CHICAGO AREA WATERWAY SYSTEM HABITAT EVALUATION AND IMPROVEMENT STUDY:

HABITAT EVALUATION REPORT

Prepared for:
The Metropolitan Water Reclamation District of Greater Chicago

January 4, 2010

LimnoTech
Water | Environment | Scientists | Engineers

Ann Arbor, Michigan
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EXECUTIVE SUMMARY

This report documents a study of aquatic habitat in the Chicago Area Waterway System. The Chicago Area Waterway System Habitat Evaluation and Improvement Study (the Study) was conducted by LimnoTech under contract to the Metropolitan Water Reclamation District of Greater Chicago. The Study objectives addressed in this report are as follows:

- Determine physical habitat characteristics for all reaches of the CAWS, using applicable physical habitat metrics and data collected from the CAWS.
- Use a multi-metric habitat index to evaluate physical habitat conditions in the CAWS.
- Use physical habitat data and the above multi-metric index to assess the relative importance of physical habitat to fish in the CAWS.
- Determine, to the extent possible with the data and analysis developed in this Study, a system of classifying or categorizing reaches within the CAWS according to their physical habitat.

Detailed physical habitat data were collected and the entire CAWS Study area was characterized. A number of physical habitat impairments were identified and have been described in this report. The major conclusions drawn from the habitat evaluation and data analysis conducted in this study are:

- Aquatic habitat is inherently limited in the CAWS by the system’s form and function. Habitat in the CAWS is significantly limited by the design of the CAWS, most of which is manmade. The manmade reaches of the CAWS were built to support wastewater effluent conveyance and commercial navigation. The reaches that were once natural streams have been heavily modified to serve these purposes and the changes are unlikely to be reversed as long as the CAWS needs to serve these functions. The form and uses of the CAWS impose severe limitations on physical habitat in the system.
- Physical habitat is more important to fish in the CAWS than dissolved oxygen. When key physical habitat variables and dissolved oxygen metrics are statistically compared to fish data collected between 2001 and 2008 in the CAWS, it is apparent that habitat is much more important to fish than dissolved oxygen. Multiple linear regression shows that the dominant habitat variables identified in this study had an r-squared of 0.48 with fish, indicating that these habitat variables explain as much as 48%, or about half, of the variability in the fish data.
- The ability of physical habitat to explain about half of the variability in fish data is excellent, considering the natural variability in the fish data itself. As

stated above, about half of the variability in fish data in the CAWS is explained by physical habitat, in particular certain key habitat variables identified in this study. Of the half of fish data variability not explained by the key habitat variables, most is explainable by natural variation in the fish data from one sampling event to another at each location. In other words, fish samples exhibit large temporal variability at any given location in the CAWS and when the portion of fish data variability not explained by habitat is statistically analyzed, it is most related to the variation at sampling locations over time, independent of habitat changes.

- Dissolved oxygen is relatively poor at explaining variability in fish data in the CAWS. Dissolved oxygen does not, for the most part, have a statistically significant relationship with fish in the CAWS. Various measures of dissolved oxygen were tested, including compliance with existing and proposed water quality standards, average and minimum DO, and percent of time below various DO concentration thresholds. The strongest relationship identified between any of these metrics and the combined fish metric had an r-squared value of 0.27, which is about half as good as the key habitat variables identified in this study. The other four DO measures tested had r-squared values ranging from 0.02 to 0.08. This indicates that physical habitat, not water quality, is the most limiting factor for fish in the CAWS today.

Six key habitat variables were identified through a process of sequentially reducing the habitat variables and ultimately through multiple linear regression with CAWS fish data. This process identified the following key physical habitat attributes as being critically important to fish in the CAWS:

- Maximum depth of channel
- Off-channel bays
- Percent of vertical wall banks in reach
- Percent of riprap banks in reach
- Manmade structures in reach
- Percent macrophyte cover in reach

Statistical analysis of habitat data with fish data from the CAWS showed that 48% of the variability of fish data collected from 2001 – 2007 can be explained by these key habitat variables. DO alone can only explain between 2% and 27% of the variability in the same fish data set.

The relative importance of physical habitat to fish in the CAWS was determined through statistical analysis of habitat, fish, and water quality data. Addition of a key water quality metric (percent of time dissolved oxygen is less than 5 mg/L) in the multiple linear regression with the key habitat variables only increased the explanatory power of the regression by only 4%.

A CAWS-specific habitat index was created using the six key habitat variables identified in this Study along with other important variables. The CAWS-specific habitat index was used to score individual sampling stations as well as the major reaches in the CAWS, in order to determine whether the findings of this Study can help classify the reaches according to the physical habitat variables that are most important to fish in the CAWS. When applied to fish data averages over the period of 2001 – 2008, the CAWS habitat index compared well ($r^2 = 0.48$), indicating that the index is good indicator of habitat suitability for fish in the CAWS.

1. INTRODUCTION

This report documents a study of aquatic habitat in the Chicago Area Waterway System. The Chicago Area Waterway System Habitat Evaluation Study (the Study) was conducted by LimnoTech under contract to the Metropolitan Water Reclamation District of Greater Chicago (the District).

1.1 REPORT STRUCTURE

This report is structured to present the Study in a logical, explanatory manner and to facilitate its use by readers with a range of technical backgrounds. The major sections of the report are as follows:

- Section 1: Introduction – This section presents the Study objectives and an introduction to the CAWS.

- Section 2: Habitat Evaluation Approach – This section provides an overview of the approach used in this Study and the scientific rationale for that approach.

- Section 3: Data Summary – Section 3 describes the types, sources, and quantities of data used in this Study.

- Section 4: Description of Habitat Conditions in the CAWS – This section provides a summary description of the physical conditions in the CAWS that are relevant to physical habitat evaluation, based on observations and the data described in Section 3.

- Section 5: Description of Aquatic Biota in the CAWS – This Section summarizes existing aquatic life in the CAWS, based on the data used in this Study, focusing on fish and macroinvertebrates.

- Section 6: Habitat Data Analysis – Section 6 discusses the process used to identify key habitat variables in the CAWS, through a systematic review and reduction of potential variables. It also presents the analysis of fish and habitat data from the CAWS, to identify the most significant habitat variables to fisheries and to understand the relative importance of physical habitat, as compared to other factors such as water quality.

- Section 7: Development of a CAWS Habitat Index – Section 7 presents the development of a system-specific habitat index for the CAWS, based on the results of the analysis presented in Section 6.

- Section 8: CAWS Habitat Evaluation Summary – Section 8 presents a summary of the key findings of habitat evaluation conducted in this Study.

1.2 STUDY OBJECTIVES

This Study was undertaken, in part, to better understand the current state of aquatic habitat in the CAWS and to identify key habitat impairments, particularly with respect to fish. The key objectives of the habitat evaluation portion of the Study are as follows:

- Determine physical habitat characteristics for all reaches of the CAWS, using applicable physical habitat metrics and data collected from the CAWS.
- Use a multi-metric habitat index to evaluate physical habitat conditions in the CAWS.
- Use physical habitat data and the above multi-metric index to assess the relative importance of physical habitat to fish in the CAWS.
- Determine, to the extent possible with the data and analysis developed in this Study, a system of classifying or categorizing reaches within the CAWS according to their physical habitat.

1.3 CHICAGO AREA WATERWAY SYSTEM OVERVIEW

As the name implies, the Chicago Area Waterway System (CAWS) is a system of waterways in the vicinity of the Chicago metropolitan area (Figure 1-1), used primarily for conveyance of treated municipal wastewater, commercial navigation, and flood control. The overall length of the CAWS is approximately 78 miles, of which about 75 percent are manmade canals (District, 2008). The rest are formerly natural streams that have been dredged, straightened, widened, realigned, and otherwise modified to facilitate the uses listed above. The construction and modification history of the reaches of the CAWS are summarized in Table 1-1.

Figure 1-1: The Chicago Area Waterway System Habitat Evaluation and Improvement Study Area.

Table 1-1: Construction and Modification History of the CAWS (Greenberg, 2002; Hill, 2000; Ramey, 1953; Solzman, 2006)

Waterway	Length (mi)	Construction History
North Shore Channel	7.7	Completely manmade; excavated 1907-1910
North Branch Chicago River	7.8	Straightened, widened, deepened; 1904 onward
North Branch Canal	1.1	Completely manmade; excavated 1850s
Chicago River	1.6	Mouth modifications; widened, deepened; focus of development since time of first settlement; flow reversed; modifications 1816-1939
South Branch Chicago River	4.6	Straightened, widened, deepened; flow reversed; major straightening in 1928-29; West Fork completely filled in 1920-1930s
Bubbly Creek	1.5	Straightened, widened, deepened, rerouted, tributaries filled; 1860s-1920s
Chicago Sanitary and Ship Canal	31.3	Completely manmade; excavated 1892-1900
Calumet-Sag Channel	16.1	Completely manmade; excavated 1911-1922; widened in 1960s
Little Calumet River	6.1	Straightened, widened, deepened; flow reversed; modifications started in the 1870s

Just as the origin of natural rivers is important to understanding their physical habitat, it is equally important to understand the origin of the CAWS. As stated previously, most of the CAWS are excavated channels for conveyance of wastewater effluent and navigation, and these continue to be the primary purposes for which the CAWS are maintained today. The reaches that were originally natural streams or rivers have been so extensively altered that they bear little or no resemblance to their original condition. Brief summaries of each of the major reaches of the CAWS are provided below.

1.3.1 North Shore Channel

The northernmost segment of the CAWS is the North Shore Channel, which extends from Lake Michigan at Wilmette Harbor in Wilmette to the confluence with the North Branch Chicago River near Foster Avenue in Chicago and was constructed between 1907 and 1910 (see Figure 1-2). The North Shore Channel was designed to increase flow for dilution and flushing of wastewater in the North Branch Chicago River by connecting it to Lake Michigan. The Channel consists of relatively straight segments (see Figure 1-3) and is approximately 7.7 miles long, 90 feet wide, and 5 to 10 feet deep. Pumps at the Wilmette Pumping Station convey water from Lake

Michigan into the channel which flows south toward the North Branch Chicago River. This flow supplements flow from the North Branch Chicago River watershed, which is regulated by a dam at the confluence of the two waterways.

1.3.2 North Branch Chicago River

The lower 7.8 mile portion of the North Branch Chicago River lies within the CAWS (see Figure 1-1). Although the North Branch Chicago River was once a natural meandering river with consistent bank overflow, modifications to the channel to improve drainage began as early as the 1850s (Hill, 2000). Large scale straightening, widening, and deepening of the North Branch Chicago River was conducted between 1904 and 1907. The upper 5.1 miles of the North Branch (Figure 1-4), above Touhy Avenue, retains some bends, but has been significantly altered. Its width varies between 150 and 300 feet and it is 5 to 10 feet deep. The lower 2.6 miles (Figure 1-5) has been significantly straightened and channelized, with a width of approximately 90 feet and a depth of about 10 feet.

Figure 1-2: North Shore Channel Construction, 1910 (Chicago Daily News).

Figure 1-3: North Shore Channel, 2008.

Figure 1-4: Northern Segment of North Branch Chicago River, 2008.

Figure 1-5: Southern Segment of North Branch Chicago River, 2008.

1.3.3 North Branch Canal

In 1857, the 1.1-mile North Branch Canal was constructed to bypass a major bend in the North Branch Chicago River to reduce travel time up the river. The land isolated by the construction of the canal is now known as Goose Island. The North Branch Canal is 80 to 120 feet wide and 4 to 8 feet deep.

1.3.4 Chicago River

The 1.6-mile Chicago River extends from Lake Michigan west to the confluence of the North Branch Chicago River and the South Branch Chicago River (Figures 1-6 and 1-7). The mouth of the Chicago River was modified as early as 1816 (Hill, 2000) and river redesign continued through the 19th century as wastewater and drainage flows increased. Modifications included deepening, straightening, widening, and channelization. The Chicago River originally flowed into Lake Michigan, but with the completion of the Chicago Sanitary and Ship Canal in 1900 (see below), flow was reversed. The Chicago River Lock & Controlling Works began operating in 1939 to control the flow of Lake Michigan water into the Chicago River. The Chicago River is 200 to 400 feet wide with mostly vertical walled sides and is 20 to 26 feet deep.

Figure 1-6: Chicago River, 1929.

Figure 1-7: The Chicago River, 2008.

1.3.5 South Branch Chicago River

The South Branch Chicago River (Figure 1-8) is approximately 4.6 miles long and flows west-southwest from the confluence of the Chicago River and the North Branch Chicago River. Although it generally follows its original course, major straightening and channelization of the South Branch to facilitate navigation occurred between 1928 and 1930. Like the Chicago River, the South Branch originally flowed toward Lake Michigan but its flow was reversed with the completion of the Chicago Sanitary and Ship Canal. The West Fork of the South Branch was completely filled in the 1920s and 1930s (Hill, 2000). The South Fork of the South Branch exists today and is described below. The South Branch is generally between 200 and 250 feet wide and its depth ranges from 15 to 20 feet.

Figure 1-8: The South Branch Chicago River, 2008.

1.3.6 South Fork of the South Branch Chicago River (Bubbly Creek)

The South Fork of the South Branch Chicago River (Figures 1-9 and 1-10) is a tributary to the South Branch and is approximately 1.5 miles long. The South Fork has been known as Bubbly Creek for more than a century because it received wastes from the Chicago stockyards starting in the second half of the 19th century and the decomposing organic waste on the bed of the creek created gases that bubbled to the surface. In 1866 the Union Stock Yards were located on the South Fork to centralize disposal of slaughterhouse wastes as a public health measure. Bubbles from gas production in the sediments are still visible today. Portions of Bubbly Creek have been straightened and channelized over time and the arms of Bubbly Creek were filled in the 1910s and 1920s. Bubbly Creek originally drained wetlands south of the City, but the only flows it receives today are urban storm water and occasional combined sewer overflow from the Racine Avenue Pumping Station. It is between 100 and 200 feet wide, with an average depth of 10 feet.

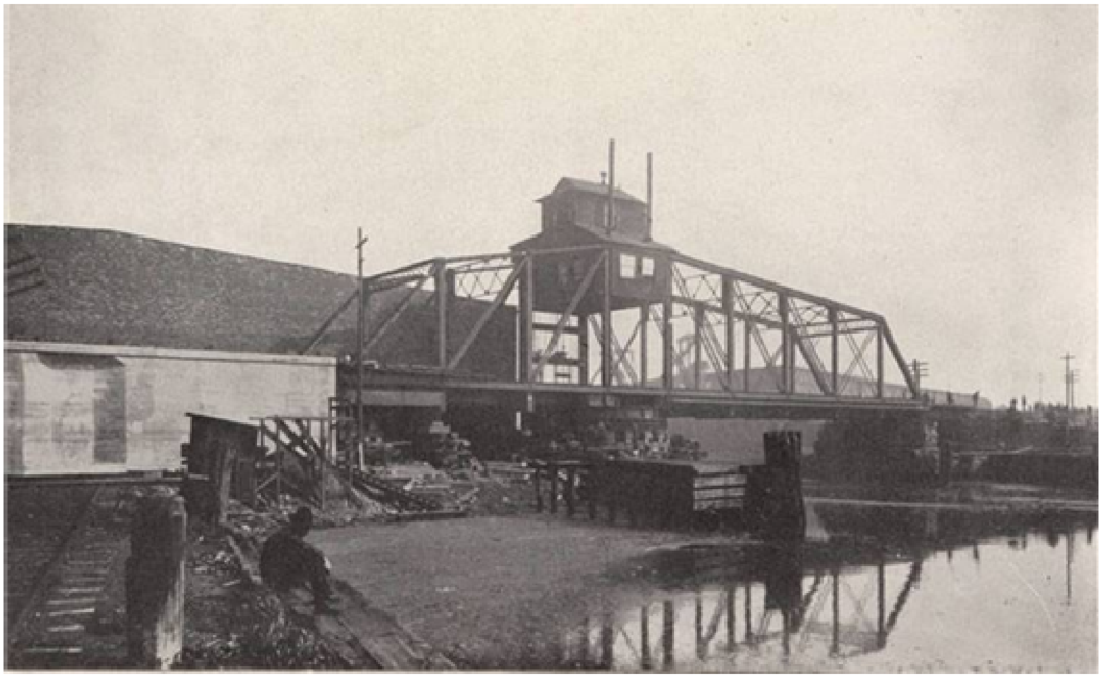

Figure 1-9: Bubbly Creek, 1902 (University of Illinois at Chicago).

Figure 1-10: Bubbly Creek, 2008.

1.3.7 Chicago Sanitary and Ship Canal

The Chicago Sanitary and Ship Canal (CSSC) was constructed between 1892 and 1900 with the specific intention of reversing flow from the Chicago River system. Wastewater discharges and urban drainage from Chicago flowed into Lake Michigan prior to that time and had grown to threaten the City's drinking water intakes in the Lake. The 31.3 mile CSSC was constructed to drain the Chicago River system and the City's effluent westward, away from Lake Michigan to the Des Plains River. The CSSC completes a commercial navigational waterway connecting Lake Michigan to the Mississippi River. Near the southern terminus of the CSSC is the Lockport Powerhouse and Lock, just upstream of the confluence of the CSSC with the Des Plaines River. The CSSC is a generally straight canal with a few major bends. Its width varies between 160 and 300 feet and its depth varies between 20 and 27 feet over most of its length. Portions of the CSSC were excavated into bedrock (see Figures 1-11 and 1-12).

Figure 1-11: The Chicago Sanitary and Ship Canal under Construction, Santa Fe Railroad Bridge at Lemont, October 18, 1899

(Chicago Historical Society, The Electronic Encyclopedia of Chicago, 2005).

Figure 1-12: The Chicago Sanitary and Ship Canal in 2008.

1.3.8 Calumet-Sag Channel

The 16.1 mile Calumet-Sag (Cal-Sag) Channel (CSC) is a manmade canal constructed between 1911 and 1922 to reverse the flow of the Calumet River away from Lake Michigan, westward to the Des Plaines River (Figures 1-13 and 1-14). The CSC was excavated through limestone and bedrock (Hill, 2000). Upon completion, the CSC connected the Little Calumet River to the CSSC. It was widened in the 1960s to improve navigation. Today, the CSC is approximately 225 feet wide and 10 feet deep.

Figure 1-13: The Cal-Sag Channel under Construction, 1914
(Chicago Historical Society, The Electronic Encyclopedia of Chicago, 2005).

Figure 1-14: The Cal-Sag Channel in 2008.

1.3.9 Little Calumet River

Originally a reach of the Grand Calumet River, the 6.1 mile Little Calumet River (Figure 1-15) underwent major hydrologic modifications beginning in the 1870s. Flow from the Grand Calumet River was diverted into the widened, straightened, and deepened Little Calumet River. With the completion of the Calumet-Sag Channel and the Blue Island Controlling Works (operational from 1922 to 1965) the flow of the Little Calumet River was reversed to flow westward into the Calumet-Sag Channel. The Little Calumet River is between 250 and 350 feet wide and is approximately 12 feet deep.

Figure 1-15: The Little Calumet River in 2008.

The construction and modification of the CAWS is summarized in Figure 1-16.

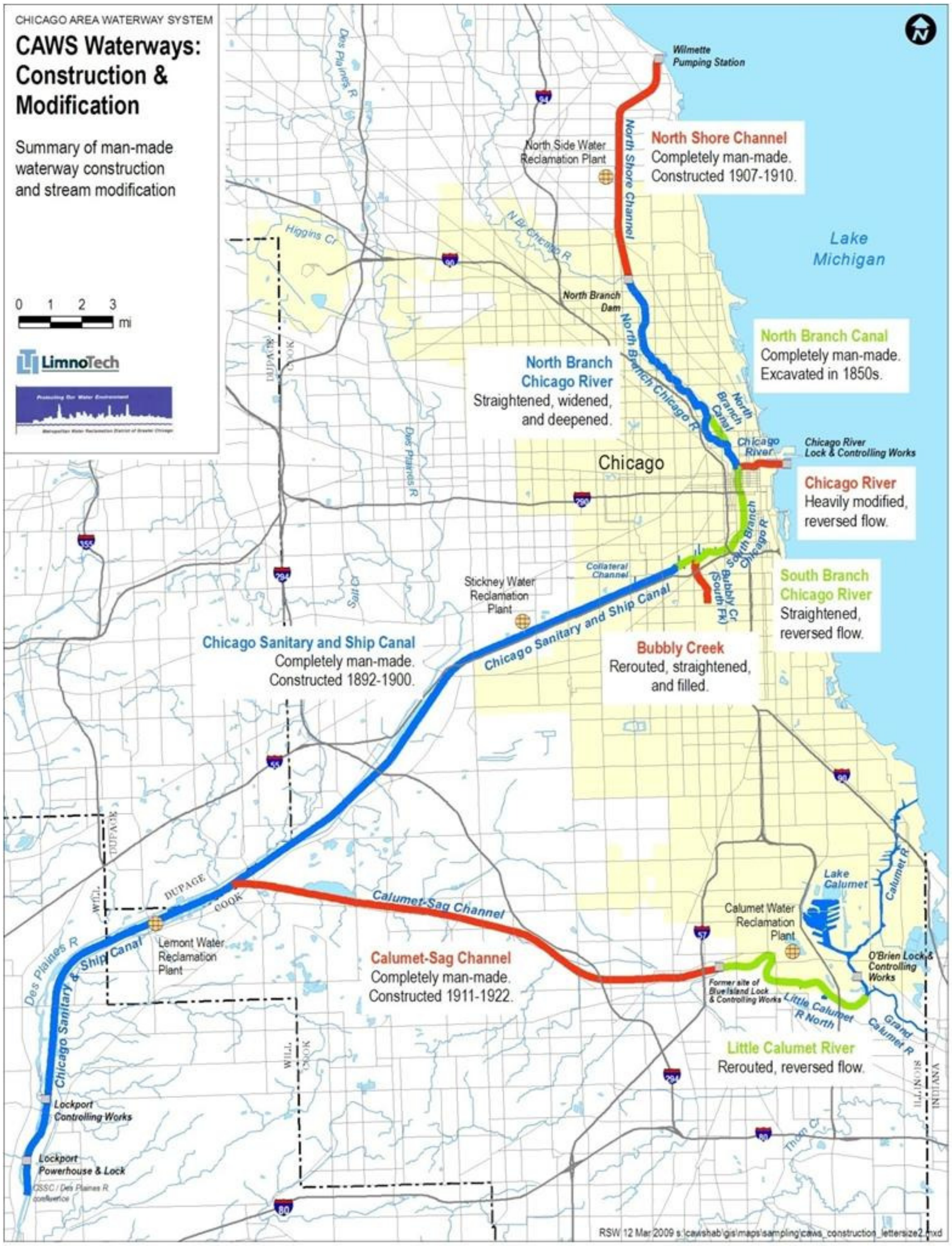

Figure 1-16: Construction and Modification History of the CAWS.

2. HABITAT EVALUATION APPROACH

Because the objectives of this Study focused on understanding the importance of physical habitat to aquatic life in the CAWS and on identifying which particular habitat factors are relatively more important than others, it was logical to use bioassessment as the basis for the study. As stated in recent technical guidance published by the United States Environmental Protection Agency (USEPA):

> "The aquatic life of streams and rivers (fish, insects, plants, shellfish, amphibians, etc.) integrates the cumulative effects of multiple stressors generated by both point source and non-point source (NPS) pollution. Bioassessments, consisting of surveys and other direct measures of aquatic life, are the most effective way to measure the aggregate impact of these stressors of waterbodies. Bioassessments allow evaluation of the biological integrity of a waterbody…" (Flotemersch et al., 2006)

This approach was especially relevant in light of current proposals for modification of the water quality standards for the CAWS and the designated aquatic life uses that are part of those proposed standards. This section provides a brief background on the history, use, and applicability of bioassessments in ecological evaluation of surface waters and describes the general methodology used in this study.

2.1 BIOASSESSMENT OVERVIEW

Bioassessments are used by water quality management agencies in their establishment of water quality standards, assessment of designated use attainment, evaluation of the effectiveness of mitigation and restoration activities and as a contributor to the Total Maximum Daily Load (TMDL) process (Flotemersch et al., 2006). Bioassessments more accurately detect and identify water quality conditions and sources of impairment, however it appears that the designation of impairment through many regulatory programs do not necessarily identify the pollutant or stressor causing the impairment (D'Ambrosio et al., 2009).

Although surface water body regulation often focuses on water quality, there are other key factors that must be considered when evaluating the health of aquatic ecosystems. These key factors combine to form the biological integrity and ecological health of a system (Karr, 1995; Rankin, 1995; Karr and Yoder, 2004) and are at the interface of anthropogenic stressors and aquatic biota (Figure 2-1).

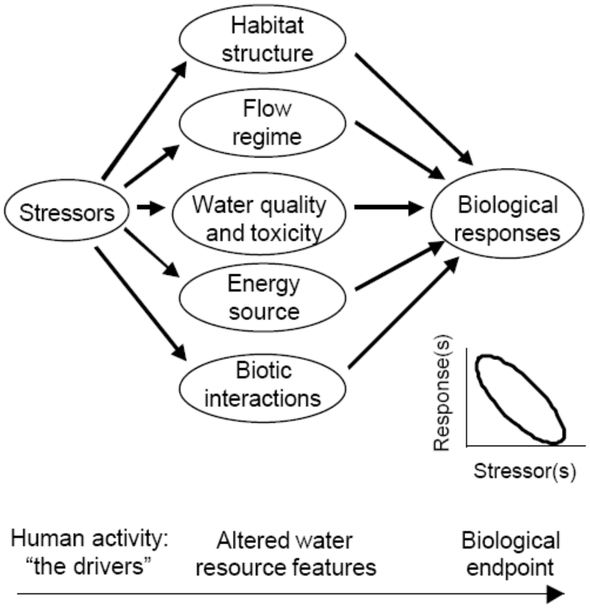

Figure 2-1: Key Factors Related to Health of Aquatic Systems (from Karr and Yoder, 2004).

Monitoring programs across the country are applying a range of approaches for assessing aquatic system conditions. Given the anthropogenic alterations imposed on most large rivers, programs could improve their assessment of biotic conditions by evaluating patterns of variation against anthropogenic stressors rather than attempting to evaluate conditions against natural sources (Emery et al., 2003). This seems to hold particularly true for a large system like the CAWS where the constructed and regulated conditions are the foundation around which the biotic conditions have developed.

Within urban systems, bioassessment approaches are challenged by the definition of appropriate benchmarks for target conditions under the complex range of modifications and multiple stressors that limit aquatic potential (Barbour et al., 2007). There is an expanding base of literature evaluating the stressors imposed on large urban stream systems (Coles et al., 2004; Brown et al., 2005; Flotemersch et al., 2006; Wilhelm, 2002; Lyons et al., 2001). Studies that have evaluated large urban systems have identified a large number of confounding impacts that include riparian and in-stream habitat loss, landscape fragmentation, impervious surface expansion, reductions in water quantity and quality, and numerous other effects that result in a degraded aquatic community (Booth et al., 2002; Kennen et al., 2005; Wilhelm, 2002). Reash (1999) states that the confounding impacts for urban systems described above are further blurred by establishment of lentic habitats created by damming.

Finally, bioassessment approaches can further support the interpretation of biological response to cumulatively increasing levels of stressors across a biological condition gradient (BCG), such as that depicted in Figure 2-2 (USEPA, 2005). The BCG (Figure 2-2) provides an example of how some key attributes of aquatic systems change in response to anthropogenic stressors regardless of assessment methods or geography (USEPA, 2005). The development of an appropriate, interpretable bioassessment program for the CAWS will allow for an evaluation of the many unique stressors within the system that have formed the limited biotic gradient of conditions across the system.

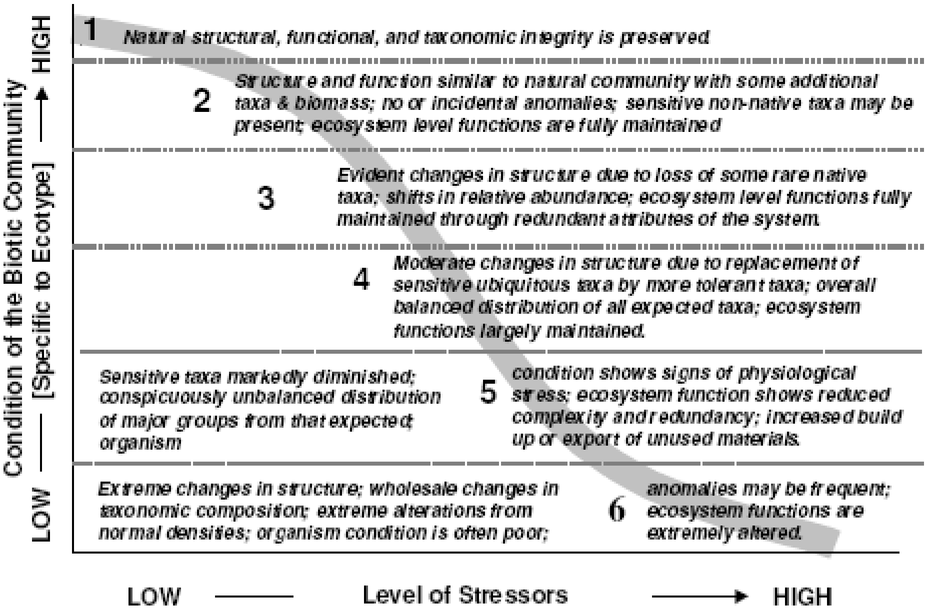

Figure 2-2: Relationship of Biological Response to Increasing Condition Stressors (from EPA, 2005).

2.2 IMPORTANCE OF HABITAT ASSESSMENT

As depicted in Figure 2-1 (Karr and Yoder, 2004), aquatic habitat is one of the five key components forming biological integrity and ecological health of aquatic systems. Although these factors are collectively important, habitat can be the factor most limiting aquatic community potential, and the existing conditions are usually the result of both hydrogeomorphic features and anthropogenic alterations (Rankin, 1995). Habitat assessments are a critical component of the bioassessment toolkit because they can explain much of the variation in biological diversity within a system, aid in the classification of reaches, identify disturbance gradients and effect, and can be used as a basis for restoration activities (Flotemersch et al., 2006). Habitats in large rivers tend to have long histories of physical degradation that provide a limited gradient of impacted conditions that illustrate the importance of characterizing habitats in these unique environments (Flotemersch et al., 2006).

Rankin (1995) identifies seven essential components of any habitat assessment index and Table 2-1 expands on functional applicability of these identified components as they apply to the CAWS.

Table 2-1: Essential Habitat Assessment Index Components (Rankin, 1995)

Habitat Component (Rankin, 1995)	Summary of Functional Value to Biota	CAWS Relevance
Substrate Type and Quality	The type and composition of substrate determines the quality of spawning habitat and cover for many fish species as well as influences benthic macroinvertebrate composition and production (McMahon et al., 1996). Fine substrates resulting from sedimentation are generally considered an important source of degradation of aquatic communities (Rankin, 1995). Waters (1995) recognizes the relationship between sedimentation and reduced macroinvertebrate availability for fish production, but states that research on the direct link between poor substrate quality and fish production is lacking. However, Waters (1995) states that the general relationship between benthic macroinvertebrates and fish production is well established.	The bed of much of the CAWS is cut through solid rock (most of the CSSC and Calumet-Sag Channel) or dug through consolidated silt and clay deposits which have lower pore space and interstices compared to natural silt beds. On top of this, inflows of storm runoff deposits fine sediment from the urban drainage area. Thus, the substrate in the CAWS is less ecologically functional than similar substrate in natural systems.
In-stream Physical Structure and Cover	The in-stream physical structure has a significant influence on aquatic organisms and its importance is well documented for both fishes and macroinvertebrates (Rankin, 1995; McMahon et al., 1996). McMahon et al. (1996) describe numerous examples of structure and cover types and state that cover preferences should be identified based on the species under study.	The constructed nature of the CAWS (for navigation and effluent conveyance) has eliminated much of the cover within the system. High turbidity prevents direct observation of cover in the system.
Channel Structure/ Stability/Modification	Modifications of channels alter stream flow, aquatic biota and many habitat characteristics (Rankin, 1995). Such changes have resulted in biotic effects to fisheries recruitment and trophic assemblages (Rankin, 1995). Aquatic organisms have been dramatically affected by channel alterations associated with navigational construction and maintenance (Wolter and Arlinghaus, 2003). The degree of channel alteration should be used as a measure of influence on the biotic expectations (Flotemersch et al., 2006; Reash, 1999).	Most of the CAWS have been constructed for navigation and effluent conveyance. This has resulted in generally uniformly shaped channels that are long and straight.

Table 2-1 (continued): Essential Habitat Assessment Index Components (Rankin, 1995)

Riparian Width/Quality	Typically, riparian areas play an important role in defining channel morphology, controlling stream temperature and creating and maintaining fish habitat (McMahon et al., 1996). The scale of riparian influence on rivers is associated with the river size, that is, smaller rivers are more influenced by the effects of riparian vegetation than larger rivers (Giller and Malmquist, 1998). Riparian disturbance effects appear to be better predictors of adverse biotic affect as their scale increases, rather than immediately adjacent to disturbed sites (Rankin, 1995). Common benefits of well developed riparian vegetation include buffering of surface generated nutrients, stabilization of stream banks and decreased sedimentation, provision of organic inputs, shading of water, and woody material recruitment (Rankin, 1995; Giller and Malmquist, 1998).	The width and quality of riparian areas across the CAWS has had no role in channel development. The maintenance of the channel for conveyance and navigation results in the removal of debris typically considered to be important to riparian habitat.
Bank Erosion	Bank erosion tends to be associated with riparian vegetation disturbance and erosion can contribute to sedimentation (Rankin, 1995; McMahon et al., 1996). Navigation generated sheer stress and wave action can increase bank erosion where bank stabilizing features are absent (Weigel et al., 2006). The adverse effects to biota from bank erosion are similar to those described for substrate and riparian conditions previously.	Bank erosion within the CAWS is generally limited because of the armoring and constructed nature of the system.
Flow/ Stream Gradient	Stream flow characteristics influence many aquatic habitat attributes (Rankin, 1995). Hill (Rankin, 1995), described four flow regimes that maintain physical and biological resources in stream systems: 1) flood flows, 2) overbank flows, 3) in channel flows for physical habitat function, and 4) in channel flows to meet biota requirements. Flows that are altered by anthropogenic means have been shown to strongly influence fish assemblages (Rankin, 1995). Systems regulated by locks and dams for navigation flows create impounded conditions that can favor lentic species (Sheehan and Rasmussen, 1999).	The flow and hydraulic gradient within the CAWS is controlled and regulated by the Lockport Powerhouse and Lock. The average hydraulic residence time within the CAWS is over 8 days, suggesting very low flow conditions.
Riffle-Run/ Pool-Glide Quality/ Characteristics	Geomorphic channel units (riffles, runs, pools, etc.) are fluvial habitat types that describe scouring, channel shape and overall habitat patterns in rivers and streams (Flotemersch et al., 2006). Lobb and Orth (Rankin, 1995) identified five guilds associated with large stream pool-riffle habitats that included 1) edge pool, 2) middle pool, 3) edge channel, 4) riffle, and 5) generalists. They suggest that the degradation of these habitats can eliminate or reduce the abundance of species within these guilds.	The constructed nature of the CAWS precludes the development of these fluvial habitat types.

The CAWS study area is entirely composed of nonwadeable (also called boatable) waters. Many management programs have avoided evaluating nonwadeable waters because of the logistical difficulties in monitoring large bodies of water. Numerous programs attempt to apply wadeable approaches to nonwadeable systems, and other programs eliminate certain quantitative measures in lieu of qualitative assessments (Flotemersch et al., 2006).

2.3 AVAILABLE APPROACHES FOR HABITAT ASSESSMENT

Most of the waterways in the CAWS are not rivers per se; they are large, nonwadeable, lotic waters. Because they are wide, deep channels conveying flowing water, they resemble large rivers. However, it is important to note that, most of the time, water moves through the CAWS at extremely low velocities, making them substantially different than natural rivers. However, the nearest analogies for studying such waters come from the study of large rivers and the scientific literature on the study of large rivers was reviewed for this study.

Several approaches are available for large river habitat assessment. The selection of an appropriate approach depends on the principle objective of the study, which is often either to conduct a thorough characterization of the physical habitat as a primary indicator of ecological condition or, when combined with biological surveys (as in this Study), to characterize those physical elements most likely contributing to the capacity of the system to support the survival and reproduction of biota (Flotemersch et al., 2006).

Most large rivers in North America have been modified to meet a range of anthropogenic uses and no single habitat evaluation approach is suitable for all large rivers because each is unique and heavily modified rivers contain a range of habitats not found in natural systems (Sheehan and Rasmussen, 1999). Flotemersch et al. (2006) provides a review of the major non-wadeable habitat assessment approaches in current use; these are summarized in Table 2-2. Screening of these approaches for use in this Study is discussed in the next section.

Table 2-2: Summary of Major Large River Habitat Assessment Protocols (Flotemersch et al., 2006)

Program	Protocol	Citation
Primary objective: characterizing long-term spatial and temporal patterns in habitat condition as its own independent indicator of ecosystem condition		
USEPA EMAP-Surface Waters	National and regional program for characterizing status and trends on ecological condition. Characterize seven general physical habitat attributes: channel dimensions, channel gradient, channel substrate size and type, habitat complexity and cover, riparian vegetation cover and structure, anthropogenic alterations, and channel-riparian interaction. Primarily quantitative measures.	Kaufmann, 2000
USGS NAWQA	National program to characterize water quality condition and develop an understanding of factors influencing quality. Quantitative measures taken to characterize habitat at 4 hierarchical scales: basin, segment, reach, and microhabitat	Fitzpatrick et al., 1998
Primary objective: evaluating habitat to understand biological condition		
Large River Bioassessment Protocol	Characterize 6 of 7 EMAP attributes: channel dimensions, channel substrate size and type, habitat complexity and cover, riparian vegetation cover and structure, anthropogenic alterations, and channel-riparian interaction. Reach length set to correspond to biotic assemblages being sampled. Semi-quantitative measures from six transects	Blocksom and Flotemersch, 2005; Flotemersch and Blocksom, 2005
Non-Wadeable Stream Habitat Index (NWHI)	A multi-metric index developed for characterizing habitat in Michigan non-wadeable streams and rivers. Features used in index include: riparian width, large woody debris, aquatic vegetation cover, sediment deposition, bank stability, substrate size, and off-channel habitat. Primarily quantitative measures.	Merritt et al., 2005; Wilhelm et al., 2005
Qualitative Habitat Evaluation Index (QHEI)	A multi-metric index developed for characterizing habitat in Ohio streams. Composed of six variables: substrate, in-stream cover, channel morphology, riparian zone and bank erosion, pool/glide and riffle/run quality, and gradient. Primarily qualitative scoring of metrics	Rankin, 1989

2.4 REVIEW AND SCREENING OF EXISTING INDICES

Relatively few habitat indices for large river systems have been developed due to the complex nature and sampling difficulties associated with the development and application of such indices (Wilhelm et al., 2005). The programs for which existing habitat indices were developed may have different objectives than the study at hand, resulting in an index that may not fit a particular application. When selecting an index for a particular purpose, there are several factors that should be taken into consideration. Some of these are identified below.

