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State-of-the-Art Approaches for Assessment of Great Lakes
Nearshore and Large River Fish Habitat
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EXECUTIVE SUMMARY

The Great Lakes coastal zone generates much of the fishery production within the lakes and is heavily influenced by the interaction between large river, coastal wetland, and nearshore areas. Nearshore and large river habitats are utilized for spawning, rearing, foraging and as over-winter refuge for a variety of Great Lakes fishes. Despite the ecological importance of coastal zones, only limited study of these areas has been conducted, which makes it difficult to evaluate how impacts to these areas could affect Great Lake fisheries. Classification and inventory of gains and losses of nearshore and large river habitat is considered a high priority for the Great Lakes region (GLFC 2001, 2006).

Because of the functional link between fisheries productivity and habitat condition, accurate and precise assessment of fisheries habitat is regarded as essential for fisheries protection and restoration. A wide variety of methods for measuring habitat quantity and quality are available. However, these methods differ in terms of accuracy, spatial and temporal resolution, cost, and applicability. Such differences make it difficult to accurately gage what method may be most appropriate for a particular research or management objective. Within the Great Lakes, the vast spatial extent of nearshore and large river areas is perhaps the most important factor to consider for choosing among competing methods to identify, map and catalogue critical coastal fish habitat. The spatial extent of the Great Lakes aquatic ecosystem includes a chain of lakes and connecting channels that transports water from Lake Superior to Lake Ontario and eventually to the Atlantic Ocean via the St Lawrence Seaway and Estuary. The Great Lakes have a combined shoreline length of approximately 17,700 km and a connecting channel length of 432 km. Total surface area of the Great Lakes basin is 518,000 km² and contains approximately 30,000 ha of wetlands, 676,500 ha of U.S. inland lakes at least 2 ha in size, and 437,400 km of streams and rivers.

We reviewed 282 studies and interviewed 44 researchers at 25 organizations (agencies, universities or businesses) by telephone or email about work efforts that pertained to fisheries habitat assessment in nearshore or large river habitats. Of those, 141 pertained to large rivers and 122 were nearshore studies or protocols. Of the total 282 studies, 115 were focused on the Great Lakes ecosystem; 37 of those pertained to large rivers, 84 to nearshore and 6 to both nearshore and large river studies or protocols. We also conducted numerous web-based database searches and visited over 200 web sites pertaining to riverine, nearshore, and coastal wetland habitat assessment. A digital database detailing the reviews and interviews accompanies this report (Appendix).
Gaps in Large River Habitat Study

Given the limited number of studies in large rivers in the Great Lakes region, gaps in data and knowledge are substantial. The estuary zones of most coastal rivers are not included in the USGS gaging program. These are the areas where river stage, dissolved oxygen and temperature are most critical yet we have almost no automated monitoring in place because historically backwater effects precluded straightforward flow gauging. Improving our understanding of dynamic conditions in these coastal river habitats is critical. Both monitoring and modeling of dynamic habitat conditions in key river systems across the Great Lakes would be an important first step forward. Three areas, in particular, should receive focused attention:

1) There is a serious lack of real-time monitoring of flow and chemistry in large coastal rivers and estuaries across the Great Lakes. These data could be collected at fixed monitoring stations with multiple sensors analogous to the current real-time gauging stations. Gauging by fixed Acoustic Doppler Current Profiler does not require stable relationships between stage and discharge. Even though backwater effects complicate discharge estimation, more traditionally equipped stations could collect stage, velocity, conductivity, temperature and even fish movement data.

2) A related but separate need is for detailed local channel habitat data including channel bathymetry, velocity profiles, and substrate composition. Data of this kind could be routinely collected using boat-mounted sensors on a set of benchmark rivers, or on rivers prioritized by the fishery value. Both types of data are necessary to inventory, map, and model river habitat access in the coastal zone ecosystem.

3) Although floodplain dynamics have been rigorously studied in tropical regions, studies of connected floodplains have rarely been conducted in the Great Lakes region. Development of better understanding as to how large river floodplains are structured, how they function in terms of Great Lakes fishes, and how off-channel diversity relates to main channel diversity may yield important information regarding fisheries management and conservation. Coastal river floodplains can be relatively inaccessible and are therefore good candidates for remote sensing and modeling. Satellite Synthetic Aperture Radar (SAR) and multispectral data could be used to monitor flood inundation and map off-channel habitat types at a coarse scale across the range of flows. For finer scale data detailing habitat types and elevations a combination of Light Detection And Ranging (LIDAR) and either high resolution satellite multispectral data (E.G. IKONOS) or airborne hyperspectral data could be collected during key discharge stages.

Gaps in Great Lakes Nearshore Habitat Study

While many more studies have been conducted in the Great Lakes nearshore zones than large rivers, because the nearshore zone is so large, existing data coverage is scarce and geographically scattered. No comprehensive survey of bathymetry, substrate and vegetation within the Great Lakes has been conducted. Many tools have been developed by a number of researchers, but application of these tools has been limited primarily due to lack of institutional and financial support. Technology and methodology to conduct a systematic program to map, assess, and classify nearshore zones and coastal wetlands are currently available. What is lacking is a consistent approach to large-scale mapping and inventory. We have identified four areas where substantial data gaps exist.

1) High resolution bathymetry and substrate mapping are needed for assessment and protection of critical fisheries habitat in the nearshore zones of the Great Lakes. Existing bathymetry and substrate data are available for the entire Great Lakes but at very coarse resolution and for isolated locations at a fine scale. The current Coastal Mapping Program by the U.S. Army Corps of Engineers (USACE) will
provide the bathymetry and bottom classification that is needed for the U.S. nearshore Great Lakes and will be free to researchers and agencies. Coverage of the Canadian nearshore zones, however, is very limited. This is a critical gap given that large segments of the Canadian shoreline contain pristine nearshore and coastal wetland habitat.

2) Spectral and radar imagery, both satellite and airborne, is being used to classify and map coastal wetlands and wetland vegetation in the Great Lakes but spatial coverage has been relatively sparse. Exploratory methods that combine SAR and multispectral satellite data have successfully been used to map and classify a broad range of wetland types and water levels in coastal systems. These methods provide broad spatial and temporal coverage, both seasonally and annually, which is lacking in current coastal inventories. This data would also provide an opportunity to evaluate connectivity between nearshore zones, coastal wetlands and large river mouths which is substantial gap in our study and approach to Great Lakes coastal systems. Finer scale mapping and classification of coastal wetlands has been successful using satellite multispectral data (1-4 m pixels). While spectral imagery is limited by cloud cover, cost, satellite schedules and tasking, and preprocessing, it can provide the finer scale analysis of the structure of targeted systems and is likely the scale of data needed for process-based models used to predict habitat responses to changes in regional or global level climate, water levels and development. Analyses that evaluate seasonal connectivity in conjunction with remote estimates of productivity could help identify critical habitat for spawning and nursery, evaluate the relative constraints faced by adfluvial fish, and help identify the reasons for reproductive constraints.

3) Further research is also needed to develop methodology to use imagery such as Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) to estimate productivity, turbidity and water quality of the coastal zones. This technology has been very useful in marine systems and for smaller inland lakes. Efforts to develop this technology should be supported and applied seasonally across the Great Lakes near shore and open water zones to better understand the flux of nutrients and materials between open water, nearshore and riverine systems.

4) A uniform approach to classifying and mapping coastal habitats needs to be developed. An operation GIS-based classification system would allow researchers and managers to conduct systematic stratified surveys and select representative systems for further, detailed study. We suggest a Great Lakes Coastal Habitat Assessment Framework that links nearshore, coastal wetlands and riverine systems based on functionally connectivity and material flux. This framework would be supported by a GIS database attributed with geologic, hydrologic, connectivity and physiographic factors needed for unit description and classification.

**Potential Pilot Projects**

The RFP for this research requested an evaluation of the existing technologies, methods, and protocols used to sample, measure, and monitor habitat in large rivers and the nearshore zones of the Great Lakes and to make suggestions for potential pilot projects that could be initiated to begin to address the data gaps that exist for Great Lake coastal systems. We believe the following pilot projects could significantly accelerate the development of coastal habitat inventories, assessment, and science in the Great Lakes region.

**Linked Radar and Multi-Spectral Sampling for Coarse-Scale Mapping and Inventory**

Methods have been developed combining satellite radar and multispectral imagery to map and classify nearshore and coastal wetlands and simultaneously assess hydrologic status. We propose application of this method at a whole lake-basin scale to provide needed coastal habitat inventory, and help move us towards basin-wide data acquisitions. Recent work in the Great Lakes region has identified
methods that combine satellite SAR radar and Landsat multispectral data at a medium resolution (30 m pixel) to classify wetland and nearshore habitat, map the extent of inundation in coastal habitat, including riverine floodplain areas, and using multitemporal images conduct radiometric change detection analyses. This level of resolution can merge with existing land use/cover map (e.g. IFMAP) and provide an inventory of nearshore and coastal wetland boundaries, types, and seasonal water levels, as well as and the ability to track changes in land use with changes in coastal habitat units. This type of coarse inventory could also be used to help link potential changes to coastal habitat units with changes in Great Lakes water levels due to global climate change and other effects.

Leveraging USACE LIDAR Flights

Currently the nearshore zone of the Great Lakes is being flown by the USACE using high resolution LIDAR and hyperspectral imagery. We suggest a pilot demonstration project to integrate that data with additional hyperspectral data from coastal wetland and riverine floodplains to provide spatially detailed bathymetry, morphology, vegetation type, and hydrologic patterns for coastal units. The results of this effort could lead to a consensus on a classification methodology for acquisition of fine-scale hyperspectral data. Given that LIDAR is only being flown in the U.S., the pilot project needs to occur on the U.S. shore. However, we suggest that coordination with the USACE and other U.S. and Canadian federal agencies could result in LIDAR flights of the Canadian side of the Great Lakes that include some of the most pristine sections of Great Lakes coastal system along the northern shore of Lake Huron and Lake Superior. This scale of information is essential to understand and to model the dynamic linkages between systems.

Detailed Analysis of Representative Complex Coastal Units

Freshwater estuaries in the Great Lakes provide a link between riverine and nearshore and offshore but are not well understood. Some current thinking suggests that some of the drowned river mouth freshwater estuaries might be bottlenecks for Great Lakes fish recruitment for fish that use the tributaries to spawn. We suggest a pilot project that combines multiple remote sensor data, on-board boat sensors, and fixed station monitoring to collect data needed to understand the functional links between physical processes, primary productivity, biological interactions (particularly predation) and their influences on adfluvial fish recruitment. On-board and fixed station data could be linked temporally and spatially with satellite sensor data to track productivity and integrate with nearshore bathymetry, substrate and lake wide circulation modeled data.

Development of Great Lakes coastal habitat database and classification framework

Fish habitat inventory and assessment in the Great Lakes region has traditionally been location and issue driven. Lake-wide and basin-wide efforts have been recently initiated, but still are narrowly focused on only parts of the complex coastal habitat system. The challenge is to provide a holistic framework for assessing Great Lakes coastal habitat that can be used across multiple spatial and temporal scales. We believe it is important that those who direct and fund Great Lakes habitat inventory and assessment projects have both a conceptual model and operational Geographic Information System framework to integrate investigations focusing on various aspects of the nearshore, coastal wetland, and large river estuary systems of the Great Lakes. Because there is not enough time nor funding to completely sample, inventory and assess such a large ecosystem, we believe the development of a database framework and classification system, applied to mapped functional units, is likely the only effective way to address lake-wide and basin-wide habitat issues. A database framework will allow the integration of all key habitat components for addressing lake-wide or basin-wide visionary issues, as well as provide the flexibility to incorporate additional multidisciplinary habitat components for addressing local and emerging issues.
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INTRODUCTION

The Great Lakes coastal zone generates much of the fishery production within the lakes and is heavily influenced by the interaction between large river, coastal wetland, and nearshore areas. Nearshore and large river habitats are utilized for spawning, rearing, foraging and as over-winter refuge for a variety of Great Lakes fishes. Despite the ecological importance of coastal zones, only limited study of these areas has been conducted, which makes it difficult to evaluate how impacts to these areas could affect Great Lake fisheries. Classification and inventory of gains and losses of nearshore and large river habitat is considered a high priority for the Great Lakes region (GLFC 2001, 2006).

Because of the functional link between fisheries productivity and habitat condition, accurate and precise assessment of fisheries habitat is regarded as essential for fisheries protection and restoration. A wide variety of methods for measuring habitat quantity and quality are available. However, these methods differ in terms of accuracy, spatial and temporal resolution, cost, and applicability. Such differences make it difficult to accurately gage what method may be most appropriate for a particular research or management objective. Within the Great Lakes, the vast spatial extent of nearshore and large river areas is perhaps the most important factor to consider for choosing among competing methods to identify, map and catalogue critical coastal fish habitat. The spatial extent of the Great Lakes aquatic ecosystem includes a chain of lakes and connecting channels that transports water from Lake Superior to Lake Ontario and eventually to the Atlantic Ocean via the St Lawrence Seaway and Estuary. The Great Lakes have a combined shoreline length of approximately 17,700 km and a connecting channel length of 432 km. Total surface area of the Great Lakes basin is 518,000 km² and contains approximately 30,000 ha of wetlands, 676,500 ha of U.S. inland lakes at least 2 ha in size, and 437,400 km of streams and rivers.

The goal of this project was to identify and critically assess the effectiveness of existing techniques used in fisheries habitat assessment, classification, rehabilitation, and management in the Great Lakes, and to provide analysis that could be helpful for allocating research and management efforts in the Great Lakes lower riverine and nearshore regions. This report is the result of our efforts. The organization of this report is as follows. First, we provide working definitions of habitat, large river habitat, and nearshore habitat. Second, we provide background information on some of the innovative technologies for measuring habitat that are later reviewed in the report. Third, we review methods used to map, inventory, and assess habitats organized by major aquatic habitat areas (wetlands, floodplain, river channel) or by aquatic habitat component (substrate, aquatic vegetation). This review includes descriptions of the methods, their applications, success or limitations, cost (where available), and resolution. Fourth, we provide a summary and our assessment of the applicability of available methods for large rivers and nearshore zones of the Great Lakes. Last, we present a potential framework for integrating large rivers and the nearshore zone of the Great Lakes and provide recommendations for future research and management efforts in the Great Lakes lower rivers and nearshore ecosystems. Accompanying this report is a Microsoft Access file that provides a searchable database of the studies that were reviewed for this project.
AQUATIC HABITAT

Definition of Habitat

Habitat and aquatic habitat have been defined by various researchers, managers, and agencies as referring to different combinations of physical, chemical, biological, spatial, and temporal conditions. For the purposes of this report, we restrict our definition of habitat to a physical unit of the environment that is directly used by biota for food, shelter, spawning and/or refuge. Although biological interactions can be an important part of habitat and can restrict the range and use of habitat by many organisms, including this aspect of habitat within our review of methods was not considered possible.

Physical habitat can generally be delineated geographically and often has a persistent and repeatable structural pattern that meets the needs of a species or biological community (Mackey 2005). Individual species can have habitat requirements that differ at various life stages. An extreme example of an ontogenetic shift in habitat requirements is the anadromous behavior of many species of salmonids. Other, more subtle forms of ontogenetic shifts in habitat requirements are also frequently observed in fish species, such as the bluegill’s *Lepomis macrochirus* shift between littoral and open-water zones at different stages of ontogeny. Characteristics of aquatic physical habitat include spatial and temporal extents, ecological quality, temperature and hydrological regime, optical and nutrient properties, and surficial texture and substrate features (Minns and Weichart 2006; Minns and Wichert 2005). Critical habitat is defined as habitat that limits abundance of a particular population, life stage or biological community (Rosenfeld and Hatfield 2006). Critical habitat can include the hydrologic connectivity between habitats required by fish during different life stages (Minns and Wichert 2006). In our discussion Great Lakes coastal habitat refers to both large river and nearshore habitat thus is the dynamic intersection of river and Great Lakes influences.

Large River Habitat

In scientific literature, the terms “large rivers” and “nonwadeable rivers” are both used to describe rivers that are large in size. For the purpose of this report, we considered the terms to be synonymous. Definitions of large rivers are often based on stream order, drainage area, discharge, and/or main-stem length characteristics. For example, Wilhelm et al. (2005) considered large rivers as those with stream order $\geq 5$, drainage area $\geq 1,600$ km$^2$, main stem lengths $\geq 100$ km and mean annual discharge $\geq 15$ m$^3$/s. According to the U.S. Environmental Protection Agency (USEPA), large rivers in the Great Lakes regions are rivers with stream orders in excess of 4 or 5 and drainage basins greater than 1,295 – 2,590 km$^2$ (Lazorchak et al. 2000). Some U.S. states have also identified characteristics for defining large rivers (Lyons et al. 2001).

For the purposes of this report, we have targeted our review of methods to those that can be applied to large, coastal rivers that are predominantly unwadeable during periods of low flow. Generally, this implies rivers with stream orders $\geq 5$ and drainage areas $\geq 1,600$ km$^2$. Based on this definition, there are 157 large rivers in the Great Lakes region with a total length of 23,104 km. The two largest river catchments in the Great Lakes basin are the Maumee River (17,100 km$^2$) in Ohio and the Nipigon River (25,258 km$^2$) in Ontario, Canada (Hudson et al. 1992). For the purposes of our review, we consider large river habitat to include Great Lakes connecting channels and the tributaries of large coastal rivers which are directly connected to the coastal zone, which results in somewhat of an overlap with nearshore areas.

Riverine habitat units can be hierarchically organized and evaluated at spatial scales ranging from watershed to microhabitat (Frissel et al. 1986). Below, we provide working definitions for some of the habitat units that comprise this hierarchy. These definitions are not universally agreed upon nor are the
terms used consistently across studies reviewed. Additionally, most of the definitions were developed to describe habitat units in smaller streams (stream order < 5). We nevertheless provide these definitions as a shared point of reference for readers.

*Regional Landscape* – spatially heterogeneous area
1) riverine landscape including aquatic and terrestrial areas that are directly drained by a river
2) riverscape refers to only aquatic components of river landscape.

