size decreases and the compaction increases in depth, with increasing cohesion effect. Stratification can be present in the bed, leading to high variation of the erosion rate in the vertical. Very small particles can flocculate and be eroded in chunks instead of particle by particle.

Since a relation like (43) is site-specific, it was not used for the cases presented later in this preliminary study (for which the Smith-McLean formulation was adopted). As already mentioned, the implementation of site-specific relations in STREMRHySedWq is being done.

It is underlined here that the bedload on the bed is neglected. This assumption is reasonable especially for fine sediments (grain size less than 200 μm, see Lick, 2005).

BOD transport across the bed-water interface

BOD can be present, both in the water column and in the bed, as:

- dissolved constituent;
- attached to solids.

The BOD concentrations $C_{BOD,w,d}$ and $C_{BOD,b,d}$ dissolved (subscript "d") respectively in the water column (subscript "w") and in the bed pore water (subscript "b") are expressed as follows:

$$C_{BOD,w,d} = f_{w,d} C_{BOD,w} \tag{44}$$

$$C_{BOD,b,d} = f_{b,d} \frac{C_{BOD,b}}{n} \tag{45}$$

where $C_{BOD,w}$ and $C_{BOD,b}$ are respectively the BOD total concentration in the water column (for which the simple notation C_{BOD} was used so far) and in the bed and $f_{w,d}$ and $f_{b,d}$ are the dissolved fractions (-) in the water column and sediment bed, assumed as constant.

The BOD concentrations $C_{BOD,w,p}$ and $C_{BOD,b,p}$ attached to solids (subscript "p") respectively in the water column (subscript "w") and in the sediment bed (subscript "b") are expressed as follows:

$$C_{BOD,w,p} = (1 - f_{w,d})\, C_{BOD,w} \tag{46}$$

$$C_{BOD,b,p} = (1 - f_{b,d})\, C_{BOD,b} \tag{47}$$

where $C_{BOD,b}$ is the BOD total concentration in the sediment layer (mg/l).

The total exchange of BOD across the bed-water interface is represented by three fluxes, assumed to be occurring in the vertical direction:

- diffusive exchange flux F_{diff} ((mg/l)(m/s));
- sedimentation flux F_{sed} ((mg/l)(m/s));
- resuspension flux F_{res} ((mg/l)(m/s)).

The total transport across the bed-water interface is equal to the algebraic sum of the three fluxes expressed above. The equation describing the time variation of the BOD concentration in the water column $C_{BOD,w}$ due to those fluxes is

$$\frac{dC_{BOD,w}}{dt} = \frac{F_{diff} - F_{sed} + F_{res}}{H} \tag{48}$$

while the time variation of the BOD concentration in the sediment layer $C_{BOD,b}$, which can therefore be tracked using this approach, is, considering a thickness H_{sed} of the sediment layer,

$$\frac{dC_{BOD,b}}{dt} = \frac{-F_{diff} + F_{sed} - F_{res}}{H_{sed}} \tag{49}$$

The diffusive exchange flux

The dissolved BOD fractions are subject to diffusive exchange. The difference between the concentration in the bed interstitial water $C_{BOD,b,d}$ and in the water column $C_{BOD,w,d}$ is the driving force for mass transport. The diffusive exchange flux F_{diff} ((mg/l)(m/s)) is therefore expressed by the following equation

$$F_{diff} = \frac{E_{diff}}{H_b}\left(C_{BOD,b,d} - C_{BOD,w,d}\right) \tag{50}$$

where E_{diff} is the BOD diffusion coefficient (m^2/s) and H_b is the depth of the sediment layer where the diffusive BOD exchange occurs (m).

The sedimentation flux

The sedimentation flux F_{sed} ((mg/l)(m/s)) is expressed by the following equation:

$$F_{sed} = F_{sed,ss}\frac{C_{BOD,w,p}}{C_{ss,w}} + v_s n C_{BOD,w,d} \tag{51}$$

The first term represents the settling of BOD attached to the solids in the water column while the second term describes the inclusion of pore water due to the bed aggradation caused by sedimentation.

Recalling, from what reported above,

$$F_{sed,ss} = v_{ss}D_s = v_{ss}\frac{C_{ss,w}}{INT(Z_R)} \tag{52}$$

and

$$v_s = \frac{v_{ss}D_s}{1-n} \tag{53}$$

the sedimentation flux can be expressed as

$$F_{sed} = \frac{v_{ss}C_{BOD,w,p}}{INT(Z_b)} + \frac{v_{ss}D_s}{1-n}nC_{BOD,w,d} \tag{54}$$

The resuspension flux

The resuspension flux F_{res} ((mg/l)(m/s)) is expressed by the following equation:

$$F_{res} = F_{res,ss}\frac{C_{BOD,b,p}}{C_{ss,b}} + v_r n C_{BOD,b,d} \tag{55}$$

The first term represents the resuspension of BOD attached to the solids in the bed while the second term describes the release of pore water due to the bed erosion caused by sediment resuspension.

With

$$F_{res,ss} = v_r C_{ss,b} \tag{56}$$

and

$$v_r = \frac{v_{ss} E_s}{1-n} \tag{57}$$

the resuspension flux can be expressed as

$$F_{res} = \frac{v_{ss} E_s}{1-n} C_{BOD,b,p} + \frac{v_{ss} E_s}{1-n} n C_{BOD,b,d} \tag{58}$$

Incorporation of the BOD bed-water exchange in the BOD-DO model

The equation (5), which describes the kinetic processes involving the biochemical oxygen demand concentration C_{BOD} (mgO_2/l) in the water column, was modified to account for the bed-water BOD exchange, adding the RHS of the equation (48) to the RHS of the equation (5), giving:

$$\begin{aligned} \frac{dC_{BOD}}{dt} = a_{oc} K_{1D} C_{ph} - K_D \Theta_D^{(T-20)} \left(\frac{C_{DO}}{K_{BOD} + C_{DO}} \right) C_{BOD} + \\ -\frac{5}{4}\frac{32}{14} K_{2D} \Theta_{2D}^{(T-20)} \left(\frac{K_{NO3}}{K_{NO3} + C_{DO}} \right) C_{NO_3^-} + W_{BOD} + \\ + \frac{F_{diff} - F_{sed} + F_{res}}{H} \end{aligned} \tag{59}$$

The fluxes F_{diff}, F_{sed} and F_{res} are calculated with the expressions (50), (54) and (58).

The bed-water interaction terms have an impact on the BOD concentration in the water column and, as a consequence, on the DO concentration, since the BOD-DO system is coupled through the oxidation term.

In summary, in the model STREMRHySedWq, the organic matter initially in the bed and resuspended is treated as BOD in the water column and is oxidized using the DO there. The consumption of DO due to the oxidation of the organic matter in the bed is modeled through the sediment oxygen demand term, which basically represents a DO flux from the water column to the bed (Chapra, 1997).

DESCRIPTION OF THE CODE

Numerical schemes

The discretization of the equations in STREMRHySedWq is based on the Finite Volume (FV) method, in which a stair-stepped (piecewise constant) discretization of the flow depth is adopted.

The depth-averaged equations (continuity, momentum, vorticity for the correction for secondary flow, turbulence variables k and ϵ and conservation for sediment and water quality substances) are transformed from Cartesian (x,y) to curvilinear coordinates (ξ, η), where $\xi = \xi(x,y)$ and $\eta = \eta(x,y)$. Every cell is transformed from the Cartesian system to the curvilinear system, on which the computations are performed. In the Cartesian plane spacings Δx and Δy are arbitrary whereas in the curvilinear plane the spacing is constant and equal to 1 ($i = j = 1$). Through this transformation, the boundary fluxes are handled more easily.

The generic advection-diffusion equation with additional source/sink terms for the transport of any arbitrary scalar can be written in curvilinear coordinates (see Bernard, 1993) and the generic scalar Ψ is calculated, for each time step in each computational cell as

$$\Psi(t + \Delta t) = \Psi(t) + \Delta\Psi \tag{60}$$

The code basically calculates separately the $\Delta\Psi$ associated to advection, diffusion and source/sink terms and adds them. An Euler upwind scheme for advection and cell-centered discretization for diffusion are used (the schemes are not reported here; the schemes originally present in the code by Bernard were replicated for solids, BOD and DO). As regards the source and sink terms, an Euler scheme is used calculating for each time step and each cell the source/sink term using the BOD and DO concentration and the temperature value in that cell at the previous time step. In symbols, for BOD and DO

$$\begin{gathered} C_{BOD}(i,j,t+\Delta t) = C_{BOD}(i,j,t) + S_{BOD,i,j,t}\Delta t = C_{BOD}(i,j,t) + \\ + S_{BOD}(C_{BOD}(i,j,t), C_{DO}(i,j,t), T(i,j,t), C_{ph}(i,j,t), C_{NO_3^-}(i,j,t), W_{BOD}(i,j,t)) \end{gathered} \tag{61}$$

$$\begin{gathered} C_{DO}(i,j,t+\Delta t) = C_{DO}(i,j,t) + S_{DO,i,j,t}\Delta t = C_{DO}(i,j,t) + \\ + S_{DO}(C_{BOD}(i,j,t), C_{DO}(i,j,t), T(i,j,t), C_{ph}(i,j,t), C_{NH_3^-}(i,j,t), W_{DO}(i,j,t)) \end{gathered} \tag{62}$$

Structure of the code

The STREMRHySedWq code, in a time-step "Do" loop, solves, for each cell, the conservation equation for the solids (for up to 10 grain size classes) and for BOD and DO.

Two versions of the code were developed:

- in the first version of the code, the hydrodynamic is "frozen". This means that, even if the bed variation due to erosion and deposition is calculated (as well as all the associated solids and BOD bed-water exchange terms), the water depths and the friction coefficients (depending on the water depths, see the equation (39)) are not updated and consequently the hydrodynamics is not recalculated considering the new depths and friction coefficients. This model has the advantage of running solids transport and water quality relatively fast, and can be considered reasonable once the bed elevation change is small compared to the water depth;

- in the second version of the code, the hydrodynamic is not "frozen". This means that, according to the bed variation, summed over all the grain size classes, the water depths and the friction coefficients are updated and the hydrodynamics is recalculated. This model has significantly longer simulation times.

Since the second version of the code sometimes experiences instability, a so called "semi-frozen" mode can be used too: the water depths are updated according to the bed variation for every time step but the hydrodynamics is not recalculated. This version allows for speeding up the code, avoiding instabilities and accounting for the change of depth in all the source/sink terms for solids, BOD and DO (i.e. bed-water fluxes and SOD).

SEDIMENT AND WATER QUALITY INPUT FILES IN STREMRHYSEDWQ

The present section illustrates the variables and the units to input in the configuration input file "STREMRSST.CFG" (relative to the sediment transport module) and in the card &WQINPH of the configuration input file "STREMRWQ.CFG" (relative to the water quality module) to run STREMRHySedWq.

Configuration file "STREMRSST.CFG"

&SSEDLIST

- SSMOD : activate/deactivate the sediment transport module ("YES" or "NO");
- SSMODF : activate/deactivate the "frozen" hydrodynamic mode ("YES" or "NO").

&SSEDPARA

- SSENTF : sediment entrainment formula ("SMITH" or "GARCIA");
- POROSITY : porosity of the bed layer (-), n.

&SSEDINPA

- SSACTV : activate/deactivate the sediment transport grain size class ("YES" or "NO"). Up to 10 grain size classes can be considered;

&SSEDINPB

- SSTINI : sediment initial concentration in the water column (mg/l), $C_{ss,w,initial}$.

&SSEDINPC

- SSTBC : sediment input concentration from the inflow boundaries (mg/l), $C_{ss,w,input}$.

&SSEDINPD

- SSTVS : suspended sediment settling velocity (m/day), v_{ss}.

&SSEDINPE

- SSTDS : sediment grain size (m), D.

&SSEDINPF

- SSTDEN : sediment submerged specific gravity (-), R.

Notice that the SSTINI values are read in case of "cold start" of the simulation, otherwise the initial concentration field, which can be spatially varying, is contained in the starting "hot" file "STREMRSSTHOT.HOT" (which can be created by the application "ssthot.exe" written for the purpose).

Card &WQINPH (configuration file "STREMRWQ.CFG")

- VS3 : suspended sediment settling velocity (m/day), v_{ss};
- FD5 : BOD dissolved fraction in the water column (-), $f_{w,d}$;
- FB5 : BOD dissolved fraction in the bed (-), $f_{b,d}$;
- Ediff : diffusion coefficient of BOD from the interstitial water in the bed to the water column (m^2/day), E_{diff};
- Hb : depth of the bed layer where the diffusive BOD exchange occurs (m), H_b.

Observations:

- the sediment settling velocity v_{ss} considered by the code is SSTVS, which is input in the file "STREMRSST.CFG", if the sediment transport module is active. Otherwise VS3, specified in the file "STREMRWQ.CFG", is considered;
- the application "wqhot.exe" can generate the spatial initial distribution of BOD concentration in the bed.
- the code does internal conversions of the units of some of the parameters input by the user to ensure the consistency of the calculations.

SEDIMENT AND WATER QUALITY OUTPUT FILES IN STREMRHYSEDWQ

Besides the output file "STREMROUT.OUT", which contains some statistics on the sediment and water quality concentrations, the two main output files, which can be opened and visualized with the program TecPlot are "STREMR-SuTec.DAT" and "STREMRWqTec.DAT".

Output file "STREMRSuTec.DAT"

The output file "STREMRSuTec.DAT", for each "printing" time, set before the run in the main input file "STREMRPC.DAT", contains:

- the sediment concentration (m^3_{ss}/m^3);
- the entrainment rate (m/s), given by $v_{ss}E_s/(1-n)$;
- the sedimentation rate (m/s), given by $v_{ss}D_s/(1-n)$;
- the cumulated bed elevation change (m), which is positive if the cumulated deposition is greater than the cumulated erosion and negative otherwise.

The results are given for up to 10 grain size classes.

Output file "STREMRWqTec.DAT"

The output file "STREMRWqTec.DAT", for each "printing" time, contains:

- the BOD concentration in the water column (mg/l);
- the BOD concentration in the bed (mg/l);
- the DO concentration (mg/l).
- the water temperature (°C).

ANALYSIS 1: SENSITIVITY ANALYSES

The Analysis 1 is a sensitivity analysis to several parameters of the model, for a simplified scenario (a straight rectangular channel). The parameters considered are:

- BOD concentration in the bed $C_{BOD,b}$;
- flow depth H and depth-averaged horizontal velocity $\sqrt{u^2+v^2}$;
- fraction of BOD dissolved in the water column and in the bed ($f_{w,d}$ and $f_{b,d}$);
- grain size (effective diameter) D, sediment settling velocity v_{ss} and submerged specific gravity R;
- porosity n of the bed layer.