- ***Statistical basis for variable selection*** – Indices are developed by statistically referencing habitat variables against another variable set, such as biota. This is done to identify key habitat variables and to validate the index. The statistical basis for the index should be considered in determining whether its use is appropriate. For example, if the intent is to use the index to measure physical habitat to better manage fish, a habitat index that was developed by referencing fish data might be preferred.

- ***System basis for index development*** – Many indices are developed for a range of river types, from relatively unimpacted rivers to rivers that are heavily impacted by human activity. Many use indices rely on the relatively unimpacted rivers as reference reaches, which represent some desired condition.

- ***Variables included in the index*** – The variables included in a particular index should be examined to determine whether they are likely to provide an accurate measure of conditions within the system. If an index includes variables that are not appropriate for the system to be studied, the index may have limited utility in measuring variation throughout the system or over time.

- ***Quantitative vs. Qualitative Indices*** – Application of some indices relies on measured data, while some indices use more qualitative, subjective observations for scoring. Some use a mixture of measured data and observations. Because of the precision associated with measured data, it may be preferential to use a more quantitative index if field information is to be collected by many people and repeated over time for a system.

Using these considerations, each of the indices identified in the preceding section were reviewed to assess their applicability to the CAWS. A summary of the key qualities of these major large river habitat protocols was provided by Flotemersch et al. (2006) and is reproduced here as Table 2-3.

Table 2-3: Comparative Summary of Major Large River Habitat Assessment Protocols (Flotemersch et al., 2006)

		Protocol				
Category	**Variable**	USEPA EMAP	Large River Bioassessment Protocol (LR-BP)	MI Non-Wadeable Habitat Index	QHEI	USGS NAWQA
Quantitative		●		●		●
Semi- Quantitative			●			
Qualitative					●	
Anthropogenic Features		●	●			
Bank and Riparian		●	●	●	●	●
	Bank angle	●	●	●	●	●
	Bank height	●	●	●	●	●
	Riparian cond.	●	●	●	●	●
Geomorphology/Hydrology						
	Dimension	●		●	●	●
	Sinuosity				●	●
	Gradient	●	●	●	●	●
	Mean annual flow			●		●
	50% exc. flow			●		●
	Flow variability			●		●
	Off-channel habitat			●	●	
Overhanging/in-stream cover		●	●	●	●	●
	Aquatic vegetation	●	●	●	●	●
	Riparian cover	●	●	●	●	●
Sediment and substrate		●	●	●	●	●
Sediment and substrate	Size	●	●	●	●	
	Embeddedness	●	●	●	●	●
	Large woody debris	●	●	●	●	●
Water quality		●	●			
	Temperature	●				

After reviewing these habitat protocols, it was apparent that none of them were well-suited to the CAWS, for the reasons discussed in the following subsections.

2.4.1 Biotic Basis of Existing Protocols

Because one of the objectives of this Study was to determine what modifications to physical habitat in the CAWS would be required to improve aquatic habitat, use of a habitat evaluation protocol that was developed and validated for aquatic biota was important. Although all of the protocols reviewed here implicitly intend to evaluate habitat for aquatic biota, only the Ohio EPA Qualitative Habitat Evaluation Index

(Rankin, 2004) was found to explicitly reference fish in its development documentation (Rankin, 1989). No specific reference was found in the documentation of the USEPA EMAP (Kaufmann, 2000) or USGS NAWQA (Fitzpatrick et al., 1998) protocols. The large river bioassessment protocol (LR-BP) documentation (Blocksom and Flotemersch, 2005) references macroinvertebrates as the biotic basis, but not fish. The non-wadeable habitat index (NWHI) developed for Michigan (Wilhelm et al., 2005) was developed for fish but was statistically referenced to disturbance gradients in the selection of habitat variables and in validation.

2.4.2 System Basis of Existing Protocols

All of the habitat protocols reviewed for this Study were developed for rivers, using data from natural rivers. Although the documentation for some of the protocols discusses the fact that some of the systems used were modified by human activity, no reference was found to the inclusion of completely manmade channels, such as those that comprise approximately 75% of the CAWS. Rankin (1995) stated that indices need to be regionally calibrated, suggesting the importance of including local conditions in the selection or development of index protocols.

2.4.3 Variables Included in Existing Protocols

Many of the variables used in the existing protocols, including some of those listed in Table 2-3, are simply not applicable to a system like the CAWS, which was constructed largely for effluent conveyance and navigation and will continue to be operated for those purposes. Examples of the variables used in the existing protocols that are not useful in characterizing habitat in the CAWS include the following:

- Sinuosity is included in both the QHEI and the USGS NAWQA protocol, but sinuosity has either been intentionally removed from CAWS reaches or was never there to begin with, by design, to facilitate navigation and improve efficiency of effluent conveyance.

- Gradient is considered in all five of the protocols reviewed, but hydraulic gradient is controlled by downstream control works to maintain navigation and prepare the system for influxes of urban stormwater inputs, rather than by the centerline slope of the channel bed.

- Large woody debris is included in all five of the protocols reviewed, but it is deliberately removed from many areas in the CAWS to eliminate navigation hazards and provide unimpeded flows for effluent discharges.

- Embeddedness is included in the NWHI, LR-BP, and QHEI, but it is not applicable in the CAWS because the channels of the CAWS are not gravel-bed streams. Furthermore, the only major input of sediment to the system is relatively fine suspended sediment carried by storm water, which results in a substrate environment dominated by fine sediments deposited on bedrock or cohesive clay (glacial till).

All of the protocols reviewed include more than one key variable that is not useful in measuring habitat variation in the CAWS, because of the near complete absence of those variables. Because this relied on the statistical comparison of habitat data with fish data using multiple linear regression to identify the habitat variables most significantly related to fisheries condition, habitat attributes that do not exhibit significant variation were not useful. This is a significant consideration in the use of these protocols on the CAWS. However, it is important to note that the near complete absence of habitat qualities like sinuosity or large woody debris is a significant habitat limitation in the CAWS.

2.4.4 Qualitative Nature of Existing Protocols

In general, a quantitative protocol was desired for this Study because of the desire to use the protocol to measure differences in a system that may not exhibit as much variation as a natural system and to distinguish potential change after habitat improvement projects. Furthermore, a quantitative protocol would be more consistently applied by multiple personnel over multiple time periods and would be less likely to be criticized for subjectivity. Of the protocols reviewed, one is qualitative (QHEI) and two have both qualitative and quantitative elements (USEPA EMAP and LR-BP). NWHI and USGS NAWQA protocols are quantitative.

2.4.5 Summary of Existing Habitat Protocol Review

The protocol review factors discussed in the preceding sections are summarized in Table 2-4.

Table 2-4: Summary of Existing Habitat Protocol Review

	Protocol				
Review Factor	**USEPA EMAP**	**LR-BP**	**MI NWHI**	**QHEI**	**USGS NAWQA**
Developed using fish data?	Unknown	No	No	Yes	Unknown
Developed for manmade systems?	No	No	No	No	No
Include variables that are nearly constant in CAWS?	Yes	Yes	Yes	Yes	Yes
Quantitative	Yes	Semi	Yes	No	Yes

Based on this review, all five of the large river habitat protocols have qualities that argue against their use in the CAWS. While three of the five are quantitative, all of them include multiple variables that are not useful in quantifying habitat quality and variability in the CAWS. None of the protocols reviewed were reported to include manmade systems in their development. Only one of them, the QHEI, was reported to be referenced to fish data in its development. To date, the only habitat index known to have been applied to the CAWS is the QHEI (Rankin, 2004). However, the applicability of this index to the CAWS is poorly suited for the reasons outlined above.

Recent guidance from USEPA (Flotemersch et al., 2006) suggests that, although there is a lack of consensus of a single most suitable habitat approach for nonwadeable systems, the selected protocol should:

1. thoroughly characterize the physical habitat as the primary indicator of ecological condition;

2. characterize physical elements that most likely contribute to the capacity of a system to support survival and reproduction of its biota; or

3. present a compromise between the two.

As described previously, biotic assessments provide a direct measure of the biological condition relative to integrity and integrate effects of multiple stressors in space and time. The linkage between habitat, biota and other aquatic components are already well established in the literature.

For these reasons, a system-specific approach to evaluating habitat that includes biota in the CAWS as part of the analysis was developed and is described below.

2.5 METHODOLOGY USED IN THIS STUDY

One of the stated objectives of this Study was to evaluate physical habitat conditions in the CAWS using a multi-metric index. Review of existing protocols for large flowing waters revealed significant limitations of existing protocols for use in the CAWS. Therefore the decision was made to develop a system-specific index for physical habitat in the CAWS. While none of the existing indices reviewed were well suited to use on the CAWS, it was noted that the procedures used in development of the Michigan NWHI (Wilhelm et al., 2005) could be readily adapted to the CAWS, with some modification. The process is outlined below.

The NWHI process used a logical, stepwise methodology to systematically reduce the field of potential habitat variables, similar to the process used in other studies (Blocksom and Flotemersch, 2005; Fitzpatrick et al., 1998; Hall et al., 1999). This variable reduction and screening process involves the following major steps:

- Screening of variables using professional judgment, as well as knowledge of the system under study and the objectives of the Study. This judgment-based process can be used to weed out variables that might not be applicable due to system conditions or that may be inappropriate in light of study objectives.

- Correlation analysis to identify and eliminate variables that are statistically redundant with other variables, based on the available data. This step involves use of a statistical comparison of the data, typically using Pearson's correlation test or Spearman's rho. Spearman's is sometimes preferred for ecological data because it is non-parametric and does not depend on the distribution of the habitat data.

- Once redundant habitat variables are eliminated using correlation analysis, principal components analysis is used to identify which of the remaining variables explain most of the variance of the data from the system.

The variable reduction process results in a reduced set of habitat variables that explain most of the variability in the habitat data and are relatively independent from each other. This process does not necessarily indicate whether the retained variables are most closely related to dependent biotic variables such as fish metrics or a fish index of biological integrity.

Once the final list of habitat variables is determined, the data for these variables are compared to biotic data to determine which habitat variables explain most of the variation in the biotic data. In this Study, multiple linear regression was used to compare the habitat data to fish metrics derived from system data. For the multiple linear regression in this Study, data from 2001 to 2007 were used. Various permutations of physical habitat data were compared to fish data using this approach to answer specific questions and to provide as clear an understanding as possible about the importance of physical habitat in the CAWS. Using this approach, one or more of the regression equations derived from the multiple linear regression can then be compared to an independent dataset to validate the regression model. 2008 fish data were used for this purpose.

The equation derived from the multiple linear regression can be used directly as a habitat index tool or it can be used as the basis of a habitat index and amended by supplemental data analyses and professional judgment. Inclusion of habitat variables in a habitat index that are not included in the original regression equation has been done (Wilhelm et al., 2005) based on professional judgment and correlation to biotic data. This is an important aspect of the index development process, which allows for application of specific knowledge of the system. The process outlined above is depicted schematically in Figure 2-3 and discussed in detail in Section 6 of this report.

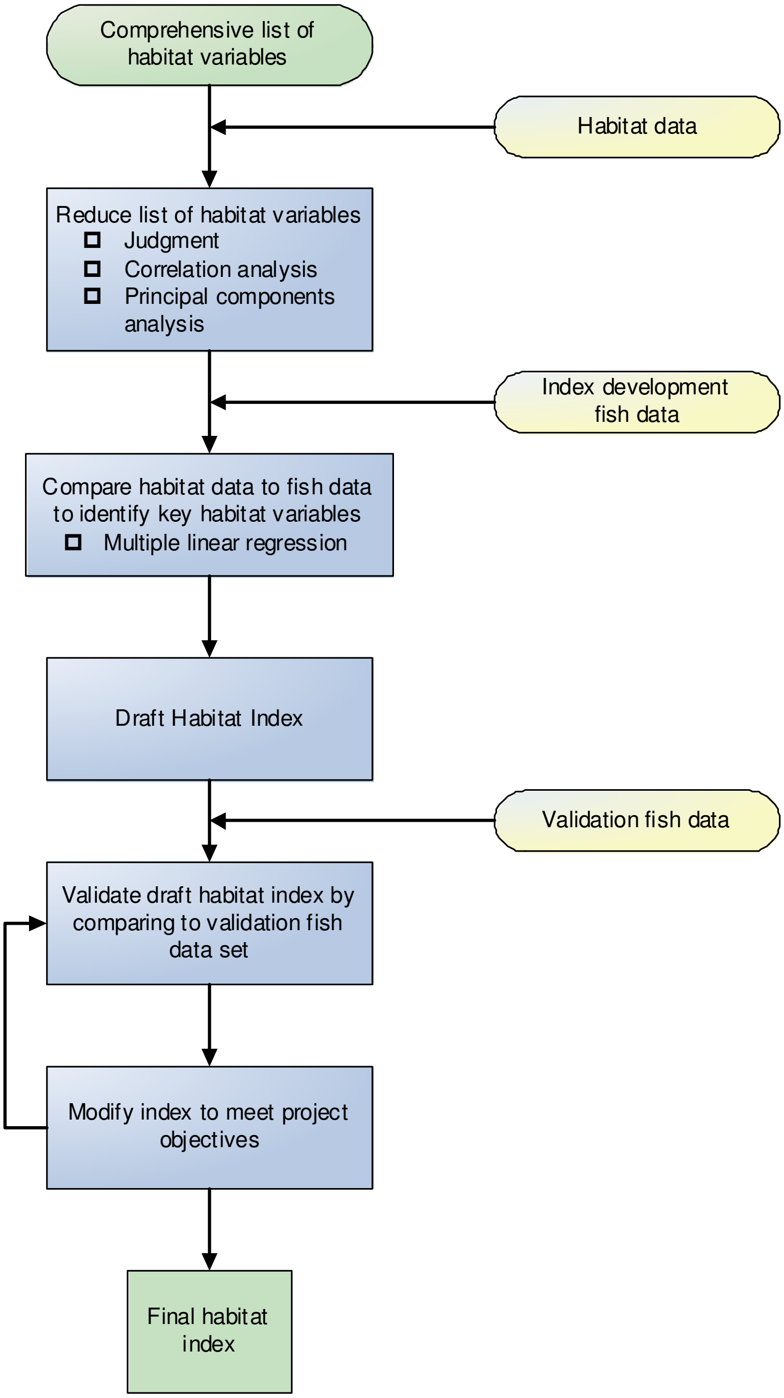

Figure 2-3: CAWS Habitat Index Development Process

2.5.1 Selection of Fish over Macroinvertebrates

Both fish and macroinvertebrate data have been collected by the District in the CAWS as part of the District's routine monitoring program. Each data set was evaluated to determine which dataset would provide the best response to habitat variables.

Flotemersch et al. (2006) states that the inclusion of macroinvertebrates into large river assessment programs is limited because of the general belief that macroinvertebrate assemblages are less diverse and more pollution tolerant in nonwadeable systems, primarily as a result of the dominance of fine sediments. Several other obstacles are cited including:

1. obtaining standardized and representative samples;
2. establishing a scale-appropriate and cost effective monitoring program;
3. identifying a reference condition given system alterations;
4. identifying specific stressors under the array of disturbances; and
5. the difficulty of sampling in navigable waterways.

An evaluation of the CAWS macroinvertebrate data was conducted to assess the structural and functional variation within the CAWS. The evaluations of the macroinvertebrate data collected by method (Hester-Dendy or ponar grab sampler), within stations, among stations, by reach or at a system level found similar results: a macroinvertebrate community dominated by pollution-tolerant taxa, represented by a few opportunistic Diperia (chironomidae) and non-insect taxa (oligochaetes) (Pott, 2009). These findings seem to support Blocksom and Flotemersch (2008) in that deep water habitats (>4 m) often have fewer sensitive taxa. Pott (2009) also suggests that legacy sediment contaminants may be affecting both sampling method results, although the Hester-Dendy samplers to a lesser degree are influenced by the high proportion of fine and resuspended sediments within the CAWS.

For the 2001-2007 analysis periods, the quantity and distribution of fish sampling events are approximately the same as macroinvertebrate sampling events. However, evaluation of the CAWS fish data found that this dataset varies more than the macroinvertebrate data, both spatially and temporally across the CAWS (Appendix A) and would likely provide a better indicator of habitat condition and response than the macroinvertebrates within the CAWS.

Fish assemblages are more commonly used in large river bioassessment programs than macroinvertebrates (Flotemersch et al., 2006). Data produced using appropriate fish sampling protocols can be used to assess use attainment, develop biological criteria, prioritize sample stations, provide impact assessments, and in status and trend analysis (Flotemersch et al., 2006). An assessment of the CAWS fish data (Appendix

A) finds a dataset with highly varied fish species and structure, which suggests that the CAWS fish dataset would be a better predictor of habitat responses than the macroinvertebrate data set. Based on this assessment, it was decided that the CAWS fish data would be used to assess the habitat index.

2.5.2 Development of Fish Metrics

Because the process for development of a system-specific habitat index for the CAWS required comparison to fish data, as described above, it was necessary to determine which metrics of fish would be appropriate for this purpose. While there is an Illinois index of biological integrity (IBI) for fish, it has some of the same limitations as the habitat indices reviewed for this Study, namely that it was developed for wadeable systems and may include metrics that are not applicable to the CAWS. So instead of using an existing fish IBI, CAWS fish data were used to identify the most representative fish metrics for the system.

The process of reviewing and screening the fish metrics followed the process used in development of many fish IBIs. Fish data collected by the District between 2001 and 2007 were used. These data were collected from 23 stations in the CAWS and represented 113 separate sampling events. The process involved review of fish metrics starting with an initial list of 46 fish metrics, identified from existing fish IBIs and published literature. CAWS fish data were reviewed to identify any CAWS-specific metrics that should be included. The metrics were then sequentially reduced as follows:

- Elimination of metrics that had no data (zero values);
- Elimination of metrics with very low ranges (2 or fewer species identified for the metric);
- Elimination of redundant metrics (using Pearson correlation tests); and
- Selection of metrics exhibiting greater variation in the CAWS.

This process reduced the number of fish metrics from 46 to 12, as summarized in Table 2-5.

Table 2-5: Fish Metrics Used in This Study

Fish Metric	Metric Name	Ecological Function Category
%DELT_(n)	% Diseased or with eroded fins, lesions, or tumors	Abundance and condition metric (ACM)
CPUE	catch per unit effort	Abundance and condition metric (ACM)
%LTHPL_(n)	% lithophilic spawners by count	Reproductive function metric (RFM)
%INSCT_(n)	% insectivores by count	Trophic function metric (TFM)
%TC_(wt)	% top carnivores by weight	Trophic function metric (TFM)
PRTOL	proportion of Illinois tolerant species	Indicator species metric (ISM)
LITOT	IL ratio of non tolerant large-substrate spawners	Reproductive function metric (RFM)
NMIN	number of IL native minnow species	Species richness and composition metric (SRC)
NSUN	number of IL native sunfish species	Species richness and composition metric (SRC)
GEN	IL ratio of generalist feeders	Trophic function metric (TFM)
%INT_(n)	% intolerant species by count	Indicator species metric (ISM)
%MOD_(wt)	% moderately intolerant species by weight	Indicator species metric (ISM)

A report was prepared to document the process of fish metric review and selection for this Study and is included as Appendix A of this report.

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3. DATA SUMMARY

Several types of data from multiple sources were used in this Study. These data included biotic data, water quality data, and physical habitat data. The nature and sources of these data are described in this section.

3.1 PHYSICAL HABITAT DATA

Efforts were made to acquire existing data where they were available. In many cases, existing data were incomplete or required field verification. Some new habitat variables had not been previously measured in the CAWS. To supplement existing data and address the data needs of this Study, crews were mobilized to the CAWS in the summer of 2008 for purposes of data acquisition. These efforts included:

- Between April 27 and May 21, boat-mounted crews from LimnoTech spent a total of eight days completing a visual inspection of the entire CAWS Study area, approximately 78 miles of waterways. This effort included a continuous digital video survey of all bank and riparian areas in the CAWS. This provided digital documentation of the banks within the entire Study area for use and reference throughout the Study.

- Between July 15 and August 15, LimnoTech field crews spent a total of ten days collecting field observations and measurements of physical habitat conditions at 28 400-meter stations in the CAWS Study area. Descriptions of the data collected during this effort are included in the discussion below. During this period supplemental bathymetric surveying was also completed using acoustic Doppler current profiling (ADCP) equipment in the North Shore Channel and North Branch Chicago River, where existing bathymetric data were unavailable.

In total, LimnoTech crews spent 18 days on the CAWS collecting physical habitat data for this Study. Supplemental data were acquired from a variety of sources including the District, the U.S. Army Corps of Engineers Rock Island and Chicago Districts, the Illinois State Geological Survey, the United States Geological Survey, and the Northeastern Illinois Planning Commission. Physical habitat sampling stations are depicted in Figure 3-1.

Several types of physical habitat data from the CAWS were collected for use in this Study, falling into the following general categories:

- Bank and riparian condition

- In-Stream and Overhanging Cover

- Channel bed condition

- Hydrology
- Anthropogenic Factors

Each of these data categories is discussed in greater detail below.

3.1.1 Bank & Riparian Conditions

Data on bank and riparian condition in the CAWS were obtained mainly from five sources for this Study: District physical habitat assessment forms; geographic land use data; aerial photography; visual inspection from the water; and detailed stations surveys. Each of these is described in more detail below.

District Physical Habitat Assessments

District personnel routinely perform physical habitat assessments (PHAs) during water quality and biota sampling on the CAWS. These data are typically recorded on a form and kept on file. For this Study, the PHA data forms from 2001 to 2007 were reviewed and transcribed into electronic format for inclusion in the electronic project database. Bank and riparian information available from the PHA forms included canopy cover, shore cover, and riparian land use.

Geographic Land Use Data

Riparian land use data for the CAWS was obtained from the Northeastern Illinois Planning Commission's 1:24,000-Scale 2001 Land Use Inventory for Northeastern Illinois. Analysis of this data set involved using geographic information system (GIS) software to create a 50 meter buffer on either side of the CAWS and classifying 30 adjacent land use types as industrial, urban, open space, or water as described below:

- Industrial land use included manufacturing, warehousing, industrial parks, and infrastructure such as freeways and waste facilities.
- Urban land use included residential areas and light commercial such as retail centers and office buildings.
- Open space included golf courses, nature preserves, and similar open grassland or forested areas.
- Water category was included only to describe when a station’s edge met open water such as a ship slip or tributary.

The land use category with the greatest area within the buffer was then identified as the dominant land use and assigned a categorical number.

Figure 3-1: Habitat and Biota Sampling Stations in the CAWS.

Aerial Photography

Digital aerial photography (2005) was obtained from the Illinois Natural Resources Geospatial Data Clearinghouse of the Illinois State Geological Survey for the entire Study area. The digital aerial photography was imported into the project GIS and orthorectified with other spatial data. The aerial imagery was then visually inspected to provide supplemental information on riparian land use, riparian buffers, and open space. Percent of riparian vegetation was calculated in GIS by creating a 50 ft buffer adjacent to each station and expressing vegetated area as a percent of total area within the buffer. Aerial photography from 2005 was used to identify these vegetated areas. An example of the aerial photography used in this Study is provided in Figure 3-2.

Detailed Station Surveys

Detailed field surveys of 28 400 meter long sampling reaches were conducted during the 2008 field season to observe and quantify a range of bank and riparian conditions including the following:

- *Riparian vegetation* – The extent of riparian vegetation data for each of the 28 sampling stations was collected by measuring the length of vegetation on both banks of each 400 meter station reach. The types of riparian vegetation were not noted in the survey, but a continuous digital video record of both banks was recorded during the 2008 field season, which can be used to review the general vegetation types present along the CAWS.

- *Bank condition and angle* – Bank condition was recorded by type (earth, riprap, sheet pile, etc.) and the estimated bank angle was determined for each side of the reach (banks flatter than 45 degrees were assigned a value of one and banks steeper than 45 degrees were assigned a value of 2).

- *Overhanging vegetation* – Overhanging vegetation was determined at each station by measuring the length of the vegetated bank and the depth of overhang. The area of overhanging vegetation was calculated as the product of these measurements and expressed as a percentage of the total area of the station reach.

- *Bank pocket areas* – The number of small pocket areas in the banks that could provide refuge for fish was counted in each reach. This attribute represents concave, semi-sheltered portions of the bank with an overall face area (height x width) of at least one square meter, but less than five square meters, and a depth greater than a few inches.

- *Off-channel bays* – Very few true off-channel bays exist in the CAWS, but there are areas that are partially or fully secluded from the main channel that can perform the same function as off-channel bays by providing refuge for fish. These areas were counted in each sampling reach if they were greater than five square meters in plan area.

Some of these habitat attributes were supplemented by system-wide review as described below.

Visual Inspection of Bank and Riparian Conditions

As mentioned previously, a digital video survey of the entire CAWS Study area was conducted in 2008. Map-based viewing software was developed to facilitate use of the video. The video was subsequently inspected to classify and quantify bank conditions throughout the system. The entire length of both banks of the waterways was classified using 8 categories: steel sheet pile, concrete wall, stone block or bedrock wall, wooden walls, riprap, "natural" bank (earth bank with vegetation), marina (open marina or boat dock), and water (turning basin or tributary confluence).

A GIS shapefile of bank condition for the entire system was created from this visual record. Measurements in each category were expressed as a percentage of the total bank length at each station.

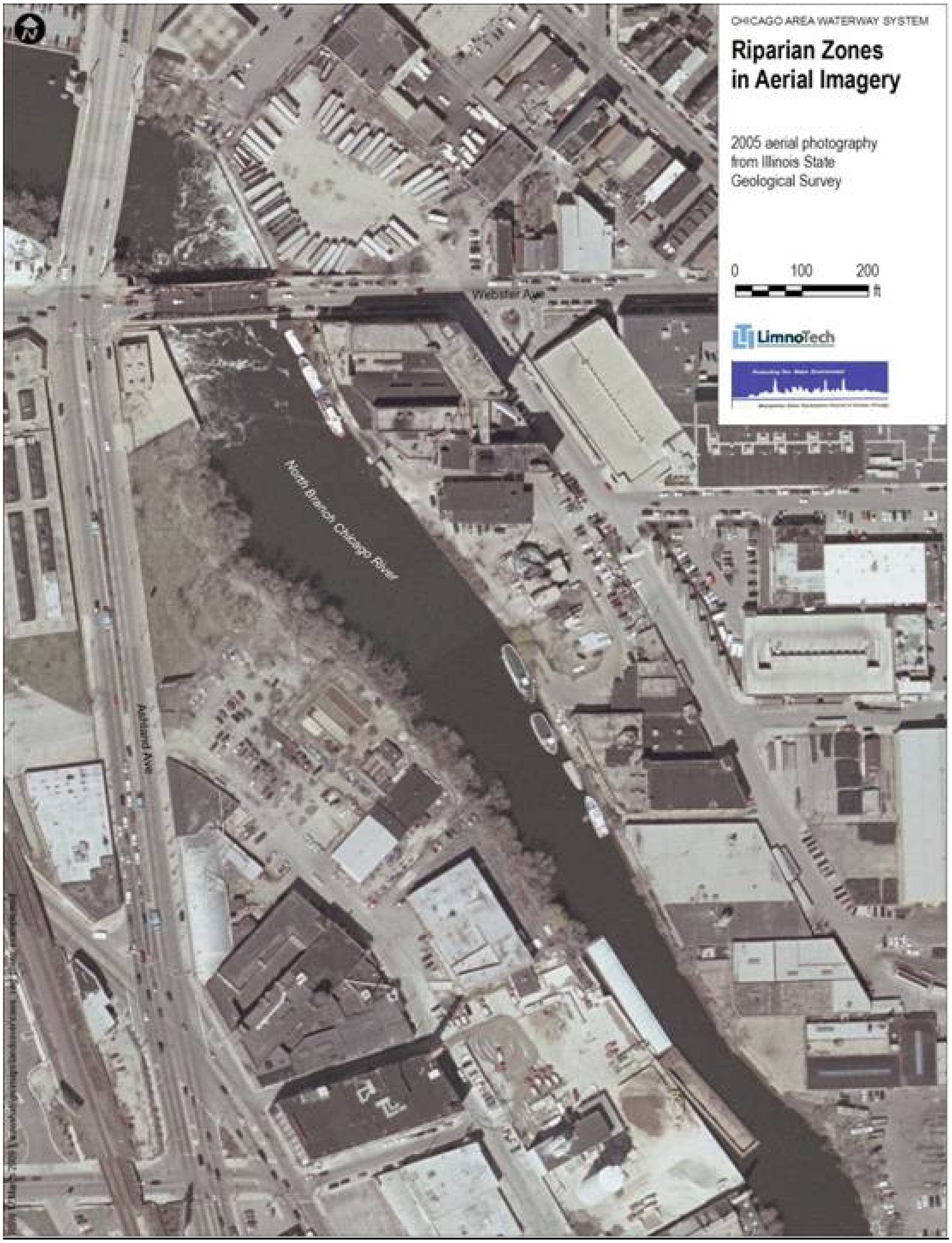

Figure 3-2: Example of Aerial Photography Used in the CAWS Habitat Evaluation and Improvement Study (Note: This figure shows the Webster Avenue Aeration Station in operation).

3.1.2 In-Stream and Overhanging Cover

In-stream and overhanging cover habitat within the CAWS was measured in the field at 28 stations during the 2008 field season. The parameters measured are described below.

Aquatic Vegetation

Aquatic vegetation was measured by direct visual observation by boat-mounted observers. Parameters measured included the following:

- Aquatic vegetation types – the number of different aquatic plant types observed in each 400-meter reach was recorded.

- Average macrophyte coverage – Macrophyte coverage (percent) was measured within representative 6-meter square field plots (minimum one per bank) within each station.

Coverage of each specific macrophyte type was not measured.

Secchi Depth

Secchi depth was measured using a standard Secchi disc at a minimum of three locations within each station.

Overhanging Cover

Depth (extent over water) and length (along banks) of shade cover were measured over the entire length of each bank within each of the 28 stations. Depth measurements were averaged for each reach based on discrete field measurements. Field measurements of channel width in each station were also collected for comparison to GIS-based width measurements and percent cover over the station reach was calculated using both field-measured channel width and GIS-measured channel width.

Submerged In-Stream Structure

Submerged in-stream structure that could provide cover for fish was not fully evaluated in this study because the high turbidity in most of the system prevented visual observation of conditions more than a meter below the surface. In efforts to overcome this limitation, two technologies were attempted in this Study: underwater digital video and side scan sonar. If successful, the imagery produced by these technologies would provide potentially valuable information on subsurface conditions, such as direct observation of submerged structures.

Underwater digital video was attempted at several locations in the system, but in reaches outside of the Chicago River, visibility was limited to less than 0.5 meter, making this technology impractical for use in the CAWS.

Side scan sonar was pilot tested at four reaches in the CAWS and although it showed promise in revealing subsurface structure and bed conditions, it was determined that the amount of data that would be required to validate the technology in the CAWS was not available and could not be practically collected within the timeframe of the Study. An example of the side scan sonar imagery from the CAWS is shown in Figure 3-3.

3.1.3 Channel Bed Conditions

Direct observation of bed conditions is not possible in the CAWS because of the depth and turbidity of the water. For this Study, information on bed conditions, including bathymetry and substrate size, was obtained from sediment grab samples and from electronic bathymetric surveys, as described below.

Bathymetry

Detailed bathymetric data for much of the CAWS were obtained from the Rock Island District of the U.S. Army Corps of Engineers (USACE), which has jurisdiction of the CAWS south of the Chicago River[1]. Bathymetric data were also obtained from the Illinois office of the U.S. Geological Survey (USGS). All bathymetry measurements were taken between 2001 and 2008. Soundings were used to generate a triangular irregular network (TIN) representation of bathymetry throughout the CAWS. Transects at upstream, center, and downstream locations for each station were sampled from the TIN. The Lockport normal pool elevation of 577.48 ft (NGVD 29) was applied as the water level for these stations. Figure 3-4 shows the extent of the various types of bathymetry used in this Study. Digital bathymetric data were imported into the project GIS for ease of use (Figure 3-5).

No digital survey data were available for the Chicago River and reaches north thereof, so LimnoTech conducted bathymetric surveys of sampling station reaches using a boat-mounted acoustic Doppler current profiler (ADCP) in July 2008, which provided accurate bathymetric measurements at the sampling stations. Depth soundings from the National Oceanic and Atmospheric Administration (NOAA) were used to extrapolate the ADP across the reaches as necessary.

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[1] The Chicago District of the US Army Corps of Engineers has jurisdiction of the CAWS north of the Chicago River. Although the Chicago District confirmed that recent bathymetric data had been collected from their portion of the CAWS, the Chicago District denied LimnoTech's request for the data, stating that the data are provisional.

Figure 3-3: Example of Side Scan Sonar Imagery from the CAWS, Overlain on Aerial Imagery (Imagery Collected in Upper North Branch of the Chicago River).

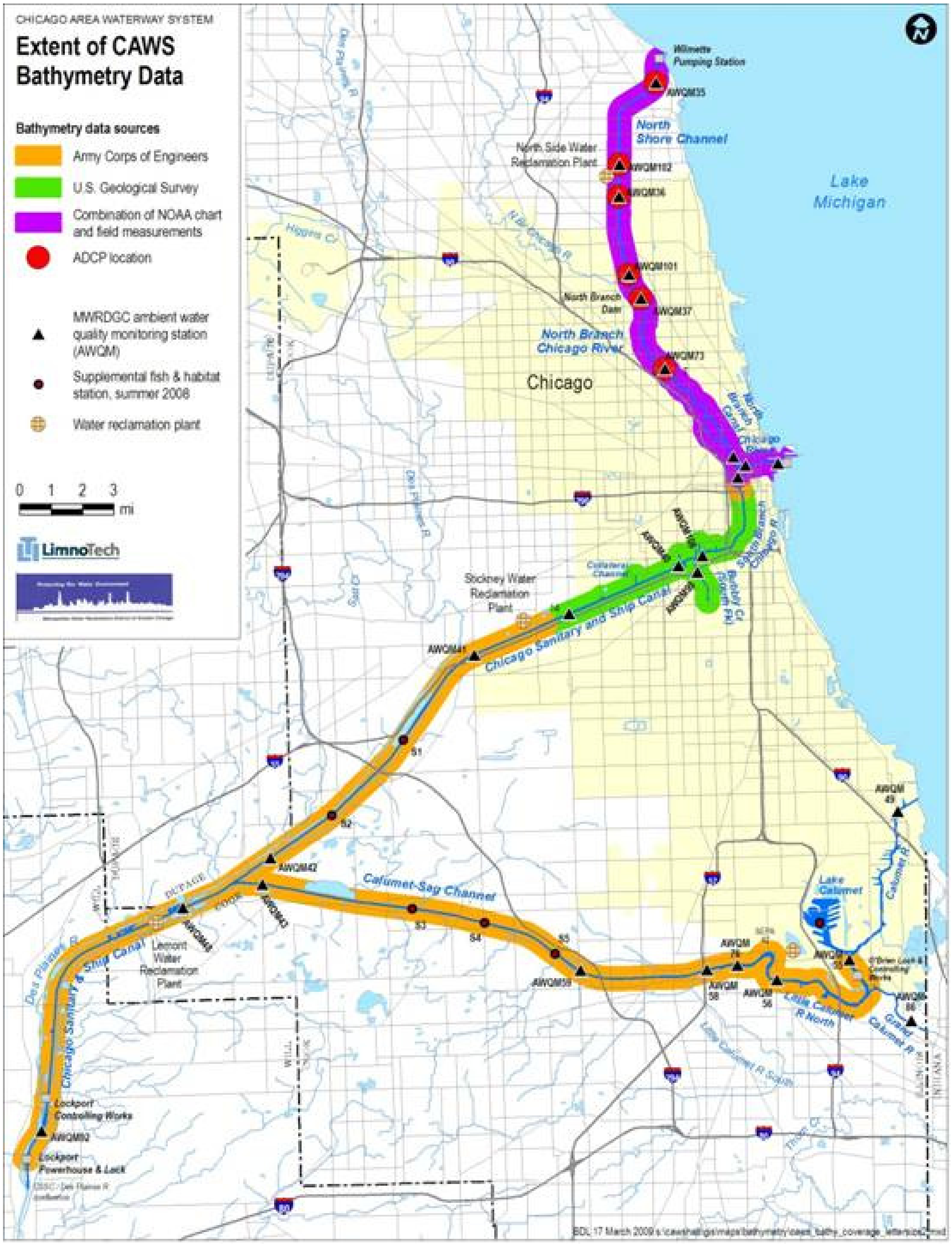

Figure 3-4: Bathymetric Data Used in the CAWS Habitat Evaluation and Improvement Study.