*Watershed* – the topographic area for surface water draining from a landscape to a channel system; a drainage basin for a hydrologic system.

*River valley segment* – a length of river channel with homogeneous channel slope and valley floor width. A river reach is physically complex and can contain multiple macrohabitats and multiple distinct biological communities. (scale: 100 -1,000 m²)

*River reach* – a length of river channel and its floodplain between tributary confluences.

*Macrohabitat* – a unit with specific, recognizable, repeatable structure within a river reach also called a Geomorphic Channel Unit. An example is a pool or a riffle in a river channel.

*Mesohabitat* – a habitat unit midway between micro and macro habitat characterized by a common slope, channel shape and structure. Geomorphically, mesohabitat is a feature having characteristic bed topography, water surface slope, depth and velocity pattern (Parasiewicz 1996). (scale: the length of a channel width)

*Microhabitat* – a localized area having relatively homogenous conditions of depth, velocity, substrate and cover (Frissell 1986). (scale: a patch within a macrohabitat or mesohabitat)

**Nearshore Habitat**

The nearshore system begins at the outer ridge of coastal wetlands or the lake shoreline and extends lakeward to where the late summer thermocline intersects with the lake bed (Dodge and Kavesky 1995; Uyl 1996). Nearshore waters occupy a band of varying width around the perimeter of each lake, and the band is narrowest where the slope of the lake bed is steep and continuous (Uyl 1996). Assuming that the late summer thermocline intersects with the lake bed at the 27-m depth contour, then the proportions of total lake area composed of nearshore areas for the Great Lakes are the following: Lake Erie = 90%; Lake Huron = 10%, Lake Michigan = 9%; Lake Ontario = 10%; Lake Superior = 5% (Uyl 1996).

The nearshore area is considered one of the most productive areas of the Great Lakes (Steedman and Regier 1987, Stephenson 1990, Willans 1992). Wetlands and lake tributaries supply Great Lake nearshore areas with water and nutrients, and provide spawning and nursery areas for migratory fishes. Nearshore areas also provide over-winter refuge for many species of fish. In turn, the wetland and tributary systems depend on upland terrestrial areas for regulating the entry of nutrients and sediment to the waterways and for supply of organic materials.
INTRODUCTION TO HABITAT SAMPLING TECHNOLOGIES AND PROTOCOLS

Site-based Field Methods and Protocols

Most site-based field sampling protocols (called field-based methods or protocols for the remainder of this report) that have been developed for rivers and streams are intended for wadeable streams. Only recently have sampling protocols for measuring and assessing habitat in large rivers been proposed and utilized. Most notably the U.S. Environmental Protection Agency (USEPA) Environmental Monitoring and Assessment Program (EMAP; Kaufman 2000) and the U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA; Fitzpatrick et al. 1998) have established protocols for evaluating habitat in large rivers. Within the Great Lakes region, the Michigan Department of Natural Resources (MDNR) has also begun to evaluate habitat in large rivers as part of its Stream Status and Trend Program (SSTP; Wills et al. 2006). Wilhelm et al. (2005) developed a habitat sampling protocol and Nonwadeable Habitat Index (NWHI) for streams in Michigan. Similarly, Ohio EPA developed a Qualitative Habitat Evaluation Index (QHEI; Rankin 2006). These are primarily site-based field sampling methods using manual techniques, although the NAWQA methods include assembling detailed map data at watershed and valley scales. Other large river protocols have been developed for U.S. Great Rivers (eg. EMAP-Great Rivers Ecosystems (EMAP-GRE)). Some wadeable stream methods could be used on large rivers with slight equipment modification. However, many of the wadeable stream protocols are centered on macrohabitat delineation and do not address the scale issues required to designate a sample reach or classify channel units for large rivers. Thus, most wadeable stream habitat methods would likely not be useful for large river systems.

The survey protocols used among these various large river sampling programs do differ. Both NAWQA and EMAP use multiple measures of physico-chemical riverine habitat and develop habitat assessment as independent measures of river condition. Several approaches measure a limited number of habitat variables usually qualitatively and visually as indicators of habitat quality (NWHI, QHEI). Sample reach length, number of transects, and levels of effort also vary (Flotemersch et al. 2006a). The EMAP large river protocol samples a reach 40-100 times the wetted width on 11 evenly spaced transects. The NAWQA sample reach is 20 times the wetted width also using 11 transects. The NAWQA method also includes considerable map and GIS effort prior to the site visit. The MDNR Stream Status and Trends Program (SSTP) protocol conducts sampling along 11 transects spaced the length of a 1.6-km (1 mi) sample reach. Michigan’s NWHI uses 11 transects along a 2-km sample reach. The Ohio EPA’s QHEI uses a 500 m reach for visual assessments. Finally, the USEPA Great Rivers habitat protocol evaluates habitat along two 500-m shoreline reaches and three cross-section transects.

Sampling designs also typically differ among habitat sampling protocols. Both NAWQA and EMAP protocols take a broad spatial and temporal approach to sampling design to establish the status, trends, and extent of ecological condition. EMAP uses a random and systematic spatial sampling design (Lazorchak et al. 1998). The sampling design allows for independence of sites and the systematic approach scales the sampling measures at each site relative to the stream size. NAWQA selects sites to represent a set of environmental conditions influenced by a combination of natural and anthropogenic factors (Fitzpatrick et al. 1998). They have two suites of sites: 1) fixed sites that are visited repeatedly and sampled for a broad set of characteristics, and 2) synoptic sites that are measured once for a limited set of characteristics. The MDNR SSTP protocol selects sites based on fish monitoring sites. An alternative sampling design is described by Parasiewicz (1996). With this sampling design, the number of transects used to measure habitat depends on the geomorphic and hydraulic character of the river. Rather then placing transects equidistant within the sampling area, transects are instead located at observed places of morphological change. At each transect location, water surface elevation, velocity, substrate
type, cover and other habitat characteristics are recorded using an electronic distance meter and automatic
data logger. The result is a map of the geomorphic character of the river mapped in the field.

Equipment that is required to measure habitat in large rivers include boats, GPS receivers, aerial
photographs, clinometer for estimating bank angle and slope, densiometer for estimating canopy cover, a
laser finder to measure distance, underwater camera for examining benthic substrate and aquatic
vegetation, sounding or depth pole to estimate substrate and measure depth, and sampling equipment such
as a Ponar to sample substrate or rakes to sample vegetation. A laser range finder uses infrared light to
electronically measure distances up to 500m. A more accurate laser level can measure distances, angles
and be used to calculate elevations (Edsall et al. 1997).

Global Positioning Systems (GPS)

The Global Positioning System (GPS) is a radio navigating system that consists of approximately
24 Earth orbiting satellites that transmit microwave signals to the Earth’s surface; GPS receivers use the
arrival time of the different satellite signals to determine location, travel direction, and speed of the
receiver. Most GPS receivers require a minimum of four satellite signals in order to estimate location of
the receiver. Increased numbers of satellite signals improve the accuracy of the location estimates.
Biases in location can occur due to satellite constellation, atmospheric condition, terrain, and user
location. A typical handheld GPS receiver has a horizontal accuracy of around 10 m; more expensive
receivers can have horizontal accuracies of 3 m or less (http://kellylab.berkeley.edu/SODmonitoring/GPS). Corrections in location biases are possible by
incorporating locations from other known positions either internally within the GPS unit or externally
using post-processing techniques (http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html). Such corrections are referred to as differential correction or differential GPS (DGPS). Differential GPS
corrections are broadcast from both land- and satellite-based transmitters. The Wide Area Augmentation
Systems (WAAS) is a correction service administered by the U.S. Federal Aviation Administration that
broadcasts satellite transmitted corrections. WAAS corrections are officially required to improve
accuracy to within 7.6 m for air traffic, but often accuracy is to within 2 m. Other forms of differential
correction can correct accuracy to within 10 to 15 cm. With survey-grade GPS receivers, corrected
location accuracies can be within 1 cm. GPS can also be used to estimate elevation. Elevation
measurements are often far less accurate than simple location estimates. Vertical error ranges from 20 m
in uncorrected units to 4 m in WAAS corrected units. To obtain sub-meter vertical accuracy, a survey-
grade GPS receiver is typically needed. GPS receiver cost varies depending on the desired level of
accuracy (http://kellylab.berkeley.edu/SODmonitoring/GPS):
  GPS receiver with ≈10 m accuracy: $200
  GPS differentially corrected receiver with ≈1 m accuracy: $5,000
  GPS differentially corrected receiver with < 1 m accuracy: $10,000
  GPS survey grade receiver with ≈ 0.1 m accuracy: $20,000

Geographic Information Systems (GIS)

Geographic Information Systems (GIS) are computerized mapping and database systems intended
for georeferenced data. In addition to mapping and database capabilities, many GIS platforms also
provide a number of tools for analyzing and organizing geographic data. Typical GIS systems use a
relational database for attributing map features with descriptive characteristics. For example, line features
can be attributed with characteristics such as sinuosity and segment length. As an analytical tool, GIS can
be used to 1) aggregate and simplify multiple data layers, 2) apply network functions to analyze flow
paths, 3) buffer features, and 4) construct spatially explicit models (Lillesand et al. 2004). GPS and GIS
have become integral tools for most biological and ecological studies.
Underwater Cameras, Video, and Remotely Operated Vehicles

Underwater cameras and video systems are equipment specifically designed for still or movie capture of underwater images. Underwater cameras and video systems often have special features that allow the capture of images in low-light situations, which is necessary because of the light absorption properties of water. Underwater camera and video systems are commonly used for ground-truthing remotely-sensed data, but also can be used directly for habitat measurement. Digital underwater cameras cost in the range of $1,000-3,000 (www.naturevisioninc.com/aquavu). Underwater cameras can also come in a frame that can be towed with auxiliary camera lighting, which can cost around $5,000-15,000 (Edsall et al. 1997). Underwater video can be housed in a self-propelled Remotely Operated Vehicle (ROV) and maneuvered by ship-board operator. Total cost for such setups can exceed $40,000. ROVs are more difficult to operate at currents above 1-2 km/h, so towed or drop systems may be preferable for larger river systems. Maneuverability of ROVs also may be hindered by underwater vegetation, thus towed or drop systems also may be preferable for nearshore systems. An onboard underwater videography system consisting of an underwater Black and White frame-mounted camera with InfraRed lighting, a DGPS unit, a laptop computer, and digital video camera has an estimated cost of approximately $3,500 (www.oysters.unh.edu/underwater_videography.html).

Remote Sensing

Remote sensing is the measurement of a feature of the Earth’s surface using a recording device not in physical contact with the object. Remote sensing data can be classified based on the imaging platform (e.g., airborne, satellite, boat-mounted) or by the type of radiation (e.g., spectral, radar). For this report, we considered boat-mounted remote sensing distinct from other imaging platforms. Airborne and satellite remote sensors are able to capture images of the Earth’s surfaces within several to many frequency bands of the electromagnetic spectrum (e.g., infrared, visible light, microwave bands). Passive systems such as aerial photography and multispectral sensors rely on naturally reflected radiation to create images. Different objects and conditions on the Earth reflect light at different intensities or wavelengths referred to as the spectral response (Rowen et al. 2004). Radar systems are primarily active systems that operate in the microwave portion of the spectrum. Radar sensors emit microwaves and record echoes or reflections of the microwaves from surface objects; images of the Earth’s surface are formed by combining individual echoes.

With remote sensing imagery, resolution of captured images is an important consideration. Resolution is the maximum power of discrimination of a measurement. A variety of resolutions types can be relevant with respect to mapping habitat. Below we provide definitions for the primary resolution types.

Spatial resolution: size on the ground covered by one pixel; affects the size of the land parcel that may be distinguished. Fine resolution (2-10 m) allows small features on ground to be resolved or identified while medium to coarse resolution (20-5,000 m) gives broad, synoptic view of landscape.

Temporal resolution: frequency that data are acquired; affects the dynamism that can be observed.

Spectral resolution: wavelength range of sensor or the number of bands and band width (some ground features may only be distinguished in certain narrow wavelengths): affects the discrimination of landscape states and conditions.
Radiometric resolution: the number of digital levels used for sensor data thus sensitivity to difference in emitted energy; controls how precisely land-use and land-cover types can be separated (Rindfuss et al, 2004)

With remote sensing, both spectral and spatial resolutions are considered particularly important factors for habitat inventory. Typically there is a trade-off between spectral and spatial resolution. For example aerial photography has limited spectral resolution (1 to a couple spectral bands) but high spatial resolution (often under 10 m). In contrast, hyperspectral data has high resolution spectral data (over 200 narrow bands) but often poor spatial resolution (30 m).

Remote Sensing - Airborne platform

Airborne remote sensing platforms are those systems carried by aircraft, either airplanes or helicopters. It includes aerial photography (film and digital), videography, spectral sensors, and laser sensors.

Aerial Photography

The earliest type of remote sensing was aerial photography. Traditionally, aerial photography has used a film-based camera aboard or mounted to an aircraft. Film sensors are silver halide crystals that are sensitive to light exposure in the visible to infrared bands of the electromagnetic spectrum (Lillesand et al. 2004). Aerial photographs were typically offered in black and white, color, and infrared with a maximum of 3 color bands. Thus, spectral resolution of aerial photographs was quite poor (Becker et al. 2007). Black and white images can be recorded on either panchromatic or infrared film, while color images typically are recorded on color film. Panchromatic film is sensitive to all wavelengths of visible light thus produces a realistic and typically high spatial resolution image, but the display is only in gray scale. Cameras used for aerial photography range from simple 35 mm to more sophisticated, high precision cameras or arrays of cameras. There are a variety of sources for aerial photographs that vary in scale, scene size, altitude, view (vertical and oblique), camera type, and cost. Several national programs take aerial photographic images of the U.S. on 5 to 6 year cycles and provide scanned and digitized aerial photographs (Table 1). Digital Orthoquad photographs are georeferenced, digitized images that have been corrected for distortions and are available in black and white, natural color and color-infrared available from the USGS in 3.75-minute and 7.5-minute area coverages (http://eros.usgs.gov/products/aerial/doq.htm). The 3.75-minute quads with 1 m ground resolution are available for most areas of the U.S. It has become a common practice to scan the film images with a densiometer to produce digital images. The resulting images would have poor spectral resolution and would be limited by the optical properties of the scanner.

Recently, capture of aerial photographic images has involved the use of digital cameras and videos. Typical digital cameras range from 35 mm (6 million pixels per frame) to 70 mm (16 million pixels per frame). Some systems use an array of single spectral band digital cameras that are then merged in post-processing to create a mosaic image. Typical ground resolution for digital images ranges from 0.15 to 1 m per pixel. Film and digital images have a similar spatial resolution (about 6 million pixels per frame), but digital imagery has faster processing time, is readily storable in digital format, and is easily linked to GPS and reproduced. Digital pictures are also more easily radiometrically calibrated from ground images. Digital photography is also limited by cloud cover, night exposures, and distortion correction. Digital aerial videography has also become common. It is less expensive than digital photography and can rapidly acquire multiple views of one scene. Digital aerial videography typically has a lower spatial resolution than digital aerial photographs.

Classification of landscapes through aerial photography typically entails visual interpretation of images, which can be problematic because image interpretations vary among viewers and viewers have
limited spectral discriminatory ability. A major benefit of aerial photography is that images are available for most of the U.S., and these images are relatively inexpensive for small areas and have high spatial resolution. Further, there is an extensive historical record of images which permits the consideration of temporal changes in landscapes. Aerial photography is limited by daylight exposure, cloud cover, processing time, and inefficiency for digital analysis. Processing of aerial photographs requires perspective distortion correction due to variation in field of view and topography, georeferencing, orthorectification, and stitching images together for large area coverage.

**Airborne Spectral**

Airborne spectral remote sensing includes multi- and hyper-spectral sensors that acquire images in the visible and infrared frequency bands of the electromagnetic spectrum (Table 1). Images produced from airborne spectral remote sensing are similar to images from aerial photography, but the captured data are digital records of electromagnetic radiation. Thus, the data can be processed automatically to identify objects or classify surface types (i.e., visual interpretation of images is not required). The lateral coverage (swath width) and spatial resolution of multi- and hyper-spectral images varies with flying height. For example, flights at a height of 300 m would have a ground resolution of 0.75 m and swath width of 600 m, while flights at a height of 12,000 m would have a ground resolution of 30 m and a swath width of 24,000 m swath. Multi-spectral sensors collect data in several broad bands in the range of 0.47-1.1 µm and thus have relatively low spectral resolution. The Deadalus system is an example of an airborne multispectral sensor. The simplest multispectral sensors record in the red, blue and green bands of the electromagnetic spectrum; together, these images can be used to form a color composite image. Multi-spectral data are best used to discriminate between various types of earth surface features (Lillesand et al. 2004). Different bands of a multispectral image have been combined in different algorithms to identify different types of vegetation (e.g., ratio vegetation index, normalized difference vegetation index). Thermal scanners are a type of multispectral sensor that acquires data in the thermal infrared portion of the spectrum.

Hyper-spectral sensors record information in many narrow, contiguous, spectral bands of the electromagnetic spectrum. Several of these bands extend beyond the range of human vision. Each pixel in the remotely acquired image has an associated spectrum similar to the spectra of the material being imaged. Hyper-spectral imagery has high spectral resolution, but spatial resolution depends on the sensor. Hyper-spectral data are best used to determine the characteristics of surface features such as the type or species of vegetation or the type of substrate. One challenge of hyperspectral imagery is determining which bands are important for particular applications (pers comm. D. Lusch, Michigan State University). This has important economic implications since hyperspectral imagery can be expensive and purchasing only a portion of the available bands could reduce the cost. Examples of hyperspectral sensors include AVIRIS, Probe-1, and CASI.