Even if the model STREMRHySedWq is two-dimensional, the Analysis 1, which considers a straight rectangular channel, treats a basically one-dimensional problem. Longitudinal profiles of concentration of suspended solids, BOD and DO in the water column, as well as profiles of bed elevation change along the centerline of the rectangular channel were compared for the different scenarios considered.

Description of the simplified scenario

A short straight channel, having similar dimensions of Bubbly Creek, the waterbody considered in the Analysis 2, was considered to run the sensitivity analyses.

A rectangular channel, 2200 m long and 50 m wide, with horizontal bed, was used. The computational grid is made of 1100 cells (220 x 5) with uniform 10-meter square cells. The resolution of the grid was found to be a good compromise between computational time and goodness of the results. Notice that, in the Analysis 2, a structured but irregular computational mesh was used instead.

For the hydrodynamic simulations, a Manning roughness coefficient of 0.024 was used (same value used later for Bubbly Creek).

For the suspended solids, an initial concentration (constant over all the domain) of 8 mg/l and an input (from the upstream inflow boundary) of 1000 mg/l were adopted. For the biochemical oxygen demand (BOD), an initial concentration of 5 mg/l and an input of 60 mg/l were set, while, for the dissolved oxygen (DO), a value of 6 mg/l was considered for both the input and initial concentration. All the values assumed are typical of combined-sewer-overflow (CSO) events, according to a study of the Chicago Waterway System by the Marquette University in Milwaukee (Alp and Melching, 2006). As regards the diffusion coefficient of the solids, it was calculated according to the the equation (3), assuming $Sc = 1$ (Lyn, 2006).

As regards the BOD kinetics, only oxidation and bed-water exchange were considered, while phytoplankton decaying and de-nitrification were set to zero. As regards the DO kinetics, reaeration, oxidation and sediment oxygen demand were considered, while photosynthesis, respiration and nitrification were set to zero. In particular, the following parameter values were used:

- oxidation: $K_D = 0.2$ day^{-1} (Colonna Rosman, 2006), $\Theta_D = 1.040$ (Marquette University analysis, Alp and Melching, 2006), $K_{BOD} = 0.5$ mgO_2/l (Colonna Rosman, 2006);
- rearation: $\Theta_a = 1.024$ (Chapra, 1997), K_a calculated with the O'Connor and Dobbins formula and C_s calculated with the Mortimer formula;
- sediment oxygen demand: $\Theta_s = 1.065$ (Zison *et al.*, 1978), $SOD = 2$ g/m^2/day (value typical of beds rich in organic content, as measured by MWRDGC in the Chicago Area Waterway System).

The diffusion coefficient of the BOD was calculated according to the the equation (3), assuming $Sc = 1$ as for the solids.

The Schmidt number for DO was calculated using the following formula (Hondzo, 2008):

$$Sc = 8.809 \cdot 10^4 - 566.85(T + 273.15) + 0.914(T + 273.15)^2 \qquad (63)$$

where T is the temperature (here set constant and equal to 20 °C). The corresponding value of Sc is 464.3, thus a value of 500 was considered for the simulations.

The Schmidt number is object of investigation and research. In this analysis it was reasonably set, further observing, through preliminary simulations, that diffusion has a minor role in the runs, dominated by advection and kinetics.

The simulations for the sensitivity analyses were made in two steps: first, the hydrodynamics was run to steady state, then it was "frozen" and sediment transport and water quality were run for a duration of 10 hours. The variation of bed elevation during the simulation was verified to be small compared to the water depth, justifying the assumption of "frozen" hydrodynamics.

Sensitivity to the BOD concentration in the bed

First, the sensitivity of the model to the BOD concentration in the bed $C_{BOD,b}$, assumed as spatially constant over the whole domain, was evaluated for a constant flow velocity of 0.2 m/s and a constant flow depth of 2 m. Three cases were considered:

- $C_{BOD,b} = 3500$ mg/l (default value reported by the model Duflow-Eutrof2, 2002);
- $C_{BOD,b} = 16000$ mg/l (corresponding to a bed organic content of 5% in terms of total organic carbon TOC (typical value from DiToro, 2001), a conversion factor BOD/TOC equal to 32 mgO_2/12 mgC (Chapra, 1997), a solids mass density ρ_{ss} of 1200 kg/m^3 and a bed porosity n of 0.9 (Alp and Melching, 2006));
- $C_{BOD,b} = 20$ mg/l (value corresponding to a BOD-poor bed).

Notice that, for all the sensitivity analysis simulations, the BOD concentration in the bed $C_{BOD,b}$ was assumed constant in time, considering the bed as an "infinite" source of BOD. This choice is convenient, because it means that no sediment layer thickness H_{sed} needs to be set (the equation (49) is not solved), and reasonable, in light of some preliminary tests showing a small time variation of the BOD concentration in the bed when H_{sed} is an input parameter.

As regards the other parameters involved in the bed-water interaction, they were set constant for the three simulations as follows:

- $D = 60$ μm (silt-sized solids);
- $R = 0.2$ (Alp and Melching (2006), corresponding to a density of solids ρ_{ss} of 1200 kg/m^3);
- $v_{ss} = 1$ m/day (Alp and Melching, 2006);
- $n = 0.9$ (corresponding to the higher limit of the range reported by DiToro (2001) and the value adopted for the Chicago Waterway System by Alp and Melching, 2006);
- $f_{w,d} = 0$ (it is assumed that all BOD in the water column is attached to the solids);
- $f_{b,d} = 0$ (it is assumed that all BOD in the bed is attached to the solids). Notice that in absence of dissolved BOD fractions in the water column and in the bed, the diffusive exchange flux is equal to zero. Moreover, it was noticed from some preliminary tests that its order of magnitude is generally lower than the one of the sedimentation and resuspension fluxes;
- Smith-McLean entrainment formula for the solids on the bottom.

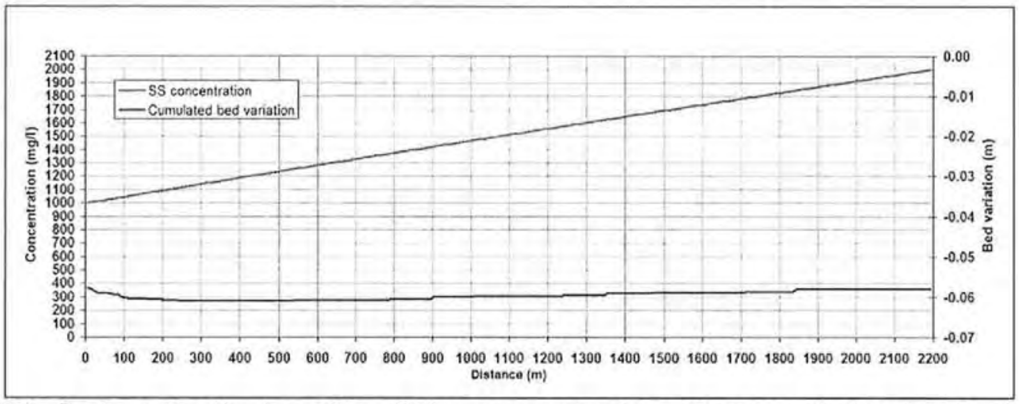

FIG. 3. Longitudinal profile of the concentration of suspended solids in the water column and of the cumulated bed variation after 10 hours.

The flow conditions are associated to erosion of the bed. Figure (3) shows the longitudinal profile of the concentration of suspended solids and of the cumulated bed variation after 10 hours of simulation. Erosion causes an increase of concentration of suspended solids in the downstream direction, from 1000 mg/l (input concentration) to about 2001 mg/l. The concentration profile after 10 hours is practically at equilibrium (steady state profile).

The bed variation is negative and sums to a maximum of about 6 cm after 10 hours. The value of the variation, which is small compared to the water depth (the ratio is 0.06 m / 2 m = 0.03) justifies the hypothesis of "frozen" hydrodynamics, i.e. the hydrodynamics is not updated according to the bed elevation change.

As regards water quality, Figure (4) and Figure (5) compare the longitudinal profiles of BOD and DO concentration in the water column after 10 hours of simulation for each of the three cases introduced above, as well as for a reference case that does not consider any bed-water interaction, in terms of resuspension and deposition.

The following observations can be made for the reference case which does not consider bed-water interaction:

- BOD: advection is responsible for a temporal increase of the BOD concentration, since the BOD upstream input is constant and greater than the initial BOD concentration in the channel. After 10 hours, the BOD concentration profile is practically at equilibrium (steady state), and the concentration profile decreases in the downstream direction because of the oxidation term. The effect of this term on the BOD levels during the simulation is small: in fact, after 10 hours, essentially all the channel, which is relatively short, is characterized by an almost constant BOD concentration equal to the input concentration, see Figure (4);
- DO: since the input and initial concentrations were set equal, the source/sink terms in the conservation equations are the ones affecting the temporal evolution of the concentration profile. In particular, since the sink terms

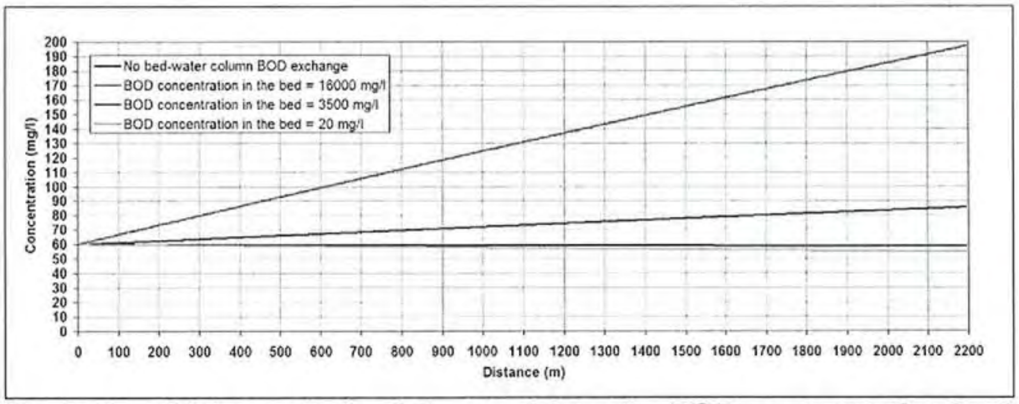

FIG. 4. Sensitivity analysis of the model to the BOD concentration in the bed: longitudinal profiles of the concentration of BOD in the water column after 10 hours.

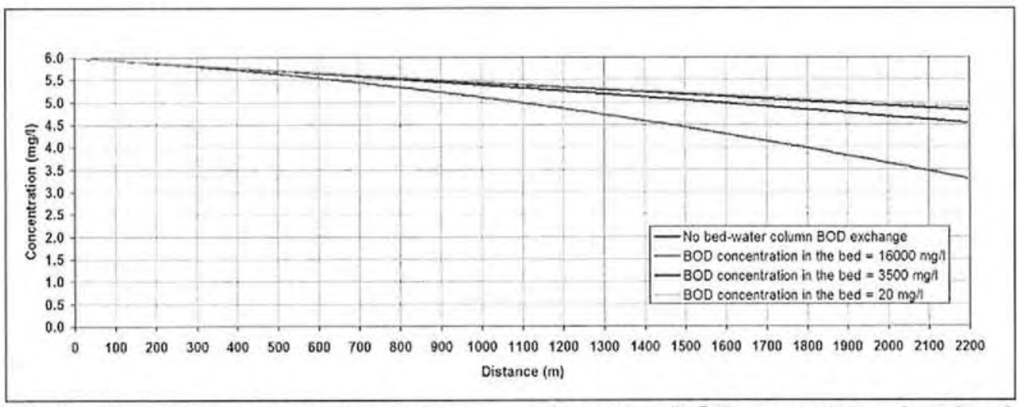

FIG. 5. Sensitivity analysis of the model to the BOD concentration in the bed: longitudinal profiles of the concentration of DO in the water column after 10 hours.

oxidation and sediment oxygen demand are greater than the source term reaeration, the effect is a decrease of the dissolved oxygen concentration in the downstream direction (see Figure (5) for the DO concentration profile after 10 hours). The maximum DO depletion after 10 hours is about 1.1 mg/l, at the downstream end of the computational domain.

Once the bed-water interaction is considered, for three different values of BOD concentration in the bed, it can be observed that:

- the results provided by the model are strongly sensitive to the BOD concentration in the bed, obviously with a greater BOD increase in the water column in the downstream direction for a greater BOD content in the bed;
- BOD concentrations in the bed of 3500 or 16000 mg/l cause a relevant downstream increase of BOD in the water column (respectively up to about

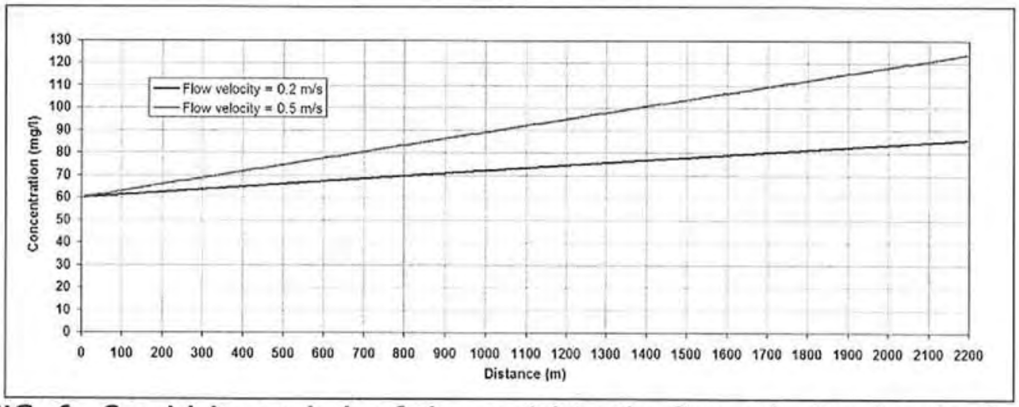

FIG. 6. Sensitivity analysis of the model to the flow velocity: longitudinal profiles of the concentration of BOD in the water column after 10 hours.

86 and 197 mg/l at the downstream end of the channel after 10 hours), associated to additional DO depletion when compared to the reference case which does not consider bed-water interaction (about 0.3 and 1.6 mg/l respectively, again at the downstream end of the channel after 10 hours);

- if the organic content of the bed is limited (e.g. 20 mg/l), even if the flow is causing erosion of the bed, the effect on the bed-water interaction is negligible. In this case the BOD levels in the water column are even lower than the reference case, because for the reference case the settling flux, proportional to the BOD content in the water column, was not considered.

Sensitivity to the flow velocity

The sensitivity of the model to the flow velocity is discussed in this section. An alternative scenario characterized by a flow velocity of 0.5 m/s is compared to the reference case with 0.2 m/s, considering in both the cases a flow depth of 2 m and a BOD concentration in the bed of 3500 mg/l. The other parameters are still the ones reported in the section "Description of the simplified scenario".