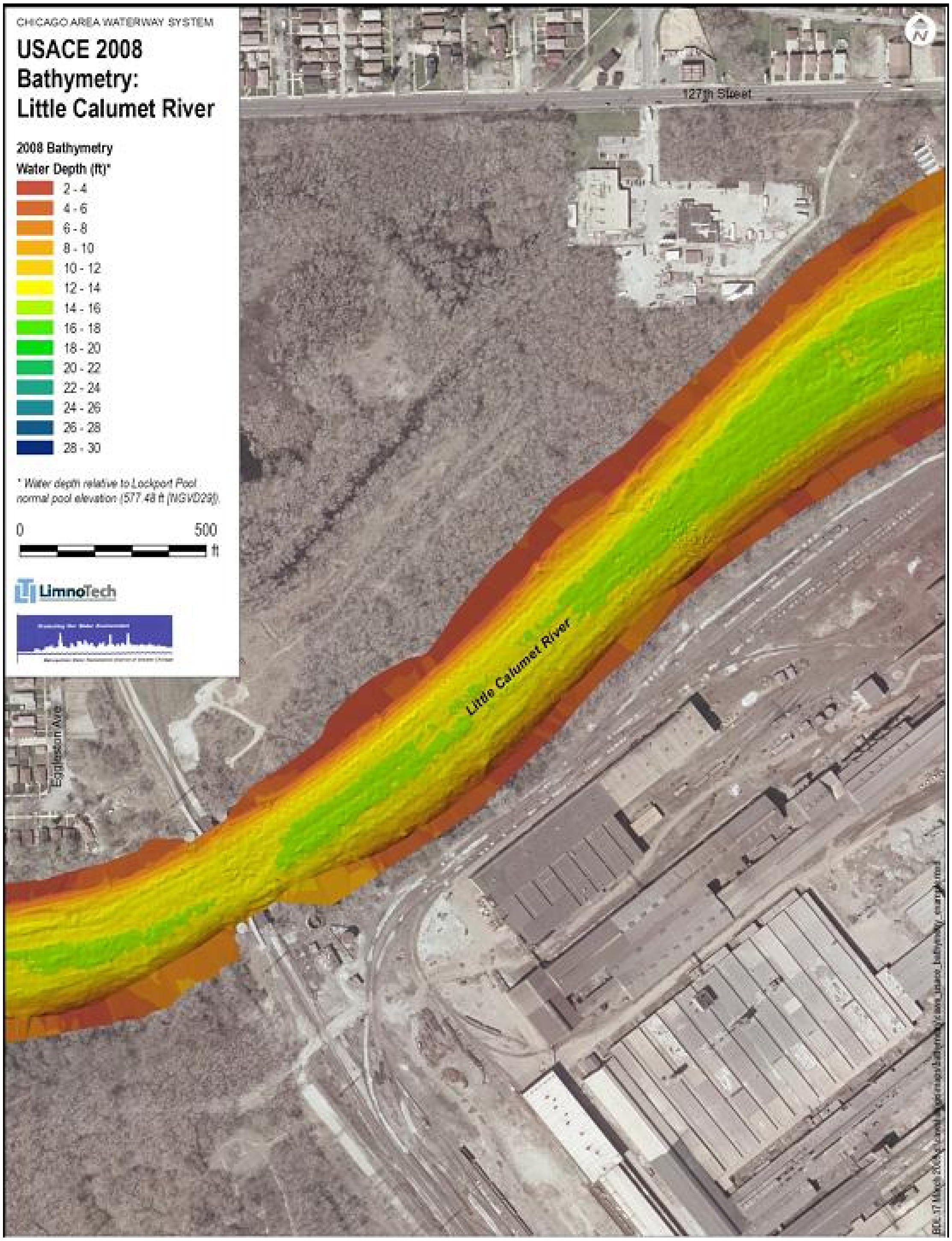

Figure 3-5: Example of CAWS Bathymetric Data in GIS.

Once data to describe bathymetry at each station was assembled, channel transects were used to develop the following geomorphology variables; average depth, maximum depth, top width, bottom width (width at 85% of the maximum depth), cross-sectional area, wetted perimeter, hydraulic radius, ratio of top width to bottom width, and ratio of top width to average depth. These variables were averaged over the three transects at stations with detailed bathymetric data.

Substrate

Physical sediment characterization in the CAWS bed conditions is routinely performed by the District as part of the physical habitat assessment portion of the ambient water quality monitoring (AWQM) program. This involves use of a 6 in. x 6 in. petite ponar dredge to obtain a sediment grab sample at mid-channel and side-channel locations at both the upstream and downstream ends of each station. Samples are characterized by estimating percent composition of the following:

- plant debris
- organic sludge
- inorganic silt
- clay
- sand
- gravel
- cobble
- boulder
- bedrock/concrete (hardpan)

In addition, depth of fines is measured using a one-inch diameter fiberglass leveling rod pushed as far as possible into the bed sediment. Since 2002, the District has conducted these assessments at 23 locations in the CAWS. Eight of these locations have been assessed annually, while the rest have been assessed once every four years. In 2008, LimnoTech performed additional physical sediment characterization at five supplemental stations as part of this Study.

The physical sediment data gathered by the District were used to develop twelve sediment and substrate variables. The plant debris, inorganic silt, and organic sludge parameters were averaged over the four sites assessed at each station and averaged over all years with available data. The rest of the sediment types were handled by keeping the mid-channel and side-channel assessment sites separate. These samples were considered to be deep substrate and shallow substrate, respectively. The bedrock/concrete parameter was averaged over these respective sites and over time to create percent hardpan-deep and percent hardpan-shallow variables for each station.

Sand and clay parameters were added together and averaged to create percent sand and fines-deep and percent sand and fines-shallow variables. Gravel, cobble, and boulder parameters were added together and averaged over assessment sites and time to create deep and shallow variables representing large substrate.

3.1.4 Hydrology

Flow data in the CAWS is recorded by USGS gaging stations located downstream from each of the three major diversion control structures. The North Shore Channel station at Wilmette monitored daily discharge from 1996 to 2003. The Chicago River station at Columbus Drive provided periodic discharge data with a continuous daily period of record in water year 2006. The Calumet River station downstream of the O'Brien Lock monitored daily discharge from 1996 to 2003. Flow was also monitored at the downstream end of the system at Romeoville Road, upstream of the Lockport Controlling Works. This location provided flow data from 1984 to 2005 but has been replaced by a station near Lemont, IL. The Lemont gage is currently the main data source for monitoring the Lake Michigan diversion, with daily discharge data available from 2004 to the present. Gaging stations also exist on several major tributaries to the CAWS. The gage data are useful for describing hydrologic conditions at a few locations, but cannot provide detail for individual AWQM stations.

The USGS gages operated at various locations in the CAWS were not well-located to provide hydrologic data at the habitat and biota sampling stations used in this Study, nor were they operated concurrently with all the years of data used in this Study (2001-2008). As an alternative for attributing flow and velocity variables to individual AWQM stations in this Study, output from a calibrated hydraulic model was used. In 2000, the District entered into an agreement with Marquette University to develop a hydraulics and water-quality simulation model to the CAWS. The model, called DUFLOW, has been used to investigate the effects of different management options in the CAWS. The model was calibrated and validated by the Institute for Urban Environmental Risk Management, Marquette University in 2003. Hourly stage measurements at the USGS Romeoville gage as well as the District hourly stage gages at Sag Junction, Willow Springs Road, and Western Avenue were used for hydraulic/ hydrologic calibration of the model. Model inflow is obtained from many different sources including USGS gage data at the three major inlets from Lake Michigan, as well as major tributaries. Operating records from water reclamation plants, pump stations and industrial sources were also used to calibrate the model. Additional ungaged tributaries and CSO sources were estimated.

The DUFLOW model divided the CAWS into 291 discrete segments. The segment nearest each AWQM station was selected to represent hourly flow and velocity output. Unsteady flow output from May 1, 2002 to September 23, 2002 was obtained and analyzed in order to develop variables which could capture spatial variability in flow and velocity. Six hydrologic variables were initially computed for the AWQM stations in the CAWS. Flow and velocity variables included:

- 50% exceedance flow
- mean annual discharge
- flashiness index (ratio of 10% exceedance flow to 90% exceedance flow)
- average velocity
- maximum velocity
- mean velocity to mean depth ratio.

The intent of both the flow and velocity variables was to measure magnitude regardless of flow direction. As the conditions in the CAWS cause occasional flow reversals, the model output for flow and velocity was handled using absolute values to prevent negative velocities from affecting the intent of the variables.

It should be noted that hydrologic parameters such as those listed above cannot be reliably estimated from a five-month modeling simulation. Such parameters usually require decades of data to quantify accurately. However, such data are not available for every monitoring location in the CAWS and the alternative to relying on the five-month modeling simulation was to exclude hydrologic variables altogether. For purposes of this study, it was deemed more useful to use approximations based on the model output than to move forward with the habitat analysis without any flow variables.

3.1.5 Anthropogenic Factors

Although not true physical habitat variables in the traditional sense, a number of anthropogenic factors were considered in this Study. This was deemed appropriate because of the constructed nature of the CAWS and the fact that the primary uses of the system (effluent conveyance, navigation, flood control) are anthropocentric. Some of these major anthropogenic factors are discussed below.

3.1.5.a Navigation

Navigation data for the CAWS is maintained by the U.S. Army Corps of Engineers (USACE) Waterborne Commerce Statistics Center. Vessel movements and commodity tonnages are reported by vessel operators to the USACE. Within the managed portion of the CAWS, vessel movements are summarized for each of 4 reaches:

- Chicago River & North Branch Chicago River (South of the North Branch Turning Basin)
- South Branch Chicago River
- Chicago Sanitary & Ship Canal
- Calumet-Sag Channel & Little Calumet River North

Detailed movements within these reaches are not available. The available data were compiled and analyzed by the Great Lakes Fishery Commission (GLFC) as part of a recent study on ecological separation of the Mississippi River and the Great Lakes (Brammeier et al., 2008). Several navigation metrics were obtained but for purposes of this Study it was decided to use two variables: through-upbound tonnage and through-downbound tonnage. These variables were reported in annual tonnages for 2001 through 2004. Because the goal was to have a relative measure of commercial navigation traffic, the variables were summed and assigned as a single variable in the database. All reaches within the managed portion of the CAWS without vessel tonnages reported were assumed to be free of heavy commercial traffic.

3.1.5.b Sediment Chemistry

Organic and inorganic sediment chemistry data on the CAWS have been collected by the District since 2002, with the exception of 2004. These data are for surface grab samples collected using a petite ponar dredge at the center and side of the 21 AWQM stations. Samples are typically analyzed for over 130 organic and inorganic parameters.

Sediment chemistry data on the CAWS were also obtained from the Great Lakes National Program Office (GLNPO) and the U.S. Army Corps of Engineers. GLNPO took sediment cores and grab samples at about 10 locations on the Chicago River, South Branch Chicago River, North Branch Chicago River, and South Fork in 2000. Samples were analyzed for about 60 parameters. USACE data covered about 18 locations on the South Fork in 2004 with sediment cores and grab samples. Samples were analyzed for about 165 parameters.

3.1.5.c Manmade Structures

Manmade structures (bridge abutments, dolphins, piers) can have both positive and negative impacts on aquatic life (Duffy-Anderson, et al. 2003). In some cases, these structures can provide shelter for fish or organisms on which fish feed. However, manmade structures are not usually built to serve the purpose of providing habitat and some other aquatic use is usually associated with them, such as navigation, transportation, and commerce. These other uses may have detrimental impact on aquatic life and if these impacts outweigh the benefits of the structures, the structures become an undesirable habitat attribute. The presence of manmade structures (Figure 3-6) in the channel in the channel was recorded at each sampling station in this study.

Figure 3-6: Examples of Manmade Structures (Dolphins) on the Chicago Sanitary and Ship Canal Near AWQM 41.

3.2 BIOTIC DATA

Biotic data used in this study included fish and macroinvertebrate data collected by the District between 2001 and 2008, as well as supplemental fish and macroinvertebrate data collected specifically for this Study in 2008. These data and their uses are discussed below. Sampling stations for biota are shown in Figure 3-1.

3.2.1 Fish Data

Fish data collected within the managed portion of the CAWS were collected using boat electrofishing procedures, because the system is almost entirely nonwadeable. Field procedures followed standard electrofishing protocol, using direct current shocking only, and only two netters collecting stunned fishes. Station sample lengths are 400 meters and include sampling primarily along the banks. Collected fishes are generally identified to species in the field, measured for length, and weighed. Each collected fish is also examined for disease, parasites or other anomalies and recorded where observed. All field identified fishes are then returned live to the waters. Minnows and other fishes that are not clearly identified in the field are preserved in 10 percent formalin and identified, weighed and measured in the lab.

The number of fish sample stations within the CAWS has varied by year for the 2001-2008 period. Table 3-1 describes fish sample locations, by date, within the CAWS. Twenty eight stations are included in the District sampling program, within the managed portion of the CAWS. In 2008, five supplemental stations were added to attempt to capture additional habitat variation in the system that may not be captured by the existing sample stations. The total number of sample station events during the 2001-2008 sample period totaled 101. The 2001-2007 fish dataset was used to build and assess the habitat index against (that is, to calibrate the index), while the 2008 dataset was used as the validation dataset.

Table 3-1: CAWS Fish Sampling Events Used in This Study

Station Description[2]	AWQM No.	2001	2002	2003	2004	2005	2006	2007	2008
NSC at Central Street	35	9/24/01				7/20/05			7/25/08
NSC at Touhy Avenue	36	9/26/01	7/31/02	7/24/03	9/29/04	7/21/05	7/10/06	7/12/07	11/6/08
NSC at Foster Avenue	101	9/27/01				9/8/05			7/25/08
NSC at Oakton Street	102	9/25/01				7/20/05			
NBCR at Wilson Ave	37	10/1/01				9/7/05			
NBCR at Diversey Pkwy	73	10/3/01				9/6/05			7/25/08
NBCR at Grand Avenue	46	10/2/01	8/1/02	7/23/03	8/27/04	7/18/05	7/11/06	7/11/07	11/5/08
LCR at Indiana Avenue	56			9/29/03				7/30/07	7/26/08
LCR at Halsted Street	76	9/12/01	9/16/02	9/29/03	9/30/04	9/27/05	7/21/06	7/31/07	10/28/08
CSC at Route 83	43			7/30/03				9/14/07	
CSC at Ashland Avenue	58			9/5/03				8/1/07	
CSC at Cicero Avenue	59	9/14/01	9/17/02	7/31/03	8/31/04	9/29/05	7/24/06	8/2/07	10/17/08
CR at Lake Shore Drive	74		8/2/02				7/26/06		
CR at Wells Street	100		8/21/02				7/27/06		7/24/08
SBCR at Madison St	39		8/27/02				7/28/06		
CSSC at Damen Ave	40		8/19/02				8/30/06		7/24/08
BC at Archer Avenue	99		8/20/02				9/5/06		7/24/08
SBCR at Loomis Street	108		8/26/02				9/12/06		
CSSC at Harlem Ave	41	9/7/01	9/3/02	7/21/03	8/24/04	8/26/05	8/21/06	7/16/07	10/29/08
CSSC at Route 83	42		8/28/02				8/31/06		
CSSC at Stephen Street	48		9/10/02				8/28/06		7/23/08
CSSC at Cicero Ave	75	9/4/01	8/29/02	7/18/03	8/23/04	8/22/05	8/29/06	7/17/07	10/29/08
CSSC at Lockport (16th St)	92	9/4/01	9/11/02	7/29/03	8/30/04	9/15/05	7/25/06	7/10/07	10/9/08
CSSC at Bedford Park	-								7/23/08
CSSC at Willow Springs	-								7/23/08
CSC at Palos Hills	-								7/17/08
CSC at Worth & Palos Hts	-								7/22/08
CSC at Alsip	-								7/26/08

3.2.2 Macroinvertebrate Data

Macroinvertebrate data collected within the CAWS were collected using two methods: artificial substrate samplers (Hester Dendys or HDs) and Ponar grab samplers. HDs were deployed at each station between May and June. Each station contains three side channel and three mid- channel HDs that are cabled to river anchors. HDs are deployed between 7 and 14 weeks. Retrieved HDs are collected using 250-micron mesh nets and HDs are stored in 10 percent formalin solution for

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[2] NSC = North Shore Channel; NBCR = North Branch Chicago River; SBCR = South Branch Chicago River; CSSC = Chicago Sanitary and Ship Canal; CSC = Cal-Sag Channel; CR = Chicago River; BC = Bubbly Creek; LCR = Little Calumet River

processing. Ponar samples were collected in triplicate at side and center locations at each station. Field samples are filtered through 250-micrometer sieve buckets and stored in 10 percent formalin solution for processing. A summary of the macroinvertebrate sampling events is presented in Table 3-2.

Table 3-2: CAWS Macroinvertebrate Sampling Events Used in This Study

Station Number	Station Description	2001	2002	2003	2004	2005	2006	2007
99	Bubbly Creek at Archer Avenue		X				X	
58	Calumet-Sag Channel at Ashland Avenue			X				X
59	Calumet-Sag Channel at Cicero Avenue	X	X	X	X	X	X	X
43	Calumet-Sag Channel at Route 83			X				X
74	Chicago River at Lake Shore Drive		X				X	
100	Chicago River at Wells Street		X				X	
75	Chicago Sanitary and Ship Canal at Cicero Avenue	X	X	X	X	X	X	X
40	Chicago Sanitary and Ship Canal at Damen Avenue		X				X	
41	Chicago Sanitary and Ship Canal at Harlem Avenue	X	X	X	X	X	X	X
92	Chicago Sanitary and Ship Canal at Lockport (16th St)	X	X	X	X	X	X	X
42	Chicago Sanitary and Ship Canal at Route 83		X				X	
48	Chicago Sanitary and Ship Canal at Stephen Street		X					
76	Little Calumet River at Halsted Street	X	X	X	X	X	X	X
56	Little Calumet River at Indiana Avenue			X				X
73	North Branch Chicago River at Diversey Parkway	X				X		
	North Branch Chicago River at Fullerton Avenue				X	X		
46	North Branch Chicago River at Grand Avenue	X	X	X	X	X	X	X
37	North Branch Chicago River at Wilson Avenue	X				X		
35	North Shore Channel at Central Street	X				X		
101	North Shore Channel at Foster Avenue	X				X		
102	North Shore Channel at Oakton Street	X				X		
36	North Shore Channel at Touhy Avenue	X	X	X	X	X	X	X
108	South Branch Chicago River at Loomis Street		X				X	
39	South Branch Chicago River at Madison Street		X				X	

Processing of macroinvertebrates in the laboratory varies by collection method. HDs are disassembled, cleaned and sieved through a 250-micrometer sieve. Side samples are combined as a single sample and mid-channel samples are combined as a single sample so each station is represented by a side and mid-channel HD sample. Ponar samples are further rinsed and screened in the laboratory using a 250-micrometer sieve, The triplicate samples are combined into a single side sample and a single mid-channel sample. All species identifications are made to the lowest practical taxonomic classification. Representative samples of chironomid head capsule deformities are determined as part of the standard procedures for the datasets.

Processed macroinvertebrate data were analyzed by Baetis, Inc., under subcontract to LimnoTech, and were used to select appropriate macroinvertebrate metrics for the CAWS, compare collection methods, and evaluate deformities as related to water quality and contaminated sediment (Appendix B).

3.3 WATER QUALITY DATA

The water quality data used in this Study consisted of data collected by the District between 2001 and 2007. The District's water quality data collection program in the CAWS includes continuous monitoring of certain parameters from several locations in the CAWS, as well as discrete sampling of water quality as part of their annual water quality monitoring program. These data collection programs are summarized below.

3.3.1 Continuous Monitoring Data

The District currently deploys continuous dissolved oxygen (DO) monitors at 33 locations in the CAWS. These monitors collect hourly data and are serviced on a weekly schedule. A detailed discussion of the continuous DO monitoring (CDOM) program is presented in Minarik et al. (2008). The DO data are collected throughout the CAWS by the District using automated data collection monitors manufactured by YSI Incorporated (YSI) of Yellow Springs, Ohio. DO is measured hourly using the YSI Model 6920 or Model 6600 monitor. For this Study, CDOM data from 23 stations in the CAWS, collected between 2001 and 2007 were used. The locations of these CDOM stations are shown in Figure 3-7. In addition to DO data, the District's CDOM program also collects continuous data on specific conductance, pH, and temperature.

Figure 3-7: Annual Water Quality Monitoring (AWQM) Stations and Continuous Dissolved Oxygen Monitoring (CDOM) Stations in the CAWS.

3.3.2 Annual Water Quality Monitoring

In addition to their CDOM program, the District also conducts an ambient water quality monitoring (AWQM) program. There are 26 AWQM stations in the CAWS, as depicted in Figure 3-1. Water quality is regularly sampled at these stations in accordance with the AWQM Quality Assurance Project Plan (District, 2007). Sampling is conducted on a monthly basis for most parameters. The water quality parameters sampled for the AWQM program include:

- Field-measured parameters (temperature, pH);
- DO
- Turbidity
- Total phosphorus and nitrogen compounds (nitrate/nitrite, ammonia nitrogen, total Kjeldahl nitrogen);
- Sulfate;
- Total dissolved solids, suspended solids, and volatile suspended solids;
- Alkalinity, chloride, and fluoride;
- Total organic carbon;
- Phenol;
- Cyanide;
- Indicator bacteria (fecal coliform and E. coli);
- Chlorophyll;
- Total and soluble metals (arsenic, barium, boron, cadmium, calcium, chromium, iron, lead, magnesium, manganese, mercury, nickel, selenium, silver, and zinc); and
- Volatile organic compounds (benzene, toluene, ethylbenzene, xylenes).

3.3.3 Use of Water Quality Data in this Study

Water quality data were used to evaluate the relationship between water quality and fish in the CAWS, separate from physical habitat. The report describing the analysis of fish and water quality in the CAWS is included as Appendix C. DO data were also used in conjunction with key physical habitat variables identified from multiple linear regression analysis of habitat data, to evaluate the degree to which water quality data helped explain variability in fish data over physical habitat data alone. These analyses are discussed in Section 6 of this report. The findings of the analysis of fish and water quality in the CAWS are presented below and described in more detail in Appendix C.

- *Fish metrics are positively correlated to dissolved oxygen, but dissolved oxygen is a poor predictor of fish metrics.* A few fish metrics showed statistically significant correlation to observed dissolved oxygen concentration, with higher dissolved oxygen concentrations resulting in slightly better metrics. This result does not necessarily indicate that oxygen concentrations are the primary factor controlling fish health. The statistical maxim "Correlation does not imply causation" applies here. Furthermore, the r-squared values between fish metrics and dissolved oxygen concentration are relatively low for the most part (i.e. generally less than 0.2). It should be noted that this finding does not necessarily indicate that oxygen concentrations are an unimportant predictor of fish health. The dissolved oxygen concentrations used in these regressions do not fully represent the historical exposure of the sampled fish to oxygen. Fish are mobile, and may be exposed to dissolved oxygen concentrations significantly different that the ones reflected at the oxygen monitoring location during the time of fish collection.

- *In terms of ability to explain fish data in the CAWS, compliance with new standards is similar to compliance with existing standards.* Fish metrics from observations where standards were being attained were generally better than fish metrics where standards were not in attainment, but most differences were not statistically significant. In addition, fish metrics showed a positive correlation to the percent of time that standards were attained at a station. These findings hold for both the current and proposed standards, although the current standards showed a higher number of significant differences than do the proposed standards. This may imply that compliance with new standards may not be as good a predictor of fish health as compliance with existing standards.

- *Some fish metrics are positively correlated to temperature, but more poorly than with dissolved oxygen.* Relatively few fish metrics showed statistically significant correlation to observed temperature data. Applying the proposed water quality standards for temperature to the 2001 – 2007 CDOM data set does not suggest that attainment of these proposed standards is a good indicator of fish health.

While no definitive statement can be made about causation from regression analysis, the weak correlations between fish metrics and dissolved oxygen indicate that incremental improvements in water quality alone may have, at best, a small benefit to fish if all other conditions affecting fish in the system remain unchanged.

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4. ASSESSMENT OF HABITAT CONDITIONS IN THE CAWS

The physical habitat data used in this Study, described in Section 3, were evaluated to develop an understanding of conditions in the CAWS. This section provides a summary description of the physical conditions in the CAWS that are relevant to the physical habitat evaluation of the CAWS, based on observations and the data described in Section 3. This section consists of three main subsections:

- Section 4.1 discusses physical habitat conditions in the CAWS from the perspective of traditional physical habitat variables.
- Section 4.2 describes navigation in the CAWs as a functional component of the system, its impact on aquatic life in general, and its critical role in impacting aquatic biota and habitat in the CAWS.
- Section 4.3 contrasts habitat conditions in the CAWS with natural rivers.

4.1 SUMMARY OF PHYSICAL HABITAT CONDITIONS

The discussion generally follows the essential habitat assessment index components suggested by Rankin (1995) and described in Section 2-2, with some modifications for the CAWS, as described in Table 4-1. It should be noted that some of the habitat attributes described in Table 4-1, such as bank erosion and riffle-run/pool-glide sequences, are important to habitat assessment in natural systems, but they not important to developing a habitat index for the CAWS because they are nearly constant or are entirely absent.

Table 4-1: Comparison of Rankin Habitat Assessment Components to CAWS Habitat Description

Essential Habitat Assessment Component Identified by Rankin	**Utility in CAWS Habitat Assessment**
Substrate type and quantity	Important in CAWS, discussed in Section 4.1; physical aspects of substrate are important in the CAWS, but chemical aspects are also important
In-stream physical structure and cover	Important in CAWS, discussed in Section 4.2
Channel structure/stability/modification	Important in CAWS, discussed in Section 4.3 as Channel Morphology; stability is not important as most of the CAWS are constructed and channelized, designed and maintained for stability
Riparian width/quality	Riparian condition is important in the CAWS, discussed in Section 4.4; width not as important due to heavy riparian development in many parts of the system
Bank Erosion	Not prevalent in the CAWS because flows are low and the system is managed to maintain stable channels, mostly through bank armoring, therefore not a useful differentiator within the CAWS.
Flow/stream gradient	Hydrology is considered, discussed in Section 4.5; due to the heavily regulated nature of flows in the CAWS this is less important than in a natural system, therefore not a useful differentiator within the CAWS.
Riffle-run/pool-glide quality/characteristics	Completely absent from the CAWS, which consists mainly of canals and straightened channels, therefore not a useful differentiator within the CAWS.

The relevant aspects of physical habitat in the CAWS are discussed in the following sections.

4.1.1 Substrate Type and Quality

Bed condition, as measured by substrate type and quality, is a valuable component of aquatic habitat because of its role in providing cover and spawning habitat. Its importance to aquatic life and a discussion of substrate conditions in the CAWS are presented below.

4.1.1.a Importance of Substrate to Aquatic Life

Substrate is a relatively complex aspect of the aquatic environment, including both mineral and organic materials forming the bottom of a water body (Allan, 1995; Armantrout, 1998). It essentially includes everything on the bottom or sides or projecting into a body of water, including human artifacts and debris (Allan, 1995). Substrate is of critical importance both directly and indirectly to aquatic biota. The surface layer of substrate is often rich in organic matter and can provide an important source of nutrients for organisms at the base of the food chain (Gordon et al., 2004). It provides habitat for most species at some point in their life history for activities such as resting and movement, reproduction and refuge as well as direct and indirect food availability (Giller and Malmquist, 1998). Species differ in their substrate association and preference requirements and the distribution and composition of sediment is an important physical factor influencing the distribution of organisms within aquatic systems (Gordon et al., 2004).

Substrate can be a repository for chemicals introduced into aquatic systems as a result of agriculture, industry, and other human activity. Although not typically considered a physical habitat attribute in natural systems, anthropogenic contamination of sediments can have a significant impact on aquatic life. Contaminants of concern in aquatic sediments range from heavy metals to organic chemicals. Although these contaminants may only be found at low concentrations in water, they often accumulate at elevated levels in sediments (MacDonald and Ingersol, 2002).

Both the physical and chemical characteristics of substrate are important. Aquatic organisms can be exposed to contaminated sediments throughout their lifecycles and through multiple pathways. Benthic macroinvertebrates live in the sediments and are directly exposed to contaminants (USEPA, 2008), usually through ingestion or absorption. Larger species may consume the contaminated benthic organisms. This allows the contaminant to move through the food web and upper trophic levels (Burton and Landrum, 2003). Fish can be exposed directly to sediments during nesting or foraging or they may consume macroinvertebrates and smaller fish that have been previously exposed to contaminants. Additionally, resuspension of contaminated sediments in the water column can occur after disturbances such as storms or boat propellers (USEPA, 2008).

Depending on the contaminant, a series of negative effects may occur. Some contaminants, if present at sufficiently high concentrations, can result in acute toxicity, where toxic levels are reached with only one exposure. Aquatic life can also experience chronic toxicity after prolonged exposures. Because direct exposure of macroinvertebrates is more common than direct exposure of fish, changes in macroinvertebrate populations may be observed due to sediment contamination. Most obvious effects are seen in benthic community structure changes (Burton and Landrum, 2003; MacDonald and Ingersol, 2002). Deformities, lesion, and tumors in fish have been observed to have higher incidences in areas with contaminated sediments (USEPA, 2008).

4.1.1.b Summary Description of Bed Condition in the CAWS

Substrate in the CAWS is dominated by fine sediments. In the deep parts of sampling stations, usually near the center of the reach, inorganic silt was recorded as the dominant substrate type in 16 out of 28 sampling stations (Figure 4-1)[3]. Only five stations (three in the North Shore Channel, one on the Little Calumet River, and the

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[3] The bar charts showing habitat variables in this section use colors to differentiate major reaches of the CAWS. The numbers at the bottom of the charts denote the sampling station identification numbers.

Harlem Avenue station of the CSSC) had sand as the dominant deep substrate, while two had organic sludge. The remaining five stations were found to be exposed to bedrock in the deep part of the reaches.

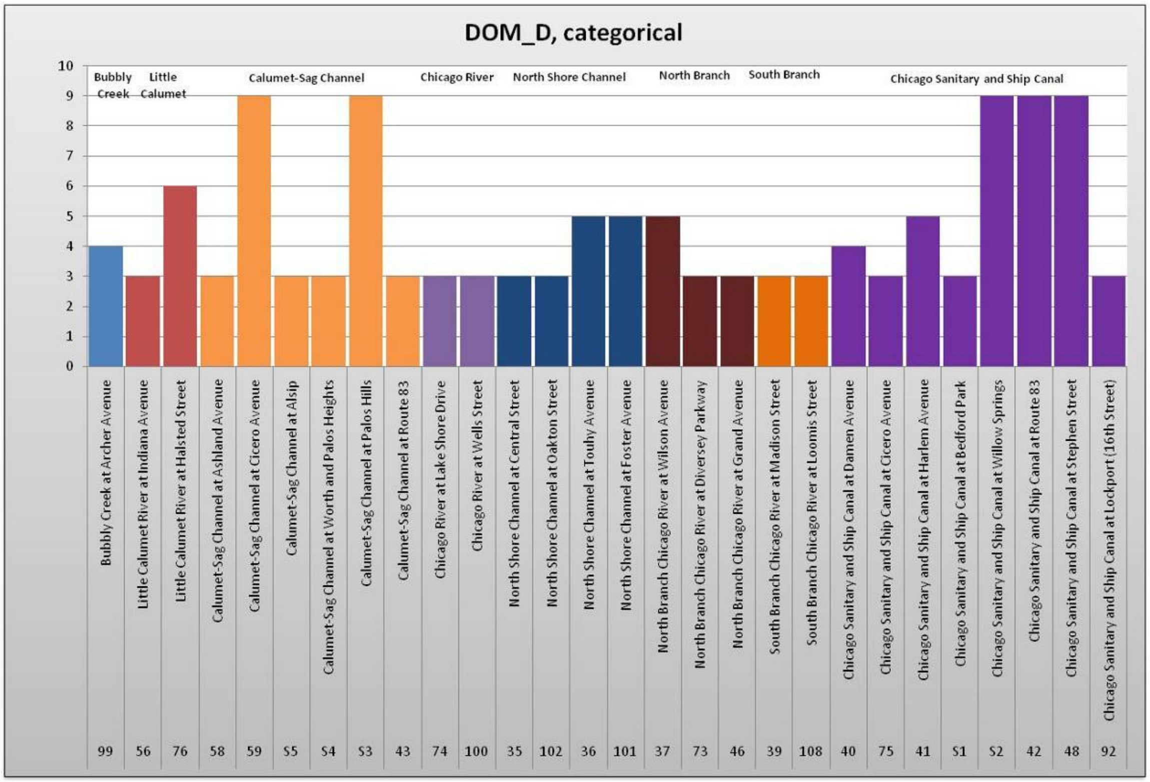

Figure 4-1: Dominant Deep Substrate (DOM_D) at CAWS Sampling Stations

(The y-axis corresponds to the variable: 1 = plant debris; 2 = clay; 3 = inorganic silt; 4 = organic sludge; 5 = sand; 6 = gravel; 7 = cobble; 8 = boulder; 9 = bedrock or hardpan; 10 = other)

Substrates in the shallower parts of the sampling reaches, nearer the sides of the channels, were slightly more varied but 14 sampling stations were found to be dominated by inorganic silts or organic sludge (Figure 4-2). Four stations had sand as the dominant shallow substrate, two had gravel, two had cobbles, and two had boulders. The remaining stations had bedrock or other hardpan beds. Where cobbles and boulders were encountered, they appeared to be remnants of failed riprap or stone walls that had collapsed into the channel.

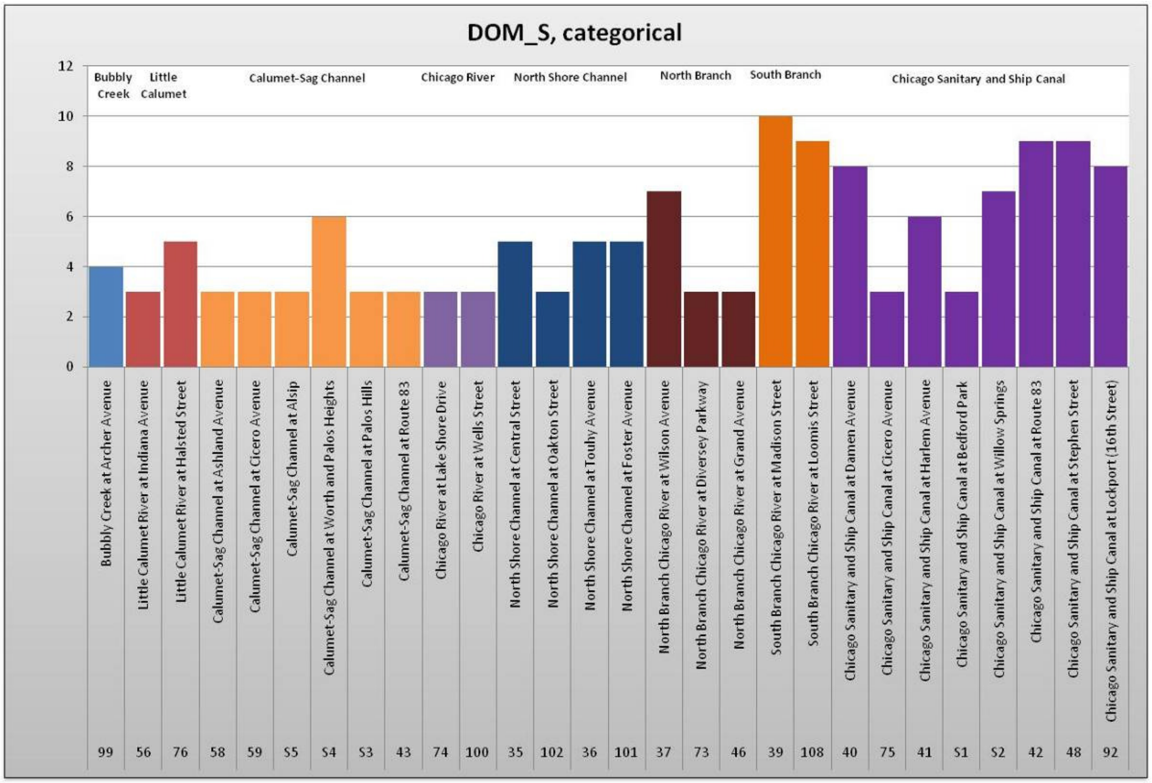

Figure 4-2: Dominant Shallow Substrate (DOM_S) at CAWS Sampling Stations

(The y-axis corresponds to the variable: 1 = plant debris; 2 = clay; 3 = inorganic silt; 4 = organic sludge; 5 = sand; 6 = gravel; 7 = cobble; 8 = boulder; 9 = bedrock or hardpan; 10 = other)

Sediment chemical data from the CAWS shows the presence of a wide range of chemicals throughout the system including pesticides, polychlorinated biphenyls (PCBs), and heavy metals. It was beyond the scope of this Study to comprehensively evaluate sediment chemistry in the CAWS, but the available sediment chemical data were compared to macroinvertebrate data collected from the CAWS. This comparison showed that many chemicals were significantly correlated with macroinvertebrate metrics ($p<0.05$) including the following:

- Several chemicals were inversely correlated with taxa richness in ponar samples including mercury ($r = -0.597$), cadmium ($r = -0.608$), chromium ($r = -0.548$), copper ($r = -0.565$), nickel ($r = -0.559$), lead ($r = -0.530$), zinc ($r = -0.524$), simultaneously extracted metals (SEM, $r = -0.630$), total PCBs ($r = -0.643$), and total semi-volatile organic compounds (SVOCs, $r = -0.548$).

- Cadmium ($r = -0.587$) and copper ($r = -0.530$) were correlated with Shannon diversity index in ponar samples.

- Cadmium ($r = -0.512$), SEM ($r = -0.565$), and total PCBs ($r = -0.570$) were correlated with Diptera richness in ponar samples.

- Several chemicals were positively correlated with the percentage of Oligochaeta in artificial substrate samples including cadmium (r = 0.593), chromium (r = 0.560), copper (r = 0.580), and nickel (r = 0.618).

- The percent of collector gatherers in artificial substrate samples was positively correlated with cadmium (r = 0.509), copper (r = 0.572), and nickel (r = 0.528).

- Functional feeding group diversity in ponar samples was inversely correlated with several chemicals including cadmium (r = -0.589), chromium (r = -0.537), copper (r = -0.541), nickel (r = -0.527), lead (r = -0.535), zinc (r = -0.530), simultaneously extracted metals (SEM, r = -0.655), total PCBs (r = -0.624), and total semi-volatile organic compounds (SVOCs, r = -0.519).

Data also show that mercury was significantly ($r = 0.659$; $p < 0.05$) correlated with head capsule deformities in macroinvertebrates collected using ponar samplers. These observations suggest that anthropogenic chemicals in CAWS sediments are affecting macroinvertebrate populations directly and suggest an indirect effect on fish as well. Based on these correlation analyses, three sediment chemical parameters were chosen for use in the habitat evaluation: cadmium concentration, total PCB concentration, and concentration of simultaneously extracted metals, which is a measure of the bioavailability of heavy metals in sediments.

4.1.1.c Sediment and Substrate Limitations in the CAWS

As described in Section 4.1.1, sediment and substrate is of critical importance both directly and indirectly to aquatic biota in natural systems. The sediment and substrate within the CAWS are generally dominated by exposed bedrock or fine materials. The fine materials include consolidated native soils into which some the channel were dug or fine sediment deposited in the system by urban runoff. The latter can be easily resuspended and redistributed. Table 4-2 describes some key habitat limitations in the CAWS, with respect to sediment and substrate, which likely limit the biotic potential of the fishery within the system.

Table 4-2: Habitat Limitations in the CAWS Related to Sediment and Substrate.

Sediment Feature	**CAWS habitat and Fisheries Response**
Suspended sediment	The CAWS is dominated by suspended sediments that result from a combination of urban surface runoff discharges, CSOs, treated discharges, and navigation resuspension. Sheehan and Rasmussen (1999) state that suspended solids have had a greater adverse influence on fish diversity and abundance in the Midwest than any other factor.
Sediment deposition	The channelized and flow regulated system has resulted in the settling and resuspension of fine sediments and subsequent deposition on surface materials. This has created a relatively homogenous condition that decreases habitat, favoring species adapted to a fine sediment environment (Wesche and Isaak, 1999).
Substrate Feature	**CAWS habitat and Fisheries Response**
Composition	Substrate in many parts of the CAWS consists of native hardpan or bedrock. The depositional environment created by the controlled flows has further resulted in surface layers within the systems that are dominated by fine sediments such as silt, clays and fine sands. Substrate is an important habitat feature for benthic organisms and those that rely on the benthos and the dominance of fine sediments across the system favors non-specialized omnivore species (Flotemersch et al., 2006; Rabeni and Jacobson, 1999).