Processing requirements for multi- and hyper-spectral images can include radiometric and geometric corrections, georectification, and stitching. Images can be purchased with different levels of post-processing. The advantage to spectral imagery is that its images can be automatically classified by matching spectral patterns or wavelengths to known classes on the earth surface. Due to the number of spectral bands, multispectral and hyperspectral data require different spectral classification methods. Processing of multispectral data typically uses statistical methods. There are three types of classifiers: supervised, unsupervised, and hybrid. A supervised classifier uses ground truth data to train the classifier based on spectral signatures of surface types and then uses mathematical algorithms such as maximum likelihood or minimum-distance-to-means to classify the remaining spectral data. In unsupervised classification, clustering algorithms such as K-means or ISODATA are used to cluster the spectral data into homogenous groups. The analyst then determines what classes represent different types of surface coverages (Lillesand et al. 2004). Hybrid approaches use a mix of supervised and unsupervised techniques to maximize the strengths of each approach. Hyper-spectral data have many bands (over 200);
thus, datasets associated with hyperspectral images can be quite large, which can make statistical analyses of these datasets complex and time consuming. In addition, hyperspectral data commonly have atmospheric distortion and noise which must be removed during processing. Instead of statistical algorithms, analysts often use models to compare hyperspectral data to known reference spectra. The simplest methods use direct comparison or ratioing of spectra. More complex models like the Spectral Angle Mapping (SAM) model treats each spectra as a vector with a direction and magnitude to estimate overall illumination levels and individual spectral signatures. Derivative analysis is an alternative approach for identifying spectral details (Lillesand et al. 2004).

**Airborne LIDAR**

Light Detection and Ranging (LIDAR) is an airborne-based laser used for bathymetric and topographic elevation mapping (Table 1). It uses a 4 to 10 kHz, fast-firing laser to measure the distance to Earth based on round trip travel time for the laser pulse. For bathymetric mapping, LIDAR uses both green (520nm) and infra-red (1064 nm) beams. The green light is capable of penetrating water and can be used to detect the bottom of a water body. Conversely, the infra-red beam has minimal water penetration so is used to detect the water surface. The difference in return time for the green and infra-red beams can be used to determine water depth. LIDAR data typically are georeferenced using location information collected during the flight. The precision of the survey depends on the number of points collected per transect, which depends on aircraft speed, altitude, ground topography and vegetation. Typical point densities range from 50,000 to 100,000 points/km², which would result in contour lines with spacing of 1 to 5 m (Bowen and Waltermire 2002).

Examples of LIDAR systems that currently are used include the Coastal Mapping Project LIDAR System (previously called SHOALS - U.S. and Canada), the HawkEye (similar to SHOALS), the Laser Airborne Depth Sounder (LADS – Australia), and the newest Experimental Advanced Airborne Research LIDAR (EAARL). The EAARL has a less powerful laser and has been used to map coral reefs and riverine habitat in shallow, gravel-bed rivers. The Coastal Mapping Project/SHOALS have been most commonly used in the Great Lakes region to map nearshore areas of the Great Lakes. Maximum depth penetration depends on water clarity but can reach 40-50 m with horizontal precision of ±3.0 m and vertical precision of ±0.15 m (Hilldale and Raff 2007). LIDAR is often used in combination with hyperspectral data to provide classification of land and benthic surfaces.

**Remote Sensing – Satellite Platform**

Satellite remote sensing platforms are systems carried by Earth orbiting satellites. Space-borne satellites scan the Earth regularly and can provide imagery every few days to weeks of the same scene. Both spectral and radar imaging are typically used with remote sensing.

**Spectral**

Like airborne systems, satellite spectral sensors rely on reflected light as the source of radiation and collect images in the visible and infrared bands (0.3-3µm) of the electromagnetic spectrum. Examples of satellite remote sensing spectral sensors currently in use include the Landsat Thematic Mapper TM, Landsat Multi-spectral Scanner (MSS) and Landsat-7 ETM+, High Resolution Visible InfraRed camera (HRVIR mounted on the SPOT satellite), the Advanced Very High Resolution Radiometer (AVHRR), and Marine Observing Satellite Multi-spectral Electronic Self-scanning Radiometer (MOS-MESSR) (Table 2). The visible and infra-red signals are sensitive to soil moisture, water turbidity, photosynthetic activity of vegetation, and vegetation patterns. Satellite remote sensing spectral sensors are unable to collect images during cloud cover, rain or other precipitation events, or at night. Such limitations can be particularly problematic when attempting to measure river habitat during flooding since floods events are often accompanied by heavy cloud cover. As with airborne systems, satellite spectral scanners can receive multispectral or hyperspectral wavelengths.
Radar

Radar satellites use the microwave region or the electromagnetic spectrum (0.3 to 300 GHz or 1 mm to 1m wavelength: Table 2) to collect images. Radar sensors can be active or passive. Passive sensors measure the amount of microwave radiation naturally reflected from the Earth’s surface. Active sensors emit and receive microwave radiation. Passive microwave radiometers such as the special Sensor Microwave/Imagers (SSM/I) typically have relatively poor spatial resolution so are limited to mapping of large areas (Smith 1997). Active radar sensors such as JERS-1 SAR or ERS-1 SAR emit microwaves and receive return signals (backscatter) which are sensitive to the dielectric and geometric properties of earth features (Aschbacher et al. 1995; Smith 1997). The dielectric constant corresponds to the amount and state of water including water in soil or the vegetation canopy. The geometric property relates to the size, shape, orientation or volume of the object reflecting the backscatter. Radar can accurately determine the boundaries between water and land due to the low specular return associated with water features. Radar is particularly sensitive to terrain roughness, which makes it useful for mapping vegetation types. Because microwave bands can differ in wavelength and polarization resulting in differing levels of penetration of vegetative canopy, active radar sensors are capable of providing substantial information about the Earth’s surface. For example, C-band microwave signals are effectively scattered by the canopy while L- and P-band can penetrate the canopy and image water surfaces below. L-band radar is commonly used to identify areas of forested inundation due to the increase in backscatter from the “double bounce between tree trunks and water” (Smith 1997) while C-band imagery is best used for emergent wetland identification. Images from multiple band radar can detect both vegetation structure within flooded forest and nearshore wetlands and determine the extent of inundation or water boundaries due to both the abilities of different microwave bands to penetrate to different levels in the canopy and to the backscatter properties of water. Radar can also be transmitted and received in different polarizations which affect the image qualities like contrast. One key advantage of radar is that it can be collected 24 hours/day and can penetrate cloud cover thus can be acquired during precipitation events.

The resolution of radar imagery is proportional to antenna length. Synthetic Aperture Radar (SAR) is a technology developed to synthesize a longer antenna from the signal history resulting in increased resolution similar to a longer antenna. SAR also incorporates the Doppler effect, which uses the frequency difference between sent and returned microwaves to calculate velocity of an element on the Earth’s surface. Interferometric SAR is a technique of using a phase shift of two SAR images slightly offset in space or time to calculate topographic relief, water velocities and change in water level or surface topography. Radar sensors are unaffected by cloud cover and night time. SAR can produce a granular appearance or “speckle” in the image which is basically noise. Processing can remove speckle but at a cost to spatial resolution (Kuttikkad 2000). SAR image analysis techniques include speckle filtering and supervised and unsupervised classification of pixels.

Sonar and Acoustic Doppler Sensors

A variety of applications of Sound Navigation and Ranging (SONAR) systems have been used in nearshore and large rivers to produce bathymetric profiles, substrate typing and mapping, sub-bottom profiling, and to measure water velocity and discharge. Examples include side-scan, single beam, multi-beam, Acoustic Doppler Current Profiler (ADCP), and newer systems like Didson.

Side-scan Sonar

Side-scan SONAR is an acoustic tool that provides images of bottom morphology and surficial features from acoustic signals reflected off the bottom surface. Acoustic data are usually collected using a towfish that is deployed at depth ranging from 1 to 3 m below the water surface. The towfish has transducers that emit acoustic pulses directed at an oblique angle toward the bottom. Reflected acoustic energy is received and processed by the side-scan sensor in order to provide a continuous acoustic image.
or map of the bottom. The information is typically recorded for playback, processing, and analysis at a later date. Sonar can be interfaced with a GPS to georeference the collected data (Mackey and Liebenthal 2005).

Image resolution varies depending on the towing speed, swath width, and kHz of the SONAR system. Side-scan SONAR swath width is 5 to 15 times water depth, so in shallow water (< 8 m) the swath width can be quite narrow and result in loss of detail. Parallel swaths of side-scan images require stitching together into a mosaic to image the entire bottom profile. In water less than 20 m deep, LIDAR is more cost-effective than side-scan SONAR for bathymetry data because the swath width remains constant with airplane height. Side-scan SONAR is more effective in depths greater than 20 m because the swath width increases with depth (pers. comm., J. Lileycrop, USACE). Side-scan SONAR can be utilized for mapping aquatic vegetation. However, the presence of aquatic vegetation can be problematic when attempting to use side-scan SONAR to map bathymetry or substrate type.

Side-scan SONAR data can be used to produce an image of the bottom surface and the image used to manually or automatically classify substrate. Automatic processing uses the first return signal to produce bathymetry and the first and second signals to classify the substrate. RoxAnn is a common automatic classification system that uses the first and second echo returns from the seabed to calculate two parameters related to seabed roughness and hardness. Different pairings of roughness and hardness are then related to different bottom types through the collection of groundtruth data. RoxAnn can interface with a GPS and laptop field computer enabling real-time seabed classification and mapping of geological and biological features using RoxMap Software. RoxAnn systems have been designed for a variety of applications from the "all-in-one" portable, seabed classification system designed to be used onboard small vessels (RoxAnn GD-X GroundMaster) to the RoxAnn GD Swath that provides multi-beam mapping of the bottom surface allowing the surveyor to increase coverage of the bottom on each pass thus decreasing survey time and costs. The RoxAnn GD-A Hydrographic system creates color coded seabed material maps in 2 and 3 dimensions and in real-time (http://sonavision.co.uk/pages/seabed_classification_menu.html).

Cost is moderate for acquisition and processing of side-scan SONAR data and complexity is moderate. A side-scan SONAR system used for a St Clair River survey cost between $60,000 and $100,000 (Edsall et al. 1997). A RoxAnn classification system used along a Lake Superior nearshore region cost about $57,000 with drop video ground truth at $15,000 (Edsall et al. 1997).

Single Beam Sonar

In highly turbid systems, acoustic signals can be deflected by suspended particles and can degrade the image quality especially for side-scan or multi-beam sonar systems. Single beam SONAR is the method of choice in turbid waters (pers. comm., UMESC personnel). The single beam SONAR sensor is typically boat-mounted or towed (http://www.csc.noaa.gov/crs/rs_apps/sensors/single_beam.htm). The transducer emits a single narrow beam running in transects along the aquatic system. The return signals are along-track point data that can be processed for bathymetry or substrate similar to side-scan SONAR. It produces accurate and reliable bathymetry. Single beam SONAR systems are relatively simple and therefore less expensive than side-scan or multi-beam SONAR.

Multi-Beam Sonar

Multi-beam SONAR uses multiple beams along a fan-shaped swath beneath the boat along a series of transects which produces a fine scale bathymetric coverage of a medium width swath (2-7 times water depth). Multi-beam SONAR typically includes GPS to correct for vessel orientation relative to the water surface. Multi-beam SONAR is like having multiple single beam SONAR sensors in one
instrument that can point in many directions, thus it produces high resolution, accurate bathymetry, and more recently the backscatter has been used to classify bottom substrate. Multi-beam SONAR return signals can identify large grained substrate, but is less effective with fine-grained material. The drawback to multi-beam SONAR is that it is sensitive to turbidity, more expensive due to the multiple sensors and complex GPS integration, and coverage is limited in shallow water. It is commonly used by the National Oceanic and Atmospheric Administration (NOAA) to map nearshore coastal marine zones where turbidity and vegetation density are low.

Sub-Bottom Profilers

Sub-bottom profilers use a single beam of low-frequency SONAR (1-100kHz) that can penetrate soft substrate to the underlying hard substrate or rock. They can be used to produce maps of the layers of soft substrate. Sub-bottom profilers can identify bathymetry, substrate hardness and density discontinuities from a cross-section perspective but can not provide information on the thickness or composition of hard substrate. Acoustic profiling of sub-bottom substrate has several inherent problems: sound may not be able to discriminate all habitats that exist; shallow or turbid water can confound the reflected sound pulses and affect ground-truthing; and, sound systems are sensitive to density discontinuities in water such as fish, plankton or turbulence (Smith et al. 2001). Gear calibration is important to ensure accurate reception of acoustic echoes.

Acoustic Doppler Current Profilers

Acoustic Doppler Current Profiler (ADCP) uses multi-beam hydroacoustic technology to measure water depth and velocity in multiple cells simultaneously using the Doppler effect. In nearshore marine habitat, up-looking ADPs are often used to measure waves and current. In rivers, ACDP is typically mounted on a boat or other towed flotation device and used to compute the mean velocity in vertical grid cells (bins) from the Doppler shift of returning acoustic signals (pings). ADCP have been designed for shallow water use (> 5 cm deep) with maximum profiling range of 10-14 m. A Pulse Coherent Acoustic Doppler Profiler (PC-ADP) has been developed to optimize high resolution velocity profiles for short-range boundary layer studies. The PC-ADCP has a maximum profiling range of 5 m in pulse-coherent mode. The ADCP can be used to estimate discharge, map channel bathymetry and measure velocity profiles in one cross-section measurement. ADCP can be linked to differentially corrected GPS for an accurate georeferenced, high resolution velocity profile, discharge, and channel cross-section data using special software to process the data. Precision estimates for depth are ±0.088 m (Hilldale and Raff 2007). The ADCP has a bottom tracking function that, in conjunction with DGPS, can account for boat velocity and trajectory when measuring discharge but can also be used to measure substrate mobility. Estimate of bottom roughness can be interpreted from the bottom signals to make rough estimates of substrate type. A typical system costs around $30,000 but with a high quality GPS and computer system is likely to cost more in the range of $50,000-55,000 (Edsall et al. 1997; pers. experience, C. Riseng, University of Michigan). ADCPs are limited to depths greater than 10 cm and data cannot be collected close to the water surface or near the water bed. However, Pulse-coherent ADCP have been developed that can sample within 5 cm of the bottom. ADCPs have a wide range of uses in assessing and mapping riverine habitat with the main disadvantage being cost of the system. Error can be introduced due to boat rocking and due to improper compass calibration.

DIDSON

A new SONAR technology called Dual Frequency Identification SONAR (DIDSON) is a high resolution, high frequency multi-beam (96) SONAR that produces high quality, video-like images in real-time (http://www.soundmetrics.com/). It was originally made to observe objects under high turbidity or darkness by the military but has more recently been used to image fish passage (pers. comm., K. Kowalksi, USGS GLSC). For fish passage, transducers are aimed sideways for identifying fish. High
quality images of the bottom profile and substrate can be obtained by directed the transducers downward. DIDSON equipment presently cannot be interface with a GPS to provide geo-referenced data.

STATE-OF-THE-ART SAMPLING TECHNIQUES BY HABITAT

Nearshore Shoreline Development

The Great Lakes basin covers more than 518,000 km² and contains approximately 30,000 hectares of wetlands, 676,500 ha of U.S. inland lakes at least 2 ha in size, and 453,700 km of U.S. streams and rivers. The Great Lakes basin is home to more than 37 million people. About 80% of the U.S. Great Lakes shoreline is privately owned, while around 20% of the Great Lakes shoreline in Canada is privately owned. Habitat loss, degradation, and fragmentation due to shoreline development of Great Lakes are recognized as some of the primary threats to the nearshore ecosystem.

The Great Lakes shoreline is constantly being reshaped by wind, waves, water level, and lake current. Both short- and long-term impacts on shoreline conditions can result from these factors. For example, shoreline erosion can be a natural process that occurs under all water level conditions, although it is often magnified during periods of high water or storms. The Great Lakes’ shoreline can be digitized and presented fairly accurately from aerial photos or satellite imagery at any one point in time. However, assessing shoreline status is challenging because of the large coverage area, its natural variability, and the continual influence of human activities. Shoreline condition assessments have focused mainly on the long-term characteristics that reflect an average condition for a given period (e.g., annual).

Lake shores have always been a preferential place for human settlement and many other human activities, which has led to extensive shoreline development in many places. Shoreline development impacts the littoral zone through alteration or loss of littoral habitat. Examples include reduction of macrophyte stands, alteration of substrate particle size, and construction of seawalls for erosion prevention, dock building for boating, and modification of shoreline vegetation for scenery. Although many state programs and individual studies have collected shoreline development data by field visits, there is no basin-wide or lake-wide effort to collect or assemble existing shoreline development data for the Great Lakes.

Great Lake Coastal Wetlands

Coastal Wetland Definition

Wetlands are transitional areas between terrestrial and aquatic systems where the water table is usually at or near the surface or else the area is periodically covered by shallow water (Dahl 2005). Wetlands collectively refer to marshes, swamps, bogs, and similar areas found between dry land and aquatic systems. The Great Lakes coastal wetland ecosystem includes wetlands located adjacent to many of the Great Lakes nearshore areas, including connection channels, Lake St. Clair, and the mouths of river systems where wetland hydrology is determined by the levels of Great Lakes and river hydrology (e.g. freshwater coastal estuaries). The coastal wetland areas include open shoreline, unrestricted bay, shallow sloping beach, river delta, restricted riverine or drowned-river-mouth, lake-connected inland, and barrier beach wetlands (Maynard and Wilcox 1997).
Coastal Wetland Functions

By definition, the Great Lakes coastal wetlands are perennial or ephemeral shallow waters distributed between the nearshore and terrestrial zones; hence, they perform many functions that influence the habitat of the nearshore zone. Although some of the greatest values of coastal wetlands lie in their habitat potential for migratory birds and waterfowl, herein we mainly focus on their value as habitat for fish.