A higher velocity corresponds to higher concentrations of suspended solids in the water column (up to 2001 mg/l for a velocity of 0.2 m/s, up to 3591 mg/l for a velocity of 0.5 m/s, after 10 hours) and higher erosion (up to 6 cm for a velocity of 0.2 m/s, up to 38 cm for a velocity of 0.5 m/s, after 10 hours).

As regards water quality, Figure (6) and Figure (7) compare the longitudinal profiles of BOD and DO concentration in the water column after 10 hours of simulation for the two values of flow velocity considered.

The following observations can be made:

- the downstream increase of the BOD is dramatically greater for high velocity values, since BOD resuspension is enhanced;
- the DO levels are affected by two competing mechanisms associated to a high velocity: high oxygen demand of the BOD resuspended into the

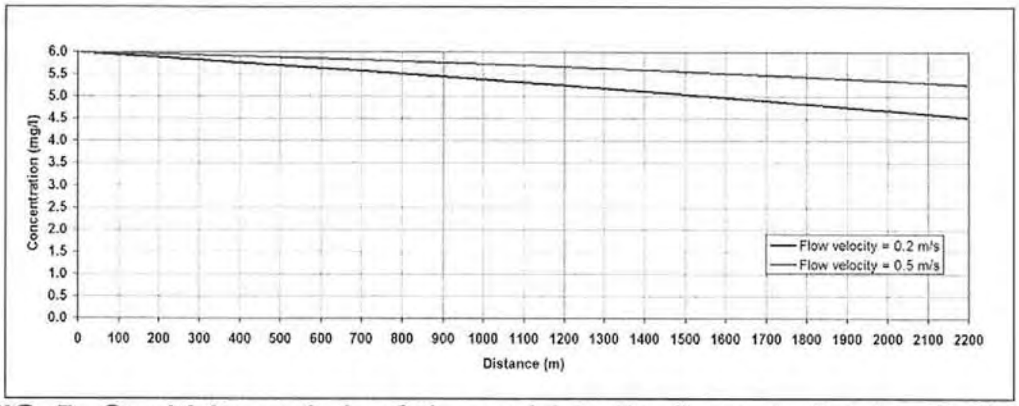

FIG. 7. Sensitivity analysis of the model to the flow velocity: longitudinal profiles of the concentration of DO in the water column after 10 hours.

water column and higher reaeration of the flow. In this case the second mechanism dominates: as a results, the DO levels are higher for a velocity of 0.5 m/s.

Sensitivity to the flow depth

The sensitivity of the model to the flow depth is discussed in this section. An alternative scenario characterized by a flow depth of 5 m is compared to the reference case with 2 m of depth, considering in both the cases a flow velocity of 0.2 m/s and a BOD concentration in the bed of 3500 mg/l. No changes were made for the other parameters (values reported in the section "Description of the simplified scenario").

The effect of a higher flow depth is basically the opposite of a higher velocity: since the friction coefficient is inversely proportional to the flow depth, a high flow depth corresponds to a low bed shear stress. As a consequence, with a depth of 5 m, the maximum concentration of suspended solids in the water column reached after 10 hours at the downstream end is 1284 mg/l (to be compared to 2001 mg/l for a depth of 2 m), while the maximum erosion after 10 hours is about 4.5 cm (to be compared to 6 cm for a depth of 2 m).

Figure (8) and Figure (9) compare the longitudinal profiles of BOD and DO concentration in the water column after 10 hours of simulation for the two values of flow depth considered.

The main observations are:

- BOD: for a high water depth, the BOD concentration increase in the downstream direction due to resuspension is significantly reduced (at the end of the channel, after 10 hours, the BOD concentration is about 66 mg/l, only 6 mg/l more than the concentration input at the upstream end);
- DO: for a high water depth, as a consequence of the reduced BOD resuspension, the corresponding DO depletion is reduced too. On the other hand, it's important to highlight that the impact of the additional BOD

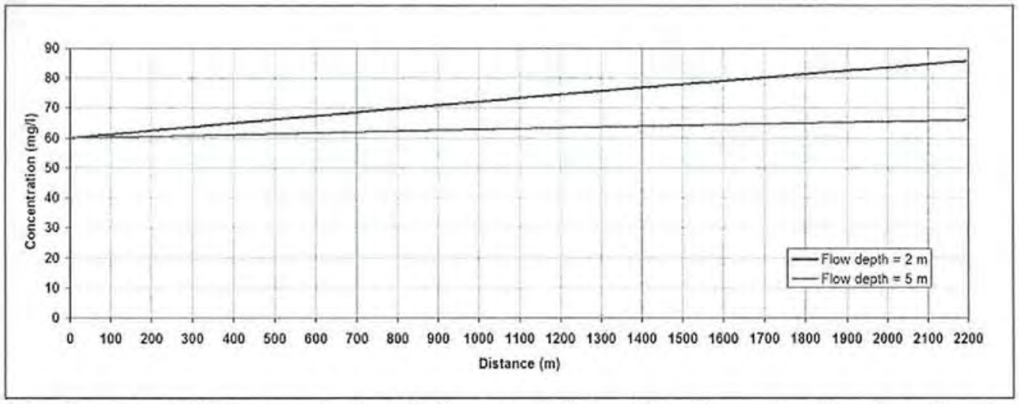

FIG. 8. Sensitivity analysis of the model to the flow depth: longitudinal profiles of the concentration of BOD in the water column after 10 hours.

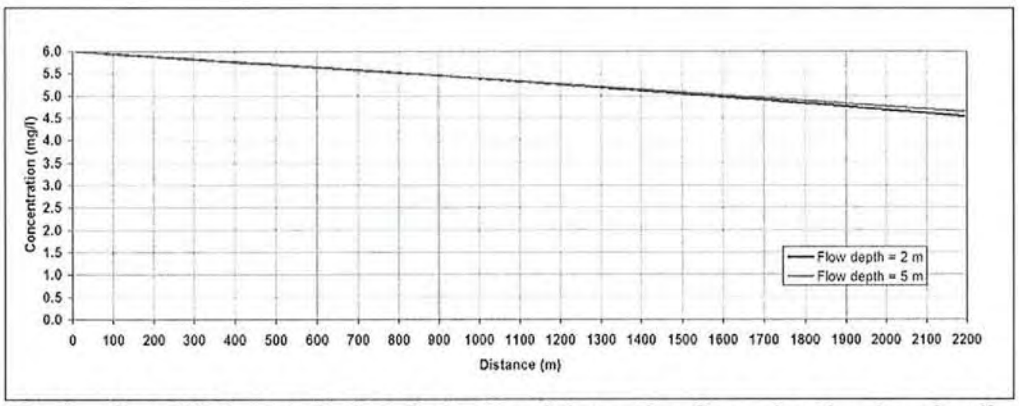

FIG. 9. Sensitivity analysis of the model to the flow depth: longitudinal profiles of the concentration of DO in the water column after 10 hours.

resuspended in the case of depth of 2 m when compared to the case with depth of 5 m is relatively low during the 10 hours of discharge, while it is expected to be greater in the hours following the discharge period.

This analysis of the impact of the flow depth on BOD resuspension is important for the case of Chicago: since most of the Chicago Waterway System is characterized by flow depths higher than Bubbly Creek (5 m is a typical value), despite presenting in some locations a high organic content in the bed, it is not expected to be affected by high DO depletion due to BOD resuspension during and after CSO events, as Bubbly Creek instead is.

Sensitivity to the dissolved fractions

The sensitivity of the model to the BOD dissolved fractions in the water column $f_{w,d}$ and in the bed $f_{b,d}$ was evaluated, considering the following alternative scenarios:

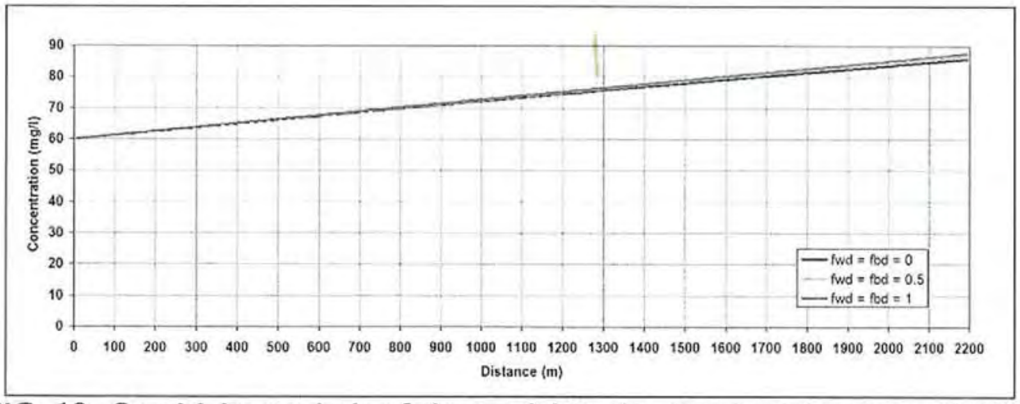

FIG. 10. Sensitivity analysis of the model to the dissolved fractions of BOD in the water column and in the bed: longitudinal profiles of the concentration of BOD in the water column after 10 hours.

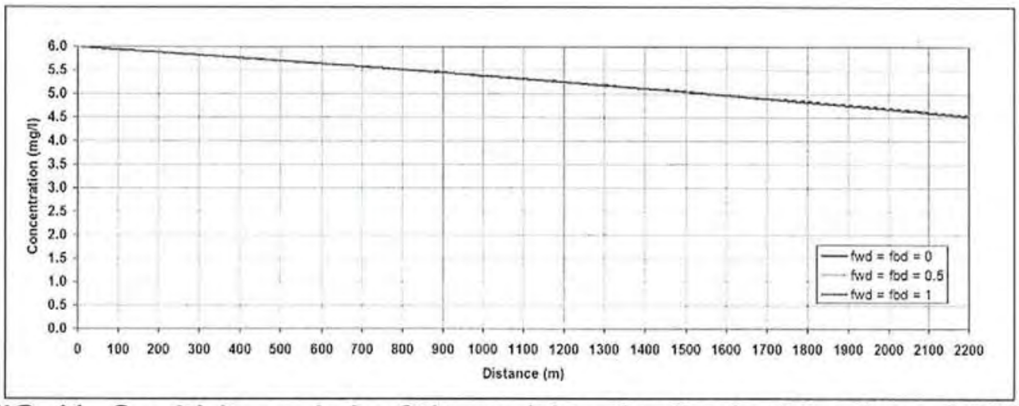

FIG. 11. Sensitivity analysis of the model to the dissolved fractions of BOD in the water column and in the bed: longitudinal profiles of the concentration of DO in the water column after 10 hours.

- $f_{w,d} = 1$ and $f_{b,d} = 1$. This scenario corresponds to the situation where all BOD in both the water column and in the bed is in dissolved form;
- $f_{w,d} = 0.5$ and $f_{b,d} = 0.5$. This scenario corresponds to the situation where the BOD in both the water column and in the bed is 50% in dissolved form and 50% attached to the solids.

A flow velocity of 0.2 m/s, a flow depth of 2 m and a BOD concentration in the bed of 3500 mg/l were considered. No changes were made for the other parameters reported in the section "Description of the simplified scenario".

The parameters $f_{w,d}$ and $f_{b,d}$ do not affect the sediments/solids transport but only the BOD and DO dynamics.

Figure (10) and Figure (11) compare the longitudinal profiles of BOD and DO concentration in the water column after 10 hours of simulation for the three scenarios considered.

Interestingly enough, the analysis shows that the model is essentially not sensitive to the BOD dissolved fractions in the water column and in the bed. In other words, even if the order of magnitude of the BOD fluxes from/to the water column associated to solids settling and resuspension (case $f_{w,d} = f_{b,d} = 0$) is different from the order of magnitude of the BOD fluxes associated to inclusion and release of bed pore water (case $f_{w,d} = f_{b,d} = 1$), the resulting "equilibrium" (steady state) longitudinal profiles of BOD and DO, already reached after 10 hours, are substantially identical in the two cases. The slight differences are due to the diffusive exchange flux which is different from zero when dissolved BOD fractions are present ($E_{diff} = 0.0002$ m^2/day and $H_b = 0.02$ m were assumed).

This result is comforting, since the value of the fractions $f_{w,d}$ and $f_{b,d}$ is difficult to estimate precisely.

Sensitivity to the effective diameter of the solids

The sensitivity of the model to the effective diameter of the solids D was evaluated too. Two cases, alternative to the reference scenario with $D = 60$ μm (higher limit for silt/lower limit for sand-sized particles, from DiToro, 2001), were considered:

- $D = 2$ μm (lower limit for silt/higher limit for clay, from DiToro, 2001);
- $D = 2$ mm (higher limit for sand/lower limit for gravel, from DiToro, 2001).

Again, a flow velocity of 0.2 m/s, a flow depth of 2 m and a BOD concentration in the bed of 3500 mg/l were considered.

The lower is the effective diameter of solids, the higher is their resuspension and the resulting concentrations of suspended solids in the water column (up to 2463 mg/l for $D = 2$ μm, up to 2001 mg/l for $D = 60$ μm and up to 1116 mg/l for $D = 2$ mm, after 10 hours at the downstream end of the channel) and the higher is the bed erosion (about 9, 6 and 1 cm respectively).

As regards water quality, Figure (12) and Figure (13) compare the longitudinal profiles of BOD and DO concentration in the water column after 10 hours of simulation for the three considered values of effective diameter of solids.

The analysis shows that finer solids are associated to higher BOD concentrations and DO depletion, analogously to what observed when the flow velocity is increased. Again, it must be underlined, however, that, the type of formula considered for the resuspension (Smith and McLean, 1977) does not account for the effect of cohesion, which becomes important for very fine particles and high organic content. This observation is related to what observed earlier about the need, in some cases, to calibrate relations like (43) when cohesion plays an important role.

Sensitivity to the settling velocity of solids

An alternative value for the settling velocity v_{ss} was considered, equal to 0.5 m/day (instead of the value assumed so far, equal to 1 m/day). Notice that,

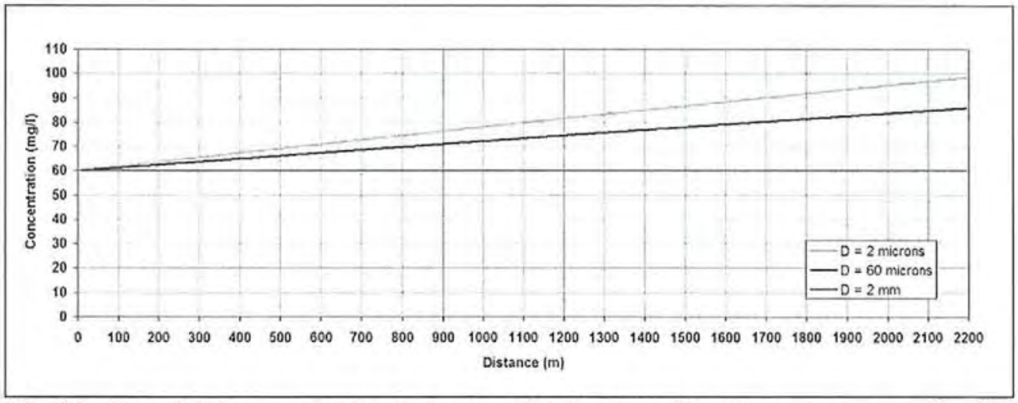

FIG. 12. Sensitivity analysis of the model to the effective diameter of solids: longitudinal profiles of the concentration of BOD in the water column after 10 hours.