Where large substrate (gravel, cobbles, boulders) are present in the CAWS, they appear to be important to fish. Future work in the CAWS should include collection of more data on large substrate and its importance to fish.

4.1.2 In-Stream and Overhanging Cover

Cover can be defined as structural material (e.g., boulders and woody debris), channel features (e.g. bank pockets, in-stream and overhead vegetation), water features (e.g., turbulence and depth), that provide protection for aquatic species from biotic and abiotic threats (Armantrout, 1998; Orth and White, 1999). It is an important aspect of physical habitat for aquatic fauna, particularly for fish.

4.1.2.a Importance of In-Stream and Overhanging Cover to Aquatic Life

The availability of cover is important for maintaining species and their various life stage components in inland waters. Cover significantly influences the composition, size, life stage and distribution of species within water bodies, although the community relationships are often complex (Bain and Stevenson, 1999). The most commonly used categories of cover include overhead bank cover, water depth, in-stream objects, and hydraulic features (Orth and White, 1999). Overhead cover includes stream bank and shoreline cover features such as riparian vegetation and woody debris which generally provide shallow water protective environments from predators and velocity as well as shading for thermal refuge. Deep waters can provide refuge for prey species from sight feeding fishes, thermal refuge during summer temperature peaks, and flow refuge for low velocity swimmers. In-stream cover includes course substrates, woody debris, emergent and submergent vegetation, and provides hiding cover, sources of food and reproductive features for a variety of species. Hydraulic features such as turbulent areas and off channel habitat can provide refuge from main channel velocities as well as serve as a source of protection from open water predators and reproductive protection from main channel flow dynamics.

4.1.2.b Summary Description of In-Stream and Overhanging Cover in the CAWS

Types of cover quantitatively evaluated in this Study include in-stream vegetation and overhanging riparian vegetation. As discussed in Section 3.1.2, in-stream submerged structure, other than macrophytes, was not measured in the CAWS because turbidity limited direct observation of submerged conditions. Side scan sonar was attempted and showed some promise, but the Study schedule did not allow for full characterization using this technology. In addition, qualitative notes on the presence and types of in-stream cover (woody debris, boulders, etc.) were available from District assessment forms. These observations were not quantified.

In-stream vegetation is limited in the CAWS; submerged aquatic macrophyte cover was non-existent at 19 of the 28 sampling stations surveyed in 2008. In fact, significant submerged aquatic macrophyte cover was only recorded in the North Shore Channel, four stations in the CSSC (Figure 4-3), the Little Calumet River, and one station in the Chicago River, near a marina. Emergent aquatic macrophytes were also measured by recording the number of different types in each station. These showed greater variety across the CAWS, but were not extensive in any areas and were limited to near-shore areas.

Percent overhanging canopy was also limited in the CAWS, although most reaches, with the exception of the Chicago River, had some overhanging canopy (Figure 4-4). Far more overhanging canopy was observed in the North Shore Channel than anywhere else and because this reach is the narrowest of the CAWS reaches, the percent of cover was much higher than any other reach.

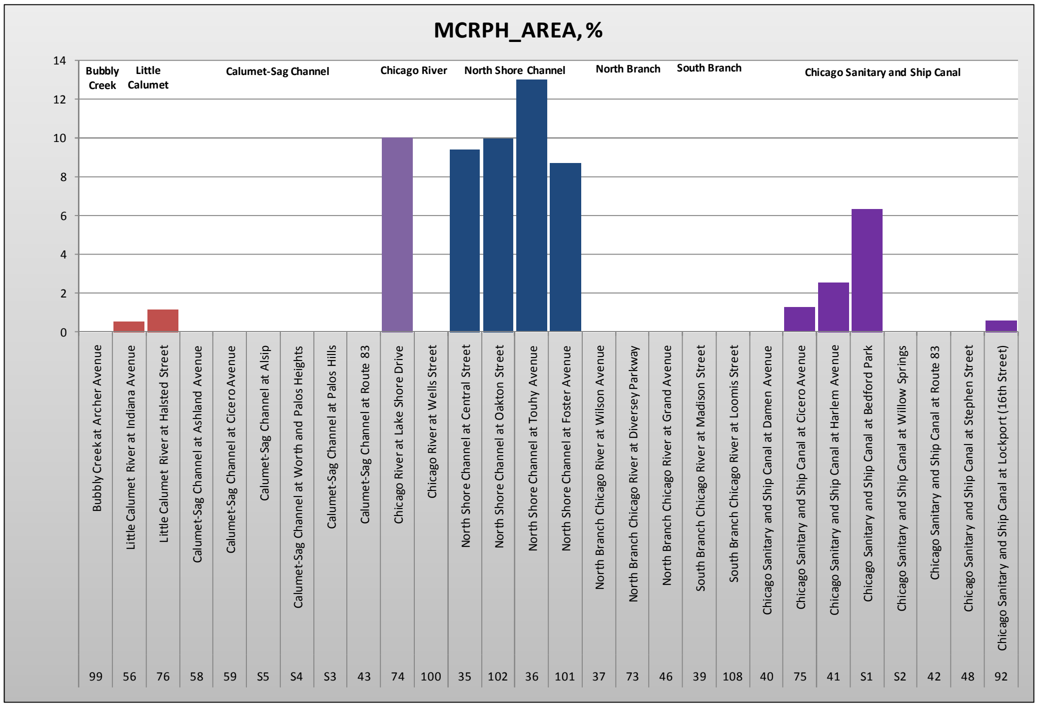

Figure 4-3: Submerged Aquatic Macrophyte Cover (%) in CAWS, 2008.

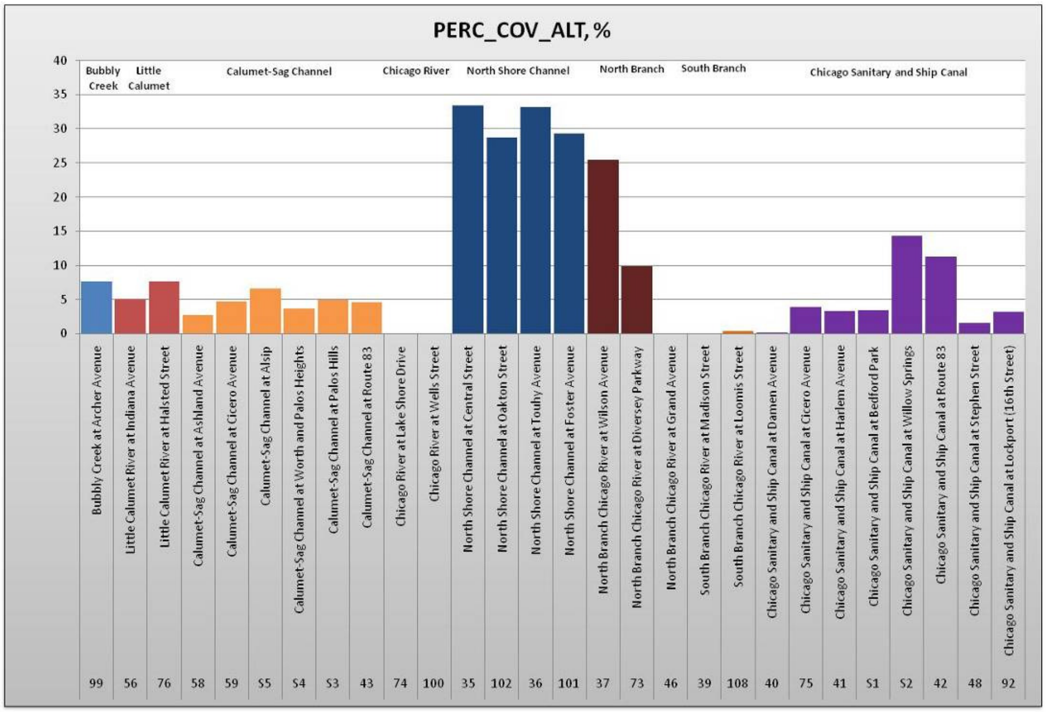

Figure 4-4: Overhanging Cover (%) in CAWS, 2008.

The limited in-stream and overhanging cover in the CAWS presents a challenge and an opportunity. The shortage of data poses a challenge for statistical analysis of physical habitat in the CAWS, but cover may be an attribute that can be improved in the CAWS.

4.1.2.c In-Stream and Overhanging Cover Limitations in the CAWS

In-stream and overhanging cover is important for maintaining species and their various life stage components in inland waters. As discussed in Section 4.2.1, cover significantly influences the composition, size, life stage and distribution of species within surface waters, although the community relationships are often complex (Bain and Stevenson, 1999). The design and maintenance of the CAWS for conveyance and navigation uses results in the management of the system for efficient flow transport and hazard free shipping traffic by removing obstructions of in-channel features. Table 4-3 describes some key habitat limitations in the CAWS with respect to cover.

Table 4-3: Habitat Limitations in the CAWS Related to In-Stream and Overhanging Cover.

In-stream Features	CAWS Habitat and Fisheries Response
Overhead cover	The available overhead cover within the CAWS is generally in the form of vegetation that has naturally developed along riparian areas. Some areas have large, well established portions of overhanging trees (e.g. North Shore Channel and the lower Cal-Sag). Generally, these features can provide shade from thermal inputs, habitat structure, and organic inputs for the fishery (Flotemersch et al., 2006).
In-stream vegetation	In-stream cover includes near-shore submerged and emergent aquatic vegetation that can provide essential littoral habitat. Within the CAWS, this form of in-stream cover is generally limited spatially because of the dominance of deep water (bank to bank) segments.
Water depth	Water depth is a direct result of the purposeful construction for either navigation (i.e., shallow draft or deep draft) or conveyance of effluent and flow controls within the system. The system is entirely non-wadeable. The depth, as a function of total volume, likely allows a dominance of fishes adapted to lentic water habitats and abundances greater than in rivers of greater channel diversity (Sheehan and Rasmussen, 1999).
In-stream structure	In-stream structure is limited in the CAWS. These features are generally considered obstructions to efficient flow conveyance or potential hazards to navigation traffic and are removed as part of channel maintenance procedures in large portions of the system. The absence of these in-channel features (e.g., root wads, snags, trees, etc.) likely affects the production potential for both macroinvertebrates and fish (Flotemersch et al., 2006) and results in a predominance of pelagic and transient species.
Hydraulic features	Some manmade features in the CAWS, such as SEPAs or pumped aeration stations may contribute to turbidity. Off channel habitats are rare and exist in the form of constructed dead-end canals (e.g., barge storage areas), areas within the few turning basins, and the limited number of fish passable tributaries within the system. The general lack of these features across the systems likely favors pelagic and transient species and limits refuge to support a more diverse fish community.

4.1.3 Channel Morphology

Channel morphology refers to the physical structure and shape of a waterway at a range of scales. In natural rivers, these qualities are referred to as fluvial geomorphology, but this term is not applicable in the CAWS because of its constructed and modified condition. Channel morphology in the CAWS differs dramatically from natural waterways. Neither the cross-sectional shape of CAWS channels nor their plan forms are similar to natural streams and rivers. This can have significant impacts on aquatic life, as discussed below.

4.1.3.a Importance of Channel Morphology to Aquatic Life

The importance of channel morphology to aquatic life has been recognized by ecological and fisheries professionals for decades (Edwards et al., 1984; Resh et al., 1988; Orth and White, 1999). Natural rivers and streams have sinuous plan forms that have evolved, and continue to evolve, through a balance of the sediment mobilization and transport capabilities of the flowing water and the geological materials that form their bed and banks. Straightening of natural channels reduces longitudinal and lateral variations in velocity within the channel, which reduces the variability of sediment erosion and deposition patterns. This variability is important as different aquatic fauna require variations in substrate for breeding, foraging, and refuge. As stated in Orth and White (1999):

> “Channelization creates unfavorable stream habitat…stream straightening results in loss of important fish habitat features associated with natural meandering and pool-riffle patterns…As a consequence, habitat diversity is reduced…Abundance of sport fish can be 8 – 10 times greater in natural channels than in channelized parts of the same stream.”

Large sections of the CAWS were intentionally constructed with straight, uniform channels and other sections were intentionally straightened and dredged. In light of the above discussion, the relevance of this aspect of the CAWS with respect to fisheries is apparent.

4.1.3.b Summary Description of Channel Morphology in the CAWS

Channelization, involving straightening, widening, deepening, and armoring or walling of banks, is the major factor affecting channel morphology in the CAWS. In the CAWS, channels are very straight. The calculated sinuosity of the major CAWS reaches are summarized in Table 4-4.

Table 4-4: Summary of Reach Sinuosity in the CAWS

Reach	Length (mi)	Sinuosity
North Shore Channel	7.7	1.08
North Branch Chicago River	7.8	1.13
Chicago River	1.6	1.03
South Branch Chicago River	4.6	1.25
Bubbly Creek	1.5	1.06
Chicago Sanitary and Ship Canal	31.1	1.08
Cal-Sag Channel	16.1	1.02
Little Calumet River	6.0	1.29

To put these values in perspective, a perfectly straight channel has a sinuosity of 1.0. In natural rivers, sinuosity of 1.2 or less is considered low, whereas 1.5 or more is considered high (Rosgen, 1996). The lack of sinuosity in the CAWS is by design and not only has an impact on habitat, but has implications for selection of a habitat assessment protocol as discussed in Section 2.4.

At a smaller scale, channel cross-sectional geometry is another important aspect of channel morphology. Variations in depth along and across river channels are the natural result of the local soils, riparian condition, and system hydrology. These variations support the development of local habitat variations. In the CAWS, which consists of canals and modified channels, most reaches tend to be uniform and many reaches are dredged to maintain depth for navigation. The design and maintenance of the channels in the CAWS, along with the lack of a natural sediment load from the watershed, help to maintain channel uniformity. This is illustrated by the channel cross-sectional area measurements collected at the CAWS sampling stations for this Study, depicted graphically in Figure 4-5. This figure shows that, for most of the reaches, cross-sectional area is relatively uniform along the length of the channel. Notable exceptions are:

- On the Chicago River, the station at Lake Shore Drive has a significantly larger cross-sectional area than that at Wells Street because it is actually within the Chicago harbor area.
- The cross-sectional area at Loomis Street on the South Branch Chicago River is significantly larger than at Madison Street because the west end of the Loomis Street station includes a large slip.

- The Chicago Sanitary and Ship Canal at Lockport (16th Street) has significantly larger cross-section than other stations on the CSSC because this area is a wider part of the canal, used for staging barges.

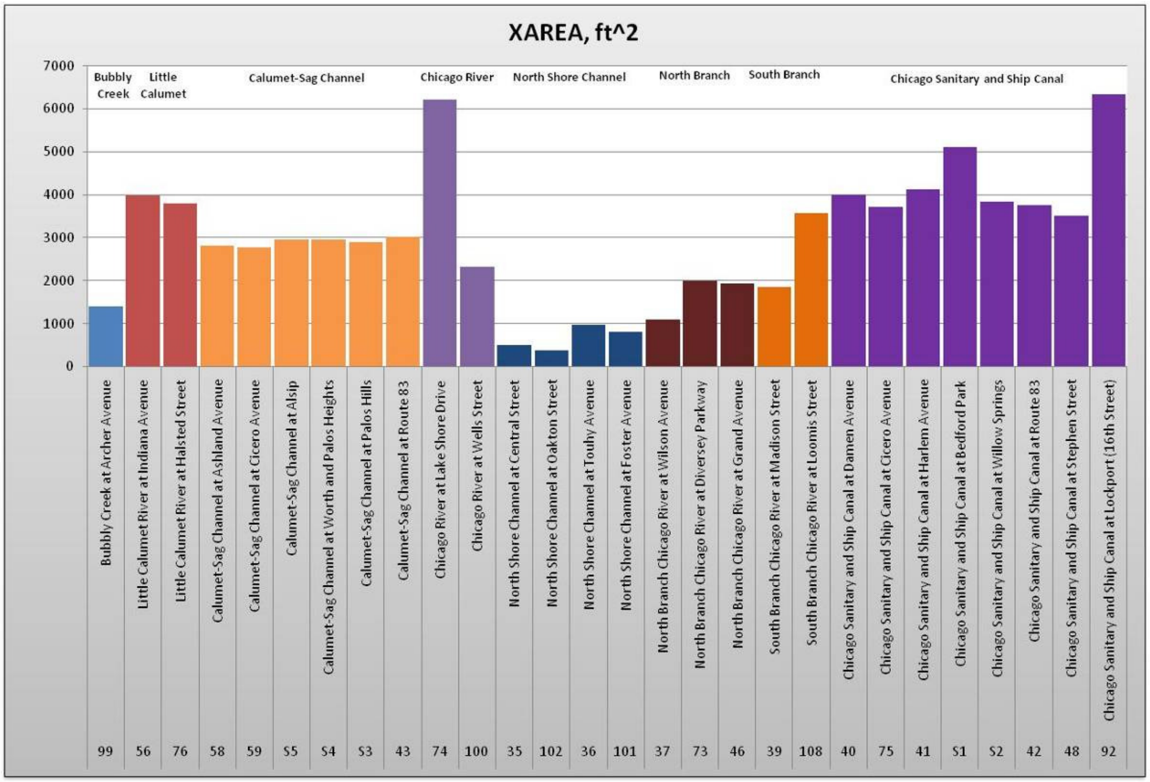

Figure 4-5: Channel Cross-Sectional Area at CAWS Sampling Stations

Aside from these exceptions, the data show fairly uniform cross-sections over long reaches. For example, the Cal-Sag Channel cross-section remains almost the same over approximately 16 miles of length.

The CAWS channels are also generally deep by design to support the primary functions of effluent conveyance, commercial navigation, and flood control. Figure 4-6 depicts the maximum channel depth at CAWS sampling stations used in this Study.

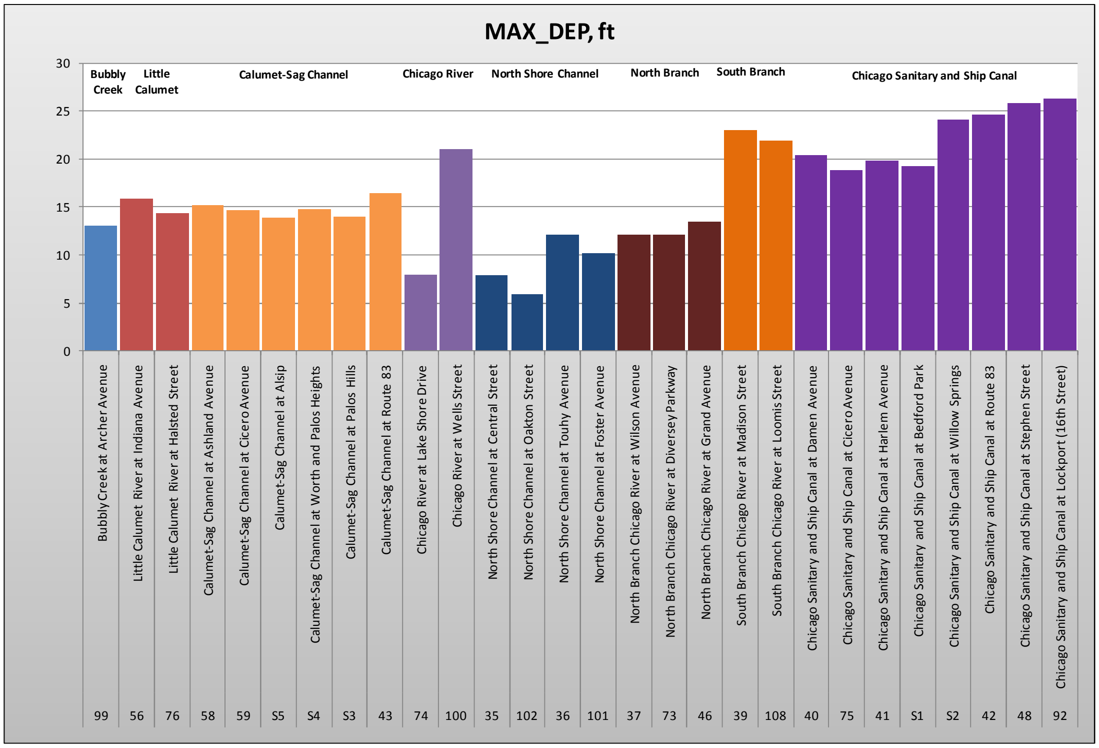

Figure 4-6: Maximum Channel Depth at CAWS Sampling Stations[4].

4.1.3.c Channel Morphology Limitations in the CAWS

Traditional geomorphology aims to understand landform features created by the dynamic processes of surface flowing waters (Gordon et al., 2004). Geomorphic features are used in biotic evaluations under the assumption that the physical characteristics help define the potential biotic characteristics (Gordon et al., 2004).

Within the CAWS, vague remnants of natural channels make up a relatively small component of the system, while the remainder of the system has been constructed through native soils and bedrock, where no channel existed previously. The plan and profile of the constructed channels in the CAWS offer relatively little variation compared to the characteristics offered in large, naturally formed, river systems. Some of the habitat limitations that these conditions impose are summarized in Table 4-5.

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[4] It should be noted that the maximum depth at station 74 (Chicago River at Lake Shore Drive) represents the depth in the marina on the south side of the sampling station where, according to District personnel "most of the fish come from this area around the docks" (Minarik, 2009). Because the habitat data were compared to concurrent, collocated fish data in this study, it was important to characterize habitat at the location that best represented the fish sample. The actual maximum depth of the main channel of the Chicago River at this station is 23 feet.

Table 4-5: Habitat Limitations in the CAWS Related to Geomorphology.

Geomorphic Features[1]	CAWS Habitat and Fisheries Response
Entrenchment	Constructed channels make up most of the CAWS and no recognizable floodplain connection exists. Little or no off-channel refuge, developed littoral zone or shallow bank areas exist for various life stage needs of fish. Fishes adapted to lentic water habitats dominate (Sheehan and Rasmussen, 1999).
Width-Depth	Channels in the CAWS offer relatively little width-depth variation. Fishes adapted to lentic water habitats are dominant and their abundances are greater than in rivers of greater habitat diversity (Sheehan and Rasmussen, 1999).
Dominant channel materials	Fine sediment- and silt-dominated channel beds with intermittent reaches of bedrock are the most common bed condition. Resuspension from navigation maintains dominance of fine sediment surface materials. Limited channel material variation limits substrate uses to those species adapted to fine sediments and resuspension conditions.
Slope	Slope in the system is low and is managed and flow is controlled by the downstream control works at Lockport. System maintenance favors lentic species.
Bed features	Many of the CAWS channels are dredged for navigation and efficient conveyance and bed variation is limited. Limited features favor transient and open water species.
Sinuosity	Sinuosity generally removed from the system for the purpose of navigation passage and efficient conveyance. Limited features favor transient and open water species.
[1]Rosgen (Gordon et al., 2004).	

4.1.4 Hydrology

Hydrology is an important aspect of aquatic ecology in natural systems, but in highly regulated systems like the CAWS, its importance is less clear. This subject is discussed below.

4.1.4.a Importance of Hydrology to Aquatic Life

Flowing water serves many functions for aquatic biota including delivery of nutrients and food, and the removal of wastes (Allan, 1995). Faster flowing, more turbulent waterways are typically better aerated and contain higher levels of DO, essential for aquatic life. The velocity of flow in a channel is also important in determining sediment erosion and deposition. Channel modifications that cause significantly reduced velocities (such as impoundment by locks or dams) can result in increased deposition of fine sediments. Many aquatic organisms prefer either fast or slow moving water, but are less tolerant of experiencing both (Allan, 1995).

4.1.4.b Summary Description of Hydrology in the CAWS

The hydrology of the CAWS is not like that of a natural system. Hydrologic inputs to the system are nearly all regulated and affected by human activity. Figure 4-7 depicts the locations of the major controlling structures and sources of flow into the CAWS. Diversion of water from Lake Michigan into the CAWS is regulated by U.S. Supreme Court decree and by Federal regulations for the Chicago River (33 CFR 207.420, *Chicago River, Ill.; Sanitary District controlling works, and the use, administration, and navigation of the lock at the mouth of river, Chicago Harbor*) which state, in part, that:

> "The controlling works shall be so operated that the water level in the Chicago River will be maintained at a level lower than that of the lake, except in times of excessive storm run-off into the river or when the level of the lake is below minus 2 feet, Chicago City Datum."

Federal regulations also require control of the Calumet River (33 CFR 207.425, *Calumet River, Ill.; Thomas J. O'Brien Lock and Controlling Works and the use, administration and navigation of the lock*) which states, in part, that:

> "The controlling works shall be so operated that the water level at the downstream end of the lock will be maintained at a level lower than that of Lake Michigan, except in times of excessive storm run-off into the Illinois Waterway, or when the lake level is below minus 2 feet, Chicago City Datum."

The U.S. Army Corps of Engineers operates the locks referred to above, as well as the lock at Lockport, located at the southern end of the CAWS, which is the only hydrologic outlet from the system. These and other major hydrologic structures and sources on the CAWS are depicted in Figure 4-7.

Major flows into the CAWS include the Chicago River Controlling Works and the O'Brien Lock and Controlling Works, referenced above, as well as the Wilmette Pumping Station located at the northern end of the North Shore Channel, which pumps water from Lake Michigan into the North Shore Channel. Flows from the upper North Branch Chicago River are regulated by the North Branch Dam before entering the CAWS.

The District operates the Wilmette Pumping Station at the North end of the North Shore Channel, the sluice gates at the Chicago River Controlling Works, and the Lockport Powerhouse and Controlling Works at the south end of the Chicago Sanitary and Ship Canal. To manage storm flows and water levels in the CAWS, the District must lower the water level in the CAWS, sometimes by feet, in anticipation of significant storm events by reducing flow from Lake Michigan at Wilmette and the Chicago River Controlling Works and by diverting more water through the Lockport powerhouse.

Figure 4-7: Major Hydrologic Structures and Flow Sources on the CAWS.

As shown in Figure 4-7, the District operates four water reclamation plants (WRPs) on the CAWS:

- The Northside WRP discharges to the North Shore Channel.
- The Stickney WRP discharges to the Chicago Sanitary and Ship Canal.
- The Lemont WRP discharges to the Chicago Sanitary and Ship Canal below the confluence with the Cal-Sag Channel.
- The Calumet WRP discharges to the Little Calumet River.

Together, these four WRPs discharge approximately 459 billion gallons of treated wastewater effluent to the CAWS annually[5]. A hydrologic balance using typical flow rates from various sources is summarized in Table 4-6. Review of these figures indicates that, on an annual average basis, 70% of the flow into the CAWS is effluent from these four WRPs. It is reported that during dry weather, mainly in winter months, approximately 100% of flow into the CAWS is WRP effluent and that in wet weather, mainly during summer months, WRP effluent accounts for approximately 50% of flow into the CAWS.

Flow is not measured in all reaches of the CAWS. In lieu of these data, flows and velocities calculated by a hydraulic model of the CAWS were used in this Study. This model, called DUFLOW, was developed by Dr. Charles Melching at Marquette University for simulation of water quality under unsteady flow conditions in the CAWS (Alp and Melching, 2008). The average flows and velocities predicted at the District's AWQM stations are depicted graphically in Figures 4-8 and 4-9, respectively.

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[5] This total is based on reported average annual flows totaling 1,258 million gallons per day (District, 2008)

Table 4-6: Summary of Major Flows Into and Out of the CAWS

Flows Into CAWS	**Flow (cfs)**	**Notes**
Water Reclamation Plants		
North Side Water Reclamation Plant	377	1
Calumet Water Reclamation Plant	438	1
Lemont Water Reclamation Plant	4	1
Stickney Water Reclamation Plant	1,128	1
Wilmette Pumping Station	40.4	1
Locks and Controlling Works		
Chicago River Lock & Controlling Works	127.5	1
O'Brien Lock & Controlling Works	83.5	1
WPS Leakage	1.3	1
CRCW Navigation	27.4	1
CRCW Lockage	13.8	1
CRCW Leakage	14	1
OL&D Navigation	8.7	1
OL&D Lockage	19.1	1
OL&D Leakage	8.9	1
Pumping Stations		
North Branch PS	27.7	2
Racine Avenue PS	59.7	2
95th Street PS	-	5
122nd Street PS	-	5
125th Street PS	10.9	2
Tributaries		
Grand Calumet River	14	6
North Branch Chicago River at Albany Avenue	246	6
Little Calumet River	195	7
Tinley Creek	17.8	6
Midlothian Creek	18.7	6
Mill Creek + Stoney Creek (W)	30.7	8
Narajo Creek + Calumet-Sag Basin	7.2	8
Stoney Creek (E)	21.9	8
Calumet-Sag End Watershed	18.6	8
Lower Des Plaines basin	13.2	8
Calumet Union Ditch	21.9	8
Total Average Flow Into CAWS	**3,000**	
Flows Out of CAWS	**Flow (cfs)**	**Notes**
Lockport Controlling Works (LCW) /Lockport Powerhouse & Lock (LPL)	2582	4
Total Average Flow Out of CAWS	**2582**	

1. Reported as average annual flow for calendar year 2006 (District, 2008)
2. Data reported as average daily flows from July 12 to November 9, 2001 (Alp and Melching, 2008)
3. Average annual flow for 2005, measured by USGS at Romeoville Road (District, 2008).
4. Average annual flow for calendar year 2005, measured by USGS at Romeoville Road (USGS).
5. Unknown.
6. River Data reported as average daily flows from July 12 to November 9, 2001 (Alp and Melching, 2008)
7. Average discharge at USGS gage at South Holland, 2001 – 2008.
8. River Data marked as estimated flows and reported as average daily flows from July 12 to November 9, 2001 (Alp and Melching, 2008)

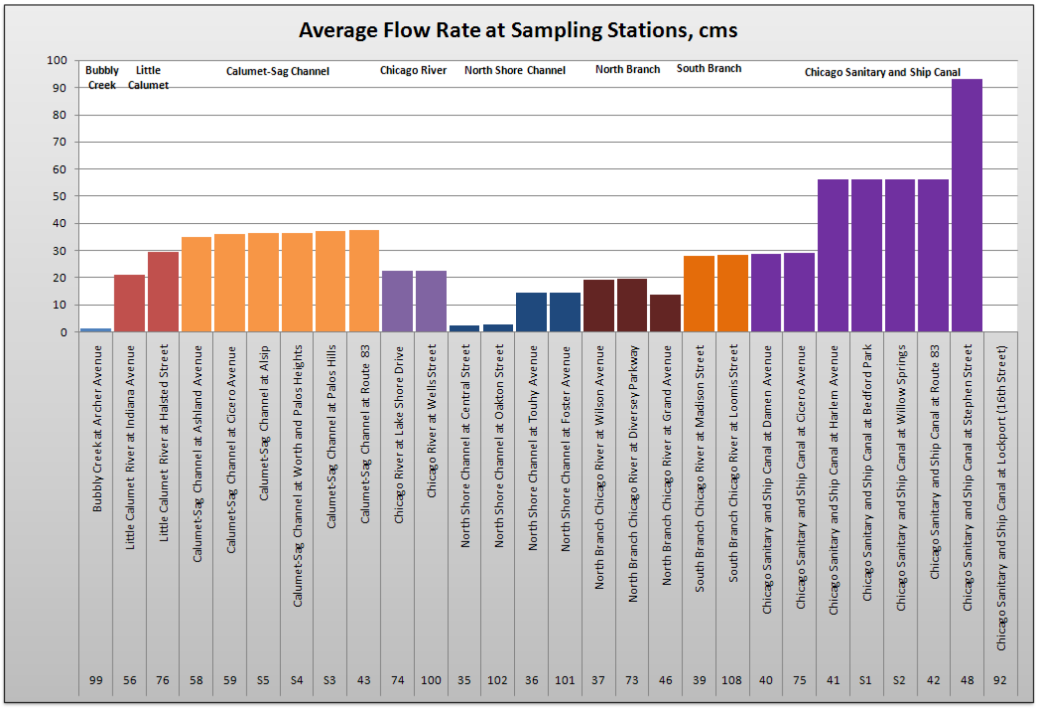

Figure 4-8: Average Flow Rate at CAWS Sampling Stations.

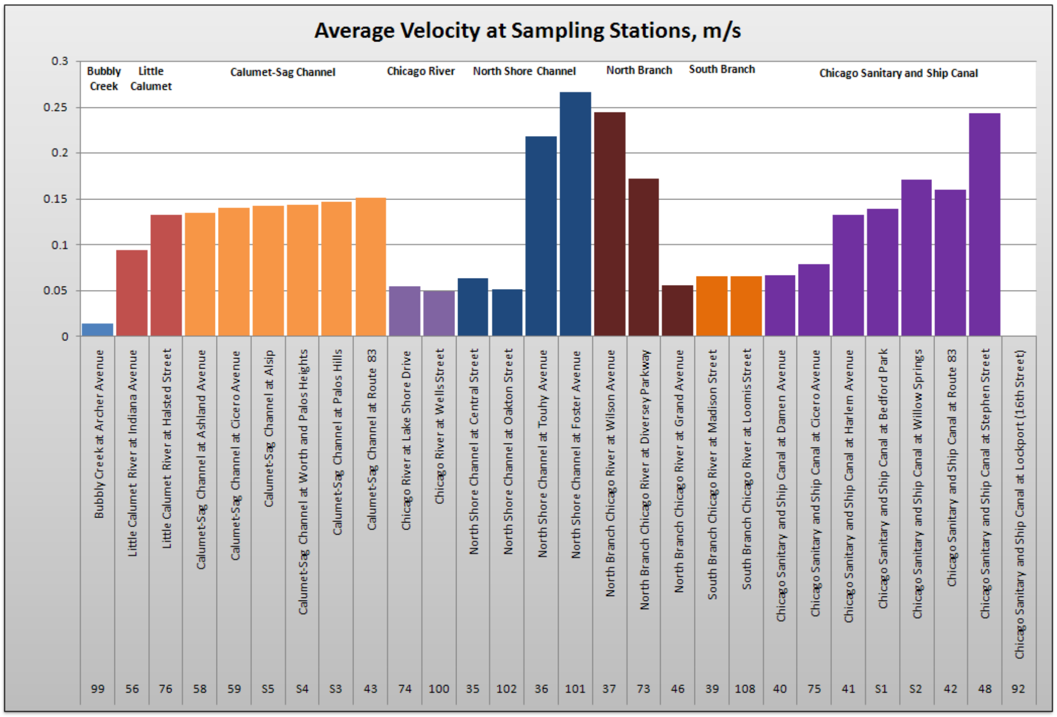

Figure 4-9: Average Velocity at CAWS Sampling Stations.

The DUFLOW model indicates that many parts of the CAWS experience very low flows, particularly Bubbly Creek and the North Shore Channel. Flow conditions in Bubbly Creek are typically stagnant; flow only occurs when the Racine Avenue Pumping Station discharges combined sewer overflow. The North Shore Channel upstream of the North Side WRP typically experiences little flow. Exceptions occur during wet weather events, when flow from the 11 large gravity CSO outfalls upstream from the North Side WRP exceed the dry weather flows in the North Shore Channel.

The CAWS was specifically designed to convey effluent and provide navigation passage and requires hydraulic controls both upstream and downstream to meet its designed uses. These controls have been described previously and have resulted in a system that functions similar to a reservoir. The CAWS is modeled to have a hydraulic residence period of over 8 days, although this varies depending on wet weather management needs for the system. The constructed nature of the CAWS and the operation of the flows within the system are likely adversely influencing the composition and distribution potential of the biota within the system. Orth and White (1999) describe that artificial flow manipulations in systems are well documented to adversely affect fishes, although the specific effects on the biota within the CAWS remain unknown. Hayes et al. (1998) suggests that reservoir systems contain a relatively simple trophic structure that is particularly vulnerable to the flow operation of the systems. This is significant because of the reservoir-like operation of the CAWS.

4.1.4.c Hydrology Limitations in the CAWS

Hydrology is regarded as a key driver of river and floodplain ecosystems and has been called the “master variable” of aquatic integrity (Gordon et al., 2004). In natural systems, the flow regime affects the structure and function of in-stream habitats as well as biotic factors such as distribution, abundance and competition (Flotemersch et al., 2006). As discussed in Section 4.5, the CAWS functions entirely under a regulated and managed system of controls for the purpose of conveyance and navigation stage maintenance. The hydraulic residence time in the CAWS (> 8 days) suggests that the system may function more like a lake or reservoir than a river system and its biota may be responding as such. Table 4-7 describes habitat limitations in the CAWS related to hydrology.

Table 4-7: Habitat Limitations in the CAWS Related to Hydrology (after Bunn and Arthington, 2002)

Hydrology Feature	CAWS habitat and Fisheries Response
Flow	Flow is regulated within the CAWS for navigation, effluent conveyance and stormwater management. Bunn and Arthington (2002) cite flow as the major determinant of physical habitat and biotic composition in river ecosystems. The artificial nature of the physical habitat and regulation of flow suggests that the CAWS biota would be unlike that of systems formed by under the influence of flow. Further, flow associated with the navigation lockage allows intermittent passage of fishes, while the downstream portion of the system contains an electric barrier that prevents upstream or downstream passage past the barrier.
Flow regime	As described previously, the flow is regulated within the CAWS. The resemblance of a natural flow regime within the system has also been removed. Bunn and Arthington (2002) state that species whose life history strategies have evolved with defined flow regimes may experience recruitment failure in managed systems. These altered systems promote the establishment, spread and persistence of exotic and introduced species (Bunn and Arthington, 2002).
Longitudinal and lateral connectivity	The CAWS is maintained within a narrow stage range for specific uses. Deep channels are maintained across the system. Laterally varied habitats are rare due to the constructed nature of the system. The limited lateral connectivity may lead to recruitment failure (Bunn and Arthington, 2002) or a general decrease in the abundance and diversity of juvenile fishes (Wesche and Isaak, 1999).

4.1.5 Bank & Riparian Conditions

Bank and riparian conditions are important in any system, but become particularly important in urban waterways where extreme modification of banks can occur and where urban land uses typically impinge closely on waterways to provide access to the water or simply to maximize available land area.