The function of coastal wetlands can be generalized into three major areas. First, coastal wetlands provide a buffer between nearshore zones and upland systems. Coastal wetlands minimize impacts of upland of terrestrial systems on nearshore zone by slowing water flow, serving as sediment and nutrient sinks, and excluding human development. Second, coastal wetlands improve water quality clarity by removal and retention of excessive sediments, nutrients, such as nitrogen and phosphorus, and organic pollutants from terrestrial zones. This serves to reduce open water eutrophication and turbidity. Third, coastal wetlands can provide critical spawning and nursery habitat for a variety of aquatic species and life stages and thus help to increase primary and secondary productivity within aquatic systems. Submerged and emerged macrophytes stands increase the presence of invertebrate prey species and provide a highly productive source of zooplankton and benthos, which are used as fish food resources (Meixler et al. 2005). More than 75% of Great Lakes fish species are believed to utilize coastal wetlands during some portion of their life cycle (Stephenson 1990; Willans 1992). It has been estimated that coastal wetlands provide critical habitat for more than 80 species of fish in the Great Lakes (Jude and Pappas 1992; Wilcox 1995)

Coastal Wetland Status

The total area of coastal wetlands in the Great Lakes has been estimated at 1,741 km² (Mayard and Wilcox 1997), although this number is believed by some to be an underestimate of actual coastal wetland area. While a number of small scale studies have attempted to evaluate the status and trends of local Great Lakes coastal wetlands, a comprehensive inventory and evaluation of coastal wetlands for the entire Great Lakes region has never been conducted.

The broadest inventory and evaluation of Great Lakes coastal wetlands in Canada has been the Evaluation System for Wetlands of Ontario South of the Precambrian Shield, which was an attempted inventory of coastal wetlands along the Canadian shoreline (Ontario Ministry of Natural Resources 1993). Although this system has inventoried and evaluated the majority of coastal wetlands in Ontario, several sections of the Great Lakes Canadian shoreline were not included (Mayard and Wilcox 1997). Along the U.S. shoreline, the most comprehensive inventory and description of the Great Lakes coastal wetlands was provided by Herdendorf et al. (1981). This effort was based on a comprehensive literature search of journals, governmental agency publications, gray literature, and personal contacts. However, the inventories and evaluations were completed more than 25 years ago, and a consistent methodology for inventorying wetlands was not used. The most comprehensive evaluation of both Canadian and U.S Great Lakes coastal wetland status was conducted by Mayard and Wilcox (1997). This evaluation was conducted using data from the two aforementioned databases (Herdendorf et al. 1981, Ontario Ministry of Natural Resources 1993) with additional information gathered from literature and personal communication. The Mayard and Wilcox (1997) report concluded that although regional or local efforts for mapping Great Lakes coastal wetlands were underway, a comprehensive inventory and evaluation program was lacking.
Wetland Inventory Methods

Many wetland inventory methods have been developed and applied to assess the coastal wetlands of Great Lakes. Those methods can be generalized as: (1) inventorying wetland spatial extent and its loss and gain, and (2) inventorying wetland plant community composition and detecting its change over time.

Inventorying Wetland Spatial Extent

Aerial photography

This approach to wetland inventory generally involves in a combination of three efforts: gathering existing databases, interpreting/digitizing aerial photos, and field verification. One example of a large effort using this approach is the wetland mapping, inventory and evaluation of all southern Ontario wetlands initiated in 1981 by the Wildlife Branch of the Ontario Ministry of Natural Resources and Lands Directorate/Canadian Wildlife Service of Environment Canada (Snell 1987, Smith et al. 1991). The primary goal of the wetland inventory and evaluation was to rank wetlands for the purposes of setting planning and management priorities to facilitate informed land use decisions (Smith et al. 1991).

The southern Ontario wetland inventory and evaluation included field identification and mapping of vegetation communities, summary of existing knowledge about rare species, and measurement of other variables such as exposure to wave action (Smith et al. 1991). When completed, these field data were coupled with knowledge of local biologists and naturalists and translated into evaluation scores using metrics laid out in the wetland manual. These scores were then used to rank the wetlands into seven classes, class one being the highest or most valuable and class seven being the lowest rank. Both the inventory and evaluation dealt with biological, social, hydrological, and special feature information. In the scoring scheme, each of the equally weighted four components had a maximum score of 250 points that were summed to determine the final wetland ranking (Smith et al. 1991).

The largest effort of Great Lakes coastal wetland inventory was the one developed by the bi-national initiative Great Lakes Coastal Wetland Consortium (GLCWC) to create a single, hydrogeomorphically classified inventory of all coastal wetlands of the Great Lakes Basin. This inventory was built upon the most current and comprehensive wetland data available for the Great Lakes and connecting channels. For the U.S., the National Wetlands Inventory, Wisconsin Wetland Inventory, Ohio Wetland Inventory, and U.S. Fish and Wildlife Service reports and corresponding topographic maps, were the major database sources. The Canadian dataset was built off “The Ontario Great Lakes Coastal Wetland Atlas”. This dataset summarized all known data for coastal wetlands and identified numerous data gaps in the existing information. The inventory contained the spatial extents, hydrogeomorphic classification, hydrologic modifiers, name, centroid position and area measurement for all known coastal wetlands of the Great Lakes basin. The GLCWC working group developed hydrogeomorphic criteria to delineate wetlands as described in the Great Lake Commission's Great Lakes Coastal Wetlands Classification First Revision. The scale of the data varied with the source and was not intended for use at finer than the source scale.

This type of wetland inventory utilizes existing databases and captures the historical data, which makes it feasible to assemble a database for a large region, such as the Great Lakes basin. The weakness associated with this type of inventory is that the data are collected by many agencies with many different objectives. Therefore, the data are often collected with inconsistent methodologies, scales, and classification frameworks; sampling efforts are often unevenly distributed within the Great Lakes basin; and, the inventory is often incomplete in temporal and spatial scales.
With the relatively recent development and expansion of GIS and remote sensing technology, it is feasible to capture the spatial extent (type, size, and location) of wetlands in the entire Great Lakes basin at a given temporal interval. The changes in spatial extent of wetlands among the temporal intervals can be used to assess wetland loss and gain for the entire Great Lakes basin. In fact, in the U.S. Emergency Wetland Resources Act of 1986 (1988 and 1992 amendments), Congress directed the National Wetlands Inventory program to 1) update and improve the wetlands information by 1990 and at 10-year intervals thereafter and 2) estimate the number of acres of wetland habitat in each U.S. state in the 1780’s and 1980’s (http://water.usgs.gov/nwsum/WSP2425/mapping.html). Notably, the Congressional mandate includes only the U.S. portion of the Great Lakes. The Great Lakes coastal wetlands are unique; they are the largest freshwater coastal system of the world and managed by multiple national, provincial and state jurisdictions. Therefore, a coastal wetland inventory is needed that has consistent sampling design, data capturing and processing technologies, temporal intervals, and spatial resolutions for the entire Great Lakes basin.

Remote sensing

Remote sensing has been used in wetland mapping for several decades. The early inventories were conducted mainly through image interpretation of aerial photographs. More recently, automated classification methods have been used for data obtained from satellite multispectral sensors (e.g. Landsat Multi-spectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+)), hyperspectral imagery (e.g. satellite Hyperion and airborne Probe-1), and approaches combining satellite radar and multispectral imagery have been tested in the Great Lakes.

Rosso et al. (2005) assessed the adequacy of using hyperspectral imagery to determine the structure of wetlands of San Francisco Bay, California. In their study, they compared spectral mixture analysis (SMA) and multiple endmember spectral mixture analysis (MESMA) techniques applied to Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) imagery to investigate their appropriateness to characterize marsh plant species. AVIRIS collects radiance data in 224 optical channels that covers the spectral region from 380 to 2500 nm with pixel resolution of about 20 m. Vegetation used as reference for classification accuracy assessment was obtained from high resolution color-infrared photography aided by ground verification and a polygon-based vegetation map. Because some vegetation types, water, geological minerals, and other features could be identified in the image as spectrally distinct candidate endmembers, this study focused on evaluation of candidate endmembers selection procedures. For SMA, the endmembers were selected by trial and error until the most accurate results were obtained. In contrast, MESMA allowed for the inclusion of an unlimited number of endmembers because it tested models on a pixel-by-pixel basis and selected the best fit endmember for each pixel, thus avoiding over fitting from too many endmembers. They concluded that both SMA and MESMA were suitable for mapping the main components of marsh habitat, although MESMA seems more appropriate since it incorporated more than one endmember per class.

Bourgeau-Chavez et al. (2004) merged the capabilities of microwave (radar) and optical sensors to optimize satellite-based remote mapping and monitoring of coastal wetlands in the Great Lakes. Multi-spectral sensor data can provide information on cover type and wetness information in open canopied ecosystems while Synthetic Aperture Radar (SAR) provides flood condition and extent of flooding of forests and other closed canopy ecosystems. SAR can penetrate cloud cover, which allows the data to be collected under most conditions. The two types of sensors were utilized to collect complementary information for land cover and wetland identification. Landsat is an optical, passive sensor that collects reflected/re-radiated energy that comes from the earth’s surface. The Landsat sensor is positioned such that it always collects the nadir (straight down) position and effectively differentiates anthropogenic features from natural features, and separates numerous vegetation groups, based solely upon spectral information. In contrast, radars are active sensors that always collect at an angle off nadir. SAR off-nadir operation allows for biomass and structural aspects of target material to be collected (e.g., roughness and
stem density). The radar system allows for information to be collected that compliments the purely nadir, optical imagery of the Landsat imagery.

Bourgeau-Chavez et al. (2004) conducted three types of analyses to develop methods for mapping and classifying wetlands in the Great Lakes region. They used Landsat imagery (1970’s and current) in combination with land cover maps (1970’s National Wetlands Inventory (NWI) maps and the current MDNR Integrated Forest Monitoring and Assessment Prescription (IFMAP) land use/cover coverage) and combined categorical change from the land cover maps with radiometric change from the Landsat images. They were able to minimize errors by 1) setting a threshold limit for radiometric change that was greater than “noise” and 2) using categorical change to classify the type of land cover change that has occurred. This procedure resulted in 65-95% accuracy compared to manual map analysis and 89% accuracy compared to field data. Challenges to this method include matching classifications within land cover maps from different time periods. Secondly, they used JERS-1 SAR L-band radar data to map inundation in coastal forested wetlands using two approaches: 1) they used an image from one time period and estimated inundation from SAR brightness; and, 2) they used multi-temporal images to create a composite image and automatically extract potentially flooded areas. The ability of SAR data to map inundation extent provides the ability to monitor extent of flooding and effects of water levels changes. The third approach was to combine SAR radar and Landsat multispectral data to create land cover maps. They found that creating separate maps from radar and spectral data, then combining the maps maintained the unique radiometric properties of each set of data and provided the best classification. They used both L-band and C-band radar complimentarily to map forested and herbaceous wetlands, respectively. They used maximum likelihood classification to classify 4-6 wetland types with around 65% accuracy. They compared costs-benefits of three mapping techniques based on the time required to process imagery and create wetland maps on an 80x100 km per-scene basis. All the methods were less-time consuming than aerial photography analysis which was estimated to take 1,000 hours for a similar scene. The land cover/use change analysis from Landsat and categorical maps took 26 hours, the SAR forested wetland inundation map took 8.5 hours and the Landsat-SAR merged classification map took 13 hours. They suggest that the most efficient method for mapping wetlands is to conduct a change analysis using existing land cover maps with Landsat imagery to detect change and minimize errors of omission and commission. One potential limiting factor would be the availability of existing land cover maps for the Canadian coastal region. They also note that new double polarization radar data will more effectively discriminate between forested and emergent wetlands, which would be important for classification of coastal wetlands.

Great Lakes coastal wetlands of Lake Huron were mapped and classified using IKONOS satellite multispectral images using 3-4 broad bands in the 380-1050 nm wavelength range (Wei and Chow-Fraser 2007). They used field data gathered from boat and shore surveys for a supervised classification (pers. comm., Dr. Chow-Fraser, McMaster University). They found overall classification accuracy into five main classes was 84.5% (Wei and Chow-Fraser 2007). Dr. Chow-Fraser suggested that IKONOS works well in the Georgian Bay because the water is very clear but that in more turbid waters such as Lake Erie or Ontario a combination of hyperspectral and LIDAR data might be needed. Dr. Chow-Fraser indicated a preference for IKONOS over Landsat imagery due to the improved spatial resolution with IKONOS imagery. The trade-off is that IKONOS imagery is also more expensive ($500,000/year to cover the Georgian Bay).

**Inventorying Wetland Plant Community Composition**

Methods used to sample wetland plant community composition depend upon the level of accuracy and detail required to meet the needs of the inventory. For the purpose of evaluating quality of wetland plant communities as fisheries habitat and detecting their change over time, medium level accuracy and detail is sufficient.
Site-based field sampling

Traditionally, information on wetland plant community composition has been obtained through field sampling using one of several approaches. The most commonly used approach is to first identify wetland boundary and size, which usually involves wetland mapping process in the laboratory and in the field. Then one of the following ecological sampling techniques is typically used to identify plant community composition. Plot or quadrat sampling methods are commonly used to intensively study a small portion of a wetland in order to obtain a representative sample. Most often plot samples are replicated a number of times, in a random or haphazard way, to ensure that the data represent an unbiased picture of the system. Point-quarter sampling is more complex but expands on plot sampling in an attempt to reduce the amount of intensive labor involved in plot sampling. Rather then attempting to quantify the exact make-up of a specific plot, a random number of individuals are selected to provide an unbiased estimate for the entire plot. Replicate samples using this method are also taken to ensure statistical validity. Transect sampling is another often-used method for sampling wetland systems. This method may be visualized as a long, narrow plot with multiple transects perpendicular or parallel to shore. Measurements are taken of all individuals that occur along a transect.

The traditional approaches provide reliable and detailed information on wetland community composition. They are suitable for inventory of species diversity, species composition, invasive and native species, and detecting changes over time. These protocols are also suitable for developing wetland health assessment indices. For example, Lougheed et al. (2001) sampled macrophyte community structure for 62 coastal and inland wetlands in the Great Lakes basin. They first choose sampling locations by a brief inspection of wetlands from accessible nearshore areas to select a sheltered location that contained relatively dense macrophytes for sampling for each wetland. They then counted every species of macrophytes encountered within a 3-m radius of the selected vegetated site. In wetlands where macrophytes distribution was sparse, they conducted an expanded survey along an approximately 100-m shoreline. They last linked the wetland plant community structure with water quality and watershed land uses to develop a habitat quality index.

These traditional field approaches are very time and resource consuming, which is not feasible if the goal of the inventory is to assess a large portion or the entire Great Lakes wetland plant community structure. For assessing the Great Lakes fish habitat provided by the coastal wetland plants, not only detailed plant community composition and their function need to be understood, but also their large-scale distribution and availability need to be assessed.

Remote sensing

Recently, considerable efforts have been devoted to developing remote sensing techniques for wetland macrophyte community mapping with broad scale classification that would not require field surveys except for validation or image training data. Provided that there are effective ways to represent accurate on-the-ground information through collected imagery, remote sensing is cost effective in terms of area surveyed and has the potential to update surveys by repeatedly sampling over large areas. Although there still are many technological areas that need to be improved, studies have made considerable progresses and are beginning to provide promising results.

Recent literature has shown that narrow, strategically placed spectral bands or ratios of bands of satellite images can provide significant improvements over broad bands for wetland vegetation identification. Although not widespread, several studies have produced promising results and the current research efforts are focusing on providing spatial and spectral resolution that more effectively differentiate wetland vegetation types. For example, Wang et al. (1998) acquired data from Modular Airborne Imaging and Senstron Airborne Imaging Spectrometers and analyzed their data based on derivative spectral matching. They first reduced low frequency background noise on target spectra by
derivative transformation of hyperspectral data, then collected field spectral data as “endmember” spectra for matching with hyperspectral image.

Pengra et al. (2007) used hyperspectral data collected from the Hyperion satellite to map the invasive species, *Phragmites australis*, in Great Lakes coastal wetlands. They used known locations of *Phragmites* to identify the bands that most effectively mapped this invasive species at a spatial resolution of 30 m. Overall, the authors were 81.4 % accurate in the identification of *Phragmites*. Alternatively, the use of airborne hyperspectral Probe-1 data had a 91% identification accuracy at a spatial resolution of 5 m. However, the authors concluded that airborne hyperspectral imagery was likely too expensive to be effectively used at a broad scale.

Several issues associated with identification of wetland vegetation using hyperspectral data need to be addressed. Hyper-spectral sensors generate vast quantities of data, which can be challenging to store and analyze. Other issues include hyperspectral band redundancy, identification of appropriate bands for analysis, and sensor limitation. Becker et al. (2005) identified the fewest number of narrow bands in the visible NIR range that optimally differentiates vegetation types within the coastal wetlands of the Great Lakes. They collected *in situ* radiance measurements (252 bands, 365-1125 nm) using an SE-590 spectroradiometer that was positioned approximately 1 m above the vegetation during growing season in Lake Huron. They first transferred the spectra from 82 sampling locations into percent reflectance, and then divided them into seven categories based on their plant community type. The individual reflectance spectra within each category were averaged to yield a single spectrum representative of that group. After importing the reflectance spectra into image processing software, they used 2nd-derivative approximation to transform the spectra into vegetation types.

More recently, Becker et al. (2007) tested several band selection strategies and determined the optimal spatial resolution of imagery to be used in Great Lakes coastal wetland mapping. They found that a minimum of seven bands in the VIS-NIR wavelength region were necessary to maintain classification resilience above 85% threshold. The seven bands that produced the highest resilience were 425, 514, 560, 685, 731, 812, and 916 nm. They concluded that the optimal spatial resolution of Great Lakes coastal wetland imagery was 1 m or less. The programmable airborne imaging systems possess the spatial and spectral characteristics needed to map and monitor Great Lakes coastal wetlands with high classification accuracy. Collection of a limited number of bands can reduce the cost of hyperspectral imagery thus providing more coverage for dollar invested (pers. comm., J. Lillycrop, USACE).

**Wetland classification**

The general goals of wetland classification are to describe ecological units that have certain homogeneous natural qualities, to arrange these units into systems useful for management and evaluation, to provide useful units for inventory and mapping, and to establish common communication language among managers, researchers, and policy makers within a region and across regions (McKee et al. 1992). Although a great deal of work has been done in the inventory and classification of wetlands in the Great Lakes basin, no existing classification system is accepted as the standard system. However, several early established wetland classification systems have been used specifically on the Great Lakes coastal wetlands.