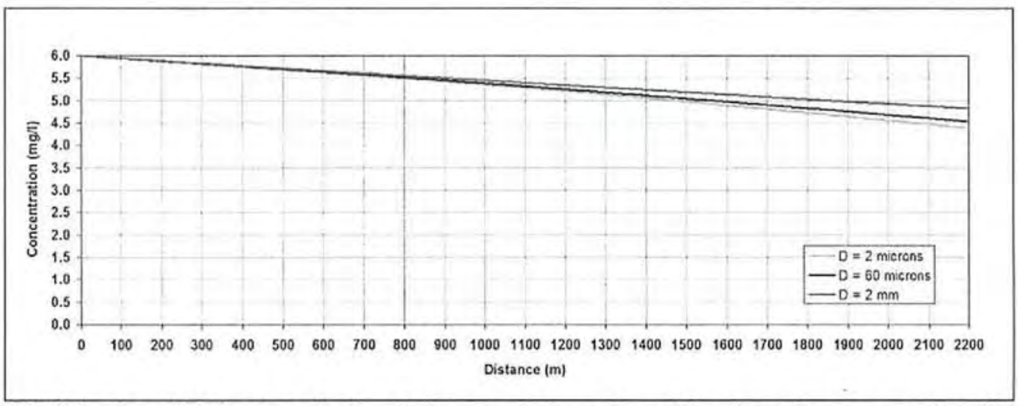

FIG. 13. Sensitivity analysis of the model to the effective diameter of solids: longitudinal profiles of the concentration of DO in the water column after 10 hours.

in general, particles in natural waters have complex shapes, so that the value of settling velocity for modeling is determined by direct measurement or model calibration, not by calculating it using Stokes' law.

Again, a flow velocity of 0.2 m/s, a flow depth of 2 m and a BOD concentration in the bed of 3500 mg/l were considered.

As expected, since the net erosion in the model is proportional to v_{ss}, halving v_{ss} means halving the concentration of suspended solids in the water column at equilibrium (steady state), and since in the runs all BOD was assumed to be attached to solids, it means also halving the concentration of BOD in the water column at equilibrium (see Figure (14) for BOD profiles and (15) for the corresponding DO profiles).

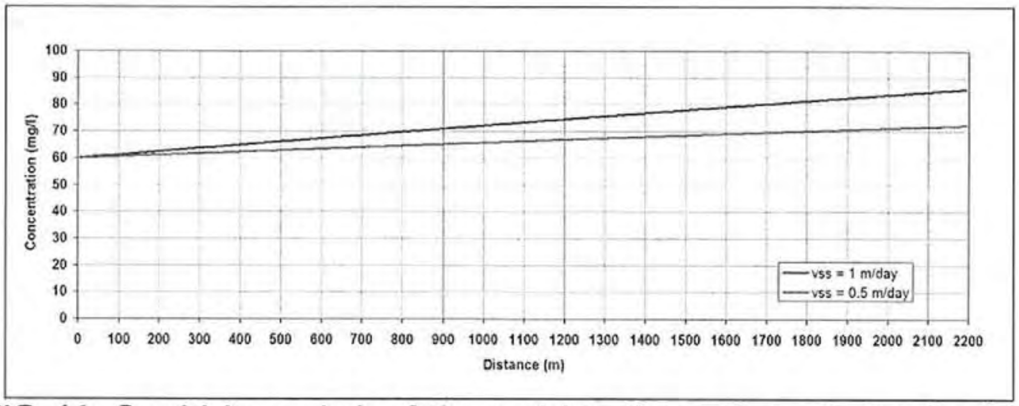

FIG. 14. Sensitivity analysis of the model to the settling velocity of solids: longitudinal profiles of the concentration of BOD in the water column after 10 hours.

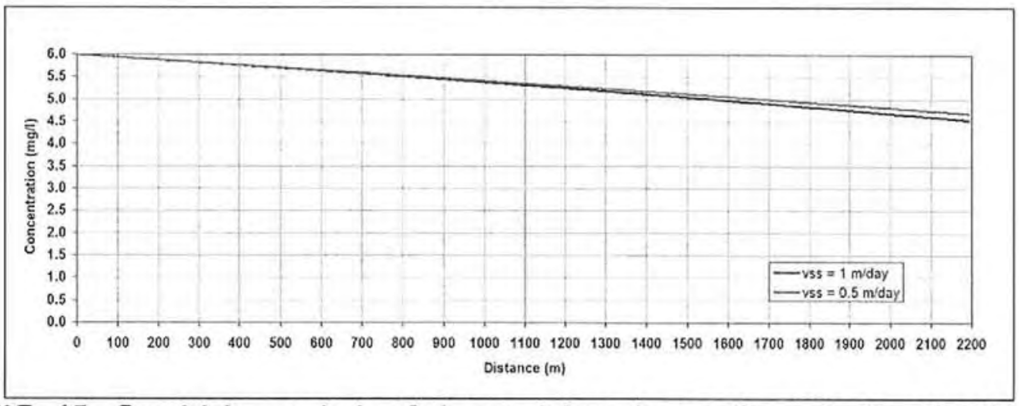

FIG. 15. Sensitivity analysis of the model to the settling velocity of solids: longitudinal profiles of the concentration of DO in the water column after 10 hours.

Sensitivity to the submerged specific gravity of solids

An increase of the particle submerged specific gravity from 0.2 to 1.65, corresponding to a density of solids ρ_{ss} equal to 2650 kg/m^3 (siliceous minerals), shows similar effects of a decreased flow velocity, an increased particle effective diameter or a decresed settling velocity as shown in Figure (16) and in Figure (17).

Sensitivity to the bed porosity

The bed elevation change rate, governed by the Exner equation (29) with (31) and (30), depends on porosity: the greater is the porosity, the greater is the net erosion or deposition rate.

As regards the concentration of solids in the water column, governed by the equation (26), it does not depend on the porosity since $F_{res,ss}$, from (28) and (31) and $C_{ss,b}$ = 1-n, is

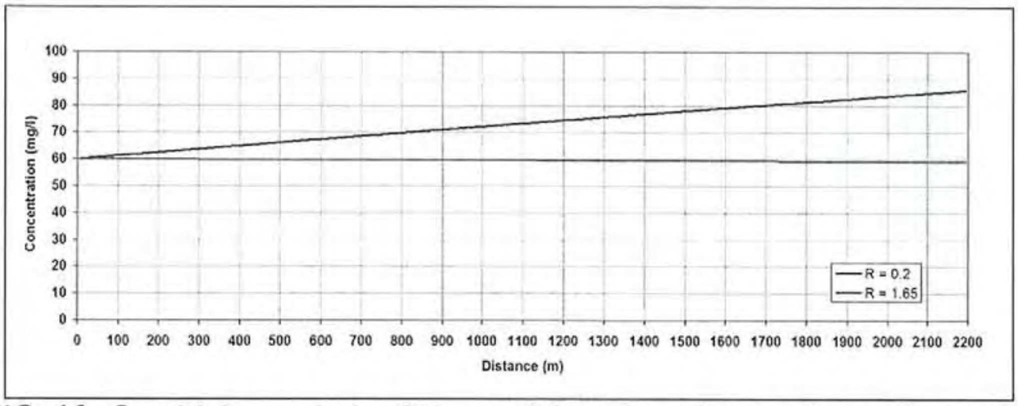

FIG. 16. Sensitivity analysis of the model to the submerged specific gravity of solids: longitudinal profiles of the concentration of BOD in the water column after 10 hours.

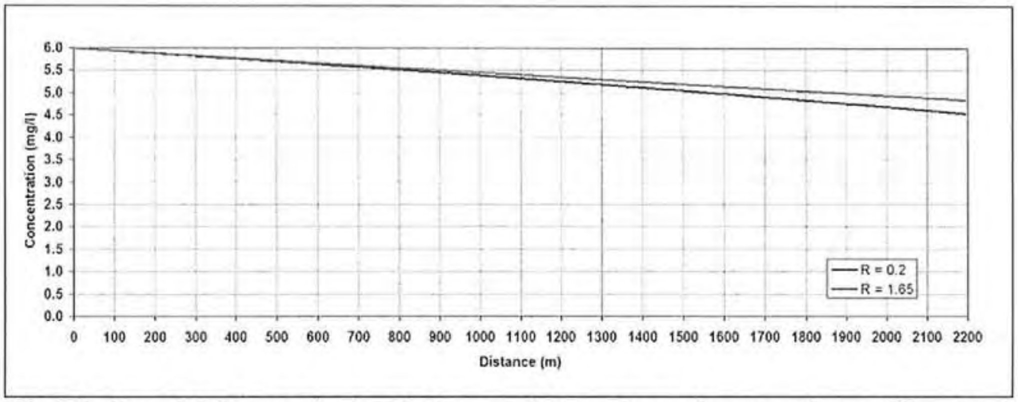

FIG. 17. Sensitivity analysis of the model to the submerged specific gravity of solids: longitudinal profiles of the concentration of DO in the water column after 10 hours.

$$F_{res,ss} = v_r C_{ss,b} = \frac{v_{ss} E_s}{1-n}(1-n) = v_{ss} E_s \tag{64}$$

which does not depend on the porosity n.

What observed for the solids in the water column is valid also for the BOD concentration in the water column, when all BOD is assumed to be attached to solids. In fact, the deposition flux does not depend on n, see the first term in the RHS of equation (54), while the dependency on n shown by the first term in the RHS of equation (58) is only apparent, since the concentration of BOD attached to the solids in the bed BOD, b, p is proportional to (1-n) (it is assumed that the BOD concentration in the bed is a fraction of the solids concentration in the bed, that is equal to (1-n)), which cancels out with (1-n) at the denominator.

The absence of dependency from n can be proved also if BOD is entirely dissolved in the water column and in the pore water in the bed.

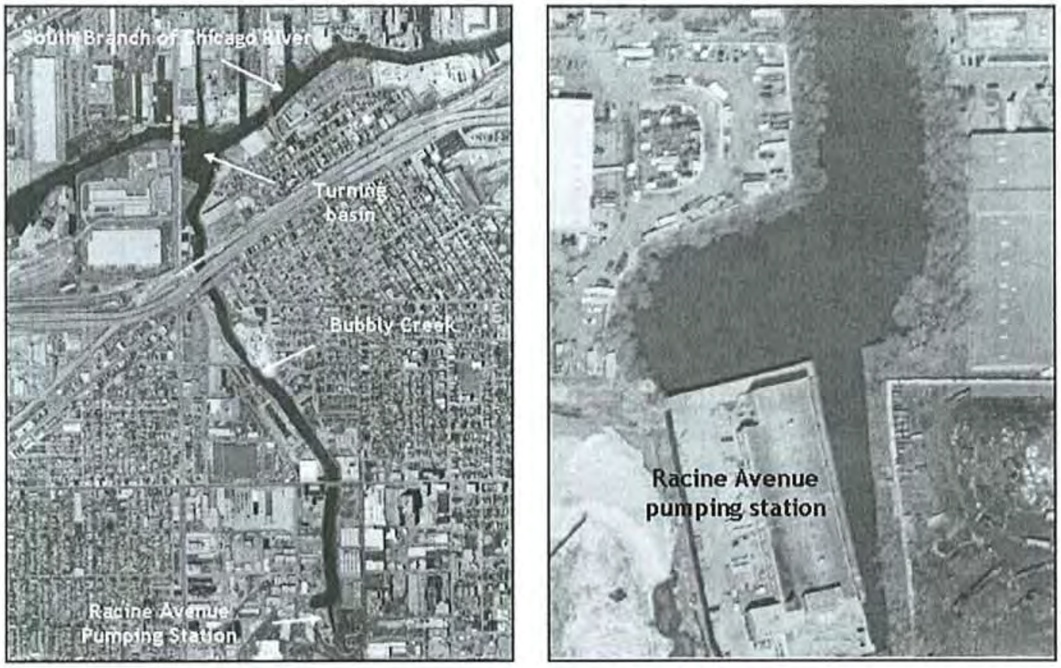

FIG. 18. Aerial view of Bubbly Creek and detail of the Racine Avenue Pumping Station (RAPS).

ANALYSIS 2: BUBBLY CREEK CASE STUDY

The Analysis 2 is an application of the model STREMRHySedWq to the case of Bubbly Creek in Chicago.

In this analysis the model STREMRHySedWq was tested for a stream characterized by irregular shape cross sections and varying depth and width in the longitudinal direction.

Moreover, the analysis provided a description of what can happen during and after a combined-sewer-overflow (CSO) event in the creek, both qualitatively and, to the extent allowed by a relative uncertainty on some of the parameters, quantitatively.

Description of the creek

Bubbly Creek, located South-West of Chicago (see Figure (18)), is the South Fork of the South Branch of the Chicago River, having a length of approximately 2200 meters, a mean width of about 46 meters and a fairly straight channel alignment. The mean channel bottom slope is about 0.001, but this is misleading because the channel bottom varies so much. The upstream 60% is shallow due to the lack of navigation (see Figure (19)). The downstream 40% is scoured by periodic barge traffic, during the long periods when the creek is stagnant, since, as better described below, the only times when there is flow in the creek are during combined-sewer-overflow (CSO) events.

From 1865 to 1939, Bubbly Creek was used as a drainage channel for the

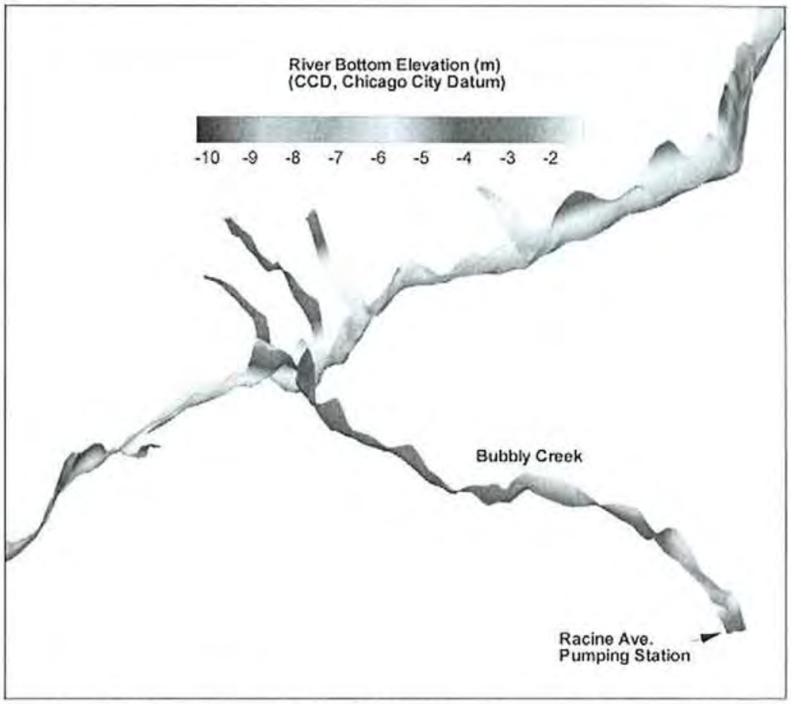

FIG. 19. Typical bathymetry of Bubbly Creek and the South Branch of the Chicago River. The reference is the Chicago City datum (CCD) at 176.63 m above sea level.

waste resulting from Chicago's stockyards. Today, this historically industrial area, characterized by the presence of industrial plants, trucking terminals, rail and construction material yards, is being transformed into a residential development, with strip malls and residences. As a consequence, water quality in the creek has become a very important issue, particularly during the summer months, when dissolved oxygen levels are very low. The water quality of the creek is therefore here analyzed in terms of DO levels.