4.1.5.a Importance of Bank and Riparian Conditions to Aquatic Life

As the transitional zone between a watercourse and the surrounding land, bank and riparian areas have a direct effect on aquatic life. The shape and material of banks affects the ability of aquatic organisms to utilize the bank for cover and spawning. A vertical walled channel will offer very different physical habitat from a natural sloped bank. Materials such as rip-rap can offer a habitat for warm water fishes that is often beneficial (Fischenich, 2003). Banks which lack cover expose eggs and nests to higher flow velocities and wave-induced turbulence. Riparian vegetation can moderate water temperature by shading and slowing heat loss (Kohler and Hubert, 1999). Vegetation also reduces nonpoint source pollution by filtering overland flow and reducing sediment and nutrient loads. In natural systems, riparian vegetation provides bank stabilization and leaf litter energy inputs (Kohler and Hubert, 1999).

Riparian land use affects the volume and composition of water entering a watercourse. Activities on adjacent land can disturb biota through direct runoff of sediment and contaminants. Proper characterization of aquatic habitat involves consideration of bank and riparian condition.

4.1.5.b Summary Description of Bank and Riparian Condition in the CAWS

About seventy-five percent of the CAWS waterways are manmade and located where no previous waterway existed. Long stretches of banks consist of near-vertical walls designed to prevent erosion and to provide access for commercial and industrial activities. These urban channels provide efficient stormwater conveyance and flood control.

Bank and riparian conditions vary widely in the CAWS. The North Shore Channel has more riparian vegetation than most of the CAWS, with open space being a common riparian land use. Along the North Shore Channel, banks have a natural appearance, with little structural reinforcement. In waterways nearer to downtown Chicago such as the Chicago River, the North and South Branches, and the South Fork, commercial and industrial land uses dominate and riparian vegetation is largely absent. Banks are typically walled concrete or steel, offering little shelter for aquatic life. The Chicago Sanitary and Ship Canal has interspersed riparian vegetation and riparian land use changes from industrial in the east to more open space toward the west.

The banks are a mix of bedrock, steel sheet piling and more natural-looking banks. The Little Calumet River and the Calumet-Sag Channel have more riparian vegetation than the CSSC, with open space being common due to the Palos-Sag Forest Preserves (CDM, 2007). Like the CSSC, the banks are a mix of stone blocks, steel sheet piling and earthen banks with vegetation. Riprap banks are common throughout the CAWS. Table 4-8 summarizes the lengths of riprap and vertical-walled banks (including bedrock, stone block, steel sheet pile, wooden bulkhead, and concrete) in the CAWS, by reach. These measurements were obtained through visual inspection of the entire CAWS, using the digital video survey collected for this study.

As shown in Table 4-8, nearly 95 miles of the approximately 156 miles of banks in the CAWS (61%) are riprap or vertical walls, imposing potentially significant limitations on aquatic habitat. Bank revetments, intended to stabilize bank and prevent erosion, can impact aquatic life by disconnecting the channel from the riparian zone and limiting shallow littoral zones. Shallow bank areas that can provide refuge for fish are virtually eliminated.

Table 4-8: Bank Modification in the CAWS, by Reach

Reach	**Total Length of Riprap Banks (mi)**	**Total Length of Vertical Walled Banks (mi)**
North Shore Channel	1.1	0.4
North Branch Chicago River	5.2	8.0
North Branch Canal	0.5	1.5
Chicago River	0.0	3.1
South Branch Chicago River	0.4	8.0
Bubbly Creek	0.1	1.3
Chicago Sanitary and Ship Canal	3.3	35.5
Cal-Sag Channel	17.2	6.1
Little Calumet River	2.2	0.6
Total	**30**	**64.5**

Riparian vegetation is common in some parts of the CAWS, particularly in the North Shore Channel and parts of the CSSC and Cal-Sag (Figure 4-10). Riparian vegetation was not catalogued in detail, but ranges from low shrubs to larger overhanging trees. It should be noted that, because of extensive bank modifications in much of the CAWS, the presence of riparian vegetation has limited impact on aquatic habitat. The vertical walls or riprap embankments act as a physical separation between the aquatic environment and the riparian environment in many cases. Where riparian vegetation overhangs the water, there is a benefit from partial shading and deposition of organic material, but the benefit is not as full as it would be in the absence of this physical separation.

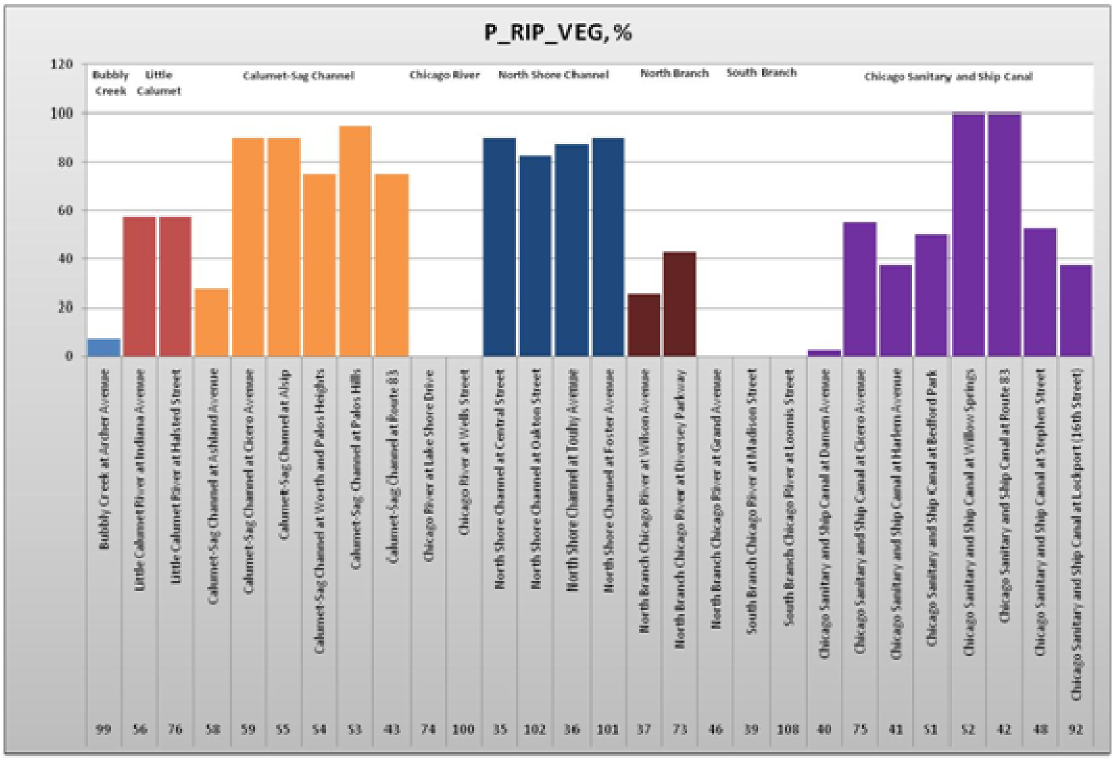

Figure 4-10: Percent Riparian Vegetation at CAWS Sampling Stations.

Another important aspect of bank condition in the CAWS is the presence of small and large areas that can provide fish refuge. Small areas of refuge in the banks were measured in this Study and are prevalent, as shown in Figure 4-11. These bank pocket areas were defined as small protection areas (greater than 1 square meter), visible to field crews, that may serve as refuge.

In addition to small pocket in the banks, there are some larger areas of refuge in certain parts of the CAWS. These were quantified and the results are depicted graphically in Figure 4-12.

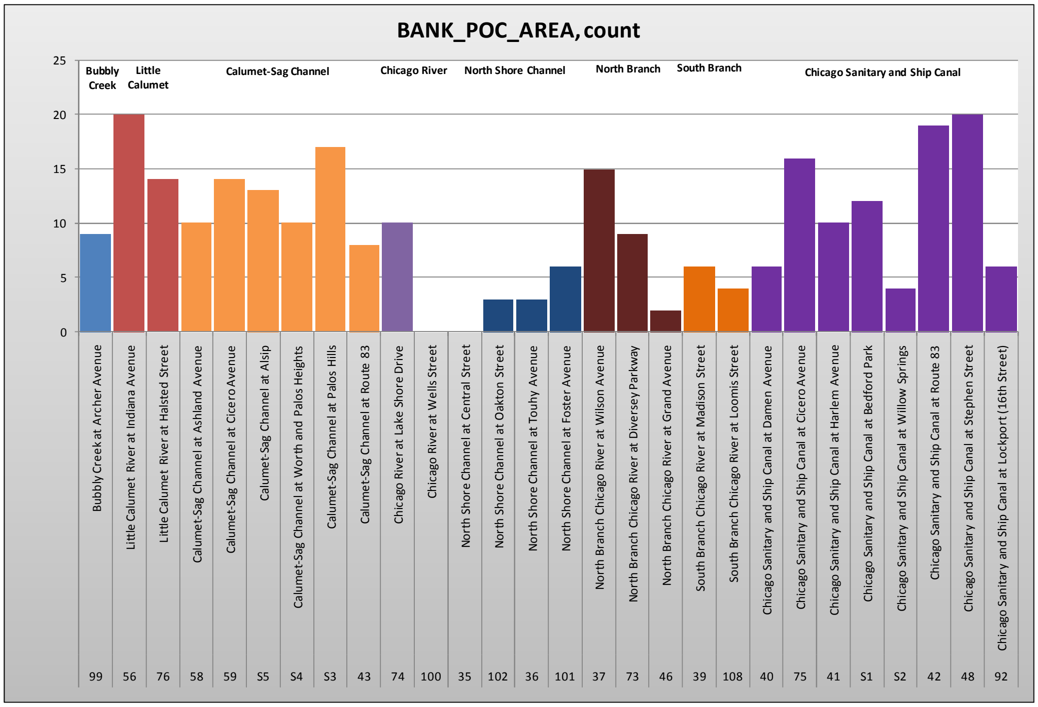

Figure 4-11: Bank Pocket Areas in CAWS Sampling Reaches.

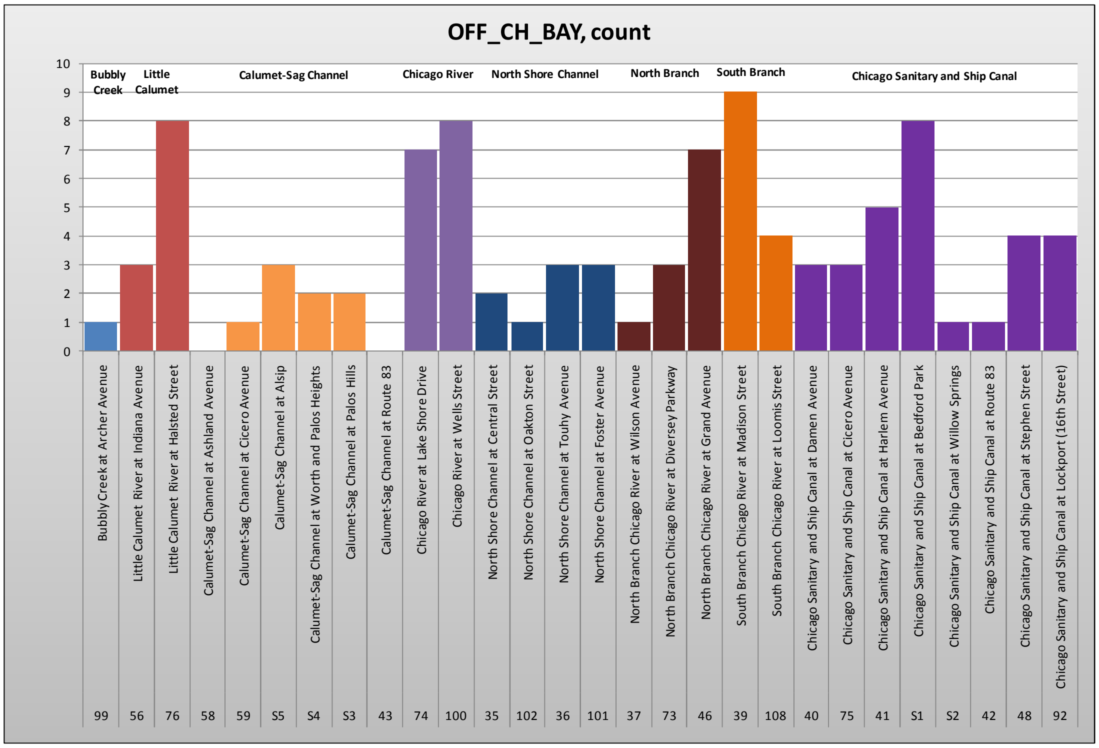

Figure 4-12: "Off-Channel Bays" in CAWS Sampling Reaches.

4.1.5.c Bank and Riparian Condition Limitations in the CAWS

Bank and riparian areas have a direct effect on aquatic life, as the shape and material of banks affects the ability of aquatic organisms to utilize the bank for cover and spawning. In addition, activities on riparian land can disturb biota through direct runoff of sediment and contaminants. Most of the entire length of the CAWS has modified or constructed banks and/or urban riparian conditions. These conditions range from long segments of sheet-piled, industrial loading facilities to natural banked reaches with dense riparian vegetation. Table 4-9 describes some bank and riparian condition limitations in the CAWS.

Table 4-9: Habitat Limitations in the CAWS Related to Bank and Riparian Condition

Bank and Riparian Features	CAWS Habitat and Fisheries Response
Riparian Land Use	Riparian land use within the CAWS includes a mix of uses from protected forest preserves in the lower Cal-Sag, to heavy industrial uses on the CSSC. The constructed and urban developed nature of the CAWS has created a unique system where typical watershed runoff conditions do not apply. Surface flows across the system do not generally drain towards channels because the channels were constructed where none existed previously. Slopes towards the channels exist only immediately adjacent to the channel, and tend to be flat or even sloping away from the channel outside the channel. Thus, within the CAWS, riparian land use effects are generally limited to immediately adjacent to the channel. Numerous authors have linked riparian alteration to degraded aquatic conditions (Flotemersch et al., 2006), and the effect on the fisheries are likely similar to those described previously for the overhead bank cover.
Bank Angle	Bank angle within the CAWS is a direct result of the construction. Much of the system (over 60 percent) has some form of armored banks and much of that portion has reinforced vertical walls. Bank angle within typical rivers is a descriptor of stability under various flow regimes and watershed influences, and a dominance of steepened banks are common in modified systems. These modified shorelines are commonly associated with poor fish habitats (Flotemersch et al., 2006). Within the CAWS, bank angle tends to be similar above the water line as below, so a vertical wall above the waterline typically describes a deep shore condition. Bank angles of less than 90 degrees suggest some form of littoral zone that may be used by fishes for feeding or refuge.
Bank Type (Material)	Bank types within the CAWS tend to consist of vertical walls (e.g., wood, sheet pile, concrete, stone block), boulder rip-rap, or natural vegetated banks. Much of the system has reinforced banks (i.e., walls or rip-rap) while the remainder consists of earthen constructed banks. Modified banks and shorelines are commonly associated with poor fish habitats (Flotemersch et al., 2006). The vegetated banks tend to be occupied by trees or large shrubs that serve a similar purpose to fishes as overhanging bank cover.
Riparian Vegetation	Riparian vegetation within the CAWS, where present, consists of mature stands of trees and shrubs adjacent to the channel up to several meters away from the channel. Much of the benefit to the CAWS channels come from the vegetation immediately adjacent to the channel because the channels do not have naturally sloping banks. The riparian vegetation, where present, serves a similar purpose to fishes as overhanging bank cover although in natural systems the extent, connectivity and quality of riparian vegetation is often linked to ecological condition (Flotemersch et al., 2006).

4.2 NAVIGATION IMPACTS IN THE CAWS

A majority of the CAWS was constructed, where no channel previously existed and is managed specifically for urban uses such as treated effluent conveyance, but much of the system was also designed to support commercial navigation. Navigation is not a true physical habitat attribute, but it represents a functional attribute of the system that has direct and indirect relevance to fish and their habitat. Any evaluation of habitat in the CAWS would be incomplete without consideration of navigation through the system. The impact of navigation on aquatic biota and habitat in the CAWS is discussed below.

4.2.1 Summary Description of Navigation in the CAWS

The Chicago Sanitary and Ship Canal, the Cal-Sag Channel, the South Branch Chicago River, Chicago River, and the Little Calumet River are all used for commercial navigation. No new measurements of navigation traffic were collected in this Study, but as described in Section 3.3.5, navigation data collected by the U.S. Army Corps of Engineers (USACE) Waterborne Commerce Statistics Center and subsequently processed for a study by the Great Lakes Fishery Commission were obtained to better understand commercial navigation patterns in the CAWS. These data were reported in terms of commodity tonnages (Figure 4-13) and the data used covered the period of 2001 through 2004.

As expected, the Chicago Sanitary and Ship Canal, the Cal-Sag Channel, and the Little Calumet River are the most heavily used reaches for commercial navigation, with each passing more than 25 million tons of commercial cargo between 2001 and 2004. In the same period, the South Branch Chicago River passed a little more than 5 million tons and the Chicago River passed less than 1 million tons. As stated earlier in this report, data on detailed movements within these reaches are not available (Brammeier et al., 2008). However the data verify the heavy usage of certain reaches for commercial navigation and allow for characterization of the reaches, compared to reaches that experience relatively light recreational navigation. A map showing the distribution of commercial navigation traffic in the CAWS is shown in Figure 4-14.

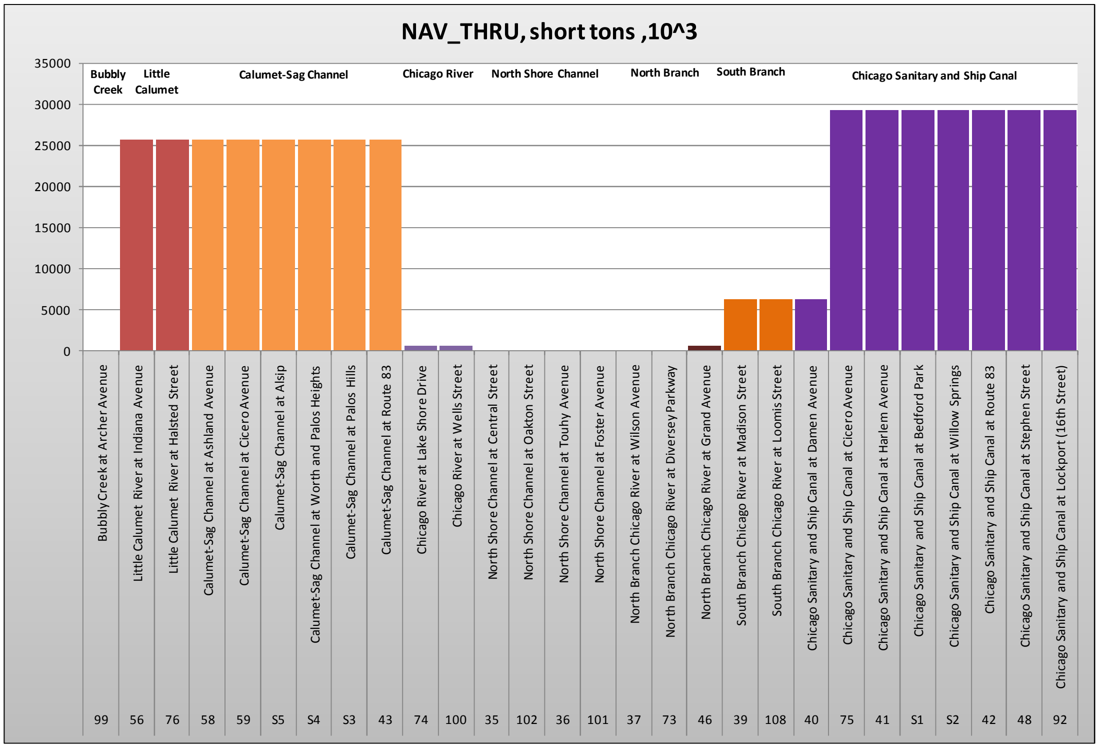

Figure 4-13: Commercial Navigation Through the CAWS, as Indicated by Tonnage.

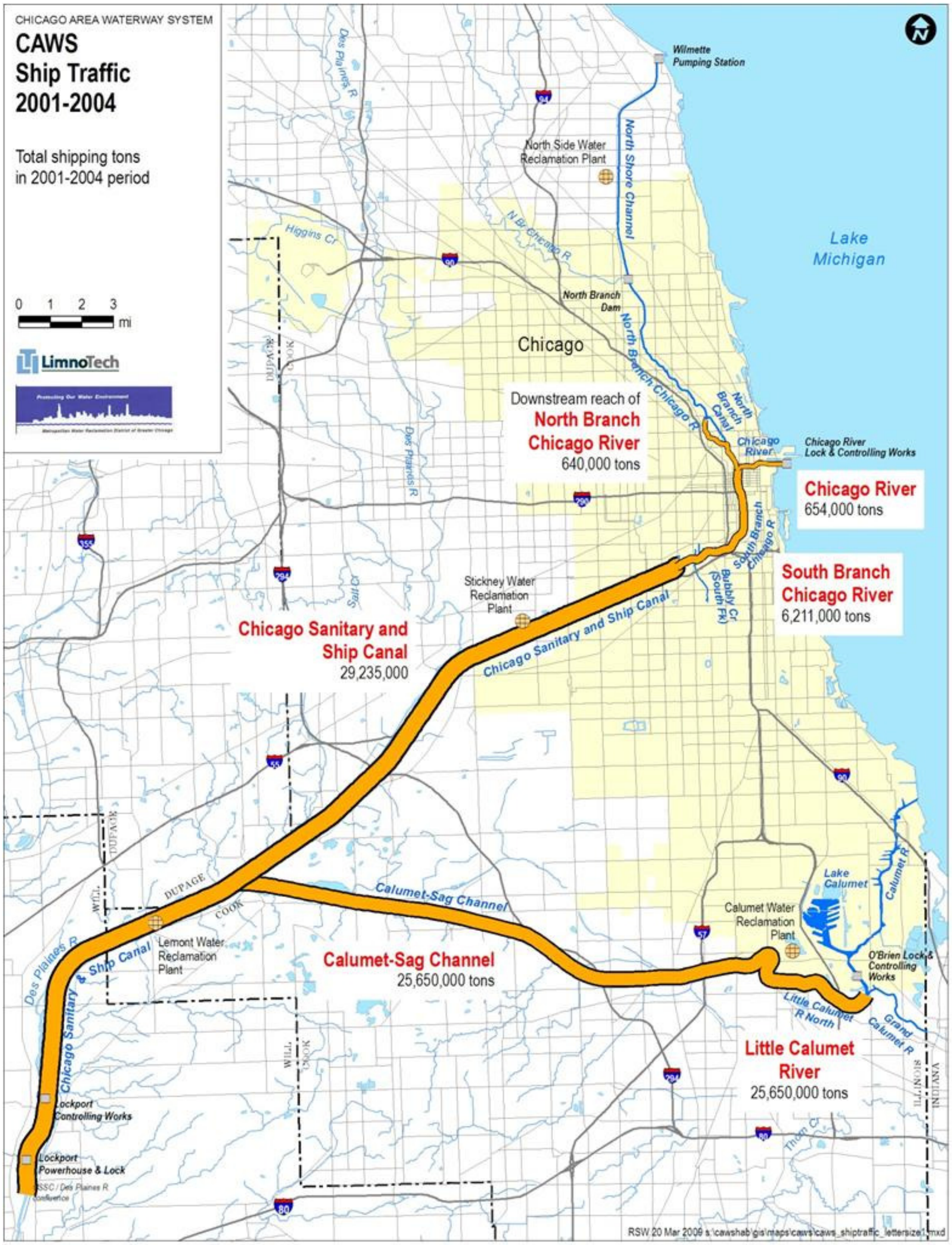

Figure 4-14: Commercial Navigation Through the CAWS.

4.2.2 Impacts of Navigation to Aquatic Life

The impacts of navigation on aquatic habitat and biota are numerous and well-documented in the scientific literature. These impacts are summarized below:

4.2.2.a Channel Modification for Navigation

Wolter and Arlinghaus (2003) provide a summary of the multi-use nature of navigation systems, describing the additive impacts resulting from straightened channels, dredging, shoreline stabilization and flow regulation. These authors also state that the cause and effect relationship is always similar: habitat fragmentation, habitat simplification, habitat loss (especially spawning and nursery habitats for migratory species), and the adverse hydraulic forces that directly affect aquatic species. Channel modification to support navigation has the following impacts:

- Straightening – Straighter channels are more efficient for navigation because they are easier to navigate and provide a shorter distance between points. Straightened navigation channels lack sinuosity and have less flow variability.

- Deepening – Commercial navigation vessels have deeper drafts than non-commercial vessels, requiring deeper channels. Dredging provides that depth and deepening often includes deepening from bank to bank, particularly in areas where barges and other vessels must dock. This results in lack of depth variability and loss of shallow areas which many species require.

- Bank modification – Wakes from vessels can cause bank erosion and traditional methods of erosion prevention include hard revetments such as riprap or sheet piling. Vertical sheet piling and bulkheads are also used for bank protection in docking areas. These modifications effectively disconnect the water from riparian areas and further reduce shallow water areas.

- Floodplain disconnection – Channelization (the combination of the three factors above) often result in disconnection of the floodplain from the channel.

- Substrate removal – Navigation channels, like the CAWS, require maintenance dredging which removes substrate and completely disrupts the benthic zone. This has a direct negative impact on benthic biota.

- Hydrologic regulation - Lock and dam structures are often required to control water levels, as is the case on the CAWS. Historically, the engineering of rivers to meet these requirements has lead to waterways which lack natural or diverse habitat. Research has shown that there is a clear relationship between the lack of habitat and aquatic life assemblages in navigable waterways (Wolter, 2001; Wolter and Arlinghaus, 2003). The controlling of water levels can also lead to the loss of spawning areas and negatively affect stock recruitment (Barlaup et al., 2008, Schramm et al., 2008). Sheehan and

Rasmussen (1999) suggest that the lock and dam systems developed and operated for navigation creates a lentic environment favoring lentic aquatic species.

All of these impacts are apparent in the CAWS. The CAWS consists mostly (about 75%) of manmade waterways that were designed to be straight and deep, where no floodplain originally existed and where the substrate is largely the native earth into which the channels were first dug. The rest has been modified and much of it exhibits the characteristics described above. These characteristics impose severe limitations on aquatic habitat and the biota that depend on it.

4.2.2.b Direct Impacts on Fish

In addition to the effects resulting from channel modification described above, navigation traffic also directly impacts aquatic life. As a ship travels through restricted waterways a series of forces are exerted including propeller wash, bank-directed current, return current opposite to the direction of the moving vessel, and drawdown (Wolter et al., 2004). These forces cause negative effects which can be divided into direct and indirect categories. Direct effects of navigation are a result of physical forces on aquatic life caused by moving vessels (Wolter and Arlinghaus, 2003). Indirect effects are associated with vessel induced disturbances which prevent normal aquatic life behaviors (Wolter and Arlinghaus, 2003). Many different levels of aquatic biota are negatively affected by these forces.

- Propeller impacts – The most direct way that navigation can affect fish is by propeller impact. Moving ship propellers can injure or kill fish by direct impact, but injuries to fish in proximity to propellers can also occur due to shear stress or pressure changes (Gutreuter et al., 2003).

- Increased shear stress – Moving vessels create moving water, which can increase shear stress on substrate, banks, and organisms themselves. It has been documented that navigation in channelized waterways can kill fish eggs and larvae by causing rotation or deformation (Morgan et al., 1976).

- Increased velocities – In addition to shear stress, water velocities caused by navigation may be too fast for small juvenile fish and force washing out, injury, or displacement (Wolter et al., 2004; Arlinghaus et al., 2002).

- Dewatering – Dewatering can also cause direct effects on aquatic life. Passing vessels displace water which is pushed to the sides of the channel, resulting in temporarily increased water levels, but in the wake of the vessel’s passage, the water quickly moves back into the channel and can dewater nearshore sediments due to temporary water level drawdown. Drawdown forces at intervals associated with navigation traffic have been shown to significantly increase mortality for walleye and northern pike eggs (Holland, 1987).

- Wake impacts – Indirect impacts of navigation on aquatic life, although not immediately lethal, can pose a serious threat to certain species. As ships move through restricted waterways, their waves can disturb benthic invertebrate assemblages colonizing littoral zones and force detachment from bottom substrates (Gabel et al., 2008).

- Noise – Navigation traffic also results in noise of high amplitude and frequency. This noise has been shown to increase the levels of cortisol secretion and indicate elevated levels of stress in fish (Wysocki et al., 2006). Heavy boat traffic has also been shown to decrease the food conversion efficiency of fish when compared to similar species from other habitats (Penczak et al., 2002).

- Suspended sediment – As described above, passing vessels can increase shear stress on substrate, causing resuspension of unconsolidated fine sediments. This increase turbidity in the water column which can have harmful effects on fish gills and, particularly in urban waterways like the CAWS, it can introduce potentially toxic anthropogenic chemicals from the sediments to the water column. The repeated suspension and redepositon of fine sediments from vessel passage can spread sediment-bound contaminants and clog coarser substrate materials.

Although there are insufficient data at present to quantify these effects on biota specifically in the CAWS, the impacts almost certainly are occurring and cannot be ignored. Further research would be required to document and quantify navigation-related impacts to aquatic biota in the CAWS, but navigation clearly presents significant limitations to aquatic biota in the CAWS. Furthermore, the channel design/modification to support navigation presents significant limitations to the habitat improvement potential in the CAWS.

4.3 CONTRAST BETWEEN CAWS AND NATURAL RIVERS

The assessment of habitat in the CAWS cannot ignore two key aspects of the system:

- ***Most of the system is manmade.*** Seventy-five percent of the CAWS is not natural, having been excavated to provide conveyance of treated wastewater and urban drainage away from Lake Michigan and support commercial navigation. The design of the manmade channels of the CAWS, particularly the Chicago Sanitary and Ship Canal and the Cal-Sag Channel, incorporates qualities to support their function which are at odds with habitat qualities found in natural systems. The rest of the system has been so modified that it bears little resemblance to its original form. These facts should not be overlooked and must be considered when evaluating the habitat of the CAWS.

- ***The primary uses of the CAWS today are effluent conveyance, navigation, and flood control.*** Not only was the system designed and built for these

> purposes, but it continues to function primarily to serve these purposes today. Access to the CAWS is structurally controlled by locks, dams, and pumping stations and every connection point to external water systems. Most of the flow in the CAWS at any given time is treated effluent from water reclamation plants, not natural flow from a watershed. The hydrology of the CAWS is completely manipulated to support these uses.

The constructed and heavily modified conditions within the CAWS, combined with the management of the system for its intended uses of wastewater conveyance and navigation, have limited the structural and functional conditions for aquatic habitat. These limited habitat features have resulted in a biotic community (as measured by fish) that is tolerant of the modified conditions. These conditions also impose a significant limitation on the potential of the CAWS to support fish communities different than what presently exist there.

5. DESCRIPTION OF AQUATIC BIOTA IN THE CAWS

As stated elsewhere in this report, the District has collected fish and macroinvertebrate data in the CAWS for several years. For purposes of this Study, data collected since 2001 were used, in order to reflect current conditions. These data are briefly described in this section.

5.1 FISH

The District has been collecting fish data annually since 1974 (with the exception of 1981 and 1982) within the Study area. However, to focus this Study on current conditions, the fish data analysis is limited to the data collected between 2001 and 2008. Fish data collected from 2001-2007 were used to analyze physical habitat data and develop a draft physical habitat index for the CAWS, while the 2008 fish data were used as the validation dataset.

5.1.1 Sources of Data

Between 2001 and 2008, the District collected fish data at 34 stations within the CAWS (Figure 3-1) on a routine basis. Twenty-three of these 36 stations are part of the District's Ambient Water Quality Monitoring (AWQM) program and those stations were used in the development of the habitat index for the 2001-2007 sample period. In 2008, five supplemental stations within the managed portion of the system were included in the fish sampling regime in an attempt to capture system habitat variation that may not have been included previously. The 2008 fish sampling included a total of 20 fish sampling stations within the Study Area. In total, 38 stations have been sampled for fishes within the Study Area during the 2001-2008 period (Table 5-1). The sample collections and processing follow the protocol described in Section 3.3.1.

Table 5-1: CAWS Fish Sampling Events, 2001 – 2008 (the numbers in the table represent species richness and total number of individuals in parentheses).

Stn. ID	Station Description	2001	2002	2003	2004	2005	2006	2007	2008
35	North Shore Channel at Central Street	12 (132)				11 (139)			8 (48)
36	North Shore Channel at Touhy Avenue	11 (596)	12 (147)	14 (335)	11 (249)	9 (276)	16 (496)	14 (387)	14 (68)
37	North Branch Chicago River at Wilson Avenue	9 (75)				11 (122)			
39	South Branch Chicago River at Madison Street		10 (138)				6 (99)		
40	Chicago Sanitary and Ship Canal at Damen Avenue		10 (148)				12 (164)		19 (277)
41	Chicago Sanitary and Ship Canal at Harlem Avenue	9 (88)	11 (188)	10 (225)	13 (193)	14 (758)	15 (388)	12 (282)	12 (186)
42	Chicago Sanitary and Ship Canal at Route 83		5 (32)				5 (10)		
43	Calumet-Sag Channel at Route 83			7 (43)				9 (261)	
46	North Branch Chicago River at Grand Avenue	12 (53)	7 (28)	8 (67)	9 (88)	5 (77)	10 (158)	13 (117)	6 (59)
48	Chicago Sanitary and Ship Canal at Stephen Street		4 (24)				5 (24)		4 (9)
56	Little Calumet River at Indiana Avenue			17 (452)				18 (322)	13 (81)
58	Calumet-Sag Channel at Ashland Avenue			13 (95)				12 (131)	
59	Calumet-Sag Channel at Cicero Avenue	10 (127)	13 (174)	12 (56)	10 (147)	10 (453)	15 (214)	12 (297)	4 (66)
73	North Branch Chicago River at Diversey Parkway	7 (58)				13 (164)			10 (36)
74	Chicago River at Lake Shore Drive		8 (22)				7 (83)		
75	Chicago Sanitary and Ship Canal at Cicero Avenue	10 (118)	10 (136)	9 (138)	13 (191)	7 (184)	11 (205)	13 (280)	11 (58)
76	Little Calumet River at Halsted Street	16 (210)	17 (163)	13 (219)	17 (207)	19 (913)	22 (405)	21 (281)	12 (45)
92	Chicago Sanitary and Ship Canal/Lockport (16th St)	2 (77)	6 (67)	7 (67)	4 (22)	9 (179)	8 (64)	6 (64)	10 (171)
99	Bubbly Creek at Archer Avenue		5 (21)				13 (156)		5 (8)
99.1	Bubbly Creek at I-55			6 (31)	10 (60)	5 (31)			
99.2	Bubbly Creek at 35th St.			5 (39)	8 (27)	5 (26)			
99.3	Bubbly Creek at RAPS			7 (151)	10 (97)	5 (62)			
100	Chicago River at Wells Street		11 (136)				10 (250)		9 (27)
101	North Shore Channel at Foster Avenue	15 (179)				17 (273)			14 (115)
102	North Shore Channel at Oakton Street	2 (2)				17 (151)			
108	South Branch Chicago River at Loomis Street		10 (76)				13 (142)		
Supl.	Calumet-Sag Channel at 104th Street							10 (92)	
Supl.	Calumet-Sag Channel at Kedzie Avenue							8 (87)	
Supl.	Calumet-Sag Channel at Southwest Highway							13 (127)	
S1	Chicago Sanitary and Ship Canal at Bedford Park								16 (118)
S2	Chicago Sanitary and Ship Canal at Willow Springs								2 (7)
S3	Calumet-Sag Channel at Palos Hills								9 (53)
S4	Calumet-Sag Channel at Worth and Palos Heights								7 (50)
S5	Calumet-Sag Channel at Alsip								10 (74)
SEPA2	Little Calumet River at SEPA 2					16 (529)	12 (218)		
SEPA3	Calumet-Sag Channel at SEPA 3			13 (148)		16 (253)		14 (407)	
SEPA4	Calumet-Sag Channel at SEPA 4			11 (93)	11 (82)	14 (663)	9 (79)	15 (417)	
SEPA5	Calumet-Sag Channel at SEPA 5			12 (232)	7 (41)	16 (443)	7 (37)	17 (216)	
SEPA5_CSSC	Chicago Sanitary and Ship Canal at SEPA 5			5 (18)	8 (53)	6 (306)	8 (34)	9 (178)	

5.1.2 Summary Description

Fifty-two (52) species, including five hybrids, of fish were identified at the 34 CAWS monitoring stations between 2001 and 2007 (sample period). For the 2001-2007 sample period, the number of non-hybrid species collected across the CAWS stations ranged from 27 at AWQM Station 76 (Little Calumet River at Halsted Street) to only five at Stephen Street (Chicago Sanitary Shipping Canal; CSSC). The most frequently observed species across all stations included gizzard shad (*Dorosoma cepedianum*), common carp (*Cyprinus carpio*), and largemouth bass (*Micropterus salmoides*), respectively (Figure 5-1). The most numerous observed species within the CAWS included gizzard shad (n=6906), emerald shiner (*Notropis atherinoides*; n=2082) and common carp (n= 2055), respectively (Figure 5-2). Eleven species are represented by only a single observation for the 2001-2007 period. Finally, gizzard shad, common carp, and largemouth bass have been observed at all stations during the sample period.

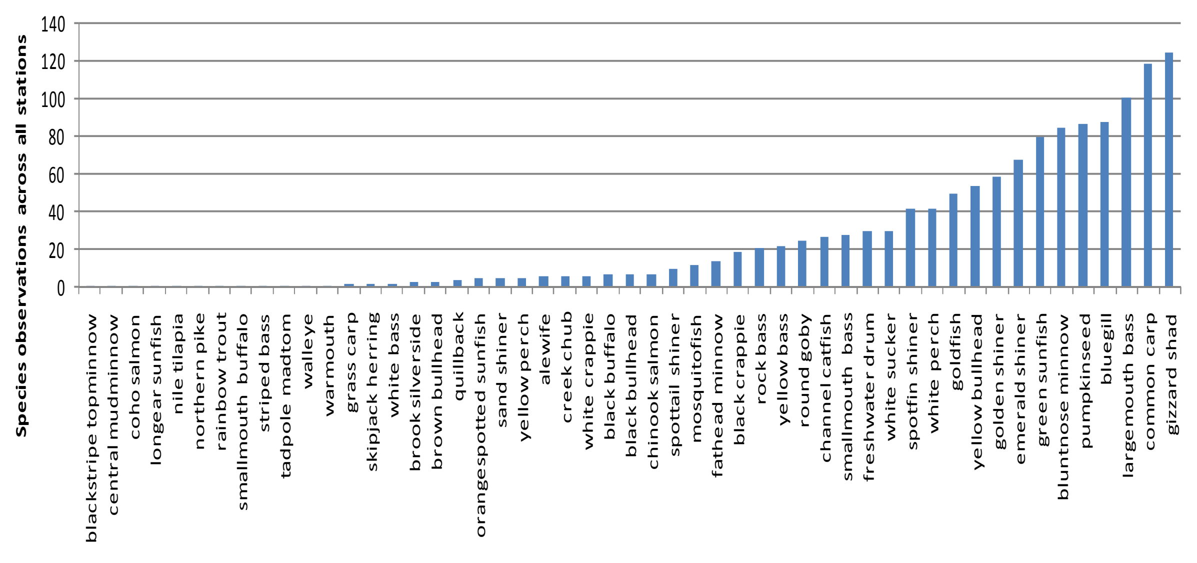

Figure 5-1: Non-Hybrid Fish Observations in CAWS Study Area, 2001-2007.