The Classification of Wetlands and Deepwater Habitats of United States (Cowardin et al. 1979) was initiated in 1974 and developed, refined, and field tested over a 5-year period by the U.S. Fish and Wildlife Service (USFWS Wetland Classification). The purposes of this classification system were to: 1) describe ecological units having certain common natural attributes; 2) arrange the units in a system that will facilitate resource management decisions; 3) furnish units for inventory and mapping; and, 4) provide a nationwide uniformity in wetland concepts and terminology. From 1979 to 1991, the USFWS applied
this system for inventorying wetlands in the lower 48 states, including 95% of the Great Lakes coastal wetlands in the U.S. (McKee et al. 1992).

The USFWS Wetland Classification system has several hierarchical levels, including major system, subsystem, class, and subclasses. The major system level includes five categories - marine, estuarine, riverine, lacustrine, and palustrine. The marine, estuarine, and lacustrine major systems are further divided into two subsystems; the riverine major system is divided into four subsystems, and the palustrine has only one subsystem. At the class level, each of the subsystems is further divided into one to eight classes depending on how diverse the subsystem is. The class level describes the appearance of the wetland in terms of vegetation or substrates where vegetation is inconspicuous or absent. Each class is further divided into subclasses and subclass into dominance types based on modifiers, such as hydrology, water chemistry, and factors related to human activities.

The Geomorphic Classification of Great Lakes Coastal Wetlands is a simple geomorphic view of wetlands as basins occupied by plant communities and wetland boundaries dictated by landform (Jaworski and Raphael 1979). This system categorizes several Great Lakes wetlands into five types based on their geomorphic structure. The first type is sheltered lagoons bounded by sand barriers on the lakeward side and by upland on their flanks. This type occurs along shoreline and the sand barriers are formed from near shore current transporting littoral sediment along the shoreline. The second type is formed by deltas at places where sediments are deposited by a river along the banks of tributary channels. Marshy wetlands develop in protected waters around these estuarine structures. The third type is a flooded river estuary, which is formed in deep river valleys excavated during low water levels. Sand barriers are deposited by nearshore currents to form protected structure across the river mouth where wetland vegetations are found. The fourth type is formed along shorelines where nearshore sandbars provide protective sandbars. Wetland vegetation develops in the depressions and in the nearshore zone. The last type is characterized by an upland glacial lakeshore terrace and a coastal barrier, such as a spit, a beach bridge, or a sand barrier.

The Hydrogeomorphic Model (HGM) has been applied for wetland classification at a range of geographic and geologic conditions (Brinson 1996) and has been expanded to Great Lakes coastal wetland classification (Keough et al. 1999, Albert and Minc 2001). In 2002, the members of the Great Lakes Coastal Wetland Consortium developed a hydrogeomorphic wetland classification system that can be used to consistently characterize and potentially map all of the coastal wetlands of the Great Lakes (Albert et al. 2005). With the HGM classification system, the Great Lakes coastal wetlands are divided into three hierarchical levels based on hydrogeomorphic structure. The first level classification includes lacustrine, riverine, and barrier-protected systems based on their hydrologic types. The lacustrine is divided into open lacustrine and protected lacustrine; the riverine is divided into drowned river-mouth, connected channel, and delta; and barrier-protected is divided into barrier beach lagoon and swale. More complex second level classes are based on their geomorphic types. Each of the second level classes is further divided into two or more third level subclasses. For example, based on geomorphic modifiers, open lacustrine, protected lacustrine, barrier beach lagoon, swale complex, drowned river-mouth, and delta are each divided into two subclasses and connected channel is divided into seven subclasses.

The HGM classification system differentiates the greatest physical and biological differences among coastal wetlands at the hydrologic system level, resulting from differences in water-flow characteristics and residence time (Albert et al. 2005). The lacustrine system includes all the wetlands directly connected to the Great Lakes. The members of riverine system are characterized by flowing waters that are influenced by the Great Lakes water chemistry and movement. The barrier-protected system are wetlands that are nearly or completely separated from the open Great Lakes by barriers created by waves or current deposition of mineral sediment, such as sand-dune-capped beach ridges and gravel and cobble bars.
Each of the above mentioned classification systems has associated strengths and weaknesses for Great Lakes coastal wetlands. The USFWS Wetland Classification system defines wetlands as those water bodies having enough water at some time during the growing season to cause physiological problems for plants or animals that are not adapted to live in water or in saturated soil. The system does not define a minimum mapping unit, although it assumed that wetlands \( \geq 1 \) ha are mapped. This classification system is flexible and can be readily adapted to apply to different environment without major modification. The hierarchical framework permits classification at different scales and precision to meet the needs of classification objectives. The Geomorphic Classification system is simple and is developed to focus more on broad measures of the physical features of the Great Lakes coastal wetlands. This classification system provides information only on physical structure of wetland habitat, but it does not provide information on biological communities. The HGM functional classification is developed primarily as a tool for better understanding and assessing the dynamic processes and biota of coastal wetlands (Albert et al. 2005). It provides finer distinctions among wetland types of the Great Lakes region. Classifying wetlands based on how they function narrows the focus of attention to a specific type or subclass of wetland, the functions that wetlands within the subclass are most likely to perform, and the landscape and ecosystem factors that are most likely to influence how wetlands function. Use of the HGM for wetland assessment increases the accuracy of the assessment, allows for replications, and reduces the time needed to conduct the assessment.

**Summary**

The most comprehensive binational Great Lakes coastal wetland database is the one assembled by the Great Lakes Coastal Wetlands Consortium program, the Great Lakes Coastal Wetlands Inventory (http://www.glc.org/wetlands/inventory.html). This database was built upon the best existing coastal wetland data, incorporates a standard classification process, and provides a standard reference for the Great Lakes wetland community. All the data have been standardized and the wetland polygons have been stitched together into one seamless GIS coverage, which is now available to download. Although this database is the most broadly accessible, comprehensive inventory for assessing status of coastal wetlands, it would be difficult to use this approach to resample the entire Great Lakes coastal area for assessing trends because this database has taken decades to collect and years to assemble. The recent development in remote sensing technology provides a promising, cost-effective way to achieve the goal of sampling the entire Great Lakes coastal area within a relatively short time frame and periodically updating the survey. This is because using remote sensing to map wetland boundaries and broad scale community types essentially does not require extensive on-ground-surveys.

**Riverine Floodplain Habitat**

Floodplains are transitionary zones between terrestrial and aquatic systems and are considered an integral part of large river ecosystems. Floodplains can be highly dynamic systems due to the interaction between land and water; floodplain functions are dependent on the hydrologic regime, connectivity between the river and its floodplain, and river valley morphology (Amoros and Bornette 2002; Townsend and Walsh 1998). Floodplains are characterized by the exchange of nutrients, organic matter, sediments and living organisms between terrestrial and riverine systems. Floodplain dynamics are characterized by the flood-pulse concept of natural hydrologic regimes that results in predictable patterns of seasonal floods which in turn has led to biologic adaptation to these temporary aquatic habitats (Amoros and Bornette 2002; Thorp et al. 2006). In temperate rivers a typical flood pulse would occur in the spring with spring rains or snow melt. Many riverine fish spawn during flood rise periods and juveniles move into the floodplain nursery and refuge habitats during the draw down period. Flood pulses typically release nutrients and organic matter, which, in combination with increased temperature (due to increased solar input across the floodplain), result in increased plant and invertebrate productivity and provide
excellent nursery habitat for young fish. Connectivity of a river to its floodplain has been shown to result in increased fish production (Bayley 1995). Flood pulses create shifting patterns of expansion and contraction of terrestrial and aquatic habitats that increase habitat heterogeneity in river-floodplain systems dependent on connectivity between river and floodplain (Tockner et al. 2000). Floodplain expansion and contraction can also occur at below bankfull conditions due to hyporheic flow, tributary water, overland runoff, and soil water. Flooding can be caused by both over bank flow which can be contained within permanent channels and main channel water backing up into low elevation areas such as meander bends, tributaries and drainage channels. Functions of riverine floodplains have been altered due to farming, hydroelectricity, wetland removal, land use change and transportation resulting in fragmentation of the riverine ecosystem.

Riverine floodplains contribute to the biocomplexity of riverine ecosystems. Floodplain habitats include floodplain lakes, oxbows, meander scrolls, natural levees, side channels, forests, wetlands and backwater (Sparks 1995). The spatial and temporal patterns and diversity of these floodplain habitats depend on hydrologic connectivity, distance from the channel and valley hydrogeomorphology (Amoros and Bornette 2002).

Many organisms depend on floodplains for important life history stages. Many important ecological processes occur in floodplains such as primary and secondary productivity, decomposition, and fish rearing that are essential to riverine biota. Organisms have adapted to the temporal and spatial variability of floodplain habitats which contribute to the physical and biological diversity of large riverine habitats. Both wadeable and nonwadeable field methods evaluate riparian habitat at some standard width or limited to what is visible from a boat and attributes like vegetation type, cover and density, and bank stability and conditions are estimated or measured. However, floodplain ecosystems typically extend far beyond these riparian buffers, especially in large rivers. For large rivers where the floodplain is an important ecological component it would be important to include explicit evaluation of the floodplain in any river habitat assessment protocol although this is rare.

**Site-based field methods**

In our review of methods for inventorying floodplain conditions, we found two approaches that combined field-based sampling and GIS technology for the evaluation of floodplain conditions. Baker and Wiley (2004) related field sampled riparian/floodplain forests in Michigan to landscape-based variables indicative of regional climate and catchment hydrology and character. They identified seven types of floodplain/riparian forest that were best explained by climate, geology, flood duration, and river power. This method suggests that riparian/floodplain character may be accurately predicted from map-based variables based on limited field sampling.

A nonwadeable habitat index (NWHI) for rivers in Michigan used a combination of map and GIS based measurements (Wilhelm et al. 2005). They measured a large number of variables and statistically identified seven key variables based on importance to riverine habitat and association with measures of disturbance. Two of these variables were relevant to floodplains, although floodplains were not explicitly identified or measured: riparian width and off-channel habitat. They used regression models to weight the seven variables in the NWHI and found that riparian width had the highest weight and off-channel habitat the lowest.

Nine of the reviewed methods that evaluated floodplains as a component of riverine habitat used a combination of field, GIS and aerial spectral imagery and one method incorporated thermal imagery. Several established European and Australian methods (RHS, SEQ-MP, LAWA-vor-Ort, River Styles) for classifying and assessing river habitat include characterization of the floodplain as part of the assessment (Raven et al. 2002, Jeffries 1998, Brierley and Fryirs 2000). Each of these methods employ map data and
visual observations conducted during walking surveys of either large river segments or the entire river and incorporate visual assessment of riparian and floodplain conditions into river type classification. These river types are then compared to reference sites based on expert opinion. In the SEQ-MP riverine and floodplains are scored separately and combined later. The UK RHS uses a combination of map and field data to classify sites and includes valley shape (floodplain type) as one component of stream classification (Jeffers 1998). For example, digitized GIS layers of hydrography (1:50,000 scale), DEM, flow direction grid, solid and drift geology, catchment land cover and extent of "flood defense" were combined in GIS to preliminarily classify rivers under the RHS protocol and to define the boundaries of study reaches based partially on the presence of a 100-year floodplain (Dawson et al. 1997). These methods seem designed for small to medium rivers but could potentially be adapted to larger rivers by adjusting sample length and transect spacing (Raven et al. 2000).

Muhar et al. (2000) described an assessment method for river/floodplain systems in Austria that expands on the European methods described above. They employ a 4-tiered evaluation protocol that first uses maps and aerial photos to classify rivers and define reference reaches then detailed field investigations are conducted to verbally describe the extent of wetland-vegetation and types of water bodies within the floodplain. Two of the five characteristics of reference condition are based on the condition of the floodplain. Characteristics evaluated visually in the field include extent and structure of floodplain vegetation, site specific hydrologic conditions, and connectivity between river and floodplain.

GIS was used to identify critical floodplain fish habitat and streamline the field effort prior to conducting fish surveys in large rivers in Bangladesh (Graaf et al. 2003). In Bangladesh rivers critical floodplain habitat is a complicated network of ponded water, floodplains and river/canal. To identify floodplain habitat they used a "risk of flooding" method to calculate total inundated area and classify floodplain areas by flood hazard type. Total inundation was calculated in GIS from modeled or interpolated measured water levels, depending on data availability, and floodplain habitat classified. They compared floodplain habitat classification using GIS and SAR radar data and found that monthly averages used in their GIS analysis provided more useful classification for stratifying floodplain habitat versus SAR one-time data.

**Satellite Radar Data**

A number of studies we reviewed used remote sensing combined with GIS applications to estimate flood extent and flood-stage discharge. Both spectral and radar satellite imagery have been used to map flood extent and to estimate flood stage and remotely estimate discharge. Water surface elevations can also be measured from a combination of satellite radar images and topographic maps or digital elevation maps. Field measured spot surface water elevations must be established but then radar can image the change in water surface area so that flood volumes and extent can be estimated.

The earliest work in flood inundation mapping was with MSS (Landsat-1), which used Band 7 (0.80-0.1 um) to discriminate dry land from water because water strongly absorbs in the near infrared (Smith 1997). Inundation can be underestimated in flooded forest or areas occupied by aquatic macrophytes because vegetation is highly reflective in the visible and near-infrared. Satellite visible and infrared photographs are useful for delineating flood boundaries in areas without trees or other vegetation; however, they are unable to image during cloud cover, rain or other precipitation events. This is a significant limitation for identifying and tracking flood events since many flood events are also accompanied by heavy cloud cover which prohibits imaging.

Townsend and Walsh (1998) used a combination of radar and optical remote sensing with GIS models of flood inundation to predict flooding potential in lowland Roanoke River, NC. They developed a DEM-based GIS normative model, the Position Above the River Index (PARI), that calculated the
difference in elevation between locations on the river and on the adjacent floodplain (25 m horizontal and 1 m vertical resolution). They also developed a GIS model of flooding potential based on FEMA floodplain estimates. Each of these models was used to predict flooded surfaces under different flood scenarios. They then used multi-temporal optical and radar imagery to determine whether the GIS models adequately predicted flood surface conditions. They used the time series of radar images to classify pixels relative to the change in flood conditions and then statistically tested the relationship of the index of change detection to the flood surfaces predicted in GIS. They found that the JERS radar satellite most accurately identified flood boundaries, likely because JERS uses the longer wavelength L-band which can penetrate forest canopies. The ERS sensor uses the shorter wavelength C-band which can not penetrate forest canopy as well. The optical Landsat TM images were not adequate for identifying floodplain limits because optical imagery cannot penetrate leaf cover and detect flooded conditions under leafed out conditions.

The effectiveness of Radarstat SAR for mapping flooding beneath forest canopies in leaf-on and leaf-off conditions was tested using 32 multi-temporal SAR images in the Roanoke River, NC (Townsend and Foster 2002). They found that leaf off conditions were mapped with >95% accuracy while leaf on conditions with >85% accuracy. Incident angles for leaf on conditions affected interpretations as well. Forest structure did not affect flood mapping but different types of forest required different interpretations. The SAR imagery provided a synoptic view of spatial extent of flooding that could not be acquired from traditional field methods or hydrologic modeling. In a similar floodplain system, Wang (2004) used a threshold decision tree analysis on dry and wet season JERS SAR images to detect inundation with 90% accuracy.

SAR interferometric technique has been used to measure flood extent and floodplain elevation (Alsdorf et al. 2001; Wdowinski 2003). The coherent JERS-1 L-band echos and interferometric phase measurements were used to detect water level changes in the Amazon River floodplain and the Everglades. Flooded forests and floodplain lakes with emergent shrubs permit a double-bounce from water and vegetation surfaces which allows phase coherence to be maintained and water elevations extracted (Alsdorf et al. 2001b). They estimated change in water elevations of 7-11 cm per day for tributaries close to the main channel and 2-5 cm per day for more distant flooded areas, which were in close agreement with main channel gage estimates. Further analysis of the inundated vegetation density necessary for interferometric image analysis showed that 1-2 leafless trees per 25 m² was sufficient to return the coherent radar pulse due to double bounce from vegetation and water (Alsdorf et al. 2001a). They also used radar altimetry (TOPEX-POSEIDON every 10 days) to measure and validate the SAR (JERS-1) estimate of water surface elevations and found that combining the high temporal resolution of altimetry with broad spatial coverage of SAR provided complete mapping of floodplain elevations and flood waves. Wdowinski et al. (2003) also used this L-Band interferometric method to detect water level changes in the Everglades using JERS-1 radar imagery.

Repeat pass SAR interferometry has also been used to identify impacts of floods on floodplain topography. Satellite SAR was used to detect changes in erosion and deposition in a glacial braided river valley in Iceland due to a large flood (Smith et al. 2000). They applied processing algorithms to paired before and after ERS-1 and ERS-2 radar images to estimate three aspects of riverine landscape change in response to a flood: landscape morphological changes from temporal changes in backscatter intensity; surface disturbance (erosion or deposition) from interferometric phase correlation (where uncorrelated phases indicate a different landscape geometry); and, volumetric change from elevation differences in interferometric DEMs. The interferometric images provided good spatial resolution (20m) and broad spatial coverage (100 km²) but since erosion and deposition processes destroy the original landscape surface the images can not be analyzed for cm-scale elevation accuracy. Instead elevation changes were estimated by constructing DEMs from each image then differencing the interferometric DEMs to estimate elevational changes. DEM differencing was complicated by errors in DEM construction so that only
areas of greater than 4m of erosion or deposition could be identified. Centimeter scale precision for measuring changes in elevation could be obtained by combining SAR with airborne laser altimeters.

**Airborne Spectral and Photographic Imagery**

River channel and floodplain features in a river in Alaska were mapped using a fusion of digital aerial photographs and thermal imagery to map habitat features of the river and floodplain (Prakash 2006). They found that different combinations of classification algorithms and imagery resulted in varied classification success: max likelihood classification of spectral properties of digital aerial photos were best for classifying floodplain vegetation, dry sand/gravel, wet sand/gravel (73-98% accuracy), optical spatial classification of digital aerial photos were best for identifying large woody debris (LWD; 96% accuracy), and thermal infrared supervised classification was best for identifying water (94.1% accuracy). They used weighted habitat indicators (channel, edge, pool and LWD) from imagery to map potential salmon habitat using GIS.