Following is a description of the regimes of Bubbly Creek:

1. during dry periods, the water in Bubbly Creek is stagnant;
2. with light rainfall events there are no noticeable changes, since the combined-sewer-overflow (CSO) coming from the 36 square miles service area (463400 people and 169900 households served) is conveyed to the MWRDGC Stickney Water Reclamation Plant and not discharged to the creek;
3. during heavy storms, the Racine Avenue Pumping Station (RAPS) discharges CSO to the creek, so that the water flows northward into the South Branch of the Chicago River;
4. for excessively heavy storms, several CSO outfalls located along the channel may discharge to the creek depending on the intensity of the rainfall event. There are 9 such outfalls along the banks of the creek.

For the purposes of the present analysis, the regimes 1 and 3 were analyzed, with the goal to describe the biochemical oxygen demand and dissolved oxygen temporal and spatial variation in the creek during a CSO discharge event and in the following hours.

In a scenario of restoration of the creek, several "purification" solutions are currently being analyzed too. One of the solutions envisioned to increase the dissolved oxygen levels using flow augmentation: the bed-water BOD exchange model described in this document represents therefore a useful tool to find a "safe" range of flow rates to be "forced" in the river without causing significant resuspension of BOD with consequent DO depletion. This kind of analysis, however, is not presented in this report.

CSO events

Herein the CSO discharge events from the Racine Avenue Pumping Station (RAPS) are analyzed. In the period 1992-2001, pumping from RAPS into Bubbly Creek occurred 17 times per year on average (maximum 27 times in 1993, lowest 10 times in 1997, data by MWRDGC).

In the period from January 2005 to March 2007, the information made available by MWRDGC (*htpp://www.mwrd.org/*) shows that the average overflow volume was about 300 MG (maximum value 1172.40 MG on 10/02-03/2006, minimum value 70.87 MG on 02/25/2007), the average overflow duration was about 8.6 hours (maximum value 29.81 hours on 01/12-13-14/2005, minimum value 3.02 hours on 02/25/2007) and the average mean discharge was about 35.1 m^3/s (maximum value 69.4 m^3/s on 09/13/2006, minimum value 22.0 m^3/s on 01/12/2005).

The Racine Avenue Pumping Station has two sets of pumps, one set given even numbers and the other set given odd numbers. For small CSO events, only the 9 even-numbered pumps work, discharging through 9 pipes. The 5 odd-numbered pumps can pump either to Bubbly Creek or to the Stickney Water Reclamation Plant. For each CSO event, MWRDGC records the volume discharged by each single pump as well as the discharge duration.

The impact of the CSO discharge location (even-numbered, odd-numbered or both sets of pumps) on the overall hydrodynamics of the creek was already investigated in the past (Motta *et al.*, 2007). In the present analysis, the CSO inflow discharge is distributed uniformly along a cross section located at the upstream end of Bubbly Creek, right downstream of the basin immediately outside from the Racine Avenue Pumping Station (see Figure (18)).

25 CSO events were considered in the years 2005, 2006 and in the first three months of 2007. For these events, MWRDGC provided the CSO discharged volume and the start and end times of the operations on the pumps. It was therefore possible to associate a mean CSO flow rate to each of the CSO events.

As regards the water quality, Bubbly Creek has two monitoring stations at 36^{th} Street (close to the Racine Avenue Pumping Station) and I-55 (close to the outlet of Bubbly Creek into the South Branch of the Chicago River), which measure every hour the dissolved oxygen and the water temperature (see Figure 20).

FIG. 20. Dissolved oxygen and temperature monitoring stations in Bubbly Creek.

The dissolved oxygen is measured hourly using a YSI model 6920 or model 6600 continuous water quality monitor. Notice that, in this study, the DO concentrations measured at the two stations were compared with the depth-averaged or area-averaged concentrations simulated: this approach is, strictly speaking, incorrect, since the vertical profile of the concentration should be computed and measured and simulated values should be compared at the right depth into the water column. The one used here, anyway, is a reasonable first approach.

Figure 21 shows the temporal evolution of the dissolved oxygen for the biggest CSO event in terms of mean CSO discharge in the period from January 2005 to March 2007 occurred on September 13 2006. The plot shows the temporal evolution of the DO measured at the two monitoring stations. The input hydrograph associated to the CSO event, in the hypothesis of constant flow rate, is plotted too. The assumption of constant flow rate was used for the simulations with STREMRHySedWq, given the hypothesis of rigid lid (i.e. steady flow) mentioned above. More accurate but time consuming simulations could be run by assigning to the CSO event an unsteady hydrograph modeled in steps characterized by constant flow rate, each corresponding to a simulation with STREMRHySedWq. This approach, however, is beyond the scopes of this analysi.

The main observations, valid for the CSO event on September 13 2006, are:

- once the CSO event starts, the DO increases at both the stations. This can be due to two factors: reaeration of the flow (associated to the increased flow velocity in a previously stagnant creek) and/or high DO content of

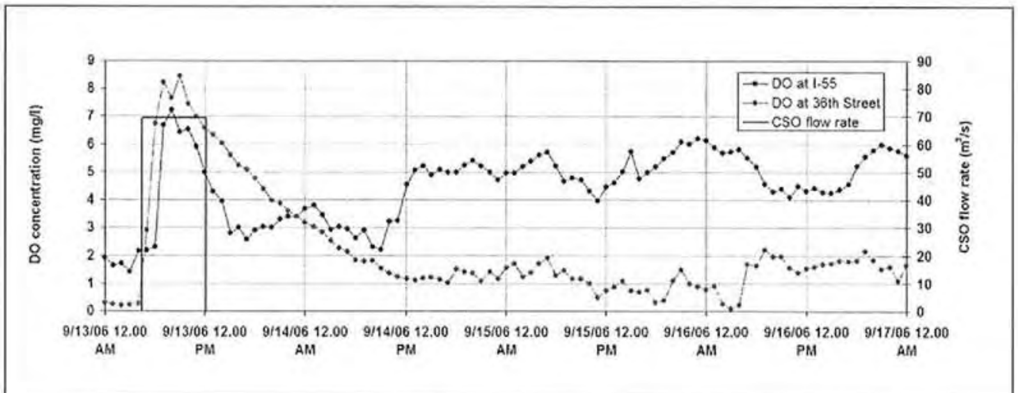

FIG. 21. Dissolved oxygen at 36^{th} Street and I-55 monitoring stations during and after the CSO event on September 13 2006.

the CSO input. The analysis reported below clarifies what is the main responsible for the fast DO increase in the creek;

- once the CSO discharge is over, an increased oxygen demand, due to the BOD inputs and/or BOD resuspension from the bed causes DO depletion. The depletion is recovered relatively quickly for the I-55 Station, which is close to the South Branch, whereas persists for days in the case of the 36^{th} Street Station, far from the South Branch.

The main question addressed in this analysis is therefore the following: during a CSO event, what are the roles played by the CSO input load from the Racine Avenue Pumping Station, by the waste layer on the bottom of the creek and by the concentration variability within the event?

Modeling tools for a CSO "event"

The CSO "event" was divided into two phases:

- "Phase 1": CSO discharge flowing. This phase was modeled using the two-dimensional depth-averaged model STREMRHySedWq widely described above, which is able to handle the bed-water exchange (the BOD resuspension into the water column is expected to play a relevant role during the CSO discharge). The 2-D nature of the code allows for accounting for the cross-sectional variation of the shear stress and, consequently, of the BOD resuspension and settling;
- "Phase 2": Bubbly Creek is stagnant again. This period was modeled with a one-dimensional area-averaged model, accounting for diffusion and kinetics of BOD and DO. The initial condition is given by the BOD and DO concentration fields present in the creek when the CSO discharge stops (end of "Phase 1").

"Phase 1" modeling

Data for hydrodynamics

The CSO event considered is the one occurred on September 13 2006 (see Figure 21). The characteristics of the event, as recorded by MWRDGC, are

- start pumping: 09/13/2006 at 4:30 a.m.; end pumping: 09/13/2006 at 12.10 at p.m.;
- overflow duration = 7.66 hours;
- overflow volume = 505.84 MG;
- mean discharge = 69.43 m^3/s.

Data for solids and bed

The following data were selected for the solids and the bed:

- $D = 60\ \mu m$ (silt-sized solids, according to the measurements by MWRDGC in 2006 at 33^{rd} Street, about 850 m downstream from the Racine Avenue Pumping Station, and at the Turning Basin, where Bubbly Creek widens at the outlet into the South Branch of the Chicago River);
- $R = 0.2$ (value from a former study on the Chicago Waterway System by the Marquette University in Milwaukee, Alp and Melching (2006), corresponding to a density of solids ρ_{ss} of 1200 kg/m^3);
- $v_{ss} = 1$ m/day (Alp and Melching, 2006);
- $n = 0.9$ (Alp and Melching, 2006).

As regards the initial concentration of suspended solids in the creek, a value of 8 mg/l was selected (Alp and Melching, 2006). It must be observed, anyway, that the simulation results do not depend on the initial concentration of suspended solids in the water, whose evolution depends on the input from the inflow boundary and from the bed-water interaction.

As regards the input condition $C_{ss,w,input}$, since there are no measured data for the Racine Avenue Pumping Station for the CSO event considered, it was determined using a regression equation based on the CSO volume and the mean input concentration, which was determined with a regression analysis by Alp and Melching (2006), based on the historic data at the Racine Avenue Pumping Station listed in Neugebauer and Melching (2005).

$$log_{10}C_{ss,w,input} = -0.723 \cdot log_{10}(OverflowVolume) + 4.7366 \tag{65}$$

where $C_{ss,w,input}$ is in mg/l and the overflow volume is in MG. The suspended solids input concentration decreases with the CSO volume. For an overflow volume of 505.84 MG, the corresponding solids input concentration is 604.8 mg/l, that is the value that was used in the analysis.

Data for water quality

The following data were selected for water quality (BOD and DO):

- $f_{w,d} = 0$ (assumption based on the observations made in the sensitivity analysis to $f_{w,d}$ and $f_{b,d}$);
- $f_{b,d} = 0$ (ditto);
- oxidation: $K_D = 0.2$ day^{-1} (Colonna Rosman, 2006), $\Theta_D = 1.040$ (Alp and Melching, 2006), $K_{BOD} = 0.5$ mgO_2/l (Colonna Rosman, 2006);
- reaeration: $\Theta_a = 1.065$ (Chapra, 1997), K_a calculated with the O'Connor and Dobbins formula and C_s calculated with the Mortimer formula;
- sediment oxygen demand: $\Theta_s = 1.065$ (Zison *et al.*, 1978).

In order to quantify the uptake of oxygen by sediment at various locations throughout the Chicago Waterway System (CWS), *in situ* sediment oxygen demand (SOD) was measured by MWRDGC during 2006 at 11 sites in the system suspected of being significant DO sinks (MWRDGC, 2007).

Each site consisted of an off-channel embayment or side channel location and SOD was measured at the site, as well as at locations in the main channel upstream and downstream of the site. In addition, a transect across the channel at each SOD measurement location was probed with a calibrated leveling rod to quantify the area covered by at least six inches of soft sediment. This measurement gives some indication of the amount of oxygen consuming sediment present across the channel width.

The percent composition of a sediment grab sample collected at each SOD measurement location was also qualitatively characterized by observation in a plastic tray.

The SOD was measured using a semi-cylindrical open-bottomed chamber containing a YSI Model 600 recording DO monitor.

In general, low SOD values may be explained by the lack of significant CSO inputs and clay sediment with low oxygen demand. High values are associated to decreases in current velocity in wide river cross-sections that encourage oxygen-demanding solids deposition at the measurement location.

As regards Bubbly Creek, it showed the highest average side channel SOD rate, equal to 3.26 g/m^2/day. Both measurement locations in Bubbly Creek (33^{rd} Street and the Turning Basin) showed high SOD values:

- average SOD in the main channel = 1.38 g/m^2/day;
- average SOD in the side channel area = 3.26 g/m^2/day.

From these measurements, a spatially constant value for SOD of 2.32 g/m^2/day (average of the main channel and side main channel values) was adopted in the analysis for simplicity's sake.

During the SOD measurements at the two locations of 33^{rd} Street and Turning Basin in Bubbly Creek it was observed that 100% of the cross-sectional transect is covered by oxygen demanding solids.

As regards the initial concentration for BOD in the water column $C_{BOD,w,initial}$, it was set equal to 5 mg/l (Alp and Melching, 2006). Analogously to the initial concentration for suspended solids, the simulation results do not depend on the initial concentration of BOD, whose evolution is essentially determined by the upstream input and the bed-water exchange. Therefore, the BOD input concentration $C_{BOD,w,input}$ and the BOD concentration in the bed $C_{BOD,b}$ had to be carefully selected.

In this analysis, the BOD input concentration was assumed constant in time and distributed all over the upstream inflow boundary, since this is what allowed by the code STREMRHySedWq in its current version. In reality, the BOD input concentration reaches its maximum at the very beginning of a CSO event, then exhibits an exponential die-off: this represents the first-flush phenomenon, whereby the material lying in the bottom of the sewer is picked up as the flow in the sewer increases. A regression formula for the mean BOD input concentration was proposed by Alp and Melching (2006). It was observed, however, that it is characterized by a high degree of uncertainty, because of the limited amount of events considered and the high variability among events. It was therefore decided to consider $C_{BOD,w,input}$ as calibration parameter, noticing that the DO depletion measured at the monitoring station at 36^{th} Street after the CSO discharge was basically due to the BOD level in the water column at that location when the discharge stopped. Since the monitoring station is close to the inflow boundary, the BOD concentration after the CSO discharge at the 36^{th} Street Station was determined basically by the BOD input concentration.