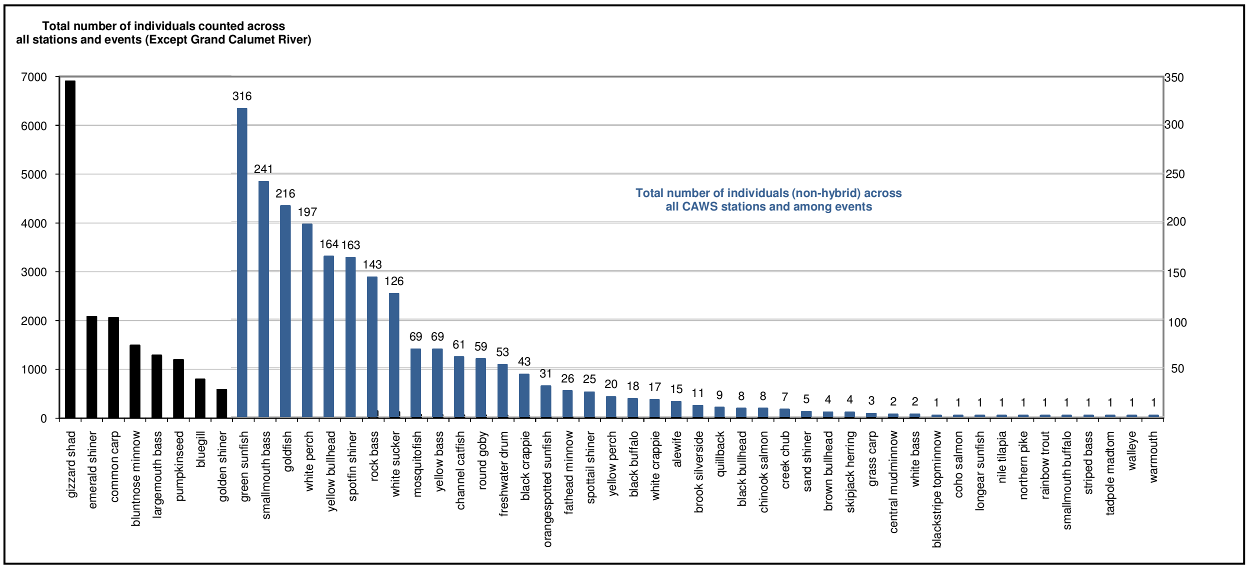

Figure 5-2: Total Number of Individuals (Non-Hybrids) Observed in CAWS Study Area, 2001-2007. (NOTE: the left-hand axis corresponds to the black bars and the right-hand axis corresponds to the blue bars).

The distribution and abundance of gizzard shad in the CAWS is not unusual for large water systems and Simon and Sanders (1999) suggest not including this species in community structure comparisons as a potential source of bias in analysis. Emerald shiner is commonly found in large rivers and appears to thrive in reservoir systems (Becker, 1983), so their numbers and distribution within the CAWS is not unexpected. Common carp are found in turbid, warm, large river systems of the Midwest (Becker, 1983) and their distribution and abundance in the CAWS is also not surprising. Largemouth bass are also abundant in large rivers of the Midwest (Becker, 1983), with a presence expected in the CAWS and serve as a popular recreation target species within the system (Personal communication, Bradley, 2008). Pumpkinseed also appears to thrive in impounded systems (Becker, 1983) so their numbers and distributions are also not unexpected.

In 2008, 43 species were identified at the 20 stations sampled within the Study Area. Eleven of those species were identified as hybrids and the newly identified species included steelcolor shiner (*Cyprinella whipplei*), not previously identified within the Study Area.

The 2008 fish data included up to 19 species at the Damen Avenue station on the CSSC and as few as 2 species at Supplemental Station 2 (Willow Springs) on the CSSC. The most numerous species were gizzard shad, common carp, bluntnose minnow and pumpkinseed.

5.1.3 Summary of Metric Selection

Fish metric selection and calculation is a common form of fish data analysis (Flotemersch et al. 2006). The general approach for screening fish metrics to determine useful and appropriate measures for the CAWS followed methods applied in development of fish IBIs, as documented in peer-reviewed scientific literature. The objective of this process was not to develop a new IBI for the CAWS, but the process of metric development involves review, analysis, and reduction of fish metrics, so the methods used in the literature to develop IBIs provided a sound basis for screening of metrics as appropriate descriptions of the fisheries data for the CAWS.

The fish dataset used in the metric selection included CAWS fisheries data collected by the District between 2001 and 2007. The general procedures for selecting an appropriate set of fish metrics included the selection of a set of candidate metrics, the screening of candidate metrics and the final selection of representative fish metrics that are sensitive and respond to both physical and water quality changes. In summary, a starting list of 46 metrics was established from previous studies (Lyons et al., 2001; IDNR, 2000; OEPA, 1989; Karr, 1981). These 46 metrics were then screened through various procedures for metric removal (e.g., those lacking data, tests for metric redundancy and tests of variance sensitivity), resulting in a final list of twelve metrics (Table 5-2). The retained metrics are representative of each of the five ecological function categories as recommended by Simon and Lyons (1995), Lyons et al. (2001), Roset et al. (2007): species richness and composition (SRC), indicator species (ISM), trophic function (TFM), reproductive function (RFM), and individual abundance and condition (ACM).

Table 5-2: Selected CAWS Fish Metrics.

Fish Metric	Ecological Function Category[6]
% Diseased or with eroded fins, lesions, or tumors	abundance and condition metric (ACM)
catch per unit effort	abundance and condition metric (ACM)
% lithophilic spawners by count	reproductive function metric (RFM)
% insectivores by count	trophic function metric (TFM)
% top carnivores by weight	trophic function metric (TFM)
proportion of Illinois tolerant species	indicator species metric (ISM)
IL ratio of non tolerant coarse-mineral-substrate spawners	reproductive function metric (RFM)
number of IL native minnow species	species richness and composition metric (SRC)
number of IL native sunfish species	species richness and composition metric (SRC)
IL ratio of generalist feeders	trophic function metric (TFM)
% intolerant species by count	indicator species metric (ISM)
% moderately intolerant species by weight	indicator species metric (ISM)

5.2 MACROINVERTEBRATES

The Metropolitan Water Reclamation District of Greater Chicago (District) has been collecting macroinvertebrate data annually since 2001 within the Study Area. Given that the focus of this Study is on current conditions, the macroinvertebrate data analysis is limited to the data collected between 2001 and 2007. This data set, as mentioned in Section 3.1.2 was used to select CAWS appropriate macroinvertebrate metrics, compare collection methods using the selected metrics, and evaluate deformities as related to water quality and contaminated sediment.

5.2.1 Sources of Data

All macroinvertebrate data comes from District collected samples from the 2001-2007 sample period. For the sample period, the Study area includes data from 22 sample stations using Hester Dendy collected data and 24 stations were included using Ponar grab sampler data.

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[6] ACM = abundance and condition metric; RFM = reproductive function metric; TFM = trophic function metric; ISM = indicator species metric; SRC = species richness and condition metric.

5.2.2 Summary Description

The evaluation of the macroinvertebrate data by station and by reach found similar results; the macroinvertebrate community is dominated by a few opportunistic Diptera (Chironomidae) and non-insect taxa (Oligochaetes). Nearly half of the taxa collected in the CAWS are from the order Diptera, and almost all are in the family Chironomidae. By abundance, oligochaetes (Phylum Annelida) dominate the benthic community, comprising over 74 percent of all macroinvertebrates collected from the CAWS during the 2001-2007 period. Two species of non-native bivalve, the zebra mussel, *Dreissena polymorpha*, and the closely related Quagga mussel, *Dreissena rostriformis bugensis* comprise 15 percent of the samples as well.

An analysis of the differences between sampling methods, i.e. grab samples (ponar) and artificial substrate samples (Hester-Dendy), show that richness measures (total richness, EPT richness, and diptera richness) are higher in the Hester-Dendy samples. In contrast, EPT taxa were nearly absent from the ponar collections with EPT richness values of zero for most ponar samples showing that the two sampling methods collected different organisms and in different quantities. The lack of EPT taxa in ponar samples suggests that lack of suitable substrate is a physical habitat limitation for benthic invertebrates. The presence of intolerant benthic EPT taxa in Hester-Dendy samples and the absence of EPT taxa in Ponar samples suggest sediment toxicity to mayfly, stonefly, and caddisfly larvae.

An analysis of macroinvertebrate metrics appropriate for evaluation within the CAWS was conducted. This analysis included a correlation analysis of macroinvertebrate metrics with sediment contamination. Five metrics were identified based on their sensitivity to contaminated sediments. These are taxa richness, percent Diptera, percent Oligochaetes, percent shredders and function feeding group diversity. The CAWS contains legacy contaminants that likely influence the metrics. The Hester-Dendy technique is sampling a population that is less exposed to environmental stress than the ponar sampling technique, which samples invertebrate communities in direct contact with sediments. The community differences were identified by a comparative analysis of the two sampling methods, which varied by metric and monitoring station. For example, ponar sampling resulted in lower species richness dominated by pollution tolerant individuals (oligocheates).

Additionally, an analysis of the macroinvertebrate dataset of the percent of head capsule deformities of larvae of the Chironomidae family (midges) was conducted within the Study Area for the 2001-2007 period. Deformities in midge larvae head capsules have been frequently observed in contaminated sediments. Deformity is generally considered to be a sublethal, teratogenic response to contamination. In an analysis of variance test, we concluded that there is no significant difference between mean rates of head capsule deformities for those collected on Hester-Dendy samplers and those collected in ponar dredge samples ($F=2.89$, $p=0.0911$). The strengths of correlation were significant ($p<0.05$) in the Hester-Dendy samples for ammonia-N (r=-0.399), iron (r=0.361), and DDx (DDT + DDE + DDD) (r=-0.396). Spearman correlation coefficients were significant for the ponar samples for mercury (r=0.659), cadmium (r=0.339), copper (r=0.439), simultaneously extracted metals (SEM) (r=0.455), SEM-acid volatile sulfides (r=0.454), total PCB (r=0.316) and semi-volatile organic compounds (r=0.323). No contaminants displayed strong correlations for both collection methods. This may reflect differences in exposure routes or pathways for macroinvertebrates in ponar samples and Hester-Dendy samples.

6. HABITAT DATA ANALYSIS

As discussed in Section 2.5, the process used to analyze habitat data in the CAWS and to develop a CAWS-specific habitat index was based on the process used to develop a non-wadeable habitat index (NWHI) for Michigan (Wilhelm et al., 2005). The process involves three major elements:

1. Sequential reduction of the list of habitat variables using qualitative screening, correlation analysis, and principle components analysis;

2. Identification of the key habitat variables that best explain fish data using multiple linear regression; and.

3. Incorporation of the key habitat variables into an index that can be applied to measure variation and change in the system.

This section describes the processing and analysis of habitat data for these purposes.

6.1 IDENTIFICATION AND SCREENING OF HABITAT VARIABLES

Based on review of the Wilhelm paper (Wilhelm et al., 2005); other relevant technical literature (Arlinghaus et al., 2002; Wolter and Arlinghaus, 2003; Short et al., 2005; Tate et al., 2005), data collected by the District as part of the ambient water quality monitoring program, and firsthand observations of conditions in the CAWS, a list of 242 habitat variables was compiled as a starting point. The starting list of 241 habitat variables is presented in Appendix E and is organized into five categories: geomorphology and hydrology; sediment and substrate; in-stream and riparian cover; bank and riparian condition; and anthropogenic factors.

Because the ultimate objective was to use multiple linear regression to analyze the CAWS habitat data with CAWS fish data, it was necessary to reduce the number of habitat variables substantially. Using the District data from 2001 through 2007, there were 81 paired sets of habitat and fish data. Multivariate statistical analyses require that the ratio of variables to data be as low as possible. It has been suggested that, for analysis of ecological data, the variable-to-data ratio be 0.1, but may be as high as 0.5 (Smogor and Angermeier, 1999). This rule of thumb suggests that the number of habitat variables in this Study should be reduced to somewhere between 8 and 40, preferably closer to the low end of this range to yield a ratio close to 0.1. The stepwise process used to reduce the list of habitat variables to a suitable number for multiple linear regression is described in Figure 6-1 and described in detail in Appendix D.

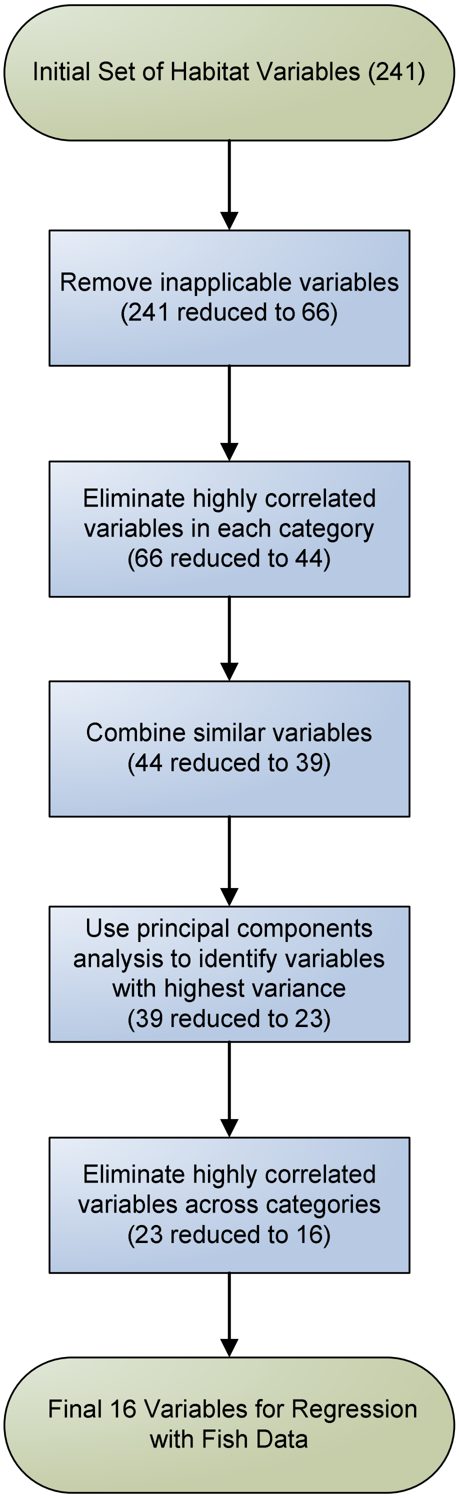

Figure 6-1: Process Used to Reduce the Set of Habitat Variables for Analysis with Fish Data.

This process outlined in Figure 6-1 was effective in reducing the set of habitat variables to 16, which represented a variable-to-data ratio of about 0.2.

Table 6-1: Final Set of Habitat Variables for Regression with Fish Data.

Variable Category	Habitat Variable
Geomorphology & Hydrology	Flashiness index Wetted perimeter of channel Maximum depth in reach Number of off-channel bays Bank “pocket” areas
Sediment & Substrate	% Gravel, cobbles, boulders, shallow % Gravel, cobbles, boulders, deep % Plant debris on bed % Organic sludge
In-Stream Cover	Average macrophyte cover In-stream cover present Secchi depth
Bank & Riparian Condition	Dominant riparian land use % Vertical walled banks in reach % Riprap banks in reach
Anthropogenic Impacts	Manmade structures

These 16 variables were carried forward for comparison to fish data, described below.

6.2 ANALYSIS OF THE RELATIONSHIP BETWEEN FISH AND PHYSICAL HABITAT IN THE CAWS

The process described in Section 6.1 and Appendix D effectively reduced 241 potential habitat variables to a much smaller set of 16, that represented the habitat variables with the least inter-variable correlation and which explained most of the variance in the habitat data set. The next task in this analysis was to analyze the relationship of these variables to fish in the CAWS. There were several objectives for this, including the following:

- Determine which physical habitat variables are the most significant to fish in the CAWS.
- Determine how much of the variability in the CAWS fish data can be explained by physical habitat.
- Compare the relative importance of physical habitat to fish in the CAWS, with that of water quality.

Statistical analysis of the fish and habitat data from the CAWS was used to attain these objectives. Specifically, multiple linear regression was used to compare habitat variables to paired fish data to determine which of the 16 habitat variables best explain variability in fish data in the CAWS. The methodology and results of this analysis are described below.

6.2.1 Methodology

Various methods can be used for comparing fish data and habitat data from a single system to address the objectives listed above. Review of the professional literature related to assessment of aquatic habitat shows a range of dependent variables and mathematical methods have been used and published in the peer-reviewed literature. No commonly accepted standards have been developed for this type of analysis, so selection of the methodology must rely to a large extent on professional judgment. In this study, the methods selected were based on the needs of the study, review of methods used by other investigators in similar studies, and on understanding of the unique aspects of the CAWS. More details on the methodology used are presented below.

6.2.1.a Representation of Fish Data in the Analysis of Habitat Data

As discussed in Section 2.5, fish were selected as the indicator biota for comparison to physical habitat data in this Study. Twelve key fish metrics were identified (Appendix A) using CAWS fish data collected by the District between 2001 and 2007 (Table 6-2). For purposes of comparing these fish metrics to habitat data, it was necessary to combine the metrics into a single value. A fish index of biological integrity (IBI) was not available that incorporated the selected metrics, although the process used to select the fish metrics was exactly the same process used in many fish IBI studies.

Statistical comparison of habitat variables with each of the twelve fish metrics would have been cumbersome and might not have yielded conclusive results regarding which habitat variables were most important to understanding fish data in the CAWS. So, as a starting point, the fish metrics were divided into the five ecological function categories and compared to habitat variables using multiple linear regression. Each of the fish metrics was first transformed to a normal distribution, if necessary, and standardized to give each metric equal weight. Then the metrics within each functional category were simply summed. Metrics that reflected positive conditions were assigned a positive value and metrics that reflected a negative condition were assigned a negative value.

Table 6-2: Selected CAWS Fish Metrics.

Fish Metric	Ecological Function Category
% Diseased or with eroded fins, lesions, or tumors	Abundance and condition metric (ACM)
catch per unit effort	Abundance and condition metric (ACM)
% lithophilic spawners by count	Reproductive function metric (RFM)
% insectivores by count	Trophic function metric (TFM)
% top carnivores by weight	Trophic function metric (TFM)
proportion of Illinois tolerant species	Indicator species metric (ISM)
IL ratio of non tolerant coarse-substrate spawners	Reproductive function metric (RFM)
number of IL native minnow species	Species richness and composition metric (SRC)
number of IL native sunfish species	Species richness and composition metric (SRC)
IL ratio of generalist feeders	Trophic function metric (TFM)
% intolerant species by count	Indicator species metric (ISM)
% moderately intolerant species by weight	Indicator species metric (ISM)

This process showed that, when grouped by function, the ACM metrics (catch per unit effort and percent diseased or with eroded fins, lesions, or tumors) had relatively weak correlation with habitat. The other four functional categories were approximately equal in their relationship to habitat. Based on these observations, a combined fish metric was calculated by summing the reproductive function, trophic function, indicator species, and species richness and condition metrics. Because a system-specific index of biotic integrity (IBI) for fish does not exist for the CAWS and other IBIs are not appropriate for the CAWS (see Appendix A) this combined fish metric was used in subsequent analyses with habitat data.

6.2.1.b Determination of Habitat Variables for Study Period

It would not be feasible to conduct this Study at present without relying on the data collected by the District in the past, as these data provide valuable measures of CAWS fisheries over many years. However, only a relatively limited set of physical habitat data were measured concurrent with the District’s fish sampling events from 2001 through 2007. Therefore, to use the District’s fish data in this Study, it was necessary to make some assumptions regarding physical habitat during that time period, as described below.

- All hydrologic variables were assumed constant from year to year, using model predictions the DUFLOW model developed by Marquette University. Given the highly regulated hydrology of the system and the fact that most of the flow entering the CAWS is from wastewater treatment plants, it is unlikely that significant variations in average or extreme hydrologic variables occurs from year to year.

- Bank and riparian conditions were assumed to be the same as observed in 2008, unless otherwise noted in the District's physical habitat observations. Given the urban, constructed nature of the CAWS, this is likely a safe assumption. No major changes in these conditions were noted in consultation with District personnel involved in routine monitoring in the CAWS.

- No quantitative measurements of macrophyte growth were available from 2001 – 2007. Quantitative measurements of littoral macrophyte coverage were made in 2008 as part of this Study, though, and the presence of aquatic macrophytes was noted on the historical habitat assessment forms completed by the District from 2002-2007. Lacking historical data, but recognizing the probable importance of macrophyte cover, the decision was made to retroactively apply 2008 macrophyte measurements to the period of 2001 – 2007. While this is likely not an accurate representation of historical conditions, it is better than disregarding macrophytes altogether. Furthermore, review of the historical habitat assessment forms generally corroborated the 2008 data.

In this Study, the assumptions regarding the similarity of physical habitat condition between 2008 and the preceding seven years are believed to be reasonable, given the relatively unchanging nature of conditions within the CAWS and the nature of the subject variables. The percentage of vertical walled banks at a sampling station, for example, was likely about the same in 2008 as it was in 2001. Although minor changes cannot be ruled out, they are likely not significant compared to the variability in fish data at these stations from year to year, which can be quite large.

One variable that is less reliably estimated in this retroactive manner is Secchi depth, which was not measured during 2001 – 2007, but was measured in 2008 for this study. Historical turbidity data collected by the District shows that water clarity can vary over time in the system, so assuming that 2008 Secchi measurements accurately reflect conditions at a location in preceding years is probably not accurate. As an alternative, 2008 Secchi data were compared to turbidity measurements from the CAWS to assess whether historical Secchi could be estimated using turbidity (Figure 6-2).

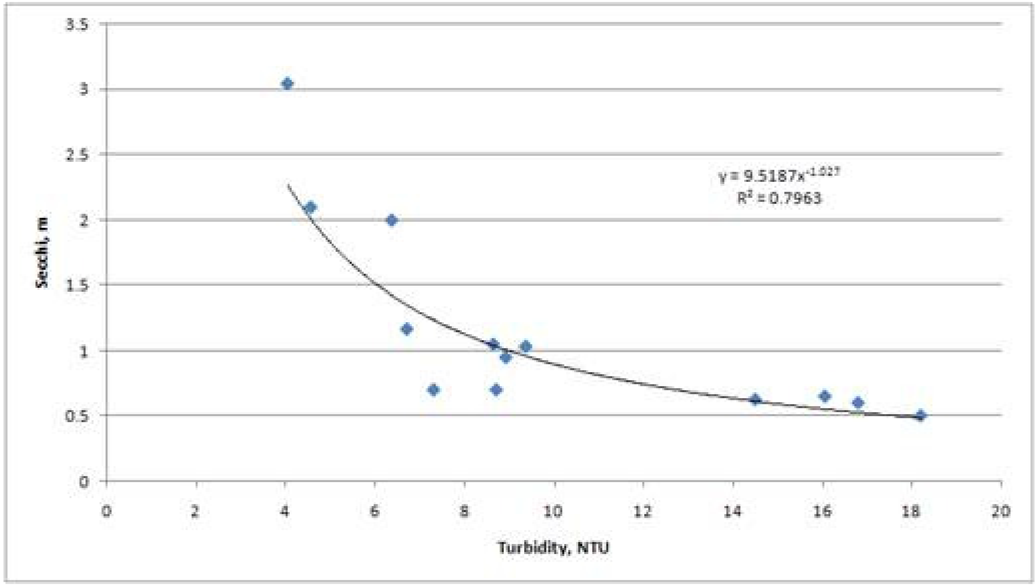

Figure 6-2: Comparison of 2008 Secchi Measurements with 2008 Turbidity Measurements.

The regression of the 2008 Secchi with the 2008 turbidity yields an r-squared value of nearly 0.8, which indicates a relatively strong relationship between the two measurements. However, there is still as much as a 0.5 m variance between actual and predicted Secchi using the regression relationship, which could result in a prediction error of approximately 50% for areas where Secchi is on the order of 1 meter depth, which is common in the CAWS. In addition, Secchi is typically used in habitat studies as an indicator of light penetration, related to the growth of aquatic macrophytes that create fish habitat and provide food. In this Study, a metric reflecting macrophyte growth was already included, so Secchi was, in this sense, redundant. For these reasons, Secchi was eliminated from the analysis, which resulted in 15 habitat variables for the regression analysis.

6.2.1.c Description of Multiple Linear Regression Method Used

For this analysis, multiple linear regression (MLR) was chosen as the statistical method for comparing habitat variables with fish data, for a number of reasons. First, MLR is a mathematically rigorous method that has been used in several habitat studies published in professional literature and for development of habitat indices. Second, MLR was used in the development of the Michigan Non-Wadeable Habitat Index, which was the model approach for this study as discussed in Section 2.5 of this report. Third, MLR provides a parametric measure of goodness-of-fit (i.e., r-squared value) that allows relatively straightforward comparison of data models to each other and that provide a quantitative measure of the degree to which the independent variable data (i.e., habitat or water quality) describe the variation in the dependent variable data (i.e., fish data).

Several MLR methods exist to choose from. The most commonly used methods are standard stepwise, forward selection stepwise, backward elimination stepwise, and best subsets. Each of the three stepwise methods involves starting with an initial set of variables in the regression model and then adding or removing variables according to a set of rules until some subsequent steps do not improve the fit of the model to the data. The best subsets method calculates all possible regression models using all possible numbers of variables. Instead of producing a single regression model, the best subsets method produces several to choose from.

Stepwise regression methods have been criticized because they do not allow the application of specialized knowledge about the data or the system being studied to inform the selection of the regression model. For this reason, the best subsets method was selected for this study. As will be shown in subsequent sections of this report, this method produced several possible regression models that allowed the opportunity for comparison between models and the application of judgment regarding model selection.

6.3 SYSTEM-WIDE COMPARISON OF HABITAT WITH FISH

The final selected set of habitat variables were compared to the CAWS fish data from 2001 through 2007 (using the “combined fish metric” described in Section 6.2.1.a) using multiple linear regression (MLR). As discussed above, this method was selected because it identified the habitat variables that statistically best explain the fish data, assigns relative weights to those variables to inform their relative importance, and produces a quantitative metric (the r-squared value) that can then be compared to the relative importance of other variables, such as water quality.

6.3.1 Interpretation of Best Subsets Multiple Linear Regression Results

The best subsets MLR method calculates regressions of all permutations of the independent variables (habitat) with the dependent variable (fish) and produces multiple regression models for inspection. The method does this by calculating a specified number of regression models using various numbers of variables from one up to the total number of variables. The MiniTab statistical software package was used to conduct the MLR analysis and it allows specification of the number of regression models produced in each variable set. For this study, the top three regression models were produced for each variable set. In other words, starting with a total of 15 variables, the analysis produced the top three regression models with one habitat variable, the top three regression models with two variables, and so on, up to 15 variables.

With multiple regression models calculated for each analysis, some means of discriminating between the regression models and for selecting a preferred model is needed. There are several factors that were considered in this study, when inspecting the MLR results:

- Number of variables – Because the best subsets MLR produced regression models with as few as one variable, and as many as 15, there was wide latitude in selecting regression models with a range of variable numbers. Although in some analyses the model with the fewest variables, all other things being equal, might be preferred, that was not the case here. The review of the regression models took into account the objectives of the study, specifically the need to support development of a descriptive index for physical habitat. In that sense, it can be argued that a greater number of variables is preferable to a fewer number of variables.

- Sign of the variables – Each variable that appears in a regression model has a positive or negative value. A positive value indicates that the habitat variable is positively correlated with the fish data and a negative sign indicates the opposite. In some cases, it was observed that variables intended to represent a positive habitat condition were assigned a negative sign in a particular regression model or vice versa. Due to the highly modified nature of the CAWS, this may have occurred in this study more than would occur in a study of natural systems. In any case, it may be counterproductive to use a regression that includes these variables. This is discussed in Section 6.3.2 below.

- R-squared and adjusted r-squared values – The r-squared value for each regression model was calculated and an "adjusted" r-squared was also calculated for each. The adjusted r-squared value accounts for the degrees of freedom in the regression. In other words, the raw r-squared value of the regression may be increased by adding more variables (degrees of freedom) but the statistical certainty of the calculated data relationship may be diminished. The adjusted r-squared value accounts for this and is, therefore, a truer measure of the regression model's descriptive ability. In comparing regression models, a higher adjusted r-squared was preferred.

- Mallow's C-p value – Mallow's C-p is a commonly used parameter in MLR analysis because it represents a measure of both the variance of the regression and the bias[7]. As more variables are added to the regression, C-p typically increases. Although a common interpretation of MLR results is to select the regression model with the lowest C-p (meaning the regression with the lowest total discrepancy (variance plus bias), such a model might not be the best fit to the data. A higher C-p value means a regression model with more discrepancies but, possibly, a better fit to the data. In general, a value of C-p that is equal to, or less than, the number of variables in the regression has the minimum bias. In comparing regression models in this study, a Mallow's C-p value less than the number of variables in the regression was preferred.

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[7] In regression analysis, bias refers to the systematic overestimation or underestimation of the dependent variable by the regression model. This is different from variance, which is the natural variability or "scatter" of the variable.

- Variable confidence – For each variable included in each regression model, a statistical confidence level (p-value) was calculated. This value reflects the level of uncertainty in each variable and a 90% confidence level was preferred (p<0.10). Trade-offs between statistical certainty and regression fit were observed. Adding more variables might, in some cases, have increased the adjusted r-squared of the regression, but it might have diminished the statistical certainty of certain variables. The variable p-values were the last item to be examined and although the inclusion of variables with p-values greater than 0.1 did not automatically eliminate the regression from consideration, this factor was weighed.

All of these factors were considered when reviewing the MLR results in this study. In addition, the application of professional judgment and consideration of the objectives of the study were integral to the process. As stated in Draper and Smith (1981) when discussing selection of regression models, "all selection procedures are essentially methods for the orderly displaying and reviewing of data. Applied with common sense, they can produce useful results; applied thoughtlessly, and/or mechanistically, they may be useless or even misleading."

6.3.2 Discovery of Counterintuitive Variable Results

The initial MLR was conducted using available paired (concurrent and collocated) measurements of fish and habitat. In all, 81 paired fish/habitat "events" were used in this analysis. Initial MLR analyses presented some counterintuitive results for certain variables, described below:

- Flashiness appeared as a positively correlated variable with fish, when it generally is believed to be a negative condition reflecting watershed urbanization and increased imperviousness. It was concluded, given the highly regulated hydrology of the CAWS, that flashiness is not a truly meaningful habitat variable in the CAWS and that it's positive relationship to fish is an artifact of the data.

- The percent large substrate (gravel, cobbles, and boulders) in deep water appeared as both a negatively and positively correlated variable with fish, depending on which other habitat variable were used in a particular regression. This suggested a degree of instability and unreliability in the data for this variable.

- Similar to the percent large substrate in deep water, the variable representing the percentage of plant debris on the channel bottom appeared as both a positive and a negative variable in the different regressions. Again, this suggested a degree of instability and unreliability in the data for this variable.

Based on these observations, these three variables were eliminated from the regression analysis, so the final regressions between habitat variables and fish data were conducted using 12 habitat variables (Table 6-3).

Table 6-3: Final Habitat Variables Used in Multiple Linear Regression with Fish Data

Variable Category	Habitat Variable
Geomorphology & Hydrology	Wetted perimeter of channel Maximum depth in reach Number of off-channel bays Bank "pocket" areas
Sediment & Substrate	% Gravel, cobbles, boulders, shallow % Organic sludge
In-Stream Cover	Average macrophyte cover In-stream cover (present or absent)
Bank & Riparian Condition	Dominant riparian land use % vertical walled banks in reach % Riprap banks in reach
Anthropogenic Impacts	Manmade structures

6.3.3 System-Wide MLR Results

The MLR between the habitat variables and the combined fish metric was first run using the 2008 Secchi data, retroactively applied at each station for the 2001 – 2007 events. Using the best subsets method, the top three regression models for each possible number of variables were identified. Table 6-4 shows the results of this analysis. The habitat variables are listed across the top of the table and each row represents a different regression equation. The variables included in each regression are indicated by an "X" in the column for that variable.

The second and third columns present the r-squared and adjusted r-squared values for each regression. The r-squared is the basic "goodness of fit" measure, which indicates how much of the data variability is explained by the regression. An r-squared of 0.4 indicates that 40% of the data variability is explained by the regression equation. In general, the r-squared value will continue to increase as more variables are added, but there is a point beyond which the statistical reliability of the regression begins to diminish. To account for this, the adjusted r-squared is calculated, which takes into account the statistical reliability as a function of the number of variables, which is why the adjusted r-squared begins to decrease after a certain number of variables is reached.

Table 6-4: Summary of Regression Models for System-Wide Comparison of Fish and Habitat Data for 2001 – 2007

No. Vars	R-squared	Adjusted r-squared	Mallows C-p	WET_PER	MAX_DEP	OFF_CH_BAY	BANK_POC_AREA	BIG_S	CAWS_ORGSLG	DOM_LU	BNK_WALL	BNK_RIPRAP	MAN_MADE_STRUC	MCRPH_CHAN	NUMCOV
1	0.25	0.24	25.2		X										
1	0.15	0.14	38.6						X						
1	0.15	0.14	39.0											X	
2	0.35	0.34	12.8		X							X			
2	0.33	0.31	16.2		X	X									
2	0.31	0.29	19.3		X								X		
3	0.42	0.4	6.1		X				X			X			
3	0.4	0.37	9.3		X							X	X		
3	0.4	0.37	9.4		X						X	X			
4	0.44	0.41	5.4		X							X	X		
4	0.44	0.41	5.5		X						X	X	X		
4	0.43	0.40	6.1		X				X		X	X		X	
5	0.47	0.43	3.5	X	X							X	X	X	
5	0.47	0.43	3.6		X						X	X	X		
5	0.46	0.42	4.9		X	X					X	X	X		
6	0.48	0.44	3.6	X	X					X		X	X	X	
6	0.48	0.44	4.0		X	X					X	X	X	X	
6	0.48	0.43	4.2	X	X						X	X	X	X	
7	0.49	0.44	4.0	X	X					X		X	X	X	X
7	0.49	0.44	4.6	X	X					X	X	X	X	X	
7	0.49	0.44	5.0	X	X			X		X		X	X	X	
8	0.5	0.44	5.2	X	X			X		X		X	X	X	X
8	0.5	0.44	5.5	X	X			X		X	X	X	X	X	
8	0.49	0.44	5.9	X	X		X			X		X	X	X	X
9	0.5	0.44	7.0	X	X			X		X	X	X	X	X	X
9	0.5	0.44	7.2	X	X			X	X	X		X	X	X	X
9	0.5	0.44	7.2	X	X		X	X		X		X	X	X	X
10	0.5	0.43	9.0	X	X	X		X		X	X	X	X	X	X
10	0.5	0.43	9.0	X	X			X	X	X	X	X	X	X	X
10	0.5	0.43	9.0	X	X		X	X		X	X	X	X	X	X
11	0.5	0.42	11.0	X	X	X	X	X		X	X	X	X	X	X

As shown in Table 6-4, the regression models have adjusted r-squared values ranging from 0.14 to 0.44. The regression models with four variables or fewer have lower adjusted r-squared values and C-p values that are greater than the number of variables, indicating relatively high bias (systematic overestimation or underestimation of the data), so these were not considered further. The maximum adjusted r-squared value of 0.44 was achieved with regression models having six or more variables. Increasing the number of variables beyond six did not increase the adjusted r-squared value, but increased the C-p values and also resulted in some significantly increased P-values (not presented in the table), suggesting there was little benefit to using a regression model with more than six variables.

The two 6-variable regression models having adjusted r-squared values of 0.44 contained five variables in common. One regression model included channel wetted perimeter as the sixth variable and the other included off-channel bays as the sixth variable. With this as the point of comparison, the model including off-channel bays was selected because this variable was more intuitively understandable in terms of its habitat benefit than channel wetted perimeter.

The six-variable regression that is selected from this process included the following habitat variables:

- Maximum depth of channel ($p=0.000$)
- Off-channel bays ($p=0.197$)
- Percent of vertical wall banks in reach ($p = 0.053$)
- Percent of riprap banks in reach ($p = 0.001$)
- Manmade structures in reach ($p = 0.019$)
- Percent macrophyte cover in reach ($p = 0.086$)

The regression calculated using these variables had a raw r^2 of 0.48 and an adjusted r^2 of 0.44. This result indicated that the six variables in the regression account for 48% of the variability in the fish data in the CAWS. The equation for this regression was:

$$\begin{aligned} \mathrm{CFM} = {} & 12.8 - 0.381 \text{ x } \mathrm{MAX\_DEP} + 1.03 \text{ x } \ln(\mathrm{OFF\_CH\_BAY} + 1) - 2.03 \text{ x } \\ & \mathrm{asin}((\mathrm{BNK\_WALL})^{0.5}) - 1.11 \text{ x } (\ln(\mathrm{BNK\_RIPRAP} + 1)) - 6.06 \text{ x } \\ & \ln(\mathrm{MAN\_MADE\_STRUC} + 1) + 0.214 * \mathrm{MCRPH\_CHAN} \end{aligned}$$

Where:

CFM = Combined fish metric

MAX_DEP = The maximum channel depth in reach

OFF_CH_BAY = the number of areas in the reach that function as off-channel bays, providing refuge for fish

BNK_WALL = the percentage of bank, by length, occupied by vertical walls

BNK_RIPRAP = the percentage of riprap banks in reach, by length

MAN_MADE_STRUC = the number of manmade structures in the reach

MCRPH_CHAN = the percentage macrophyte cover in the reach.

Each of the variables in this regression has a p-value less than 0.1, which represents 90% confidence, except off channel bays, which has a p-value of 0.197 (~80% confidence). A plot depicting this regression is presented in Figure 6-3.