A combination of LIDAR elevation data (15 cm accuracy) and digital color orthography (2 cm resolution) was used to identify side channels on the floodplain of the lower Dosewallips River, WA, targeted for juvenile salmon habitat restoration efforts (Jones 2006). LIDAR and orthophotographs were directly inspected and side channels digitized on GIS. The potential of side channels to serve as refuge was related to the relative elevation above the river channel so a digital surface of the river stage was subtracted from the LIDAR side channel grid to identify areas with high potential for restoration.

The Upper Mississippi Environmental Services Center (UMESC: http://www.umesc.usgs.gov/) began mapping floodplain vegetation on the Upper Mississippi River in 1989 as part of the Long Term Resource Management Program (LTRMP) from 1:15,000 color infrared aerial photography using 150 classes which was subsequently simplified to 31 classes (Johnson et al. 2006). They are currently completing detailed land use/land cover data and georeferenced photo mosaics for 2000 which will create an 11-year time step systematic coverage (pers. comm., Dr. Lubinski, USGS). When completed they will have land use/land cover data for years 1890, 1975, 1988, and 2000 which have been digitized and georeferenced for GIS layers. They examined use of remotely sensed imagery to produce floodplain maps by comparing three types of imagery: infrared aerial photography (1:24,000), satellite true color imagery from IKONOS (4 m resolution), and airborne hyperspectral imagery (AISA – in progress) using the 1:15,000 maps as reference base maps. They found that the aerial photography at 1:24,000 agreed with reference maps 55% of the time, which improved to 71% agreement when excluding areas < 2 acres while the IKONOS images only agreed 34% of the time. They concluded that smaller scale aerial photography is better suited for floodplain mapping and currently use part automatic and part manual photo-interpretation of orthoimagery which is then scanned and digitized (pers. comm., Dr. Lubinski, USGS).

The UMESC as part of the LTRMP is in the process of contracting for LIDAR surveys of the floodplain of the Upper Mississippi River to obtain accurate elevational data (accuracy of about 30 cm). They feel that LIDAR is the most cost-effective way of obtaining floodplain topography/elevation data at large scales (Johnson et al. 2006). Currently the U.S. Army Corps of Engineers (USACE) is proposing contracts to fly LIDAR bluff-to-bluff on the Mississippi River within Iowa and estimate it would cost around $300,000 (pers. comm., Dr. Lubinski, USGS). UMESC staff recommends working with the USGS National Mapping Program who can provide information on current mapping efforts in particular states as well as help coordinate between partners.

The floodplain of the Upper Mississippi River is a diverse ecosystem, but also has been extensively altered and modified. The USACE (USACE 2001) has developed a GIS-based model of habitat needs and availability on the Upper Mississippi River System (UMRS) as part of the
Environmental Management Plan. The Habitat Needs Assessment (HNA) is a georeferenced relational database that incorporates landscape data for terrestrial land cover and geomorphic river habitat areas throughout the UMRS. The HNA identifies five unique geomorphic types of floodplain habitats which are further classified by hydrology and vegetative communities (Theiling et al. 2000). The database includes biological matrices of species and guilds of species that occur in the system, their distribution, and their potential occurrence in all geomorphic and land cover units ranked from no to high potential occurrence. This ranking was based on literature searches and best professional knowledge. The HNA provides system-wide, large-scale qualitative and quantitative estimates of habitat needs from GIS queries and can help to identify locations for targeted restoration based on future conditions such as habitat fragmentation, connectivity and diversity. Future conditions were based on review of published reports of forecasted conditions and a rule-based model of floodplain vegetation succession (USACE 2001). The HNA database can be queried to summarize potential habitat needs for a variety of aquatic species under various riparian/floodplain habitat conditions and query results displayed in GIS format. Theiling et al. (2000) provides detailed reports of the source of the GIS data layers as well as habitat and biota specific data. The HNA has been applied to bird species that use the floodplain because relationships between bird species and habitat suitability are relatively well known. However models based on fish habitat niches are less well understood and require extensive data to develop those models with confidence (pers. comm., B. Ickes, UMESC). The approach of linking habitat maps and inventory with species occurrence habitat suitability in a web-accessible relational database could provide an important decision support tool for Great Lakes manager, researchers and the general public.

Some efforts to use remote sensing to measure river stage, discharge and flood pulse have been reasonably successfully. Satellite remote sensing of river stage and discharge require ground truthing with either topography and ground control or with field measured discharge. These methods will be discussed under the riverine channel discharge section (pages 43-45).

Summary

Riverine floodplain habitats include floodplain lakes, oxbows, meander scrolls, side channels, wetlands, and backwater that contribute to the biocomplexity of riverine ecosystems. In large coastal rivers, floodplain systems can be spatially extensive and link to other coastal systems. Due to the spatial extent of most floodplain ecosystems, potential approaches for sampling and monitoring would likely include hydrogeomorphic models or remote sensing to allow for broader spatial and temporal coverage. Promising technologies include use of SAR and SAR interferometry for a synoptic view of flood extent and flood pulses. Another potential approach would combine LIDAR with spectral imagery to provide topography and elevation of floodplain features and classification of floodplain vegetation. From these data, one would be able to map floodplain habitats such as side channels and sloughs, and, when combined with hydrologic model data, examine spatial and temporal patterns.

Riverine Riparian Habitat

Riparian zones serve several important functions for riverine ecosystems, including retaining sediment, providing a source of nutrients and organic matter, providing a buffer against nutrient and sediment inputs, helping to stabilize stream banks, and providing cover for fish (Wilhelm et al 2005, Bain and Stevenson 1999). Riparian zones also can be important sources for large woody debris (LWD) and leaf and organic matter. Riparian vegetation influences ecosystem function by the amount of shading in a river or stream which influences photosynthesis and water temperature. Riparian vegetation (terrestrial areas influenced by water) often support diverse plant communities associated with diverse hydrologic variation (Bain and Stevenson 1999). Riparian zone influences on fish cover, LWD, and water temperature thus contribute to habitat complexity. In large rivers, riparian habitat occupies relatively less area of the river channel than in smaller rivers but still provides structure and diversity to edge habitat.
Field-Based Methods

Field-based large river protocols developed by various federal and state agencies typically evaluate riparian habitat at some predetermined width, and attributes like vegetation type, cover and density are estimated or measured. Measurement of riparian habitat typically includes bank stability and condition, often including bank angle, height, vegetative cover and land use. Riparian conditions are commonly evaluated at quadrat plots at sample reach transects from a boat using surveyors rod, laser finder, GPS, compass, densiometer, and clinometer to measure characteristics such as canopy angle, riparian canopy cover, riparian vegetation structure, dominant riparian land use (visually estimated), bank angle, bank height, bank substrate and shoreline substrate. These measures are often scored and combined with other metrics to assess riverine quality. For example, in the Michigan DNR SSTP nonwadeable habitat protocol, riparian habitat was sampled from a boat using visual assessment and a laser finder in 30 x 100 ft plots for each transect. Riparian habitat attributes that were recorded included dominant vegetation type, estimated width of undeveloped land and vertical incision, and estimates of bank stability and proportion of undercut banks (Wills et al. 2006).

We reviewed four European field methods for habitat assessment that follow similar protocols for riparian habitat assessment. Riparian and bank characteristics (substrate, vegetation, land use, modifications) are visually assessed and recorded along transect or sequential river reaches within a fixed width riparian corridor (Raven et al. 2000, Diamond et al. 2002). Habitat conditions are scored based on comparison in the field or in the lab to reference conditions for rivers of similar geomorphological character. The Australian River Styles approach to classification and assessment of riverine physical habitat evaluated riparian conditions primarily based on the extent of indigenous woody vegetation (Brierley and Fryirs 2005). Similarly, Rosgen’s (1994) geomorphic classification system for rivers included detailed field surveys of riparian vegetation and bank erodability as part of its Level III river assessment although the protocols were not described.

Other large river field assessments use limited field measurements to form an indicator of habitat quality in response to stressors, and many of these include riparian assessment. Michigan’s NWHI estimated riparian disturbance and extent of riparian cover from measurements of riparian width and gaps in riparian cover in recent aerial orthophotos (Wilhelm et al. 2005). Riparian characteristics were also sampled from a boat using visual assessment and a laser finder. Riparian width (proportion of 25 m width which was the limit of the laser finder) and bank stability were two of the seven variables selected for the NWHI indicator of large river habitat. They also scored the degree of human influence from visual estimates of disturbance in the riparian plots. Likewise, the Ohio EPA (Rankin 1989) multimetric index for habitat in rivers includes riparian zone and bank erosion qualitative metric scores of the entire 500 m study reach. The Wyoming Fish and Game Department use a Wyoming Habitat Assessment Methodology (WHAM) to assess river habitat and includes a field and map characterization of riparian habitat (dominant vegetation, encroachment of upland spp, riparian width, invasive species). It was not clear if there is a stream size limit for the WHAM protocol.

Munne et al. (2003) developed a field method - QBR - for assessing riparian quality directly instead of comparison to reference condition. The size of river is not indicated. The QBR uses four measures of riparian habitat scored 0-25 to form the QBR index: total vegetative cover, vegetative cover structural complexity, cover quality (varies depending on geomorphic types), and river channel alterations. Assessment criteria and modifiers are listed on the two-page field sheet. The final score is a sum of the four component scores. The advantages of this method are that is uses simples measures, does not rely on a reference condition and is quick and simple to apply. The disadvantages are that it depends on observer subjective assessment and will necessarily include observer bias. Many of the methods use visual observations thus are prone to observer bias.
Modeling

Modeling approaches for assessing or classifying riparian riverine habitat are often landscape-based (Theiling et al. 2000; Baker et al. 2001; USACE 2001; Baker and Wiley 2004). Field surveys of riparian forest types in Michigan river floodplains were related to mapped variables representing valley morphology, river hydrology and regional climate suggesting that the relative abundance of riparian tree species and thus riparian forest types can be predicted using landscape scale variables (Baker and Wiley 2004). Terrain-based GIS hydrologic models were used to examine the role of riparian buffers in stream water quality by using GIS-based models to predict riparian hydrology, then linking hydrologic model output to patterns of nutrient export at 290 riverine sites across Lower Michigan (Baker et al. 2001). GIS landscape scale variables were used to model and predict riverine habitat for rivers of New York at 1:100,000 and 1:24,000 scale (Meixler and Bain 1999). Using an automatic, non-hierarchical GIS model, riverine habitat was classified into 18 types based on combinations of landscape attributes including riparian forest cover. Riparian cover was estimated by classifying forest cover in GIS then using discriminant analysis to classify riparian zones into closed or open canopy. For this study, automated riparian forest cover predictions were not in agreement with observed values.

Summary

In large rivers, riparian zones are most commonly evaluated using site-based field methods that examine features like cover and disturbance at some predetermined width. These assessments are often part of an index or score for riverine habitat assessment. New approaches to evaluating and understanding the role of riparian buffers in rivers have used landscape-scale variables to predict riparian hydrology and the role or riparian buffers in affecting river chemistry and to predict or classify riparian vegetation.

River Channel

The river channel is the focus of most methods to map, assess or characterize fish habitat. The distinguishing feature of riverine channels is water flow, which in combination with local geology, shapes channel morphology, sinuosity, substrate type and distribution, and habitat unit type. The river flow regime is a controlling variable in river ecosystems influencing habitat structure, water quality, material delivery, and biological distributions and abundances (Poff and Allan 1995; Poff et al. 1997). The physical structure of a river (channel shape, substrate composition) in combination with flow regime results in patterns of dynamic habitat heterogeneity (Maddock 1999). Based on stream hierarchy theory, habitat at the microscale typically defined as unique combinations of depth, flow and substrate are influenced by processes at larger spatial scales from the reach to the entire catchment. Our review of methods for assessing river channel habitat includes methods from microhabitat examinations of local and reach scale conditions through methods that examine how landscape affects stream morphology.

Site-based Field Methods

Field protocols used to measures and assess river channel morphology and channel units fall into three broad categories: methods that use the point-transect method to make numerous quantitative or qualitative observations along random transects; protocols that make qualitative, mostly visual assessments of the entire river corridor; and, methods that measure or estimate limited numbers of characteristics as part of a quality index. Most field channel assessment methods commonly incorporate GIS and/or maps and often aerial photos to define board categories of river valley types and to calculate stream morphology metrics. GIS and map geomorphic characteristics used to classify rivers include altitude, valley slope, catchment area, geology, and landscape (Fitzpatrick et al. 1998; Raven et al. 2002; Chessman et al. 2006; Rankin 2006). Several assessment protocols use maps or GIS to calculate channel reach metrics such as sinuosity and slope (Fitzpatrick et al. 1998; Muhar et al. 2000; Wills et al. 2006).
Flow velocity and discharge may be measured in the field using a current meter along cross-sections at one or more transects but more commonly, discharge is obtained from gage records or models of flow exceedence or visually assessed from hydraulic conditions.

Point and transect methods such as the USEPA’s EMAP for nonwadeable streams or NAWQA’s habitat assessment protocols establish a standardized sample reach with equidistantly placed sample transects (Fitzpatrick et al. 1998; Kaufmann 2000). Along each transect, point measurements of depth are taken using either a depth sounder or a stadia rod and wetted and bankfull width are measured with a laser finder. In addition to transect bathymetry, regular depth measurements are made along the study reach thalweg. At each sample point for both transects and thalweg, channel unit types or the dominant channel unit type are visually noted and measured. Channel habitat unit classes include pool, glide, riffle, rapid, cascade, falls, dry channel and off-channel areas (e.g. side channels, sloughs, backwater). Channel units should be at least as long as a channel width to be identified. In the EMAP-GRE protocol, river channel is characterized based on hydromorphic unit (inside or outside bend, pool, tributary mouth, and secondary channel), bank angle, bankfull height, channel width, wetted channel height, constraint, dominant land use, disturbance, development and aesthetic classifications. The NAWQA, EMAP and MDNR protocols estimate discharge from gage records and use mean annual discharge, 50% flow exceedence and flow variability values in their assessments. The EMAP method for nonwadeable rivers has a unique approach to calculating a hydraulic metric. They use shear stress formulas and measured slope and substrate size to estimate the bed stability that can be compared to regional thresholds (Kaufmann et al. 1999).

Sampling protocols that include visual assessment of the river corridor are common in Europe and Australia. These methods rely on map/GIS classification and existing data to classify rivers into geomorphic types. Field surveys walk either the entire or a section of the river corridor and visually assess channel features such as slope, channel habitat features, channel geometry, valley form and flow patterns. Hydrology and hydraulics are visually assessed based on flow type (riffle, run, rapid - RHS) or flow behavior (sediment transport - River Styles). In Austria, field estimates of attributes such as channel width or morphology and hydrologic regime are scored as a frequency class. These assessments are then compared to reference streams within that stream type, either in the field or more systematically using database comparisons. Rarely do these stream methods state the river size constraints and many of them appear to be targeted toward a wadeable streams; however, since transect measurements are not part of the protocol, the methods could be equally applied to nonwadeable rivers with only slight modification to the methods.

A number of stream habitat assessment methods were designed to measure a limited number of habitat variables and combine those variables into an index of habitat condition (Ladson et al. 1999; Parson et al. 2003; Wilhelm et al. 2005; Rankin 2006; Quist et al. 2006). Only one of these is applicable to large rivers: the NWHI (Wilhelm et al. 2005) developed for rivers in Michigan’s Lower Peninsula. The NWHI used transect and thalweg approaches to measure numerous points along a 1 km reach from a boat. They used a depth sounder or stadia pole to measure depth and laser finder to measure wetted and bankfull width and calculated slope and sinuosity using GIS. They measured velocity at approximately 1 m depth due to the limitation of the flow meter rod, thus their discharge measurements were not depth integrated. Using Principal Components Analysis and linear regression they identified seven metrics for the NWHI. Wilhelm et al. (2005) found that habitat units such as pools, riffles and runs were not useful for nonwadeable river assessment since most river reaches were classified as run or glides and the main habitat units were bends or cross-over regions. They recommended measuring thalweg depth, slope and the width/depth ratio as useful for characterizing a river but were not useful in the index of habitat condition. The Ohio EPA developed the Qualitative Habitat Evaluation Index (QHEI, Rankin et al. 2006) which is designed for wadeable streams but could be adapted for nonwadeable river. They use GIS/map
data to estimate slope and drainage area, estimate flow category and channel morphology visually (general type, pool and riffle quality), and use a laser finer to measure width.

Other sources of channel bathymetry and velocity/discharge measurements are USGS field and gage records and those from state agencies that monitor river flow (pers comm., MDEQ staff). However, USGS gages are not located in the coastal zones of large rivers to avoid influences of lake water level on stage-discharge relationships, so gage data are generally not available large coastal rivers. In addition, these records are currently difficult to acquire for most river ecologists, if they are even aware that such extensive data exists.

Beechie et al. (2005) examined habitat preferences of salmonids in a 123 km reach of the lower Skagit River in Washington which was classified as a large river based on the bankfull cross-section of greater than 100m. They identified 6 habitat types a priori based on channel location, bed morphology and flow characteristics: three mid-channel units include pools, riffles and glides and three edge units included edge, bars and backwaters. Habitat units were sampled by recording water depth (stadiam rod), surface water velocity (floating wood chip speed), and visual assessment of substrate and dominant cover type (wood, aquatic plants, cobble-boulder, other, no cover). They sampled habitat use by juvenile salmonids and found juvenile Chinook and Coho salmon densities were highest in edge and backwater habitats where flow velocities were slowest (< 15 cm/s) and cover, especially wood, were highest, and steelhead densities were highest in edge habitats. These habitat unit preferences were similar to habitat preferences in smaller streams.