Analogously to the BOD input concentration, the BOD concentration in the bed was considered a calibration parameter, given the uncertainties on its value and its spatial variation. In this case, the process of calibration was based on the observation that the DO depletion measured at the monitoring station at I-55, close to the mouth of the creek, was determined by the BOD concentration present at that location when the CSO discharge stopped (depending essentially on the amount of BOD resuspended along the bed) as well as by the dispersion coefficient in stagnant conditions ("Phase 2"), which was the the third and last calibration parameter assumed here.

The resulting values from calibration, for which all the results presented later were obtained, are $C_{BOD,w,input} = 20$ mg/l and $C_{BOD,b} = 8000$ mg/l.

For DO, the initial condition $C_{DO,w,initial}$ was set to 1.2 mg/l (average value of the measured DO level at the stations at 36^{th} Street and I-55 right before the CSO discharge on September 13 2006).

As regards the water temperature, from the data measured hourly at the two monitoring stations, it is fairly constant during the event and equal for both the stations to 18.9 °C, which corresponds to the temperature of the CSO discharge as coming from the Racine Avenue Pumping Station.

The upstream input DO concentration was set equal to the value at saturation for a temperature of 18.9 °C, which, according to the Mortimer formula (Hamilton and Schladow, 1997) is 9.4 mg/l. This is a hypothesis that was made after the observation of the rapid increase of DO in the creek in the first part of the CSO discharge event: the rate of that increase cannot be justified by simply invoking the reaeration of water previously stagnant, and it is mainly due to oxygen-rich incoming water, which can be assumed as characterized by saturation conditions. In fact, the CSO input comes from a system of shafts and pipes which forces the aeration of the flow. The hypothesis was verified in light of the results shown later in the document.

Computational mesh

Using a bathymetry of Bubbly Creek provided by MWRDGC, a structured and irregular mesh made of 5055 rectangles was built. There are 337 rectangles in the flow direction and 15 rectangles in the direction normal to flow. Details of the computational mesh are shown in Figure 22.

As regards the bathymetry, vertical banks were assumed to complete the cross sections. This assumption is considered reasonable in light of previous hydrodynamic analyses of the creek and not far from the reality, considering that in several locations along the creek the cross sections end up with vertical walls.

Preliminary hydrodynamic free-surface simulation

A preliminary hydrodynamic simulation with the 2-D depth-averaged free-surface code SV2D (Soares Frazao, 2002) was made, using the generated structured mesh, by setting an input inflow discharge of 69.43 m^3/s and, as downstream boundary condition, a water level of 175.93 m a.s.l. (data from MWRDGC). The definition of the downstream boundary condition, at the confluence into the South Branch of the Chicago River, is not simple. In fact, in the South Branch, the flow is sometimes in the East-West direction, sometimes in the West-East direction. The water level at the downstream end was here imposed considering the South Branch as a large body of water at rest, "adsorbing" the momentum coming from the creek. The initial condition consisted of a water level of 175.93 m. A roughness Manning's coefficient of 0.024 was set (Motta *et al.*, 2007).

The 2-D free-surface model was basically used to calculate the steady state water levels in the creek. The water surface drop along the creek for a discharge of 69.43 m^3/s is 31 cm, with a water level at the upstream end of 176.30 m a.s.l. and a water level of 175.99 m a.s.l. at the upstream end (the boundary condition downstream is adjusted by the code).

According to the results obtained from the simulation, the elevation of the rigid lid, representing the water surface in STREMR, was determined. The resulting flow depth field, typical in Bubbly Creek during the stagnant periods, is plotted in Figure (23).

As already introduced earlier, the upstream part of Bubbly Creek is characterized by low depths (around 2 m), while the downstream portion, because of navigation, shows higher depth values (about 3-4 m, the maximum value is about 5.9 m at the Turning Basin). This has an impact on the erosion pattern during a CSO event: as already explained above, lower depths are associated to higher friction coefficient values and therefore higher bed shear stresses.

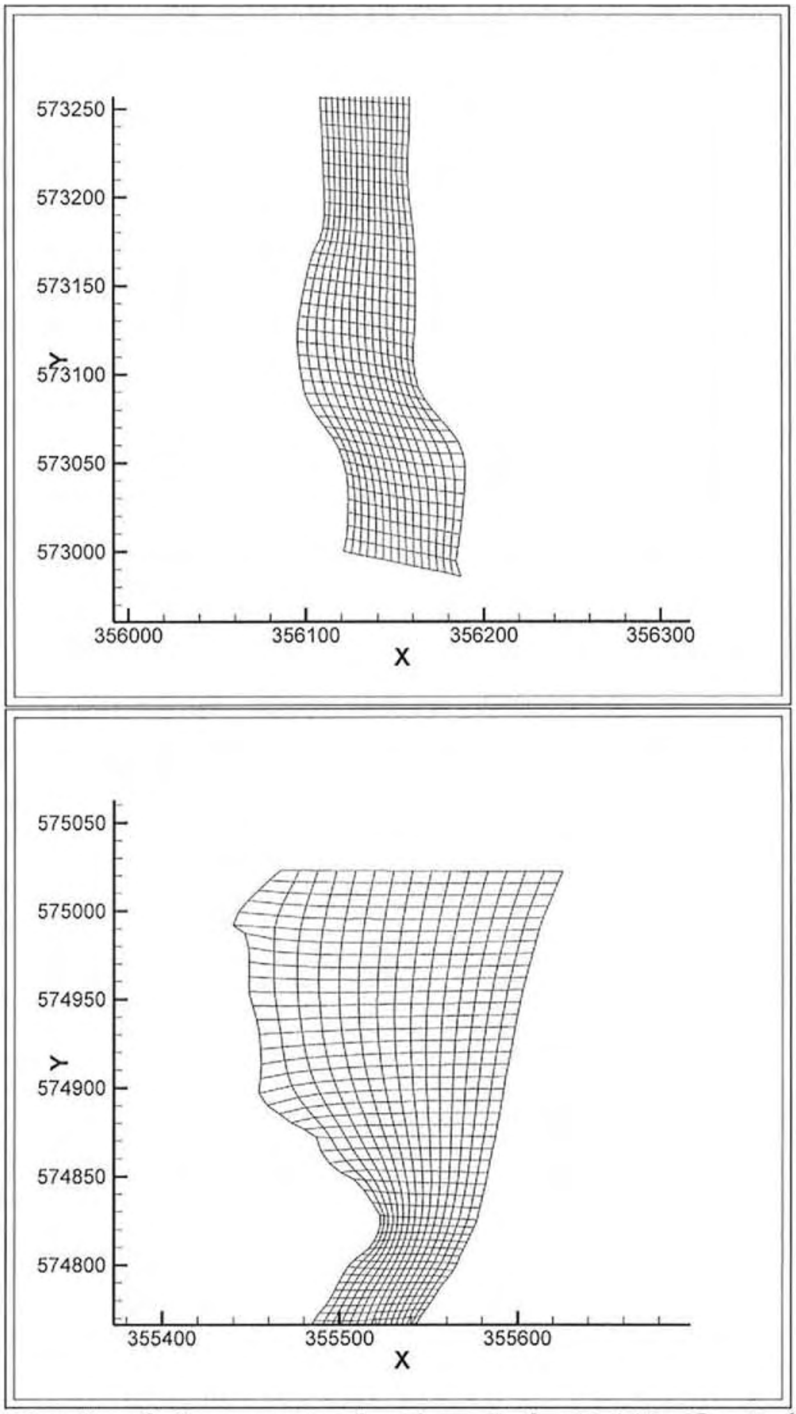

FIG. 22. Details of the computational mesh for Bubbly Creek (upstream and downstream ends).

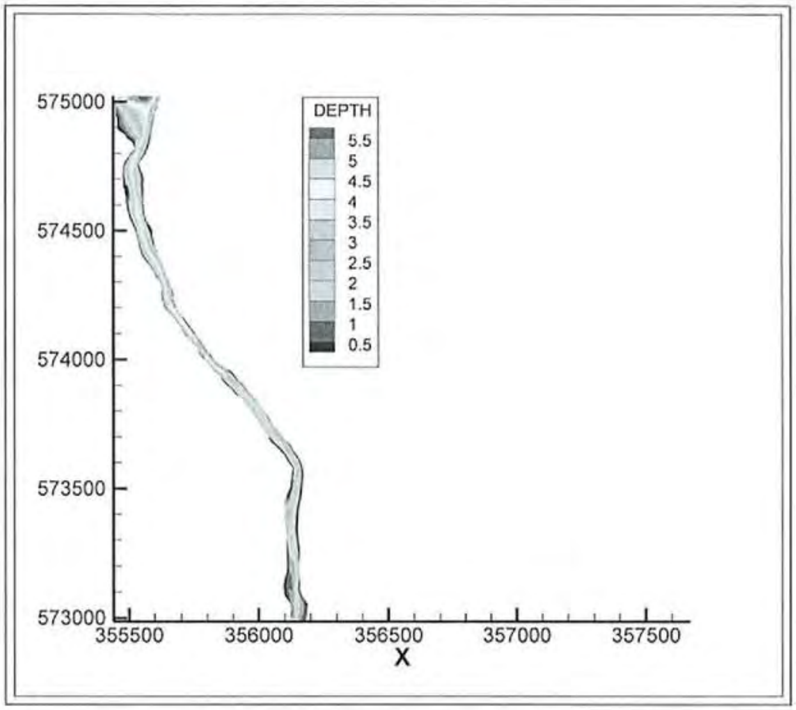

FIG. 23. Water depth field (m) in Bubbly Creek.

Hydrodynamic simulation with STREMRHySedWq

A hydrodynamic simulation was run with STREMRHySedWq, setting an input inflow discharge of 69.43 m^3/s and the flow depth field as calculated with SV2D, with a roughness Manning's coefficient of 0.024. The turbulence model and the correction for secondary flow were turned on, to get an accurate flow field.

The resulting flow velocity field at steady state is plotted in Figure (24). The Froude number is approximately between 0.1 and 0.5, so the flow is subcritical everywhere. The eddy viscosity range is between 0.12 and 0.90 m^2/s, with an average value of 0.44 m^2/s. This gives an idea about the eddy diffusivity range for solids, BOD and DO, calculated with $Sc = 1$ for solids and BOD and $Sc = 500$ for DO. Notice that, as it will be observed later in this analysis, the CSO event dynamics for solids, BOD and DO is dominated by advection and bed-water interaction, while diffusion plays a minor role.

In the upstream portion of the creek, where the water depths are low, the velocities are high (around 0.9 m/s along the centerline), while in the downstream portion the velocities are lower (around 0.5-0.6 m/s, always along the centerline). At the Turning Basin (confluence into the South Branch), the current slows down to almost zero velocity. See Figure (25).

The shear velocity field, related to the erosion of the bed, is plotted in Figure (26). As already mentioned, the upstream portion of the creek is more subject

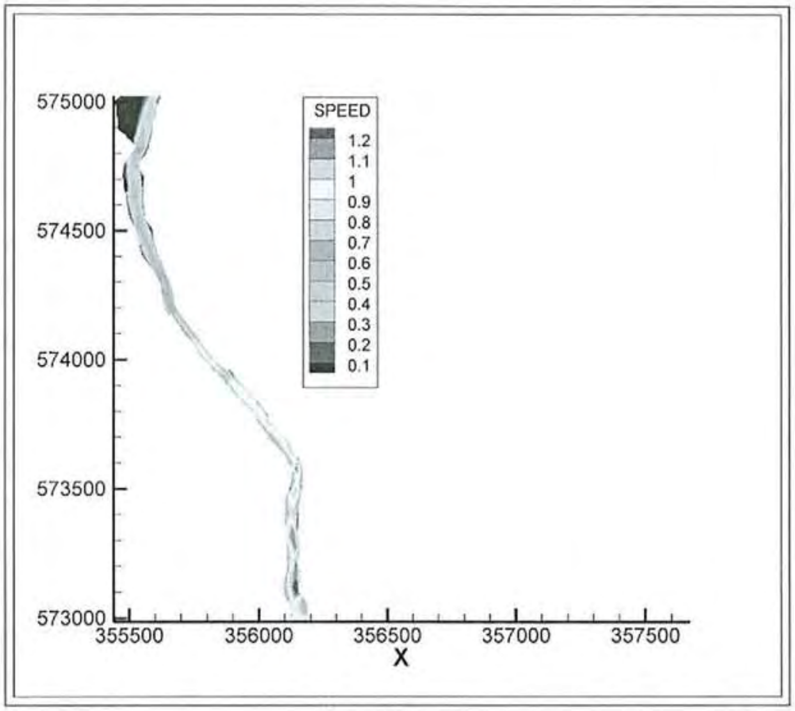

FIG. 24. Flow velocity field (m/s) for a discharge of 69.43 m^3/s.

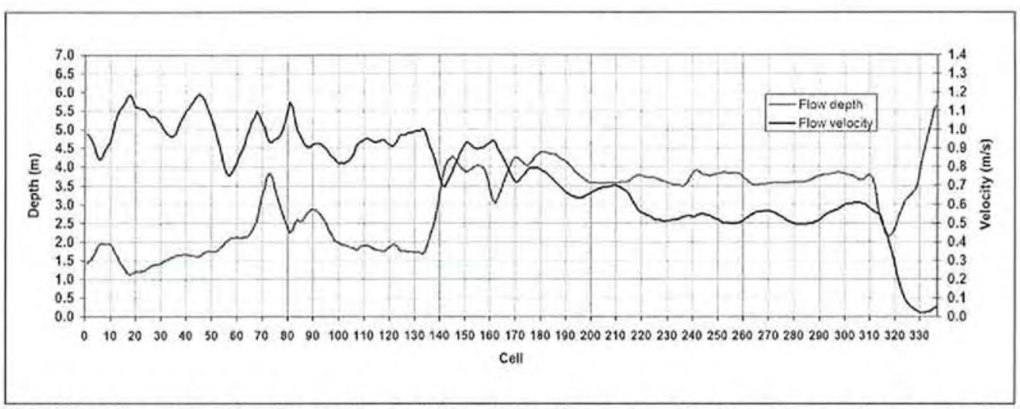

FIG. 25. Longitudinal profiles of flow depth and velocity along the centerline of Bubbly Creek.

to erosion.