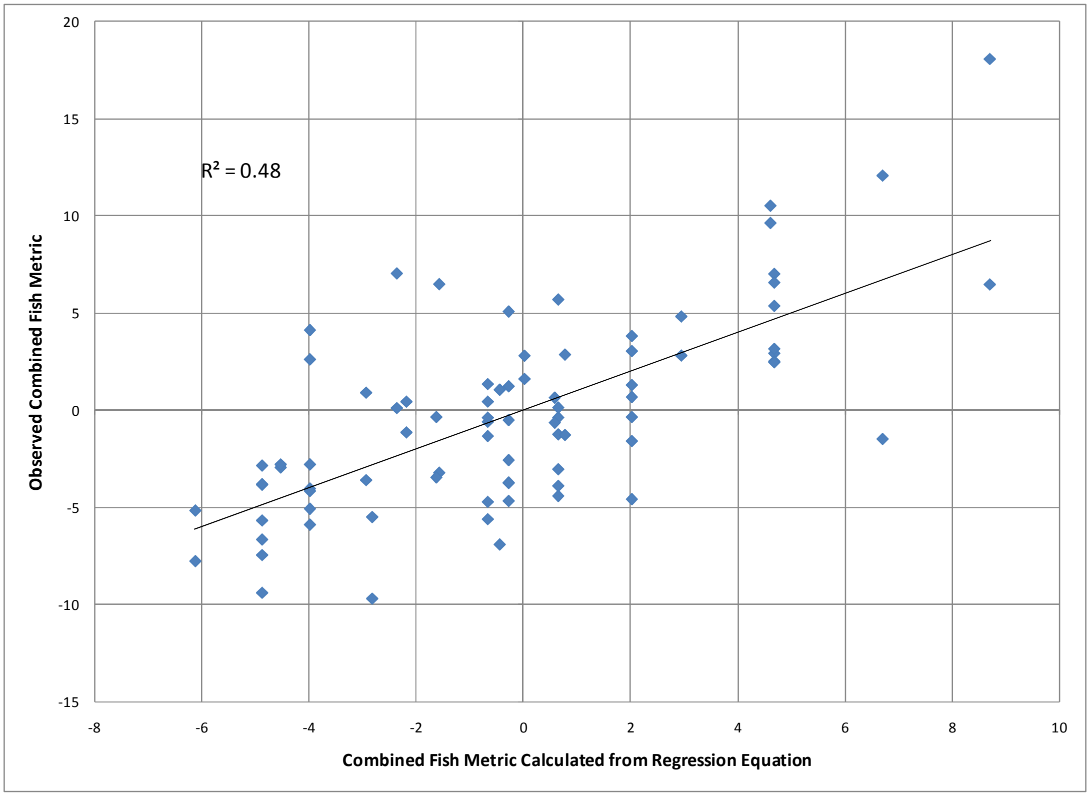

Figure 6-3: Plot of CAWS Six-Variable Habitat Regression Model with 2001-2007 Fish Data.

One of the underlying assumptions of MLR is that the regression residuals (predicted values minus observed values) follow the normal distribution. The normal probability plot depicted in Figure 6-4 shows that the residuals are normally distributed. Values in a normal distribution will fall on the diagonal line.

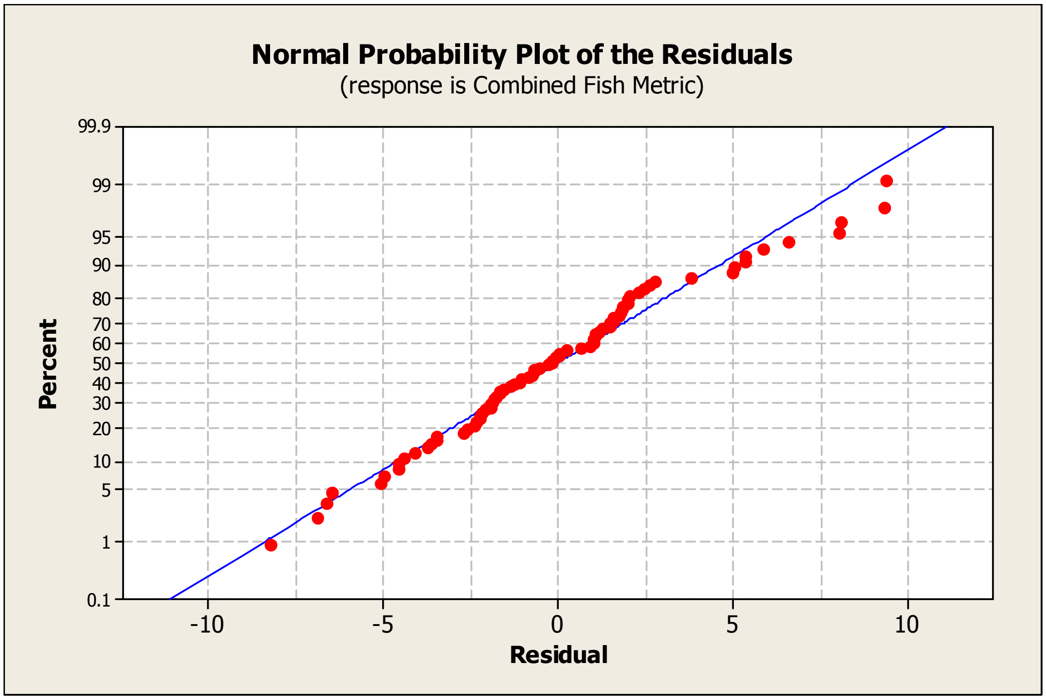

Figure 6-4: Normal Probability Plot of Regression Residuals for the Selected Six-Variable CAWS Habitat Regression with Fish Data.

In addition to the assumption of normality, it is assumed that the residuals are independent. This is evaluated using a scatter plot of residuals against fitted values, as depicted in Figure 6-5.

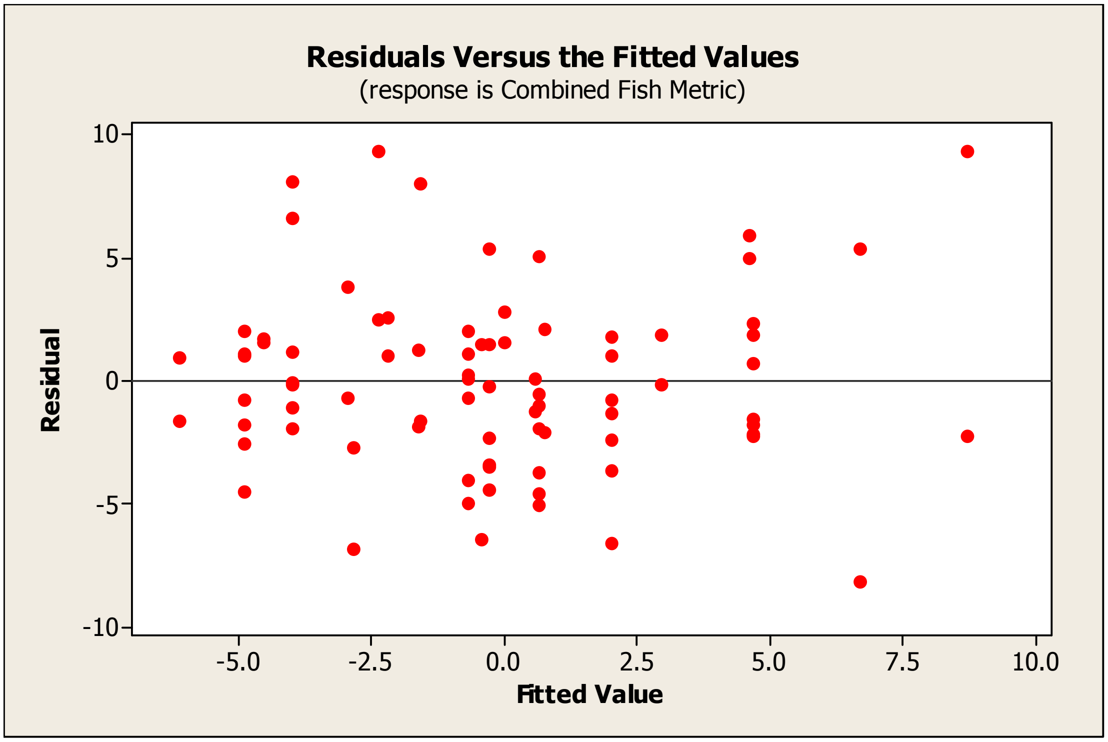

Figure 6-5: Scatter Plot of Regression Residuals vs. Fitted Values for the Six-Variable CAWS Habitat Regression.

The values of the residuals plotted against the fitted value appear to be randomly distributed, suggesting that the residuals are independent. Based on these analyses of the regression residuals, the seven-variable CAWS habitat regression appears to uphold the underlying assumptions of normality and independence.

6.3.4 Comparison of Habitat Regressions to 2008 Fish Data

To evaluate and verify the usefulness of the regression model described above, 2008 fish data were used. In 2008, fish samples were collected at 20 stations in the CAWS Study area, which included 14 stations sampled by the District and six supplemental stations sampled by LimnoTech and their subcontractor Ecological Specialists, Inc. The combined fish metric for these 20 stations was calculated from the 2008 fish data and compared to the habitat regression model described above, calculated at the 20 stations. Comparison of the six-variable regression model to the 2008 fish data is depicted graphically in Figures 6-6.

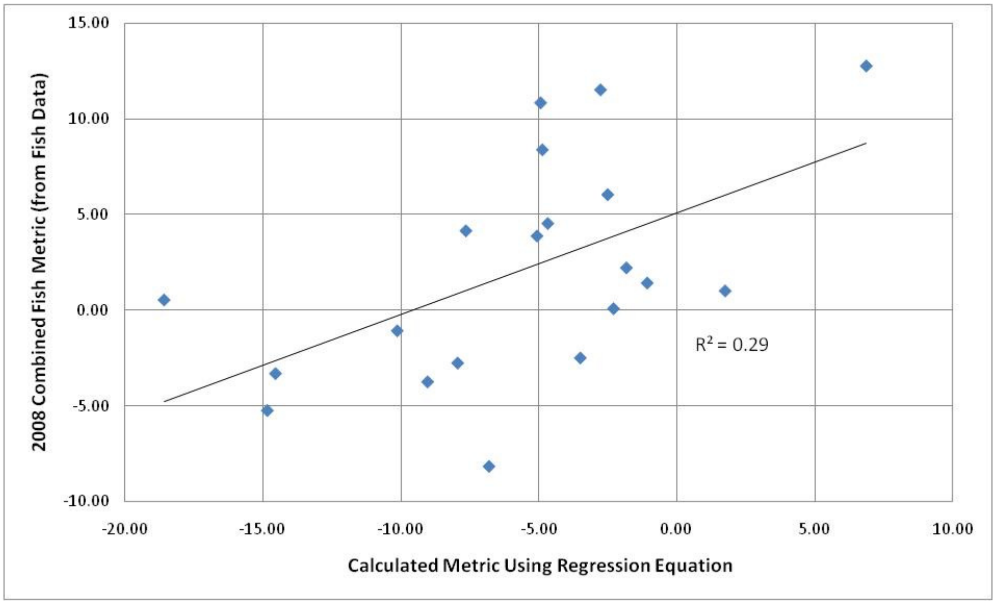

Figure 6-6: Comparison of the CAWS Habitat Regression Model with 2008 Fish Data.

As shown in Figure 6-6, the six-variable habitat regression model (developed using 2001 – 2007 fish data) shows a relatively good fit with the 2008 fish data. The r-squared value of 0.29 (p = 0.014) indicates that there is good and statistically significant correlation (98.6% confidence) between the habitat regression model and the 2008 fish data.

It is also of interest to know how this regression might correlate with long-term averages in CAWS fisheries condition. To evaluate this, the average combined fish metric at each CAWS sampling station was calculated from the 2001 – 2008 data and the regression equation was compared to these averages. Figure 6-7 shows this comparison. The regression fit the long-term averages with an r-squared of 0.51, indicating that the six habitat variables in the regression equation explain more than 50% of the variability in fish data over long periods.

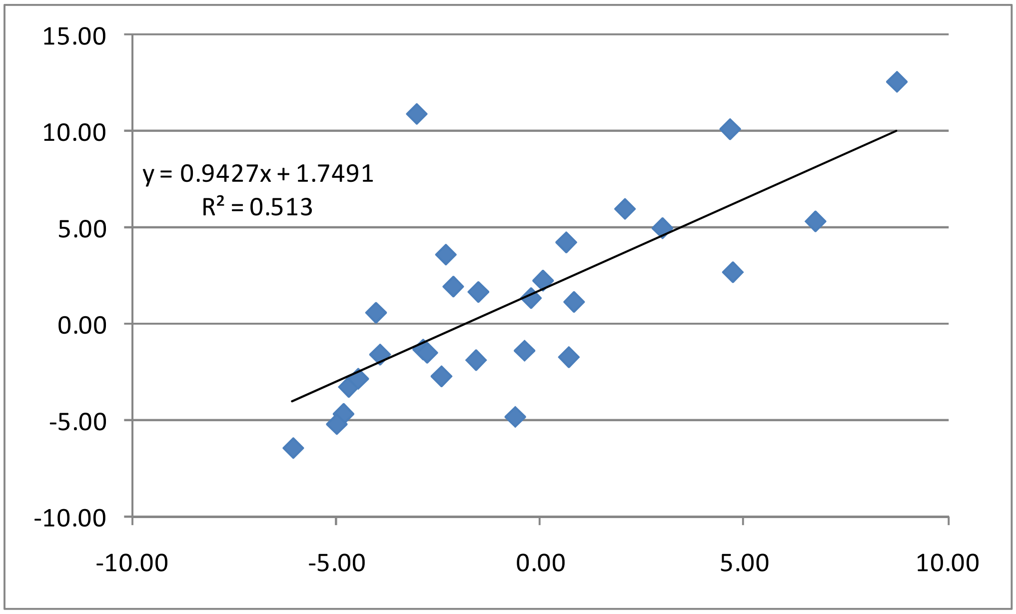

Figure 6-7: Comparison of the CAWS Habitat Regression Model with Averaged Fish Data (2001 – 2008).

This comparison is further verification of the importance of the six habitat variables in the habitat regression and indicates that the regression can provide a solid foundation for development of a habitat index for the CAWS.

6.4 RELATIVE IMPORTANCE OF PHYSICAL HABITAT IN THE CAWS

The regression analysis of physical habitat with fish can be used to evaluate the relative importance of habitat to fish in the CAWS. As previously discussed, the regression analysis shows that physical habitat can explain 48% of the fish data collected from 2001 – 2007. While this is a significant finding, it means that approximately half of the fish data is not explained by the six habitat variables in the regression. The following sections evaluate what else might be contributing to variability in CAWS fish data.

6.4.1 Variation in Fish Data Not Explained by Habitat Variation

The observation that physical habitat conditions can explain up to approximately half of the variability in fish data raises the question as to what can explain the rest of the variability in CAWS fish data. To investigate this, two evaluations were performed using the regression residuals:

- The regression residuals were compared to the station-by-station variation in fish data between the 2001-2007 dataset and the 2008 dataset. This comparison was performed to evaluate how much of the unexplained variability in fish data may be attributable to variation in fish over time.

- The regression residuals were compared to DO metrics at each station. This comparison was performed to evaluate how much of the variability in fish data, not explained by the key habitat variables represented in the regression equation, may be attributable to DO.

The regression equation used for these comparisons was the six-variable regression equation presented in Section 6.3.3. These comparisons are depicted graphically in Figures 6-8 and 6-9, respectively.

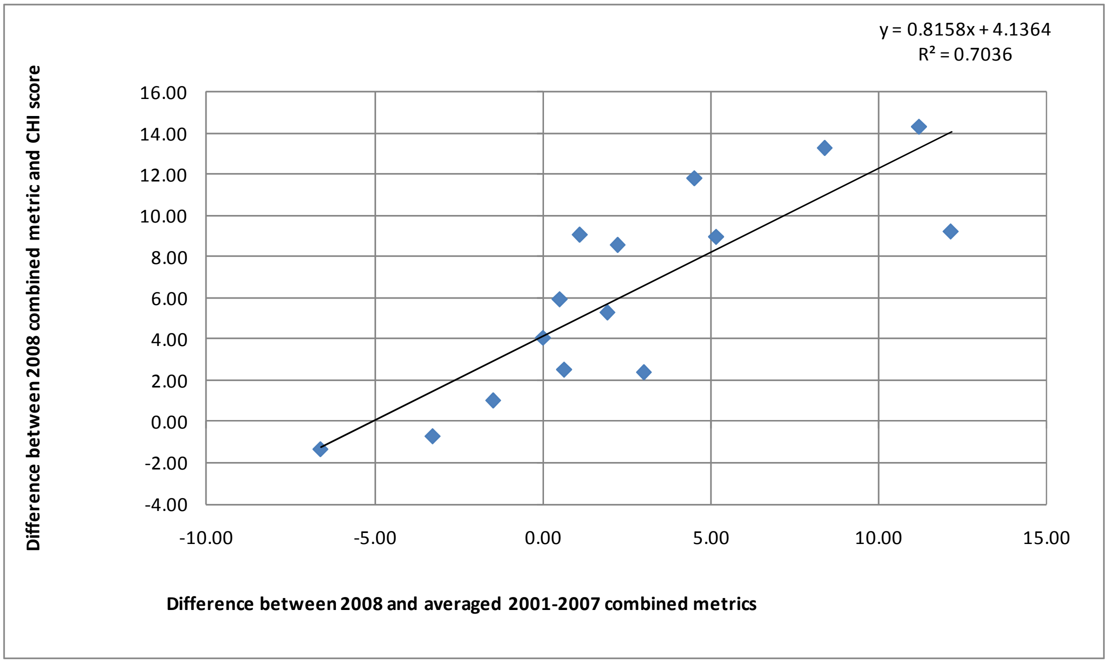

Figure 6-8: Comparison of Regression Residuals with Variation in Metrics Calculated Using Fish Data from 2001-2007 and 2008.

Figure 6-8 compares the habitat regression residuals (predicted values minus observed values) to the difference between the average fish metric values for the 2001 to 2007 data period (used for regression development) and the 2008 data set (used for regression validation). This comparison shows a relatively strong correlation (r-squared = 0.70) between the regression residuals and the change in fish metrics from the 2001-2007 period and 2008. This suggests that as much as 70% of the variability in the CAWS fish data that is not explained by the six habitat variables in the regression equation (35% of total variability in fish data) can be explained by variability in the fish samples themselves, as opposed to some other external condition, such as a missing habitat variable.

To further investigate this, the error associated with year-to-year variability of the combined fish metric at individual sampling stations was compared to the error of the regression model. Table 6-5 shows the standard deviation of the CFM at each of the stations. The mean standard deviation (the square root of variance from the mean) of the CFM measurements is 3.1 while the regression model root mean squared error (the square root of variance from the predicted value) is 3.7. The fact that the mean standard deviation is 3.1, which is nearly equal to the root mean squared error of 3.7, suggests that hat suggests that the majority of the model error is due to the year-to-year variability of the fish measurements.

Table 6-5: Standard Deviation of the Combined Fish Metric at District Sampling Stations.

Station_No	Station Name	n	Mean CFM	St Dev
1014	North Shore Channel at Central Street	2	12.3	8.2
1015	North Shore Channel at Touhy Avenue	7	0.3	2.9
1016	North Branch Chicago River at Wilson Avenue	2	-1.4	3.2
1017	South Branch Chicago River at Madison Street	2	3.6	4.9
1018	Chicago Sanitary and Ship Canal at Damen Avenue	2	-0.4	1.1
1019	Chicago Sanitary and Ship Canal at Harlem Avenue	7	-1.3	3.5
1020	Chicago Sanitary and Ship Canal at Route 83	2	1.6	6.9
1021	Calumet-Sag Channel at Route 83	2	-6.5	1.8
1022	North Branch Chicago River at Grand Avenue	7	-1.0	3.4
1023	Chicago Sanitary and Ship Canal at Stephen Street	2	-7.6	3.0
1029	Little Calumet River at Indiana Avenue	2	0.8	2.9
1031	Calumet-Sag Channel at Ashland Avenue	2	-2.9	0.1
1032	Calumet-Sag Channel at Cicero Avenue	7	-1.6	2.6
1034	North Branch Chicago River at Diversey Parkway	2	-2.9	5.6
1035	Chicago River at Lake Shore Drive	2	10.1	0.6
1036	Chicago Sanitary and Ship Canal at Cicero Avenue	7	-2.2	3.9
1037	Little Calumet River at Halsted Street	7	4.3	2.0
1045	Chicago Sanitary and Ship Canal at Lockport (16th Street)	7	-5.7	2.3
1048	Bubbly Creek at Archer Avenue	2	0.0	0.9
1049	Chicago River at Wells Street	2	2.2	0.8
1050	North Shore Channel at Foster Avenue	2	3.8	1.4
1051	North Shore Channel at Oakton Street	2	5.3	9.6
1056	South Branch Chicago River at Loomis Street	2	-1.9	2.2
	Mean across all stations (weighted by number of samples)	**81**	**-0.2**	**3.1**

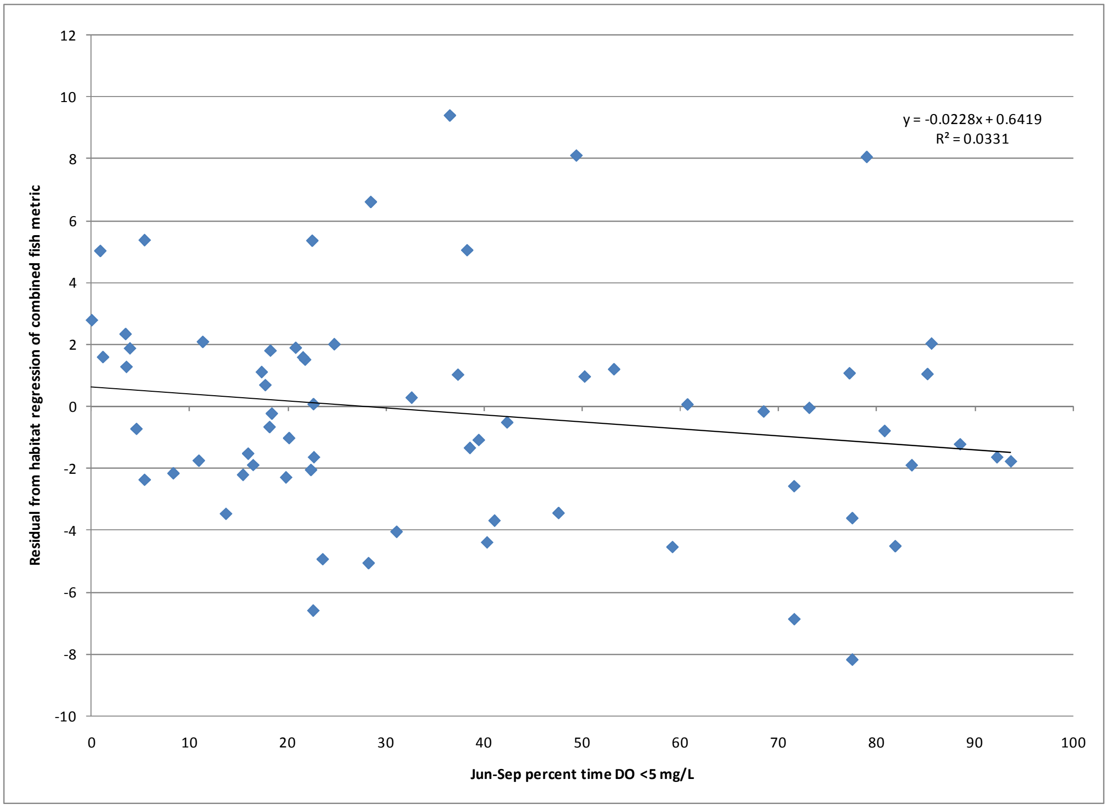

Figure 6-9: Comparison of Regression Residuals with Percent of Time Dissolved Oxygen Less Than 5 mg/L.

Figure 6-9 compares the habitat regression residual to the percent of time that DO was less than 5 mg/L at each station from June through September. This water quality metric was found to be the most highly correlated with individual fish metrics in the CAWS, as reported in Appendix C. The regression has an r-squared = 0.03, which indicates that only 3% of the CAWS fish data variability that is not explained by the six habitat variables in the regression equation (1.5% of total variability in fish data) may be explained by DO conditions at each sampling station.

6.4.2 Relative Importance of Habitat Versus Water Quality in the CAWS

The regression analysis presented in Section 6.3.3 shows that physical habitat alone can explain up to 48% of fish data collected in the CAWS from 2001 – 2007, which is significantly better than can be accomplished by evaluating water quality alone. In the analysis presented in Appendix C, the DO metric most highly correlated with fish data only had an r-squared of 0.27, meaning that DO alone can only explain 27% of the variability in the same seven years of fish data. This indicates that physical habitat is relatively more important in understanding fisheries in the CAWS than water quality.

To further investigate the relative importance of physical habitat and water quality to fish in the CAWS, A key DO metric (the percent of time that DO is less than 5 mg/L at each station from June through September) was added to a key habitat regression discussed above, to observe whether the inclusion of the DO variable would significantly improve the ability of the regression equation to explain the fish data.

It should be noted that a wide range of water quality metrics were evaluated with respect to fish data, to identify the metric most correlated to fish metrics, which was the percent of time that DO is less than 5 mg/L at each station from June through September. The six-variable regression equation discussed in section 6.3.3 was used for this test. That regression equation, developed using system-wide data, included the following variables:

- Maximum depth of channel
- Off-channel bays
- Percent of vertical wall banks in reach
- Percent of riprap banks in reach
- Manmade structures in reach
- Percent macrophyte cover in reach

The percent of time between June and September that DO was below 5 mg/l was added to this set of habitat variables because it was the water quality variable identified as having the strongest relationship to fish in the CAWS. This set of variables was then compared to fish data using multiple linear regression. It should be noted that this regression was conducted on a slightly smaller dataset (67 events) because continuous DO data were not available at all of the CAWS stations with fish and habitat data.

In the original regression using habitat variables alone, the comparison to fish data yielded an r-squared value of 0.48, meaning that the habitat variables explained about 48% of the fish data. With the reduced data set, the r-squared dropped to 0.42, probably because fewer data were used. When DO was added to the variable set and a new regression was calculated, the r-squared of the new regression with fish data was 0.46. This result indicates that including DO with the habitat variables improved the amount of fish data variability explained by the regression by about 4% over physical habitat alone.

6.4.3 Summary Findings for Relative Importance of Habitat in the CAWS

From these comparisons and the overall analysis of the relationship of physical habitat to fish in the CAWS, the following conclusions can be made:

- The two most important physical habitat variables in the CAWS that are positively correlated with fish are the amount of macrophyte cover and the quantity of areas that act as off-channel bays to provide refuge from the main channel.

- The four most important physical habitat variables in the CAWS that are negatively correlated with fish are the maximum depth of the channel, the amount of vertical walled banks, the amount of riprap banks, and the number of manmade structures.

- These six variables account for 48% (approximately half) of the variability in fish data collected in the CAWS from 2001 – 2007.

- Of the half of fish data variability that is not explained by these physical habitat variables, as much as 70% of that half can be explained by variation in fish sampling results from year to year. This means that the fish measured at a location can vary significantly from one sample event to the next and that this will lead to an inherent variability in the data that cannot be explained by changes in independent variables such as habitat or water quality.

- The percent of time that DO is less than 5 mg/L at a given station in the CAWS from June through September explains approximately 3% of the half of the fish data variability that is not explained by the six key physical habitat variables.

- DO is much less important to fish in the CAWS than physical habitat. DO alone can only explain between 2% and 27% of the fish data variability, while the physical habitat can explain 48%. The addition of the key DO metric to the main habitat variables only resulted in a 4% improvement over using habitat alone.

The use of these findings in developing a CAWS-specific habitat index is discussed in the next section.

7. DEVELOPMENT OF A CAWS HABITAT INDEX

The process outlined in Section 6 of this report systematically narrowed the field of potentially important habitat variables from 241 original variables to a final set of six habitat variables that represent the most statistically important measured habitat variables to fish in the CAWS. These six variables are:

- Maximum depth of channel
- Off-channel bays
- Percent of vertical wall banks in reach
- Percent of riprap banks in reach
- Manmade structures in reach
- Percent macrophyte cover in reach

Together, these habitat variables explain 48% of the fish data variability in the CAWS. The development of a system-specific habitat index is discussed in this section, with emphasis on the following topics:

- Objectives for the CAWS Habitat Index (Section 7.1) – The main objectives for a system-specific CAWS habitat index are outlined in this section.
- Use of the CAWS Habitat Regression Equation (Section7.2) – This section discusses the role of the CAWS habitat regression in developing a habitat index for the system.
- CAWS Habitat Index Development (Section 7.3) – Development of a CAWS-specific habitat index is discussed.
- Potential Limitations of the CAWS Habitat Index (Section7.4) – Potential limitations of the CAWS habitat index presented in Section 7.3 are described.

7.1 OBJECTIVES FOR THE CAWS HABITAT INDEX

One of the original objectives for this study, as discussed in Section 1 was to “use a multi-metric habitat index to evaluate physical habitat conditions in the CAWS and use physical habitat data and the above multi-metric index to assess the relative importance of physical habitat to fish in the CAWS.” As discussed in Section 2, no existing habitat indices for non-wadeable waters were identified that would be applicable to the CAWS, therefore development of a system-specific index would be required. The process of developing a system-specific habitat index required detailed, in-depth analysis of habitat and fish data. This process of data analysis, while paving the way for development of a system-specific habitat index for the CAWS, was also sufficient to meet the objectives for which the index was originally thought to be needed. Specifically, the evaluation of physical habitat conditions in the CAWS and the assessment of the relative importance of physical habitat to fish in the CAWS was addressed without an index, as discussed in Section 6.

As such, the objectives for a habitat index for the CAWS have shifted somewhat from what was originally envisioned. With the completion of the analysis documented in this report, the objectives for a CAWS-specific habitat index should be to:

- Provide a tool for characterization of reaches within the CAWS for purposes of comparing the range of habitat quality within the CAWS and for prioritizing locations for potential habitat improvement measures.
- Provide a tool for characterizing habitat changes in reaches over time.
- Represent the habitat attributes that are most important to aquatic biota in the CAWS, based on system-specific data.

The technical literature on the subject present different approaches for developing habitat indices and a single, universally accepted standard method has not been identified. The flowing sections address the use of the multiple linear regression analyses discussed previously in developing a CAWS-specific habitat index.

7.2 USE OF THE CAWS HABITAT REGRESSION EQUATION

One method for using the habitat regression presented in Section 6 to develop a CAWS-specific habitat index is to use a regression equation directly as an index equation to measure habitat quality in the CAWS. This has certain advantages, including the fact that the index would only include the habitat variables that are currently most important to the biotic indicator population (fish in this Study). Direct use of the variable coefficients from the regression equation as weights for the variables in the index would be the most statistically sound approach.

However, this approach has a significant limitation, in that it can ignore other important habitat variables that can be used to characterize physical habitat in the system. Using only variables from the regression analysis may omit variables that are important, but not as relatively important as those in the regression. For example, overhanging riparian vegetation was not included in the final habitat regression because it was highly correlated with vertical walled banks. This does not mean that it is not an important habitat variable. The bank pocket area variable was included in the regression analysis, but did not appear in the selected regression. This does not mean that these small bank refuges are unimportant to fish. A better approach is to use the regression analysis to inform the habitat index by pointing to important variables and by helping understand the relative importance of those variables. This allows for the application of professional judgment, informed by knowledge of the system, the data, and aquatic ecology in general. This approach is described below.

7.3 CAWS HABITAT INDEX DEVELOPMENT

As stated at the beginning of this section, the regression analyses presented in Section 6 identified six physical habitat variables that are the most important to fish in the CAWS, based on the data and analytical methods used in this study. Because they are the most important variables for understanding habitat quality, they are the best candidates for a CAWS-specific habitat index. In addition, other habitat variables were not included in the selected regression, but were evaluated for inclusion in the CAWS habitat index, as discussed below.

To evaluate the effect of including additional variables with the selected regression equation as the basis for an index, an index development spreadsheet was created using the regression equation, which would allow comparison of the regression calculation to the average combined fish metric at each station, for the monitoring period used in this study (2001-2008). This comparison was depicted graphically in Figure 6-6 and shows that the regression equation versus the average combined fish metric for each station has an r-squared of 0.51, meaning that the regression can explain 51% of the variability in long-term average fish data in the CAWS.

The index development spreadsheet also included station-by-station values of the following other habitat variables of interest:

- Bank pocket areas – This variable was used in the regression analysis but does not appear in the selected regression. It represents the count of relatively small bank refuge areas for fish and was included because it can represent an important cover variable.

- Large substrate in shallow and deep parts of the channel – These variables were also included in the regression analysis but did not appear in the selected regression. They were considered in the index development because of the general importance of large substrate to fish.

- Organic sludge – This variable was included in the regression analysis but did not appear in the selected regression. It represents a general substrate condition in some of the CAWS reaches that indicates very fine sediment with residual impacts of industrial chemicals. It was included because it may be an important local limitation to ecological health in parts of the CAWS.

- Overhanging vegetation – Overhanging riparian vegetation is recognized as important in aquatic systems for providing shade and a source of organic material and food (insects) for some fish. This variable was not included in the habitat regression analysis because it is strongly correlated with another variable, vertical wall banks. It is, however, an important habitat variable and should be included in the index.

The regression equation is simply the sum of the values for each included variable, each multiplied by a coefficient. The coefficients in the regression equation are determined by the statistical process. In adding variables to this equation, the assumption was made that none of the additional variables is more important than the variables in the original regression equation; otherwise they themselves would have appeared in the equation. Therefore, it was assumed that none of the additional variables could have a larger coefficient than the lowest coefficient already in the regression equation. In other words, the additional variable could not be weighted more heavily than a variable that appeared in the regression.

It was also recognized that the addition of variables would degrade the fit of the equation to the data. For index development, the average combined fish metric at each station was calculated for the 2001 – 2008 period. As described above and in Section 6.3.4, the regression equation had an r-squared of 0.51 with these long-term averages. It would be expected that adding variables to the equation would result in a lower r-squared, so there is a trade-off between adding variables and the r-squared value. It was decided that the addition of variables to the regression equation should not result in an r-squared less than 0.48, which was the r-squared that the original regression had with the 2001-2007 data, when it was originally developed.

With these constraints, the additional variables were tested alone and in combination, using coefficients less than 0.2, which was the lowest coefficient assigned to a variable in the original regression. Using this approach, a combination of coefficients was developed that matched the r-squared of the original regression (0.48). The variables and their coefficients are listed in Table 7-1. The variable values used in this analysis are presented in Table 7-2.

Table 7-1: Habitat Variables and Coefficients Used in CAWS Habitat Index.

Habitat Variable	Coefficient
Maximum depth of channel (-)	0.381
Off-channel bays (+)	1.03
Vertical wall banks (-)	2.03
Riprap banks (-)	1.11
Manmade structures (-)	6.06
Macrophyte cover (+)	0.214
Overhanging vegetation (+)	0.1
Bank pocket areas (+)	0.05
Large substrate - shallow (+)	0.005
Large substrate - deep (+)	0.005
Organic sludge (-)	0.08

Table 7-2: Values of Habitat Variables Assigned to CAWS Stations for Index Development.

Reach	Maximum Channel Depth (ft)	Off-Channel Bays	Vertical Wall Banks (%)	Riprap Banks (%)	Manmade Structures	Macrophyte Cover (%)	Overhanging Vegetation (%)	Bank Pocket Areas	Large Substrate – Shallow (%)	Large Substrate – Deep (%)	Organic Sludge (%)
AWQM 35 - Upper North Shore Channel	8	2	0	0	1.0	9	33	0	20	0	0
AWQM 102 - Lower North Shore Channel	6	1	0	0	2.0	10	29	3	0	0	0
AWQM 36 - Lower North Shore Channel	12	3	7	22	1.8	13	33	3	42	8	0
AWQM 101 - Lower North Shore Channel	10	3	5	6	2.0	9	29	6	25	0	0
AWQM 37–No. Branch Chicago River No. of Addison	12	1	0	100	2.0	0	25	15	85	0	0
AWQM 7 - No. Branch Chicago River So. of Addison	12	3	19	81	1.0	0	10	9	5	0	0
AWQM 46 -No. Branch Chicago River So. of Addison	13	7	100	0	1.7	0	0	2	9	3	9
AWQM 74 - Chicago River (Lake Shore Drive)	8	7	60	0	2.5	10	0	10	5	0	0
AWQM 100 - Chicago River (Wells St.)	21	8	97	0	1.0	0	0	0	19	0	6
AWQM 39 - South Branch Chicago River	23	9	100	0	1.5	0	0	6	0	0	8
AWQM 108 - South Branch Chicago River	22	4	77	0	1.5	0	0	4	3	18	4
AWQM 99 - Bubbly Creek	13	1	35	0	2.0	0	8	9	5	5	48
AWQM 40 - Chicago Sanitary and Ship Canal	20	3	67	0	2.0	0	0	6	53	0	36
AWQM 75 - Chicago Sanitary and Ship Canal	19	3	13	23	2.2	1	4	16	35	5	6
AWQM 41 - Chicago Sanitary and Ship Canal	20	5	48	0	1.8	3	3	10	60	13	5
S1 - Chicago Sanitary and Ship Canal	19	8	0	20	4.0	6	3	12	5	0	1
S2 - Chicago Sanitary and Ship Canal	24	1	100	0	1.0	0	14	4	0	0	0
AWQM 42 - Chicago Sanitary and Ship Canal	25	1	100	0	0.5	0	11	19	0	0	0
AWQM 48 - Chicago Sanitary and Ship Canal	26	4	100	0	1.0	0	2	20	3	0	0
AWQM 92 - Chicago Sanitary and Ship Canal	26	4	52	4	1.7	1	3	6	34	3	8
AWQM 43 - Cal-Sag Channel	16	0	51	49	2.0	0	5	8	25	0	13
S3 - Cal-Sag Channel	14	2	0	50	2.0	0	5	17	20	0	0
S4 - Cal-Sag Channel	15	2	8	48	3.0	0	4	10	70	2	5
S5 - Cal-Sag Channel	14	3	19	49	3.0	0	7	13	0	10	10
AWQM 58 - Cal-Sag Channel	15	0	49	51	1.5	0	3	10	25	3	18
AWQM 59 - Cal-Sag Channel	15	1	49	0	2.2	0	5	14	7	18	11
AWQM 56 - Little Calumet River	16	3	2	14	1.0	1	5	20	1	21	9
AWQM 76 - Little Calumet River	14	8	0	0	1.3	1	8	14	10	31	0

These 11 variables represent a good mix of habitat variables including bank condition, in-stream cover, substrate, and anthropogenic impact. They also represent variables that are relatively easy to measure and many may be alterable to improve habitat in the future. The equation for the raw CAWS habitat index is:

$$\begin{aligned}\text{CHI} = {} & 12.8 - 0.381 \times \text{MAX\_DEP} + 1.03 \times \ln(\text{OFF\_CH\_BAY} + 1) - 2.03 \times \\ & \text{asin}((\text{BNK\_WALL})^{0.5}) - 1.11 \times (\ln(\text{BNK\_RIPRAP} + 1)) - 6.06 \times \\ & \ln(\text{MAN\_MADE\_STRUC} + 1) + 0.214 * \text{MCRPH\_CHAN} + 0.1 \times \\ & \text{PER\_COV\_ALT} + 0.05 \times \text{BANK\_POC\_AREA} + 0.005 \times \text{BIG\_S} + 0.005 \times \\ & \text{BIG\_D} - 0.08 \times \text{CAWS\_ORGSLG}\end{aligned}$$

Where:

CHI = raw CAWS Habitat Index

MAX_DEP = The maximum channel depth in reach

OFF_CH_BAY = the number of areas in the reach that function as off-channel bays, providing refuge for fish

BNK_WALL = the percentage of bank, by length, occupied by vertical walls

BNK_RIPRAP = the percentage of riprap banks in reach, by length

MAN_MADE_STRUC = the number of manmade structures in the reach

MCRPH_CHAN = the percentage macrophyte cover in the reach

PER_COV_ALT = the percent overhanging vegetation

BANK_POC_AREA = the number of bank pocket areas

BIG_S = the percentage of large substrate (gravel, cobbles, boulders) in the shallow part of the channel

BIG_D = the percentage of large substrate (gravel, cobbles, boulders) in the deep part of the channel

CAWS_ORGSLG = the percentage of organic sludge in sediment samples

The index values calculated for each CAWS sampling station from 2001 – 2008 are graphically compared to the average combined fish metric at those stations in Figure 7-1. It should be noted that in the index development stage, the raw values of the index calculation were used. The final index is normalized to a 0 to 100 scale, as explained in Section 7.4.