**Sonar and Acoustic Doppler Current Profilers**

More recently acoustic SONAR or Acoustic Doppler Current Profilers (ADCP) in combination with GPS have been used for acquiring depth and river channel bathymetry (Hilldale and Raff 2007). The most common use of SONAR in riverine systems is to map channel morphometry (bathymetry) and to identify substrate and other bottom features. Single beam SONAR was used to map channel bathymetry of the Sulphur River, TX, and to develop an automated process to isolate LWD from the bathymetric signals (White et al. 2006). The effective survey resolution was 16 cm based on boat speed and SONAR frequency. Single beam digital SONAR was also used with DGPS to map channel bathymetry and substrate in the Lower Bad River, WI for the purpose of inventorying potential lake sturgeon habitat (Cholwek et al. 2005). Point depth and location data were imported into GIS and the water depth was interpolated to a spatial resolution of 1 m. They reported that the SONAR surveying and data processing method was fast and SONAR technology could be used in moderately turbid conditions. Brenden et al. (2006a) used single beam SONAR to map bathymetry, substrate type, and submerged vegetation presence in the New River, a large river in southeastern VA, for the purpose of studying muskellunge habitat use and selection. They found single-beam hydroacoustic equipment provided accurate measures of depth and vegetation occurrence, but identification of substrate type was relative poor.

Side-scan SONAR surveys of large river mouths and channels for Lakes Erie, Huron and Michigan have been conducted (pers. comm., Dr. S. Mackey, Habitat Solutions). These efforts have included attempts to map eight to nine Great Lakes rivers using georeferenced side-scan SONAR ground-truthed with Ponar samples and underwater video. Side-scan has been used extensively on the Colorado River to monitor sediment redistributions following flood events (Northern Arizona University web site 2007, Rubin 1994). Side-scan SONAR was used to map the benthic substrate and track sand migration and boat mounted SONAR was used in combination with a ground-based total station to record channel bathymetry and record location. The point depth locations were used to form a Triangulated Irregular Surface (TIN) in GIS and multi-temporal TINs were used to quantify sediment redistribution. TIN resolution was 1.0 m horizontal and 0.5 m vertical.
Early in the LTRMP, UMESC conducted systemic bathymetric surveys of the study reaches of the Upper Mississippi River (Rogala 1999). The data were collected by a computerized hydrographic system that integrates DGPS technology (accuracy < 1 m) with a depth sounder/digitizer (accuracy ranges from 0.03 m for shallow water to 0.12 m for deeper water). The minimum digitized water depth was 0.5 m; for shallow water < 0.5 m manual measurements were taken using a calibrated sounding pole. Data were referenced to established elevations developed by the USACE and edited in GIS to create an interpolated bathymetric amp and TIN for 2-dimensional viewing. These data were processed into GIS systems that are available online (http://www.umesc.usgs.gov/aquatic/bathymetry.html). In addition, they recently remapped wing dams and scour pools in the Middle Mississippi River using GPS and sounder with 1.6 m accuracy to map the physical dimensions of the wing dams and scour holes. They also used a range finder (accuracy = 1 m) to measure surface distances. Data collected were georeferenced and used to create a GIS overlay which could be queried and converted to a shape file for integration into the spatial database (Johnson et al. 2006).

ADCP can also be used to map river morphometry and identify substrate classes/benthic roughness. The strength of ADCP technology is that it remotely and rapidly collects water velocity profiles which are useful for characterizing flow heterogeneity and velocity gradients in addition to high resolution channel cross-sections (Gaeuman and Jacobson 2005). Used from a boat in conjunction with DGPS, ADCP technology can provide velocity profiles at multiple locations across the channel, which permits the development of spatially distributed hydraulic maps of a river system across a range of flow conditions. In the Little Tallahatchie River, MS, an ADCP was used to measured water column velocities around physical habitat structures, estimate velocity gradients, and compute metrics of habitat quality based on velocity heterogeneity (Shields and Rigby 2005). Gaeuman and Jacobson (2005) used the bottom-tracking function of an ADCP, typically used to compute the speed of the boat during data collection, to map sediment movement and identify areas of stable and unstable bed substrates. ADCP was used along with multispectral imagery and high resolution DEM to create explicit models of stream power, shear stress and velocity and classify flow regimes in western rivers (Lorang et al. 2005). The analysis was used to predict bank erosion and deposition zones, estimate the sediment budget, and to prioritize areas critical for restoration.

ADCP technology has also been used to validate or verify other methods of assessing river discharge or velocity regime. In the Skagit River, WA, Costa et al. (2000) designed a proof-of-concept field protocol for measuring open-channel river discharge using entirely non-contact methods. They used a combination of a van-mounted pulsed Doppler radar unit to collect surface velocities and cross-section area was measured using a ground-penetrating radar unit suspended over the river on a cable. The pulsed Doppler unit estimates velocities from the radar scatter produced by open turbulent water and the backscatter Doppler shift. Ground penetrating radar detects the interface between water and ground surface and produces channel cross-section bathymetry. This method was validated using both gage and ADCP data. Three non-contact measurements were made within one hour and were within 1% of the gage and ADCP discharge estimates. Non-contact methods of measuring discharge are intriguing; however, this method requires both a clear bank for sending and receiving radar signals and a cable to suspend the ground penetrating radar equipment.

Shields and Ripley (2005) found that the channel metrics measured with ADCP varied little with discharge but did vary significantly with channel features such as a channel bend or weir and channelization. The metric of rotational flow in the vertical plane discriminated best between natural river bathymetry and straightened channel form. They also found that the metrics generated by numerical models, current meter point measurements and ADCP sample data were of similar magnitude. The current meter method requires considerable time and labor for the field work while the models require effort to calibrate the models. The ADCP methods are less time consuming and can collect high resolution velocity profile data at scales relevant to river habitat (from channel width to the size of key
organisms). They found the disadvantage of ADCP was the cost of the equipment and the lack of established methods for data reduction and field protocols. In addition they concluded more research is necessary to relate ADCP data and metrics derived from ADCP data to biologic and ecologic processes.

There are several large river programs that have developed habitat sampling protocols using combinations of the above technologies to measure depth, bathymetry, substrate type and subsurface profiles that could be applied to large rivers in the Great Lakes region. A 240 km stretch of the Hudson River, NY, and estuary was mapped as part of the Hudson River Benthic Mapping Project (Nitsche et al. 2007). The Hudson River is turbid with a Secchi depth of 1 m so optical systems couldn’t function to map benthic habitat. High resolution bathymetry (< 1m horizontal, 0.3 m vertical) was obtained using multi-beam SONAR referenced to DGPS but was restricted to areas > 4m in depth due to limitations of the multi-beam SONAR. Side-scan SONAR was used to map substrates and macrohabitat units on 2 m pixel grids. Side-scan SONAR allows estimation of size and shape of a habitat unit at multiple scales (pers comm., J. Ladd, independent contractor). They also used a chirp sub-bottom profiler which penetrates a few meters below the water-substrate interface to bedrock or other hardened surface to allow estimation of erosion and deposition zones. All data were georeferenced, processed data were integrated in GIS, and channel bathymetry, substrate type and erosion/deposition zones were mapped and made accessible on a web-based interactive format (www.dec.state.ny.us/website/imsmaps/benthic/webpages/benthic data.html). One limitation of this methodology was that the multi-beam SONAR could not map shallower than 4 m so shallow depositional areas such as embayments and sand bars were not included in the survey.

In the Missouri River ecosystem, the Columbia Environmental Research Center (CERC) has developed a habitat sampling protocol that combines SONAR, ADCP and DGPS to assess aquatic habitat (Jacobson et al. 2004). The method was used to estimate geomorphic change in the river at Hermann, MO. They collected habitat data at four discharges using DGPS, SONAR, and ADCP to collected georeferenced elevation, depth, and 3-dimensional water velocity data along transects spaced at 20 m. All the data were linked in a GIS to create a 2 m interval bathymetric map. From the four time/discharge intervals they were able to compare bathymetric surfaces and compute net erosion and deposition. Using similar physical habitat protocols, the U.S. Fish and Wildlife Service and the USGS sampled 15 sites over a 100-km stretch of the Missouri River to assess habitat availability for the endangered pallid sturgeon (Elliott et al. 2004). Pairing ADCP, SONAR and DGPS for habitat sampling with telemetry to assess fish habitat use, they were able to determine that pallid sturgeon preferentially use water depths in the 3-4.5 m and 6-6.5 m ranges and prefer mean velocities of about 80 cm/s. Similar physical habitat assessment and sturgeon habitat use protocols were used on an 8-km reach of the Missouri River and the data was used to develop a 2-dimensional hydrodynamic model that predicted the depth and velocity characteristics over a 1-99% flow exceedence range (Johnson et al. 2006). Relating the inventory of hydraulic habitat with pallid sturgeon habitat use, they found that sturgeon preferred areas of high depth and velocity gradients.

As part of the Muskegon Watershed Research Partnership (MWRP), researchers mapped habitat in the lower river from a boat using DGPS, ADCP, on-board computer, underwater camera, video camera and depth sounder. Channel units and unique habitat were mapped and velocity and depth profiles were taken at selected random sites where fish and invertebrates were also sampled as well as transects in each channel unit. The macrohabitat model was coupled with high resolution DEM and air photo coverage to build a hydraulic model (HEC-GEORAS) and calibrated to a realistic water surface profile and channel geometry. These models, when coupled with multi-year hydrologic models, will drive bioenergetics models for steelhead and salmon and habitat suitability models for a variety of riverine fish.
Remote Sensing

Aerial Photography

Carbonneau et al (2006) used digital aerial photography at 3 cm resolution to map river bathymetry of the Sainte Marguerite River in Quebec. The images were first classified as either wet or dry using an automated algorithm, and then observed depth was plotted against pixel brightness using the red band ($R^2=49\%$). The maximum depth detected was 1.5 m. Estimating river depths from aerial photographic-based depth-color models was less time intensive than field survey and more cost-effective and higher resolution than multispectral imagery; however, airborne photography is limited when covering large areas due to the volume of photographs and the likely variance in exposure and aperture setting necessary to cover a large area.

Spectral Imagery

Spectral imagery has been used to estimate water depths and channel bathymetry, to identify bottom types, and to characterize channel habitat. Multi- and hyper-spectral imagery is commonly used to map coastal bathymetry and only more recently used to map and classify river habitat; however, much of the river habitat mapping and inventory work with remote spectral images has been done with smaller rivers and often clear western rivers (Wright et al. 2000). Remote sensing of river bathymetry, substrate, and channel units is challenging, especially in large rivers with deep water or higher levels of turbidity because passive optical systems are limited by light attenuation and reflectance in the water column and variability in bottom reflectance (Winterbottom and Gilvear 1997; Stumpf et al. 2003). Water depths can be measured from brightness in multispectral imagery based on the Beers-Lambert law, which relates brightness or the intensity of light passed through a medium, the intensity of incoming light, the rate of absorption, and the thickness of the medium (Carbonneau et al 2006). Since light attenuation in water increases exponentially with depth, the uncertainty of depth estimates from light reflectance of river channel increases with water depth (Philpot 1998). Increasing sediment or pigments in the water column causes increased light scattering further decreasing light penetration and the depth limit of reflected light.

Channel bathymetry has been extracted from multispectral images through application of the radiative transfer model (based on Beers-Lambert law), an exponential linear equation relating water depth to bottom reflectance, water attenuation, water reflectance and radiance received at the remote detector (Philpot 1998). Estimates of river bathymetry from multispectral images have used two basic approaches to apply the radiative transfer theory to multispectral data. One is to estimate the rate of light absorption by the medium (water) (Lyons 1992) and the second is to relate field measurements of depth to color bands of light in an image (Winterbottom and Gilvear 1997). Common to all methods is image preprocessing that corrects for errors due to atmospheric, geometric (for pixel size distortions due to aircraft position) and radiometric distortions.

Multi-spectral image analysis to extract river channel bathymetry can use either a single band, a combination of bands or band ratios to best discriminate water depth from bottom reflectance. Single band wavelengths are linearly affected by bottom albedo (reflectance) so that a decrease in albedo will result in a direct increase in estimated depth. Albedo effects can be corrected in transform models by using a linear combination of wavelengths because depth will affect different bands differently but a change in albedo will affect band similarly. Ratio transform methods take advantage of the differential absorption of different bands thus will estimate depth independent of bottom albedo (Stumpf et al. 2003).

Lyon et al (1992) used multispectral imagery of the St. Mary's River, MI, to determine bottom type classes and water depth. The multispectral data had 12 bands (0.38-14um) and 10m pixel resolution; bands 3,4, and 5 were used to classify bottom type and measure water depth, band 6 identified shallow water ,and the near red and the infrared bands were used to identify and mask upland areas. Aerial photos
(1:24,000) were also collected as well as boat survey data of TSS, Secchi depth, temperature, chlorophyll a and water depth. Water depth was estimated by first computing the light extinction coefficient from measured Secchi depth, then using the extinction coefficient in the radiative transfer model to relate image brightness to categories of water depth in 0.8 m increments up to >3m (95% accuracy). This method would not be possible in turbid or highly stained water.

There are a number of other examples of using multi- and hyperspectral imagery to obtain depth estimates and channel bathymetry; however, since depth is a function of the thickness and absorption of the medium, most applications have been for shallower or clear water rivers. For example, Winterbottom and Gilvear (1997) used a linear combination of three bands from airborne multispectral images (2m ground resolution) to derive depth estimates for a shallow gravel bed river Scotland. They found good agreement between measured depth and depths predicted from multispectral imagery up to 0.6 meters ($R^2 = 67\%$). The maximum for light penetration (<0.6 m deep) could have been affected by reduced reflectance from dense algal cover. Surface roughness in riffle areas also affected image interpretation resulting in shallower predicted depths. Airborne multispectral image data was also used to document change in channel morphology following a large flood event on the River Tay, Scotland (Bryant Gilvear 1999). Using before- and after-flood airborne multispectral images (11 bands), they developed a regression equation of water depth from 3 bands ($R^2=67\%$) for maximum water depths of 1.2 m.

Several studies have found ratios of bands in multi- and hyper-spectral imagery more sensitive to changes in depth. In a shallow, clear water stream in Yellowstone, Legleiter et al. (2004) applied the radiative transfer model to field collected spectral signatures from a range of stream flows, substrate and suspended solid conditions and showed that a ratio of radiances was more sensitive to changes in depth. However, the ability to resolve depths and substrate spectral features declined in deeper water. Legleiter et al. (2005) used theoretical models and hyperspectral imagery (AISA sensor – 34 bands) in a shallow (maximum depth 1.4m), clear-water western river and found that a ratio-based algorithm to estimate pixel-scale, mean water depth (channel morphology) produced the most robust results for estimation of both water depths and substrate type. The spectral mixture analysis assumed no scattered radiance because depths were shallow and the water clear; however, in deeper or turbid water these assumptions would be challenged. The models could be strengthened by adding terms for chlorophyll, dissolved organic matter and absorption or scattering coefficients. The method also requires site specific normalization for solar geometry and specular reflection from the water surface which would limit application to large geographical areas.

Similar results are found for marine systems. For example, high resolution satellite spectral imagery (IKONOS, 4m) was used to determine water depths in clear marine waters up to 25 m deep (Stumpf et al. 2003). They compared a linear and wavelength ratio transform methods to determine depth from the imagery, using nautical charts and LIDAR to tune the algorithms. Both algorithms compensated for variable bottom types but the linear transform could not retrieve depths below 10-15 m; the ratio transform could retrieve depths > 25m. High turbidity in lagoons limited depth retrieval and false bottoms were generated in depths greater than 15 m.

Multispectral airborne digital imagery has also been used to classify river channel into flow and depth categories by training spectral data on field data. Multi-spectral data (4 bands) was integrated with field survey site data to map relative depth and flow for the Lower Yakima river, WA, at two different flows (Whited et al. 2002). The digital imagery was processed to first identify the water features using the infrared band and the Normalized Vegetation Difference Index. Spectral imagery was trained on surveyed transect data in a supervised classification into five flow and depth categories: shallow slow, shallow fast-riffle, shallow fast-non riffle, deep slow, and deep fast. Even in highly turbid conditions, coarse classification was accomplished. This was a viable method for regional mapping of diverse riverine habitats under different flows; however field validation methods were for small rivers so would
need to be adapted for larger rivers. The method also provides an assessment of channel complexity and dynamics by analyzing different flow regimes. Expanding on this methodology, Lorang et al (2005) used ADCP depth and water velocity profiles to classify airborne multispectral digital imagery, georeferenced to USGS topo quads, into depth and velocity categories across flow regimes in the Yakima River, WA. The overall image accuracy was 66% for flow velocity and 73% for water depth. They computed channel shear stress from topographic slope and estimated depth and used calculated shear with stage-discharge relationships to predict channel and floodplain areas where geomorphic work was likely to occur. This method demonstrates the utility of integrating multispectral images with ground-based data to model fluvial processes at relatively fine spatial scale; however, how this method could apply to large river ecosystems remains to be tested. One limitation is constant to all spectral imagery, that coverage is limited by cloud cover. This method had been planned to be tested as part of the Muskegon Watershed Research Partnership (MWRP); however, cloud cover prevented its application during the period when the airborne multispectral imager was available.

Airborne multispectral and hyperspectral imagery has been used to classify channel macrohabitat units using ground surveys to train the spectral data. These studies generally found higher classification accuracy in larger rivers with larger habitat units and fewer transitional boundaries. In the Upper White River, WA, Black et al. (2003) used supervised classification of multispectral data and found that the multispectral imagery underestimated the field estimates of channel habitat units (41% accuracy). When spectral and thermal imagery were combined, however, accuracy increased to 79%. Multi-spectral imagery was also used to classify seven geomorphic units of stream reaches in MT and WY using supervised and unsupervised classifications (Wright et al. 2000). Classification accuracies ranged from 20-80%. They also found that larger units and mid-unit pixels (vs. edge pixels) were more often correctly classified. Other classification problems were due to poor georectification.

Hyper-spectral imagery with high spatial (1 m) and spectral (128 spectral bands) resolution was used to map in-stream habitat (glides, riffles, pools and eddy drop zones) using supervised classification based on training site data in 3rd-5th order western streams (Marcus et al. 2003). Regression of the principal component transformed images was used to measured depths stratified by habitat to estimate depths from the hyperspectral images. $R^2$ values decreased with increasing turbulence (67% for turbulent water to 99% for smooth water) and increased with stream size (20% in 3rd order streams) likely due to fewer mixed pixels. These studies generally found higher classification accuracy in the 5th order streams (86%) than the 3rd order streams (69%) likely due to larger habitat units and fewer transitional boundaries in larger streams (Marcus et al. 2003). Furthermore, unsupervised classification of hyperspectral images of a 5th order stream in WY suggested that spectrally based classification could more accurately represent stream habitat units, especially transition zones and heterogeneous habitats that may be mapped as one large unit by observers in the field.