Solids transport and water quality

The solid transport and water quality were then activated and a simulation was run for 7.66 hours (duration of the CSO discharge) in "semi-frozen" mode, that is, as already explained earlier, the water depth, which enters in the calculation of all the bed-water fluxes for solids and BOD and in the *SOD* term, was recalculated for each time step and each cell according to the net erosion, but

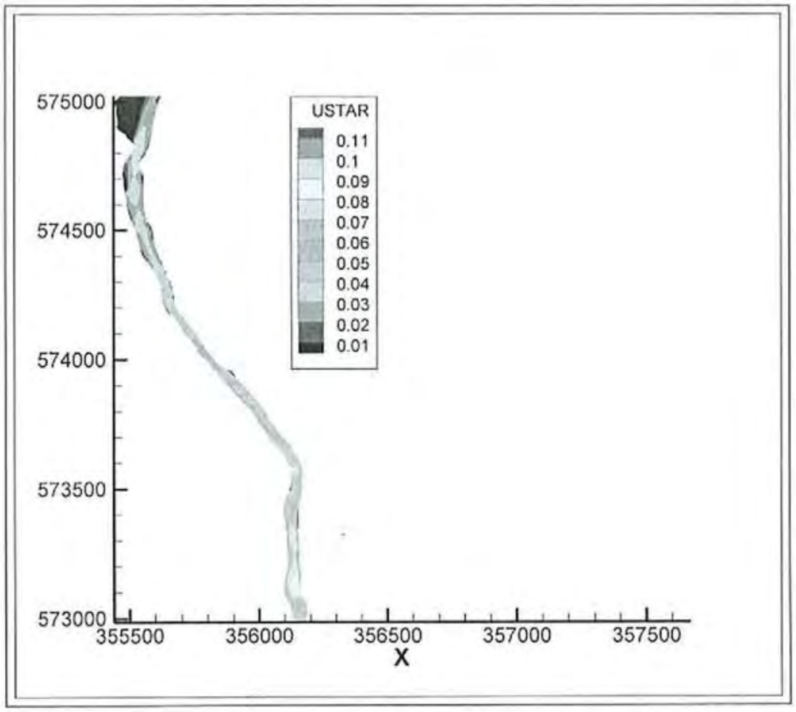

FIG. 26. Shear velocity field (m/s) for a discharge of 69.43 m^3/s.

the hydrodynamic was not recalculated. In fact, the recalculation of the hydrodynamics was observed to generate instability of the code. The causes of this instability were not investigated for this analysis, for which the only update of the water depths was considered a good compromise to get realistic results.

Figure (27) shows the cumulated bed elevation variation, for a flow discharge of 69.43 m^3/s, after 7.66 hours. The regime is net erosional (negative values of bed variation), especially in the upstream portion of the creek, where the flow depths are lower. The erosion goes from about 80 cm at the upstream end to about 5 cm at the downstream end.

Figure (28), (29) and (30) show the concentration of BOD and DO in the water column after 7.66 hours (duration of the CSO discharge).

Because of the net erosional regime, both the suspended solids concentration (reported in volume concentration) and the BOD concentration in the water column increase in the downstream direction: the suspended solids concentration is four times greater (from the input value of about 0.0005, that is 600 mg/l, to 0.0021, that is 2520 mg/l). As regards the BOD concentration, it goes from the input value of 20 mg/l to about 158 mg/l. The BOD concentration after 7.66 hours is basically determined by the input concentration in the area close to the upstream end and mainly by the resuspension of BOD in the rest of the channel.

The DO field is dominated by the input, so the effect of a CSO event, as observed, is to increase temporarily the DO levels in the creek, as measured

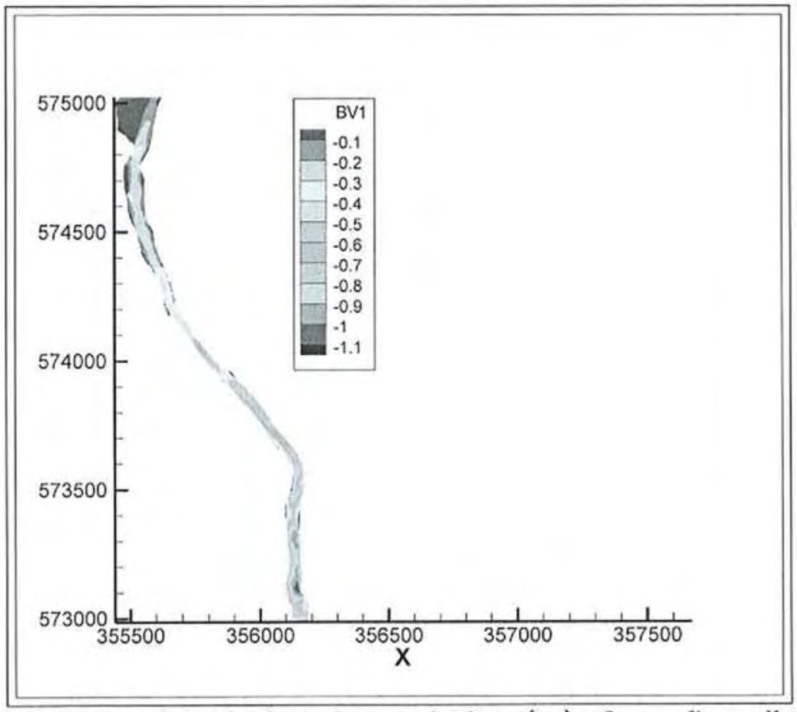

FIG. 27. Cumulated bed elevation variation (m), for a flow discharge of 69.43 m^3/s, after 7.66 hours.

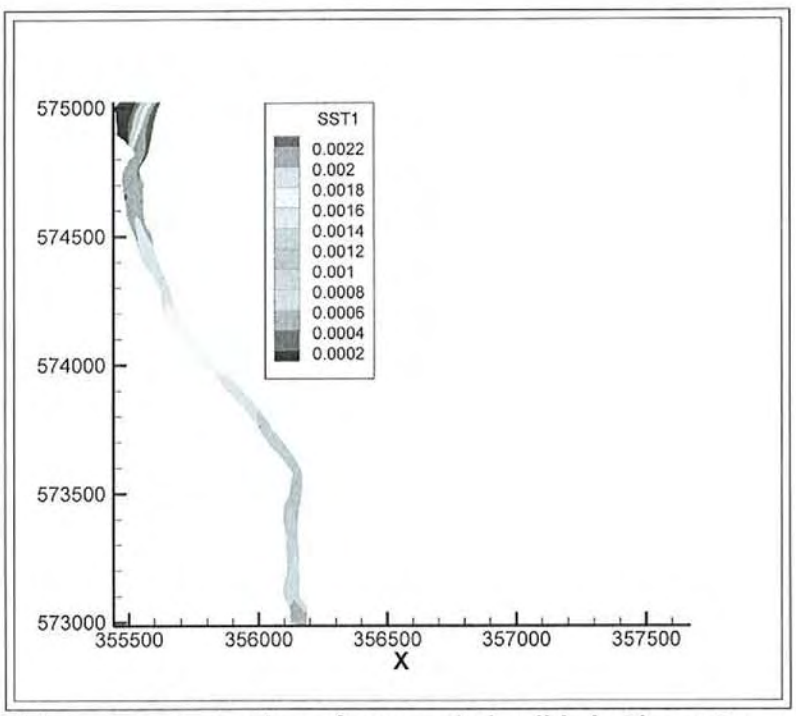

FIG. 28. Volume concentration of suspended solids in the water column, for a flow discharge of 69.43 m^3/s, after 7.66 hours.

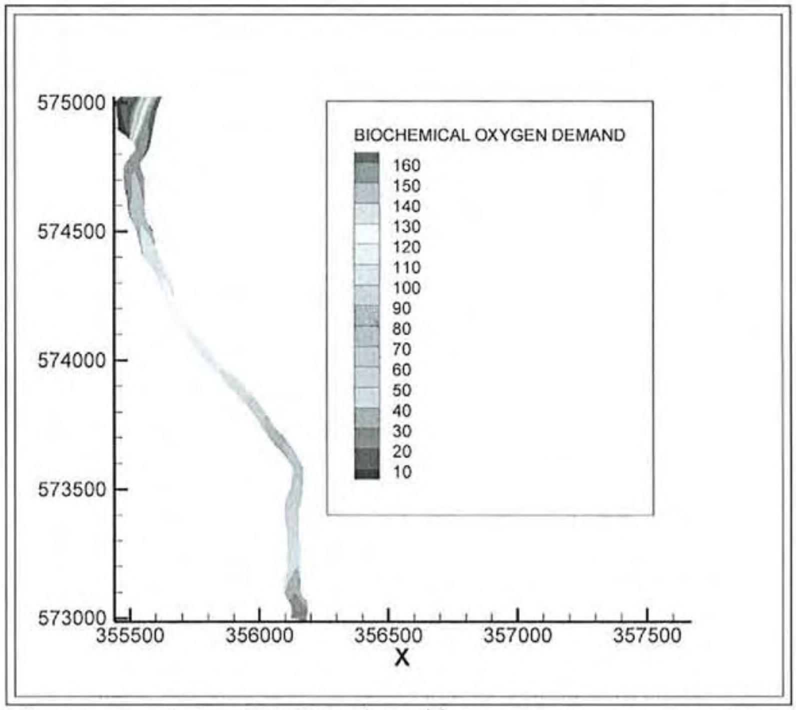

FIG. 29. Concentration of BOD (mg/l) in the water column, for a flow discharge of 69.43 m^3/s, after 7.66 hours.

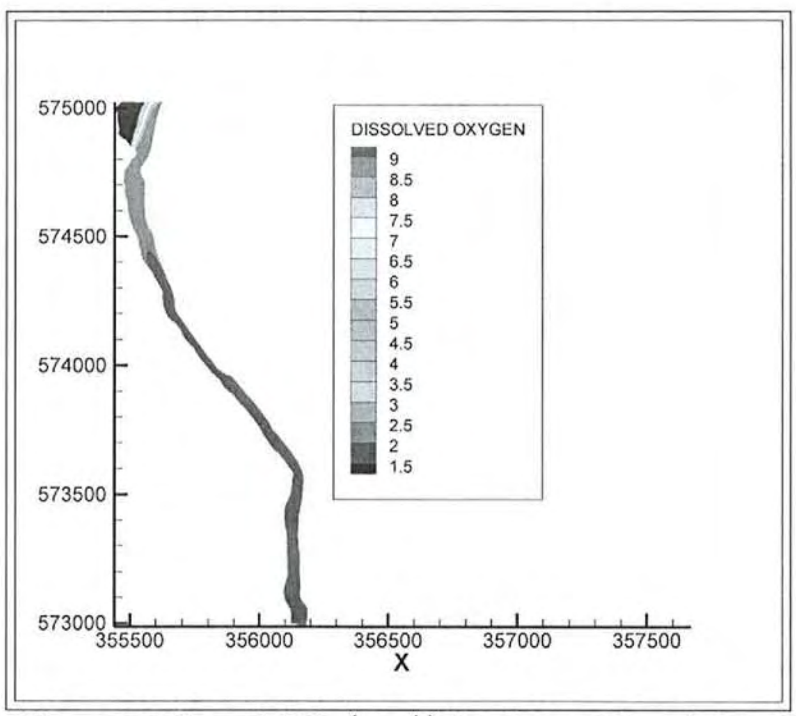

FIG. 30. Concentration of DO (mg/l) in the water column, for a flow discharge of 69.43 m^3/s, after 7.66 hours.

during the CSO discharge event.

"Phase 2" modeling

1-D area-averaged equations coupled for BOD and DO

In order to model the so defined "Phase 2" of a CSO "event", which is the one following the combined-sewer-overflow discharge, when water is stagnant again, a one-dimensional area-averaged conservation equation was considered for both BOD and DO. The general expression of the equation is

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = \frac{1}{A}\left(\frac{\partial}{\partial x}EA\frac{\partial C}{\partial x}\right) + S \tag{66}$$

where

- C = concentration of BOD or DO (mgO_2/l);
- t = time (s);
- u = flow velocity in the x direction (m/s);
- x = distance (m);
- A = flow area (m^2);
- E = dispersion coefficient (m^2/s);
- S = source/sink term (mg/l/s).

In absence of flow, the velocity u is equal to zero. The equation above can be therefore written, for BOD and DO, as follows

$$\frac{\partial C_{BOD}}{\partial t} = \frac{1}{A}\left(\frac{\partial}{\partial x}EA\frac{\partial C_{BOD}}{\partial x}\right) + S_{BOD} \tag{67}$$

$$\frac{\partial C_{DO}}{\partial t} = \frac{1}{A}\left(\frac{\partial}{\partial x}EA\frac{\partial C_{DO}}{\partial x}\right) + S_{DO} \tag{68}$$

Notice that the subscript "w" previously used to denote concentrations in the water column was here dropped for convenience's sake.

The sink term S_{BOD} considers oxidation and settling, already illustrated in this document:

$$S_{BOD} = -K_D\Theta_D^{T-20}\left(\frac{C_{DO}}{K_{BOD}+C_{DO}}\right)C_{BOD} - \frac{v_{ss}\left(1-f_{w,d}\right)C_{BOD}}{H} \tag{69}$$

The source/sink term S_{DO} considers oxidation, sediment oxygen demand and reaeration:

$$\begin{aligned} S_{DO} = -K_D\Theta_D^{T-20}\left(\frac{C_{DO}}{K_{BOD}+C_{DO}}\right)C_{BOD} - \frac{SOD}{H}\Theta_s^{T-20} + \\ +K_a\Theta_a^{(T-20)}\left(C_s - C_{DO}\right) \end{aligned} \tag{70}$$

where K_a can be estimated with a typical formula for standing water (Broecker *et al.*, 1978)

$$K_a = 0.864 \frac{U_w}{H} \tag{71}$$

where U_w is the wind speed measured 10 m above the water surface (m/s) and the resulting K_a is in (day^{-1}).

The BOD-DO coupled problem, was solved using an Eulerian explicit scheme, which has the advantage of easily accommodating the sink terms.

The time derivative was approximated with the forward difference scheme as follows

$$\frac{\partial C}{\partial t} \approx \frac{C_i^{n+1} - C_i^n}{\Delta t} \tag{72}$$

where n is the time index and Δt is the temporal time step.

The dispersion term was discretized as follows

$$\frac{1}{A}\left(\frac{\partial}{\partial x} EA \frac{\partial C}{\partial x}\right) = \frac{E_{i+1}A_{i+i}\left(C_{i+1}^n - C_i^n\right) - E_i A_i \left(C_i^n - C_{i-1}^n\right)}{A_i \Delta x^2} \tag{73}$$

where i is the space index, and Δx is the spatial time step.