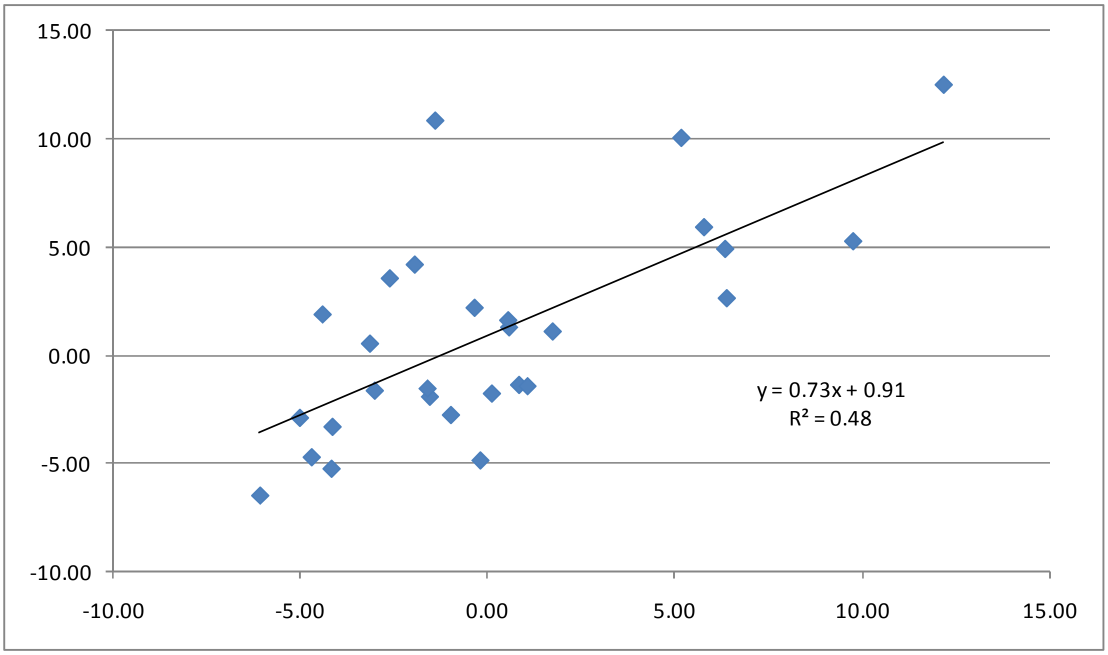

Figure 7-1: CAWS Habitat Index Compared to Average (2001-2008) Combined Fish Metric for Each Sampling Station.

As mentioned above, the r-squared of the CAWS habitat index to the fish data maintains the goodness of fit that the original habitat regression had, but it also compares well with comparisons reported for other habitat index studies that used multiple linear regression, as shown in Table 7-3.

Table 7-3: Comparison of Regression Coefficient Used in CAWS Habitat Index Development with Other Habitat Indices.

Habitat Index	Regression Coefficient for Index Development	Reference
CAWS	0.48	-
QHEI: comparison to IBI	0.45	Rankin, 1989
Maryland Physical Habitat Index: comparison to IBI	0.52	Hall et al., 1999
MI Non-Wadeable Habitat Index: comparison to catchment and riparian disturbance gradients	0.34/0.73	Wilhelm et al., 2005

The application of this index to individual reaches in the CAWS is presented in Section 7.4.

7.4 APPLICATION OF HABITAT INDEX BY REACH

The CAWS habitat index was calculated for each station as part of the index development, but it may also be useful for evaluating and comparing entire reaches in the CAWS. To do this, representative values had to be determined for each of the major reaches. The basis for assigning values of each variable is summarized in Table 7-4. The values assigned to each reach for each variable are presented in Table 7-5.

Table 7-4: Basis for Determining Reach-Wide Values of Key Habitat Variables.

Habitat Variable	Basis for Determining Variable Value
Maximum channel depth	Determined from reach bathymetry
Off-channel bays	Calculated as 2008 average of stations in reach
Vertical wall banks	Measured using bank video, in conjunction with GIS
Riprap banks	Measured using bank video, in conjunction with GIS
Manmade structures	Determined from CAWS bank video
Macrophyte cover	Calculated as 2008 average of stations in reach
Percent overhanging vegetation	Length of riparian overhanging veg. for entire reach determined by inspection of bank video and recorded in GIS. Depth of overhang calculated as 2008 average measured at stations in each reach
Bank pocket areas	Calculated as 2008 average of stations in reach, validated using bank video
Large substrate – shallow	Calculated as 2008 average of stations in reach
Large substrate – deep	Calculated as 2008 average of stations in reach
Organic sludge	Calculated as 2008 average of stations in reach

Table 7-5: Values of Key Habitat Variables Assigned to Major CAWS Reaches.

Reach	Maximum Channel Depth (ft)	Off-Channel Bays	Vertical Wall Banks (%)	Riprap Banks (%)	Manmade Structures (average # per 400 m reach, 1 significant figure)	Macrophyte Cover (%)	Overhanging Vegetation (%)	Bank Pocket Areas	Large Substrate – Shallow (%)	Large Substrate – Deep (%)	Organic Sludge (%)
Upper North Shore Channel (North of North Side WRP)	8	2	0	0	1	9	33	0	20	0	0
Lower North Shore Channel	12	2	0	7	2	11	30	3	21	4	0
Upper North Branch Chicago River (North of Addison)	12	2	9	53	2	0	25	15	85	0	0
Lower North Branch Chicago River (South of Addison)	13	5	80	18	1	0	5	6	7	2	5
Chicago River	21	8	97	0	1	0	0	0	19	0	6
South Branch Chicago River	23	7	90	4	2	0	0	5	1	9	6
Bubbly Creek	13	1	35	3	2	0	8	9	5	5	48
Chicago Sanitary and Ship Canal	26	4	59	5	2	1	5	12	24	3	7
Cal-Sag Channel	16	2	19	53	2	0	5	12	24	5	9
Little Calumet River	15	6	5	17	1	1	6	17	5	26	4

Using the CAWS habitat index equation presented in Section 7.3 and the values presented in Table 7-5, the CAWS habitat index score for each major reach can be calculated. As mentioned in the preceding section, the raw values of the index were used for station-by-station scoring during index development, but for scoring of reaches and for other applications, the index is normalized to a scale of zero to 100.

The normalization process was performed by assigning probable worst case and best case values to each habitat variable and calculating the resulting index values. For variables that are unlikely to change in the CAWS, such as maximum depth, the existing range of values was used to establish the worst and best cases. For bank condition variables, a range of zero to 100% was used because these variables could possibly be altered beyond what presently exists at a given location in the CAWS. The worst case and best case values and the calculated index scores are presented in Table 7-6.

Table 7-6: Worst Case and Best Case Values Assigned to Habitat Variables for Normalization of CAWS Habitat Index.

Variable	Transformed Value		Transformed Value	
	Value	Worst Case	Value	Best Case
Constant:		12.8		12.8
MAX_DEP	26	9.91	6	0.38
OFF_CH_BAY	0	0	9	2.37
BNK_WALL	100	3.19	0	0.00
BNK_RIPRAP	100	5.12	0	0.00
MAN_MADE_STRUC	4	9.75	0	0
MCRPH_CHAN	0	0	13	2.78
PER_COV_ALT	0	0	33	3.3
BANK_POC_AREA	0	0	20	1
BIG_S	0	0	85	0.43
BIG_D	0	0	30	0.15
CAWS_ORGSLG	48	3.84	0	0
Raw CAWS Habitat Index:		-19.01		22.45
Final CAWS Habitat Index:		**0**		**100**

After assigning worst case and best case values to each variable, the values were transformed using the transformations shown in the regression equation and summed to obtain a RAW index score (-19.01 to 22.45). The final index value was calculated by adding the minimum score (19.01) to the raw index, dividing that by the range of raw values (22.45 – (-19.01) = 41.46), and multiplying by 100. The results are summarized in Table 7-7 and depicted in Figure 7-2.

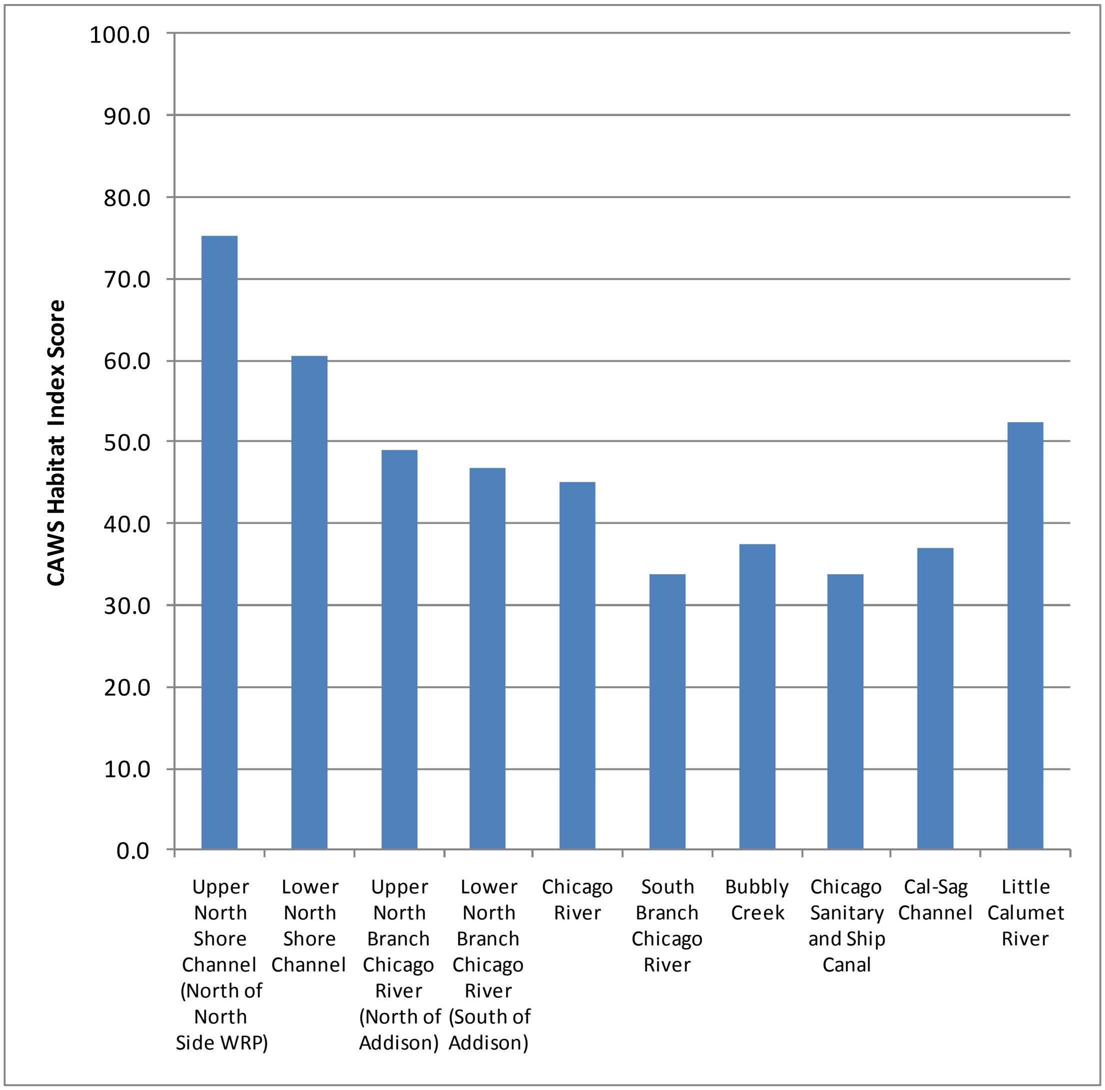

Figure 7-2: Results of CAWS Habitat Index Scoring for Major CAWS Reaches.

Table 7-7: CAWS Habitat Index Scores for Major Reaches.

Reach	CAWS Habitat Index Score
North Shore Channel North of North Side WRP	75.2
North Shore Channel South of North Side WRP	60.4
North Branch Chicago River North of Addison	49.1
North Branch Chicago River South of Addison	46.9
Chicago River	45.0
South Branch Chicago River	33.8
Bubbly Creek	37.4
Chicago Sanitary and Ship Canal	33.8
Cal-Sag Channel	37.1
Little Calumet River	52.4

7.5 POTENTIAL LIMITATION OF THE CAWS HABITAT INDEX

The CAWS Habitat Index (CHI) described above will provide a reasonable measure of physical habitat quality in the CAWS, to the extent that such a relationship can be developed with existing data. However, it is recognized that the data used to develop this index can be improved. Specifically, data were not available to adequately evaluate underwater habitat conditions in the CAWS, such as the presence of submerged structures. Because much of the system is maintained for navigation and effluent conveyance, large structures like fallen trees are routinely removed. Nonetheless, limited investigation during this Study using side scan sonar revealed the presence of some large woody debris and other submerged structures that might provide in-stream cover for fish. However, lacking sufficient data on submerged structure, it was not possible to evaluate its potential importance to fish in this Study. Further investigation of the potential for side scan sonar or some other remote sensing technology to observe and quantify the presence of submerged structure in the CAWS is recommended.

In spite of this limitation, the index presented here is useful in better understanding the relative differences in physical habitat in the CAWS.

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8. SUMMARY OF CAWS HABITAT EVALUATION

The data and analyses described in the preceding sections were used to conduct a comprehensive evaluation of physical habitat in the CAWS. The evaluation documented in this Study is summarized, including major conclusions.

8.1 MAJOR CONCLUSIONS

Several major conclusions are supported by the work conducted in this study, including the following:

- ***Aquatic habitat is inherently limited in the CAWS by the system's form and function.*** Habitat in the CAWS is significantly limited by the design of the CAWS, most of which is manmade. The manmade reaches of the CAWS were built to support wastewater effluent conveyance and commercial navigation. The reaches that were once natural streams have been heavily modified to serve these purposes and the changes are unlikely to be reversed as long as the CAWS needs to serve these functions. The form and uses of the CAWS impose severe limitations on physical habitat in the system.

- ***Physical habitat is relatively more important to fish in the CAWS than dissolved oxygen.*** When key physical habitat variables and dissolved oxygen metrics are statistically compared to fish data collected between 2001 and 2008 in the CAWS, it is apparent that habitat is much more important to fish than dissolved oxygen. Multiple linear regression shows that the dominant habitat variables identified in this study had an r-squared of 0.48 with fish, indicating that these habitat variables explain as much as 48%, or about half, of the variability in the fish data.

- ***Explaining approximately half of the CAWS fish data variability is excellent, considering the natural variability in the fish data itself.*** As stated above, about half of the variability in fish data in the CAWS is explained by physical habitat, in particular certain key habitat variables identified in this study. Of the half of fish data variability not explained by the key habitat variables, most is explainable by natural variation in the fish data from one sampling event to another at each location. In other words, fish samples exhibit large temporal variability at any given location in the CAWS and when the portion of fish data variability not explained by habitat is statistically analyzed, it is most related to the variation at sampling locations over time, independent of habitat changes.

- ***Dissolved oxygen is relatively poor at explaining variability in fish data in the CAWS.*** Dissolved oxygen does not, for the most part, have a statistically significant relationship with fish in the CAWS. Various measures of dissolved oxygen were tested, including compliance with existing and proposed water quality standards, average and minimum DO, and percent of time below various DO concentration thresholds. The strongest relationship identified between any of these metrics and the fish data had an r-squared value of 0.27, which is about half as good as the key habitat variables identified in this study. All other DO measures tested had r-squared values significantly lower than this. This indicates that physical habitat, not water quality, is the most limiting factor for fish in the CAWS today.

Some further elaboration on these conclusions is provided in the sections below.

8.2 SUMMARY OF KEY HABITAT VARIABLES

The process described in Sections 6 and 7 of this report used fish and habitat data collected from throughout the CAWS to identify the physical habitat variables most closely correlated with fish metrics in the CAWS. Those variables are:

- Maximum depth of channel
- Off-channel bays
- Percent of vertical wall banks in reach
- Percent of riprap banks in reach
- Manmade structures in reach
- Percent macrophyte cover in reach

Many of these key habitat variables are the result of the major functions that the CAWS serves. Channel depth, vertical wall banks, and riprap are all the result of the need to support commercial navigation, effluent conveyance, flood control, or all three. Other habitat variables are so uniformly absent or of such uniformly poor quality in the CAWS as a result of the origin, design and function of the CAWS that they do not register as important. These include habitat attributes that are normally important in natural systems such as substrate, in-stream cover, floodplain connectivity, and morphological variation.

Using multiple linear regression analyses, the key habitat variables listed above were able to explain 48% of the variability in fish data collected from the CAWS from 2001 – 2007. Additional analyses described in Section 7.5.2 show that most of the variability in the 2008 fish data not explained by these physical habitat variables was attributable to variability in the fish sampling results. DO was also shown to be relatively less important in explaining fish data variability than these key habitat variables.

8.3 RELATIVE IMPORTANCE OF PHYSICAL HABITAT IN THE CAWS

As stated above, the regression analysis presented in Section 6.3.3 shows that physical habitat alone can explain up to 48% of the variance in fish data collected in the CAWS from 2001 – 2007, which is significantly better than can be accomplished by evaluating water quality alone. In the analysis presented in Appendix C, the DO metric most highly correlated with fish data only had an r-squared of 0.27, meaning that DO alone can only explain 27% of the variability in the same seven years of fish data. Other important findings include:

- Of the 52% of fish data variability that is not explained by these physical habitat variables, as much as 70% of it can be explained by variation in fish sampling results from year to year. This means that the fish measured at a location can vary significantly from one sample event to the next and that this will lead to an inherent variability in the data that cannot be explained by changes in independent variables such as habitat or water quality.

- The percent of time that DO is less than 5 mg/L at a given station in the CAWS from June through September, which was the water quality metric most closely correlated with fish, explains approximately 3% of the 52% of the fish data variability that is not explained by the six key physical habitat variables.

- When the key DO metric is included with the six key habitat variables in the regression with fish data, the ability of the regression to explain variability in fish data is only increased by 4% over using habitat alone.

All of these findings indicate that physical habitat is relatively more important than water quality to fish in the CAWS.

8.4 OTHER RELEVANT HABITAT CONSIDERATIONS

It should be noted that, while the analysis conducted in this study led to the identification of key habitat variables, it is very much a data-driven analysis and although two separate data sets were used for the quantification of the relationship between habitat and fish, and the testing of that relationship, there are almost certainly other habitat factors that are or could be of value to aquatic life in the CAWS. These may include the following:

- Submerged structure: As discussed elsewhere in this report, no complete data on submerged structure were collected in this Study, although pilot testing of side s can sonar indicates that there may be value in using that technology to image subsurface conditions and identify submerged structure. If submerged structure can be quantified and if there is sufficient submerged structure in the CAWS to support statistical analysis, it may be possible to identify a relationship between submerged structure and fish in the CAWS.

- Off-channel habitat: Because of the channelized, constructed, and urban nature of the CAWS, there is little connected, off-channel habitat. Such areas can provide habitat for different life stages of fish as well as refuge. In the CAWS, they may provide shelter from boat wakes. In the general absence of such features, it is not possible to evaluate their potential value to aquatic life in the CAWS at present, because insufficient data exist.

- Navigation: Although there are insufficient data at present to quantify the specific effects of navigation on fish in the CAWS, the impacts almost certainly are occurring and cannot be ignored. Further research would be required to document and quantify these impacts, but navigation clearly presents significant limitations to aquatic biota in the CAWS, both through limitations imposed on physical habitat and through direct effects. The channel design/modification to support navigation presents significant limitations to the habitat improvement potential in the CAWS.

While these and other aspects of physical habitat are not represented in the CAWS habitat index, it does not mean that they are not important, it simply means that they either are not present in sufficient quantity within the CAWS or have not been fully measured to date.

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APPENDIX A:

REPORT ON FISH METRIC SELECTION FOR THE CAWS HABITAT EVALUATION AND IMPROVEMENT STUDY

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APPENDIX B:

TECHNICAL MEMORANDA DESCRIBING MACROINVERTEBRATE DATA (FROM BAETIS, INC.)

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APPENDIX C:

ANALYSIS OF THE RELATIONSHIP BETWEEN FISH AND WATER QUALITY IN THE CAWS

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APPENDIX D:

ANALYSIS AND SCREENING OF HABITAT DATA

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SCREENING AND REDUCTION OF HABITAT VARIABLES

This appendix discusses in detail the process used to reduce the initial list of 241 habitat variables to the final set of 16 variables that were used in multiple linear regression with fish data. Tables in Appendix E summarizes the variables eliminated and remaining at each step in the process.

D.1 Screening of Habitat Variables Not Applicable to the CAWS

The initial list of 241 variables was reviewed to identify any variables that were not applicable for use in the CAWS because of conditions in the CAWS, for which there was insufficient data, or that represented a condition that was adequately described by another variable. Some professional judgment was used in this step, but many screening selections were obvious choices. The tables in Appendix E include the rationale for elimination of variables at this stage in the process. Some examples of variables eliminated in this step include:

- Variables associated with thalweg measurements were eliminated in this step because a thalweg does not exist in most parts of this system.
- Variables associated with bankfull flow were eliminated. Most of the CAWS consists of canals and constructed channels. No natural hydrologic regime exists, so the concept of bankfull flow is not meaningful in this system.
- Large woody debris was eliminated because large woody debris is intentionally removed by maintenance crews from most of the system.
- Many variables were eliminated due to the lack of data, including many variables that characterize bed conditions. Some substrate variables were retained, but the depth and turbidity of the system do not allow direct observation of bed conditions and grab sampling can only yield limited data.

This screening process was affected largely by the nature of the CAWS and the conditions therein. As stated above, the table in Appendix C provides a summary of the reasons for eliminating variables at this stage. The habitat variable list was reduced from 241 to 66 in this step.

D.1 Correlation Analysis of Habitat Variables

Correspondence analysis was used to identify variables that are highly correlated with each other and that may be redundant. The 66 variables remaining after qualitative screening were then statistically analyzed using Spearman’s correlation analysis. This revealed variables within each of the five categories that were significantly correlated with each other with a correlation coefficient of 0.7 or greater. Matrices of Spearman correlation coefficients for each of the five habitat variable categories are included in Appendix E, along with a table listing the variables evaluated in the correlation analysis and notations on variables eliminated in this step. In selecting between two correlated habitat variables, correlation of the habitat variables with fish metrics, coefficients of variation of habitat variables, and potential to be improved in the CAWS were also considered. One habitat variable was selected from each set of correlated variables, considering both degree of variation (higher coefficients of variation were preferred) and correlation with fish (stronger correlation with fish was preferred). This process eliminated 22 habitat variables.

During this step it was also noted that several variables represented similar habitat conditions in the system:

- Habitat variables representing percent concrete walls, percent steel sheet pile walls, percent stone block walls, and percent wooden bulkhead walls all represent conditions where banks consist of vertical walls. These variables were combined to a new single variable to represent the functional effect of these conditions on fish.
- Similarly, two variables connected off-channel open water and marinas represent conditions where solid banks open to larger connected water areas and were combined to a single variable.
- Two separate variables representing number of NPDES-permitted CSO discharges and number of other non-CSO NPDES permitted discharges were combined to a single variable.

These reductions further reduced the set of habitat variables by 5, which left 39 habitat variables to carry forward in the process. Two anthropogenic variables representing distance from Lake Michigan and commercial tonnage passing were highly correlated (Spearman' s coefficient = 0.733; $p < 0.0001$), but both were carried forward because both were suspected of possibly affecting fisheries based on data observations and the desire to be able to examine both subsequently.

Table D-1: Variables Used in Principal Components Analysis.

Variable Category	Habitat Variable
Geomorphology & Hydrology[8]	Flashiness index (ratio of 10% to 90% exceedance flows)
	Maximum velocity
	Average velocity
	Wetted perimeter of channel
	Maximum depth in reach
	Number of tributary, backwater, and off-channel habitats from field observation
	Number of off-channel bays (areas isolated from main channel >5 sq. m.
	Bank "pockets" or similar areas that may serve as fish refuge along banks
Sediment & Substrate	Dominant substrate in shallow part of channel
	Dominant substrate in deep part of channel
	% Hardpan, shallow
	% Hardpan, deep
	% Sand and fines, shallow
	% Sand and fines, deep
	% Gravel, cobbles, boulders, shallow
	% Gravel, cobbles, boulders, deep
	% Plant debris on bed, from District PHA
	% Organic sludge, from District PHA
	Depth of fines, from District PHA
In-Stream Cover	Number of aquatic vegetation types
	Average macrophyte cover
	In-stream cover present
	% of canopy over water in reach – field measured
	Secchi depth
Bank & Riparian Condition	Dominant riparian land use
	Bank angle
	% Natural banks in reach (earth banks with vegetation)
	% Vertical walled banks in reach (steel, wood, stone, etc.)
	% Riprap banks in reach
	% Bank length occupied by open water (marinas, etc.)
	% Riparian vegetation
Anthropogenic Impacts	Manmade structures (bridge abutments, dolphins, etc.)
	Number of NPDES discharges
	Distance from Lake Michigan
	Distance to nearest wastewater treatment plant
	Cadmium concentration in sediment
	Total PCB concentration in sediment
	Simultaneously extracted metals in sediment

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[8] All hydrologic variables were determined from DUFLOW model output.

D.2 Principle Component Analysis of Habitat Variables

Principal component analysis (PCA) was used to further reduce the list of variables from the 39 remaining after correlation analysis. PCA is a statistical technique commonly used to identify which variables explain the most variance in the data set. It is frequently used to analyze habitat and biological data (Blocksom and Flotemersch, 2005; Fitzpatrick et al., 1998; Hall et al., 1999; Wilhelm et al., 2005). The PCA was conducted on each of the five variable categories independently, because of a desire to retain at least one variable from each category for the multiple linear regression. The variables representing presence or absence of in-stream cover and high navigation were not included in the PCA, because they are categorical variables. Procedures for using categorical and continuous variables together in PCA are not well established and may give misleading results. The variables used in the PCA are listed in Table D-1.

PCA is a variable reduction procedure used to transform a set of variables into new, artificial variables that are not correlated to each other. By transforming the original variables into new, non-correlated variables, the amount of data variance explained by each new variable can be calculated. Each of the new, transformed variables is called a principal component or principal component “axis” and the method is structured to identify which principal component explains most of the data variation (called the first principal component), which explains the second most data variation (called the second principal component), and so on.

The method also calculates the weight with which each original variable is associated with each principal component, using linear algebra to calculate each variable’s eigenvalue. The eigenvalue of each variable is referred to as its “load” and the original variable that has the highest load on a given principal component axis is the variable most strongly associated with that axis. Original variables that have relatively low loads on principal components axis are the variables that are more highly correlated with other variables, suggesting that they can be eliminated without losing significant explanatory power of the data.

The plots in Figure D-1 (called scree plots) show some of the results of the PCA, including the following:

- The number of columns on each plot indicates how many principal component axes were needed to explain 100% of the variance in the data.
- The height of the columns indicates the eigenvalue or principal component load for each axis, which was used as a screening measure to indicate how many axes to use in variable retention. Variables were retained only from axes with eigenvalues of 1 or greater.
- The line plots show the cumulative proportion of variance explained by the principle components.

In PCA, it is generally desirable to have the first three or four axes explain most of the data variance. In the case of the CAWS habitat data, between two and four axes were required to explain more than 70% of the data variance, as outlined below.

- Geomorphology and hydrology variables: The first four axes of the PCA explained 76% of the data variance and inclusion of a fifth axis did not significantly improve the variance explained. This indicates that the majority of the variability of the nine variable set can be described with fewer than nine variables. To ensure that we selected variables that described the variance of the complete data set well, we chose to eliminate variables with low loading on the first four axes. After reviewing the PCA results, three variables were eliminated from this category.

- Sediment variables: The first four axes of the PCA in this category also explained 76% of the data variance for this category, suggesting retention of at least four variables from this category. Two of the variables, representing organic sludge and plant debris, scored very close to each other, so the decision was made to combine these two into a single variable representing organic sediment. Six variables were eliminated from this category based on the PCA results.

- Overhanging and in-stream cover variables: The first two PCA axes explained 80% of the data variance, suggesting that two of the four variables could be eliminated. However, because of the perceived importance of in-stream cover in the system, only one variable was eliminated from this group.

- Bank and riparian variables: The first three PCA axes explained 73% of data variance. Close ranking among variables indicated retention of more than three variables, so only two variables were eliminated from this group.

- Anthropogenic variables: The first three axes explained 74% of data variance, suggesting retention of three variables from this group; four variables were eliminated.

The results of the PCA screening of habitat variables are summarized in Table D-2.

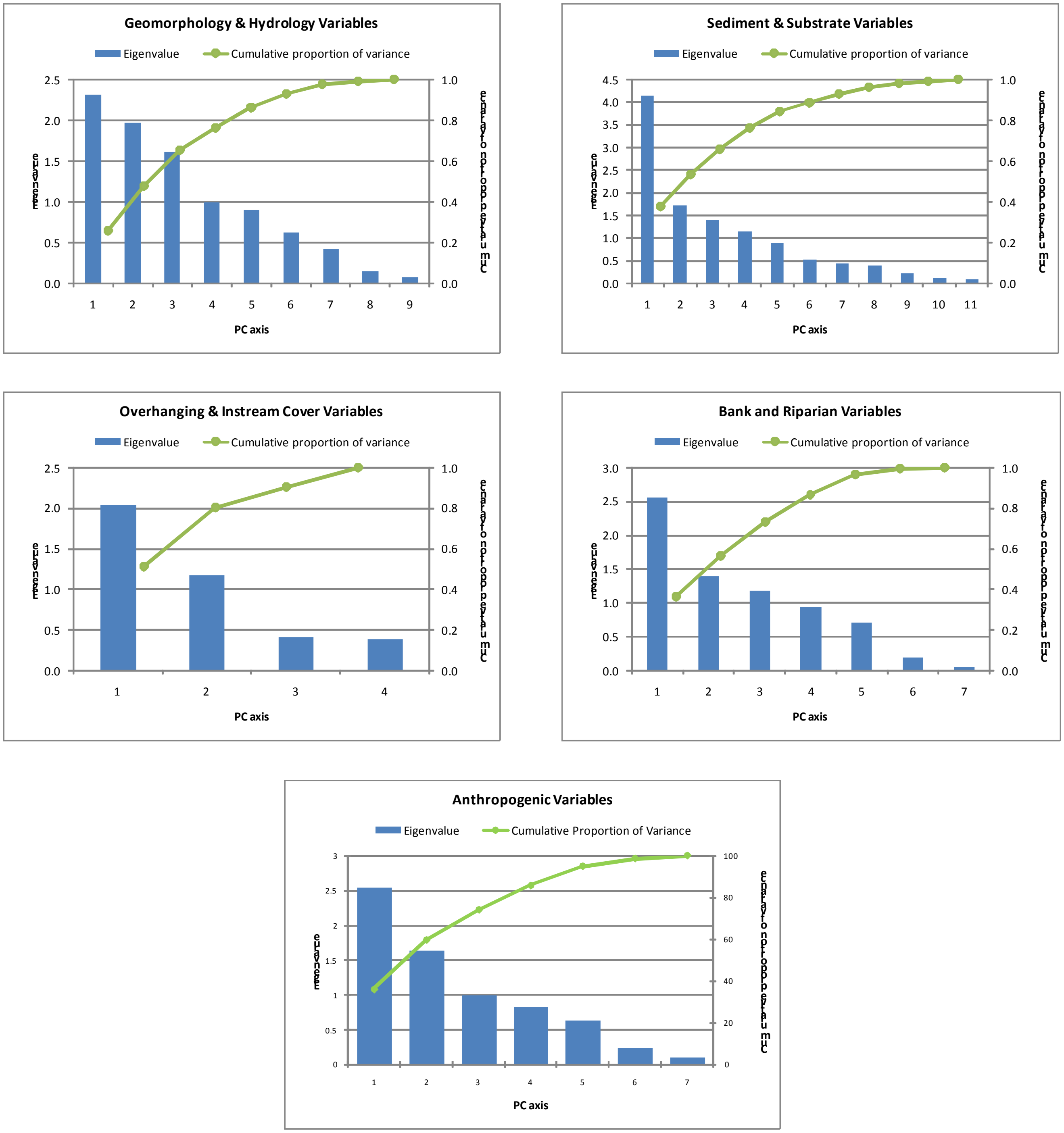

Figure D-1: Principal Components Analysis Scree Plots for CAWS Habitat Variables.

Table D-2: Results of Screening Habitat Variables Using Principal Components Analysis.

Variable Category	**Habitat Variable**	
Geomorphology & Hydrology	Flashiness index	Retained
	Maximum velocity	Eliminated: even with Flashiness on PC3, correl, w/nav.
	Average velocity	Eliminated: rel. low load on all PC axes
	Wetted perimeter of channel	Retained
	Maximum depth in reach	Retained
	Number of off-channel habitats	Eliminated: rel. low load on all PC axes
	Number of off-channel bays	Retained
	Bank "pocket" areas	Retained
Sediment & Substrate	Dominant shallow substrate	Eliminated: rel. low load on all PC axes
	Dominant deep substrate	Eliminated: rel. low load on all PC axes
	% Hardpan, shallow	Eliminated: rel. low load on all PC axes
	% Hardpan, deep	Eliminated: rel. low load on all PC axes
	% Sand and fines, shallow	Retained
	% Sand and fines, deep	Eliminated: rel. low load on all PC axes
	% Gravel, cobbles, boulders, shallow	Retained
	% Gravel, cobbles, boulders, deep	Retained
	% Plant debris on bed	Retained
	% Organic sludge	Retained
	Depth of fines	Eliminated: rel. low load on all PC axes
In-Stream Cover	Number of aq. vegetation types	Eliminated: rel. low load on all PC axes
	Average macrophyte cover	Retained
	% overhanging veg. cover in reach	Retained
	Secchi depth	Retained
Bank & Riparian Condition	Dominant riparian land use	Retained
	Bank angle	Eliminated: rel. low load on all PC axes
	% "Natural" banks in reach	Retained
	% Vertical walled banks in reach	Retained
	% Riprap banks in reach	Retained
	% Bank with open water	Eliminated: rel. low load on all PC axes
	% Riparian vegetation	Retained
Anthropogenic Impacts	Manmade structures	Retained
	Number of NPDES discharges	Eliminated: rel. low load on all PC axes
	Distance from Lake Michigan	Retained
	Distance to nearest WRP	Eliminated: rel. low load on all PC axes
	Cadmium conc. in sediment	Eliminated: rel. low load on all PC axes
	Total PCB conc. in sediment	Eliminated: rel. low load on all PC axes
	Simultaneously extracted metals in sed.	Retained

D.3 Habitat Variable Correlation Across Categories

After PCA, 23 habitat variables remained, including commercial navigation, representing a variable-to-data ratio of 0.28. To this point in the variable reduction process, habitat variables had been segregated in the five categories. As a final screening step before regression with fish data, the correlation of the remaining habitat variables with all other remaining habitat variables was evaluated using Spearman's correlation. Variables were evaluated for potential elimination if they had a Spearman's correlation coefficient with another variable of 0.6 or greater. Commercial navigation was included as an anthropogenic variable in this process. Six additional variables were eliminated because of strong correlation with other variables in other categories, as explained in Table D-3.

Table D-3: Results of Correlation of Habitat Variables Across Categories.

Variable Category	**Habitat Variable**	
Geomorphology & Hydrology	Flashiness index	Retained
	Wetted perimeter of channel	Retained
	Maximum depth in reach	Retained
	Number of off-channel bays	Retained
	Bank "pocket" areas	Retained
Sediment & Substrate	% Sand and fines, shallow	Eliminated: correl. w/ macrophyte cover (0.601)
	% Gravel, cobbles, boulders, shallow	Retained
	% Gravel, cobbles, boulders, deep	Retained
	% Plant debris on bed	Retained
	% Organic sludge	Retained
In-Stream Cover	Average macrophyte cover	Retained
	% overhanging veg. cover in reach	Eliminated: correl. w/ vertical walled banks (-0.600)
	In-stream cover present	Retained
	Secchi depth	Retained
Bank & Riparian Condition	Dominant riparian land use	Retained
	% "Natural" banks in reach	Eliminated: correl. w/ macrophyte cover (0.726)
	% Vertical walled banks in reach	Retained
	% Riprap banks in reach	Retained
	% Riparian vegetation	Eliminated: correl. w/ % dominant land use (-0.665)
Anthropogenic Impacts	Manmade structures	Retained
	Distance from Lake Michigan	Eliminated: correl. w/ bank pocket areas (0.645)
	Commercial navigation	Eliminated: correl. w/ maximum depth (0.789)
	SEM[9] in sediment	Eliminated: correl. w/ vertical wall banks (0.726)

This process reduced the set of habitat variables to 16, which represented a variable-to-data ratio of about 0.2. These 16 variables were carried forward for comparison to fish data, described in the following section.

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[9] SEM = simultaneously extracted metals

APPENDIX E:

HABITAT VARIABLE TABLES AND SCREENING RATIONALE