The solving explicit coupled equations for BOD and DO are therefore

$$\begin{aligned} C_{BOD,i}^{n+1} = (1 - d_i - b_i)\, C_{BOD,i}^n + (b_i)\, C_{BOD,i-1}^n + (d_i)\, C_{BOD,i+1}^n + \\ + S_{BOD}\left(C_{BOD,i}^n, C_{DO,i}^n, T_i^n\right)\Delta t \end{aligned} \tag{74}$$

$$\begin{aligned} C_{DO,i}^{n+1} = (1 - d_i - b_i)\, C_{DO,i}^n + (b_i)\, C_{DO,i-1}^n + (d_i)\, C_{DO,i+1}^n + \\ + S_{DO}\left(C_{BOD,i}^n, C_{DO,i}^n, T_i^n\right)\Delta t \end{aligned} \tag{75}$$

where

$$b_i = \frac{E_i \Delta t}{\Delta x^2} \tag{76}$$

$$d_i = \frac{E_{i+1} A_{i+i} \Delta t}{A_i \Delta x^2} \tag{77}$$

As regards the numerical dispersion of the scheme, it can be proved (the passages are omitted here) that the numerical dispersion E_n associated to the discretization of the terms $\partial C/\partial t$ and $\partial C/\partial x$ is

$$E_n = \frac{u\Delta x}{2}\left(-\frac{u\Delta t}{\Delta x} + 1 - 2\alpha\right) \tag{78}$$

where α is a parameter that governs the discretization of the advective spatial derivative, here absent. Since it this case $u = 0$, $E_n = 0$

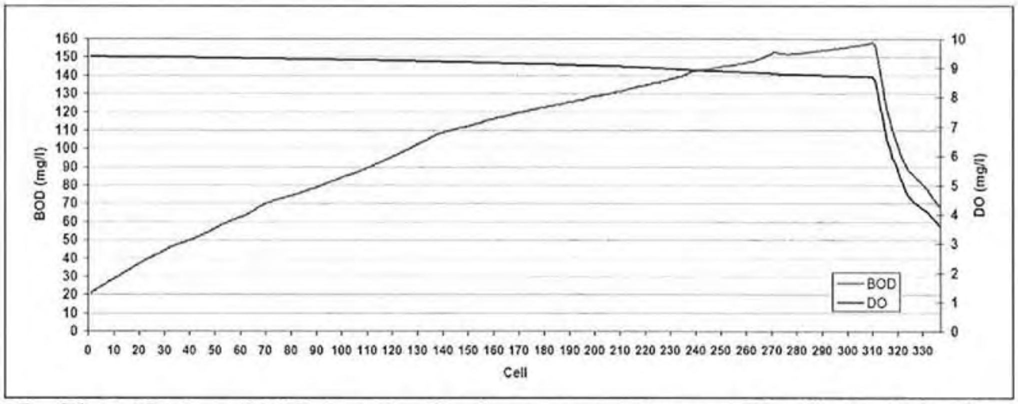

FIG. 31. BOD and DO longitudinal concentration profiles in Bubbly Creek after the CSO discharge.

As regards the dispersion term in the area-averaged equation, since it is discretized with a central difference scheme to obtain the solving explicit equations reported, no numerical dispersion is generated, while, obviously, truncation errors are generated.

The sinks terms, finally, do not contain derivatives, thus they do not generate numerical dispersion.

Initial conditions

As initial condition, the simulated BOD and DO concentration fields present in the creek when the CSO discharge stopped (end of "Phase 1") were considered. The concentrations in the cells were averaged for each cross sections weighting on the depth of each cell, being the transverse dimension of each cell constant along each cross section. The resulting BOD and DO longitudinal concentration profiles in Bubbly Creek after the CSO discharge are shown in Figure (31), where "cell" indicates the row of 15 cells representing each of the cross sections.

Boundary conditions

As boundary condition at the pumping station side ($x = 0$) the "closed system" condition was set for both BOD and DO:

$$\frac{\partial C}{\partial x}(x = 0) = 0 \tag{79}$$

The solving general numerical equation for the first numerical "node", assuming

$$C_{i-1}^{n} = C_{i}^{n} \tag{80}$$

becomes

$$C_{i}^{n+1} = (1 - d_i - b_i)\, C_i^n + (b_i)\, C_i^n + (d_i)\, C_{i+1}^n + S\left(C_i^n\right)\Delta t \tag{81}$$

At the outlet of Bubbly Creek into the South branch the boundary conditions are represented by the BOD and DO levels in the South Branch. In particular, the DO levels measured at the monitoring station at Loomis Street in the South Branch of the Chicago River, right upstream of the confluence of Bubbly Creek, were considered: a value of 7.09 mg/l, averaged over three days after the CSO discharge in Bubbly Creek, was used. As regards the BOD boundary concentration, a constant value of 5 mg/l was set (Alp and Melching, 2006).

Given the two-dimensional flow pattern at the Turning Basin, the boundary condition for the 1-D area-averaged model was set at the outlet of Bubbly Creek into the Turning Basin, i.e. the Turning Basin area was not model with this approach.

Parameters

This section lists the value of the parameters used in the simulation. The source of each of the values was already reported earlier in the report.

For BOD settling, $f_{w,d} = 0$ and $v_{ss} = 1$ m/day.

For oxidation, $K_D = 0.2$ day^{-1}, $\Theta_D = 1.040$ and $K_{BOD} = 0.5$ mgO_2/l.

For sediment oxygen demand, $SOD = 2.32$ g/m^2/day and $\Theta_s = 1.065$.

No wind-driven reaeration, in absence of wind velocity data.

The water temperature in the creek was assumed to be, for simplicity's sake, constant in space and time, and equal to the average value of the temperature measured at the two monitoring stations at 36^{th} Street and I-55 in the first 96 hours after the CSO discharge, that is 22.47 °C.

The mean water depth and the cross-sectional area for each cross section were calculated using the final bathymetry of the creek, resulting from the erosion process.

As regards the dispersion coefficient E, its value was considered as calibration parameter, observing that its order of magnitude, at least in the zone close to the outlet into the South Branch, should be typical of an estuarine area: the situation of Bubbly Creek and the South Branch is similar to the one of a river discharging in the sea or in the ocean, since the level of the South Branch at the mouth of Bubbly Creek oscillates. In other words, the dispersion in Bubbly Creek can be defined as "tidal" dispersion and the dispersion coefficient "lumps" the effect of the water stage variation (neglected during the short period of CSO discharge) on the scalar movement in water.

Figure (32) shows a typical water stage oscillation at Bubbly Creek's mouth, as modeled in a preliminary hydrodynamic 3-D simulation by Liu (2008). The water stage is relative to the CCD (Chicago City Datum), which is 176.63 m above sea level.

BOD and DO concentrations at 36^{th} Street and I-55 stations

Figure (33) and (34) shows the temporal evolution of the BOD (as modeled) and DO (modeled Vs. measured) at the monitoring stations at 36^{th} Street and I-55.

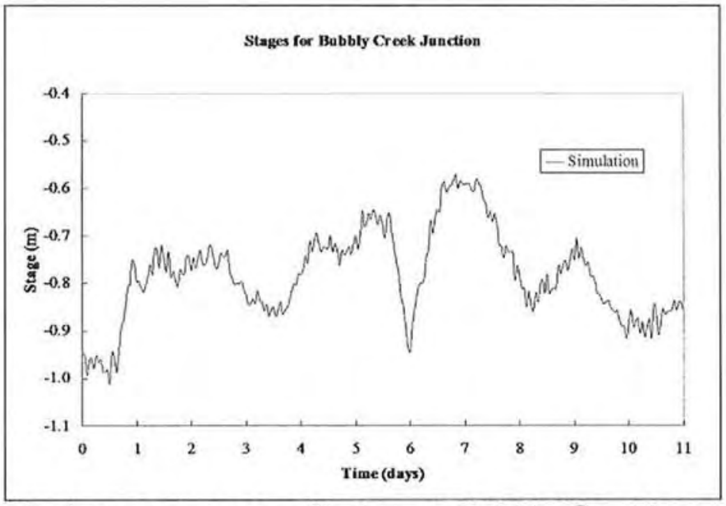

FIG. 32. Typical water stage oscillation at Bubbly Creek's mouth (results from hydrodynamic 3-D modeling).

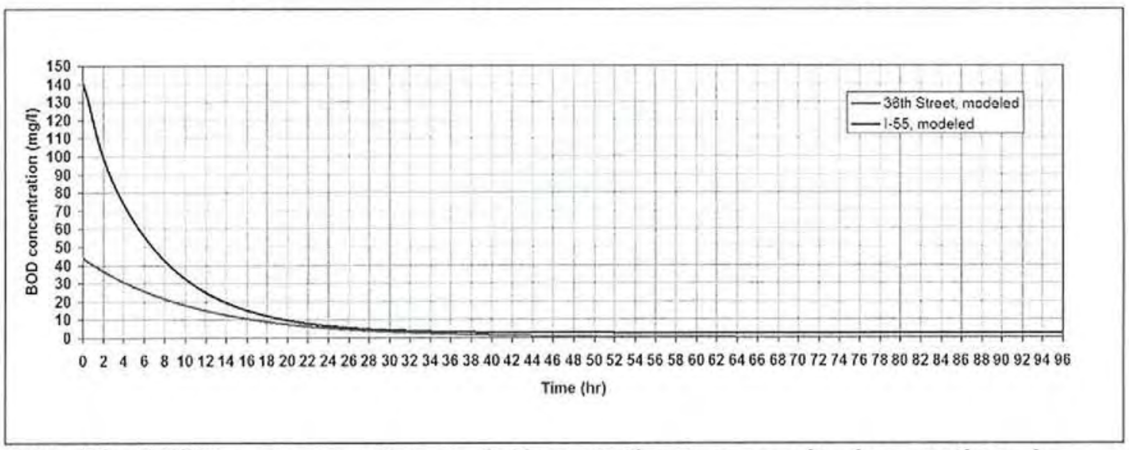

FIG. 33. BOD concentration evolution at the two monitoring stations in Bubbly Creek. Modeled values.

The 1-D area-averaged model was implemented on a 2050 m long domain for 4 days (96 hours) after the CSO discharge, considering a spatial step $\Delta x = 50$ m and $\Delta t = 50$ s, for which the solution is stable (the theoretical stability limits were not investigated here, so an appropriate Δt was sought after having set $\Delta x = 50$ m), with a calibrated dispersion coefficient E of 10 m^2/s for both BOD and DO in the downstream portion of the creek (last 700 m of the creek) while upstream the BOD and DO concentrations are exclusively governed by kinetics, since the constriction of the flow 700 m upstream of Bubbly Creek's mouth (see Figure (18)) damps down the estuarine effect.

Several observations can be made:

- the model predicts a monotonic temporal decrease of the BOD concentra-

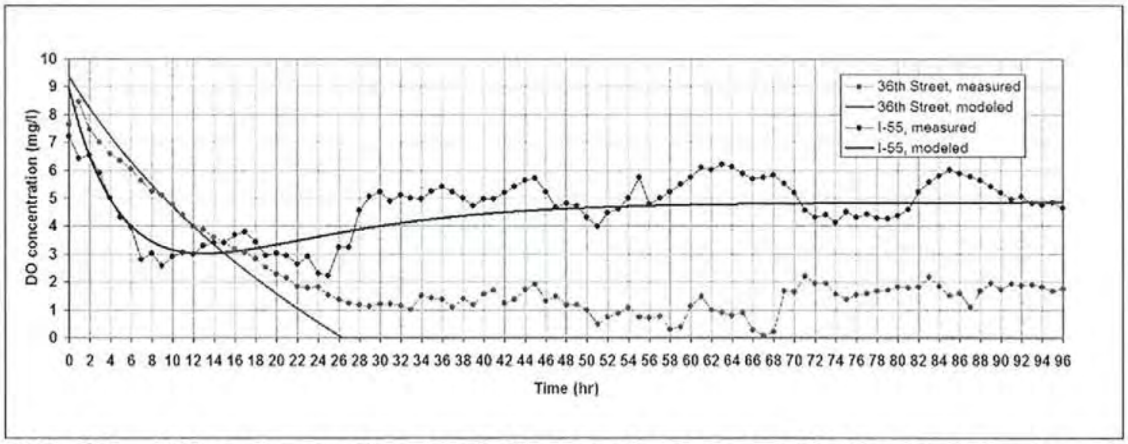

FIG. 34. DO concentration evolution at the two monitoring stations in Bubbly Creek. Measured and modeled values.

tion in the water column for both the stations, because of BOD settling and oxidation. The rate of decrease is higher for the I-55 Station, characterized by a higher BOD content in the water right after the CSO discharge (effect of the BOD resuspension from the bed);

- the model is also able to capture qualitatively the evolution of the DO level for both the stations: at I-55, that is close to Bubbly Creek's mouth, the DO decreases very rapidly for the first hours, due to the oxygen demand from the BOD (oxidation term) in the water column, entered from the pumping stations but especially resuspended from the bed. At the 36^{th} Street Station, very far (about 1850 m) from the South Branch of the Chicago River, the DO concentration decreases without recovering in the first days following a CSO discharge, because the effect of the South Branch is not felt;
- quantitatively, the DO temporal profile at the I-55 Station is captured fairly well, and the high concentration decrease rate during the first hours after a CSO discharge confirms the presence of an additional BOD in the water column due to resuspension from the bed. Also in the case of the DO measured at the 36^{th} Street Station, the decrease during the first hours is quantitatively captured fairly well;
- as regards the DO levels at the 36^{th} Street Station after about 20 hours, the predicted values are lower than the measured ones: this was expected, since the model implemented in this analysis does not correct the kinetics expressions for anaerobic conditions, which do occur in the upstream portion of the river after about 20 hours. In anaerobic conditions the rate of consumption of DO decreases (because of its lower availability), explaining why the DO concentration in reality does not go to zero. The result obtained in this study is anyway encouraging, since the DO dynamics is captured.

CONCLUSIONS

In this preliminary study, a model for the quantitative evaluation of the BOD transport across the bed-water interface in rivers was derived. Through the coupling of hydrodynamics, sediment transport and water quality, the process was described in terms of its dependency on the properties of the flow, the solids and the bed layer. The dissolved BOD fraction and the one attached to solid particles were treated separately.

The theoretical model was implemented in the two-dimensional depth-averaged hydrodynamic, sediment transport and water quality code STREMRHySedWq (Bernard, 1993; Abad *et al.*, 2007; Motta *et al.*, 2008).

A widespread analysis was performed in order to understand the sensitivity of the model to its different parameters.

A preliminary application to Bubbly Creek, the South Fork of the South Branch of the Chicago River, showed the potential use of the developed numerical tool, in a situation characterized by high discharges (as in the case of combined-sewer-overflows) and by an organic-rich bed, in the evaluation of the DO depletion associated to a high BOD content in the water column, both in the short and in the long period.

The results reported are considered preliminary and certainly to be refined. On the other hand, the described conceptual framework seems to be sound and potentially applicable to a three-dimensional model.

FUTURE WORK

As already mentioned, the analysis of Bubbly Creek and in general of the Chicago Waterway System is still ongoing and requires some future work.

In particular, it will be necessary to estimate an *in situ* relation for the resuspension of solids from the bed, in the form (43), which correlates the erosion rate to the bed shear stress and to the bulk density of the bed. This, as well as a better description of the sediment settling flux, would help clarify the importance of sediment and BOD resuspension during CSO events. The event analyzed in this study showed a high impact of the resuspension, while, for other historic events, this was not the case. This suggests that there is an influence of the degree of compaction (basically the consolidation time which affects the bulk density) on the resuspension rates.

A better characterization of the CSO inputs in terms of water quality is required too.

A sound calibration of the model should be done by monitoring a CSO event in all its characteristics, with particular attention to the evolution of the bed bathymetry.

The effect of the stratification and unsteadiness of the flow are also being currently analyzed, by means of the 3-D model EFDC.

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Attachment 4

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