**LIDAR**

River bathymetry has also been mapped using airborne laser altimetry or LIght Detection And Ranging (LIDAR). Hilldale and Raff (2007) conducted LIDAR and traditional ground surveys of channel bathymetry of the Yakima River, WA, and assessed error and precision of the methods. Water depths did not exceed 6 m. LIDAR data were collected using SHOALS and ground survey data were collected through a combination of wading and boat transit and rod and in deeper water through GPS and SONAR. Bed elevations from the two methods were compared in GIS and they found a systematic bias of higher bed elevation with LIDAR. Bowen and Waltermire (2002) also found a systematic bias in the LIDAR bathymetric data which was improved by block correction. They used LIDAR to map a section of the Green River, ID, between water surface elevation and top of the bank and found that LIDAR overestimated near channel elevations in areas where vegetation was dense and bank slopes were steep. Potential sources of bias include set up and calibration errors for both LIDAR and GPS, errors in GPS ground network, and errors in data processing.
Hydraulic models require precise channel morphology to make accurate estimates of channel hydrology and hydraulics. Hilldale (2007) used LIDAR to obtain bathymetry for 3 reaches of the Yakima River, WA and using ground data adjusted the LIDAR bed elevation estimation. They then used the LIDAR data in GIS to form a 3-dimensional land surface or Triangulated Irregular Network (TIN) as input to a 2-dimensional hydraulic model to estimate flow rates throughout the channel. Based on field validation the classification success ranged from 50-91%. The rivers all seemed to be shallower than 1 m.

Several applications of LIDAR have been used to evaluate riverine fish habitat. LIDAR elevation data (15 cm accuracy) and digital color orthography (2 cm resolution) was used to identify side channels on the floodplain of the lower Dosewallips River, WA, targeted for juvenile salmon habitat restoration efforts (Jones 2006). LIDAR and orthophotographs were directly inspected and side channels digitized on GIS. The potential of side channels to serve as refuge was related to the relative elevation above the river channel so a digital surface of the river stage was subtracted from the LIDAR side channel grid to identify areas with high potential for restoration.

Experimental Advanced Airborne Research LIDAR (EAARL) is a full-waveform type of LIDAR that is able to map subaqueous, terrestrial topography and canopy with relatively high-resolution. This new technology has mostly been used to map coral reefs but recently was used to map gravel-bed streams in ID and NB and the resulting 3-dimensional maps were used to explore how channel morphology influences spawning habitat for Chinook salmon (McKean et al 2006). Both are shallow rivers so it isn't clear if EAARL could be used to map deeper or more turbid rivers.

LIDAR technology has been used and adapted for near shore bathymetric surveys but changes in LIDAR technology could result in better river bathymetry estimations. A reduction in output power of the laser would reduce depth penetration but increase resolution and accuracy (Hilldale and Raff 2007). It is likely that depth penetration of 10 m or less would be adequate for many river studies.

**Radar**

Remotely sensed radar images have been used to validate hydrologic models Brackenridge et al. 1998, Campo et al. 2005), estimate stage-discharge relationships (Smith et al. 1996), and detect changes in river morphometry (Smith et al. 200). Campo et al. (2003) used remotely sensed images to validate a distributed hydrological model for the Arno River, Italy. They used ERS-2 SAR radar images to estimate soil moisture from radar backscatter and Landsat derived vegetation indexes (NDVI) and land cover to select pixels with little vegetation to minimize the effects of vegetation on water content of soils. They calibrated the SAR image optimization algorithms and regression relationships between soil moisture and saturation indexes with field measurements of discharge to improve discharge output from distributed hydrological model.

ERS-1 SAR images were combined with USGS topography (1:24,000) and USACE HEC-2 hydrologic models to compare predicted and observed flood peaks in an agricultural region of the Upper Mississippi River valley (Brackenridge et al. 1998). They used the C-band (spatial resolution of 26 m) to discriminate between water-land boundaries and estimate water surface elevations. HEC-2 was used to model the profile of a constant peak discharge using input variables of slope, discharge, hydraulic roughness, and valley and channel morphology. They were able to identify the position of the flood crest by comparing HEC-2 and SAR estimates of water levels and further estimated that the flood crest had 1.5-2 m amplitude. This method could be useful in identifying seiche waves in the large rivers or peak flood wave effects on floodplain habitat.

River discharge can also be estimated by correlating satellite estimates of river area with measured discharge to develop a stage-discharge relationship. This has been done with braided rivers in
Alaska and British Columbia using ERS-1 SAR radar images and field measurements of discharge to relate river discharge to satellite estimated width and generate satellite derived rating curves (Smith et al. 1996). These rating curves can be used to estimate discharge from space. Changes in relative discharge can then be estimated for ungaged rivers to estimate timing and extent of annual flows and ungaged flow can be estimated within a factor of 2 without ground control measurements. Ground control measurements could be either measured discharge or parameterization of known morphological controls (total sinuosity, valley slope, bank material and stability, hydraulic geometry). Satellite return times of 1 week were sufficient for approximating seasonal hydrographs.

Bjerklie et al. (2005) developed a method to measure discharge remotely on a variety of river types. They used a combination of aerial and digital orthophotos, SAR images, topographic maps and observed discharge to estimate discharge within a factor of 1.5-2.0 with mean estimated accuracy of 10%. Air photos (1:10,000) and digital orthoquad photos (1-m resolution) were used to measure mean water surface and maximum channel width in single channel rivers; SAR images (ERS-1) were used to estimate water surface widths for braided rivers at 10 m resolution (see Smith et al. 1996); and, airborne interferometric SAR imagery was used to estimate water surface width and velocity for the Upper Missouri River at 5 m resolution (corrected for surface wind-driven waves). All channel slopes were estimated from USGS topo maps (1:24,000). They statistically related the ratio of observed to estimated discharge to channel width and slope as a power function calibrated specific to channel types. In the Missouri River they used the estimated velocity from SAR imagery to calibrate discharge estimates. This method could be useful for regional studies of riverine discharge.

Models

Statistical

Statistical models have been used to test the relationship between measured habitat variables and fish abundance, biomass, and assemblage structure. A common feature of many fish habitat statistical models is the study of how habitat spatial scale influences fish assemblages.

A common approach that follows the general construct of geomorphic, hierarchical habitat classification theory examines which spatial scale explains the most variation in fish (or other aquatic biota) data. Poizat and Pont (1996) examined the hierarchical effects of spatial scale on fish habitat heterogeneity. They sampled juvenile fish at three habitat scales: compartment (channel vs. dike), bank-type (5 classes) and microhabitat (9 categorical variables). They examined the variation explained by each scale and found that microhabitat analyses represented patterns that could be explained by higher levels of habitat organization. They suggested that the variance explained is a measure of how much of habitat selection is hierarchical. Analysis of the relationship between environmental gradients and fish assemblages (abundance, biomass and metrics) at the site, reach and basin scale on 31 nonwadeable rivers in Wisconsin suggested site and basin scale variables defined a gradient from high conductivity, fine substrate and agriculture land cover to forest land cover and rocky substrate (Weigle et al. 2006). They also found that land cover alterations at the basin scale were most strongly related to fish assemblages across the region.

Long Term Resource Management Program (LTRMP) data for the Upper Mississippi River have been used to model community composition of fish variation temporally and spatially across geomorphic habitat units (Chick et al. 2005). They found that fish community structure and composition varied significantly across spatially and temporal scales, but only within habitat strata (back water, main channel and side channel). Community composition of fish varied primarily across large-scale reaches and smaller-scale geomorphic units. Relative abundances of fish communities varied across three spatial scales: river reach, geomorphic units, and habitat strata. Geomorphic units varied spatially due to a combination of Secchi depth, water temperature, current velocity and vegetation abundance. Barko et al.
(2005) also used LTRMP data to investigate the relationship between habitat and fish community structure and found poor association between fish and physical habitat. Possible reasons include: 1) dominance of the fish community by tolerant taxa (not sensitive to habitat variation); 2) physical habitat as measured was a poor predictor; and, 3) environmental conditions within habitat units are similar so that physical habitat units were not discriminatory. This is an important finding that suggests that habitat units in large rivers may not explain fish population structure due to similar environmental conditions and large scale of the units and that measurement of variables that are important to fish such as flow dynamics, substrate and depths are critical to understanding habitat-fish relationships.

LTRMP monitoring data was also used in statistical models to predict the probability of occurrence of submersed aquatic vegetation from flow velocity, wind fetch, bathymetry, growing-season daily water level and light extinction coefficient (Yin et al. 2007). Georeferencing of biotic and habitat data allows for spatial and causal analysis to predict distribution of submersed aquatic vegetation. Yin et al. (2007) developed a web-based interactive model allowing the user to select vegetation type and year and the results of abundance distributions displayed as GIS shape files.

**Hydrologic Models**

A wide range of developed hydrologic models developed for river reaches and for whole basins from statistical to process-based models. A GIS framework for multi-scale landscape descriptors has been used to develop flow exceedence models for the Michigan Rivers Inventory (Seelbach and Wiley 1997) and the Great Lakes Regional Aquatic Gaps Analysis Program for multiple Midwestern states (Brenden et al. 2006b). Both projects used a GIS framework to assemble digital map layers and relational databases. Geographically linked data include land use/cover, hydrography as well as calculated variables such as drainage area, channel shape, network position, sinuosity, gradient, connectivity to the Great Lakes and large rivers, and surficial geology. Statistical multiple linear regression models were developed to predict annual flow exceedence discharges and mean July temperatures for each reach from variables including catchment area, mean annual precipitation, catchment slope, % coarse textured surficial geology, % peat and muck, % agricultural land, % forested land, and % urban land.

The USEPA has developed two commonly used models: the Soil and Water Assessment Tool (SWAT) model and the Hydrologic Simulation Model in Fortran (HSMF) (Crowley and He 2005). SWAT is a comprehensive watershed model that incorporates runoff, groundwater, ET, snowmelt, channel routing and subsurface flow but uses the SCS curve number to predict excess rainfall from daily precipitation. The SCS curve number may not represent actual runoff because it does not include time lags, antecedent soil moisture, and may not separate runoff from the total hydrograph accurately. HSMF simulates the water budget, sediment transport, soil moisture and temperature but requires extensive data to calibrate which is often not available.

Miller et al (2002) integrated remote sensing data and hydrologic models to assess watershed conditions and the impacts of land use change on hydrologic response in the Cannonsville watershed in DE. They quantified land use change from remote images from 1970-1990 (Landsat-60m). They incorporated an Automated Geospatial Watershed Assessment (AGWA) tool in GIS to automate the parameterization of the SWAT (Soil & Water Assessment Tool) and KINEROS (KINematic Runoff and EROsion) distributed hydrologic models and were able to estimate the change in runoff and sediment yield with change in land use. They used AGWA to extract land use, soil, watershed area, slope (DEM) and channel networks that were then linked to look-up tables for other relevant data (precipitation, SCS curve number, roughness etc.)

The USACE has developed a Hydrologic Modeling Systems (HEC-HMS) that simulates runoff from precipitation in watersheds (http://www.hec.usace.army.mil/software/hec-hms). It is designed to be applicable in both large river/floodplain systems and smaller headwater streams. The modeling system
uses a hydrologic schematic representation of the watershed sub-basins with multiple options for inputting and transforming hydrograph data, simulating infiltration losses, representing base flow, and channel routing. There is also a geospatial hydrologic modeling extension, HEC-GeoHMS which is linked to GIS with algorithms to identify drainage paths and sub-basin boundaries.

The MRWP Ecological Modeling System has implemented hydrologic and loading models which incorporate HEC-HMS to route surface flow through the main tributary and river channels. Input to HEC-HMS include detailed precipitation data, a newly developed 2-layer groundwater flux model for improved baseflow estimates, and a basin-wide MODFLOW groundwater component that includes a 2-layer representation of the landscape and much improved phreatic surface estimates. Coupled runs of the HEC-HMS surface water model and the MODFLOW groundwater model are used to refine parameterization. This modeling system improves on existing hydrologic models by providing process-based models of groundwater flux and flow.

The Great Lakes Environmental Laboratory (GLERL) of NOAA has developed a series of hydrologic models for riverine basins of the Great Lakes (Croley and He 2005). The Large Basins Runoff model is a lumped parameter model that estimates rainfall/runoff for the 121 Great Lakes watersheds from daily precipitation, temperature, and insolation to predict net flow into channel runoff, soil zones and groundwater. Root mean square error for the model ranges from 0.18-0.62 when averaged across the five Great Lakes basins (Croley 2003). This model has been used by GLERL for hydrologic forecasting and to predict water processes in the Great Lakes. GLERL has also recently developed a more spatially-explicit Distributed Watershed Model that accounts for watershed hydrologic processes for 1 km² cells and parameterized the model for 18 watersheds. The distributed flow model has been further parameterized to predict concentration and loads of nutrients and pollutants. Most recently, GLERL modeled hydrologic conditions and the effects of climate change scenarios on three regions of the Lake Ontario-St. Lawrence Rivers system for the International Joint Commission (IJC). Hydrology data were input into a 2-dimensional hydraulic model to model water depths, elevation and velocity in a range of hydrologic conditions.

A watershed assessment program is underway for the Susquehanna River, the largest tributary (27,500 mi²) basin of the Chesapeake Bay basin. A collaborative multi-institution research effort will model and monitor human and climatic dimensions of hydrologic change (http://www.srbhos.psu.edu/default.asp). The project combines existing hydrogeologic, topographic, climate and groundwater well data in a GIS framework to develop hydrologic models. Hydrologic, evapotranspiration, airborne geophysics, and biogeochemical data are collected at network of sites from hydrologic observing systems, called the Susquehanna River Basin Hydrologic Observing System. GIS-based models of nitrogen loading and conceptual hydrogeologic groundwater storage have been developed for the basin. A web-based, multi-institution computation grid will facilitate sharing of data, ideas and models, and a River Basin Adaptive management and Modeling Plan (RAMP) will coordinate historical and current data collection to produce change detection models.

**Hydraulic Models**

Channel hydraulics are key variables influencing fish habitat (Gorman and Karr 1978, Lamouroux et al. 1999). Hydrologic variation combined with natural variation in channel morphology and plan form produce physical habitat heterogeneity which has been related to higher levels of biodiversity (Gorman and Karr 1978). A variety of methods that simulate or characterize the effects of flow velocities on hydraulics and fish have been developed. The most widely known are the various types of Instream Flow Needs techniques (IFN) that use a variety of hydrologic and hydraulic inputs to estimate the effects of change in flow on habitat availability for target fish species (Bray 1996, Lamouroux et al. 1999, Tomsic 2007, Newson et al. 1998a). There are three basic IFN modeling approaches which vary in the level of hydrologic, hydraulic, and physical habitat detail (Jowett 1997).
The simplest method uses a river’s flow regime (e.g. % of avg flow), to determine the necessary minimal flow or flow exceedence level. Adding surveyed cross-section information such as width, depth and velocity provides estimation of the effects of change in flow on river hydraulic parameters. The third approach adds physical habitat measurements critical to biologic habitat suitability such as substrate or water temperature based on habitat suitability criteria (e.g. Physical Habitat Simulation Model; Jowett 1997, Acreman and Dunbar 2004). Habitat based methods based on habitat suitability criteria (e.g. Weighted Useable Area (WUA)) tend to reduce rivers to a common denominator - the habitat used by the 'target species' - and are best used where there are clear species-related management objectives.

The Instream Flow Incremental Methodology (IFIM) is a decision support tool designed by the USFWS to analyze the effects of water management on fish habitat (Bovee et al. 1998). IFIM is a system of procedures or models that link microhabitat suitability criteria, stream discharge scenarios, and stream habitat area to estimate the area of suitable habitat for a fish species under different flow management scenarios. The Physical Habitat Simulation Model (PHABSIM), the habitat component of IFIM, was developed in the 1970’s and is now widely accepted as an approach to evaluating effects on instream habitat due to alterations in flow regime. The model uses a Habitat Suitability Index (HSI) that describes the flow, substrate, and temperature requirements of fish at various life stages to weight usable area of the river under different flows (Parasiewicz and Walker 2007). Habitat in the model is measured at the microhabitat scale and typically requires detailed fine-scale microhabitat field measurements of depth, velocity, cover, substrate and temperature to calibrate the models (Shields & Rigby 2005) as well as calibration of bathymetric and hydrologic data. Microhabitat data can be aggregated to the mesohabitat or reach scale. One-dimensional deterministic hydraulic simulations of in channel reaches or sections have typically been used to predict the effects of alterations to flow on target fish species habitat. Output of the PHABSIM model is input to the analytical decision framework of the IFIM. The assumptions of protocols like PHABSIM is that a river can be described as the sum of its composite habitats and, if the reference faunal status of the habitat is known, the expected faunal status of the river can be predicted by studying changes to habitat (Tickner et al. 2000).

There are several example of use of IFIM and PHABSIM in large rivers. Bray (1996) evaluated fish and invertebrate habitat change over time in the St. Mary's River using simplified IFIM and HSI models. Hydropsychid and rainbow trout habitat was estimated from IFIM models using four known discharges to estimate the linear relationship between total % WUA and discharge. A time series of %WUA was calculated using discharges from 1915 to 1984. Useable area was determined from depth only because substrate and velocity were not known. Northern pike habitat was estimated using a HSI model which incorporated change in area of submergent and emergent vegetation determined from black and white aerial photographs from 1935 to 1981. Their results indicated that loss of wetland areas and loss of hydrologic fluctuation have been factors contributing to habitat decline.

The IFIM methodology was modified and used to test predictions of fish community preferences for habitat hydraulics in 11 reaches of the Rhone River, France (Lamouroux et al. 1999). Instead of deterministic hydraulic models they used statistical hydraulic models to predict frequency distributions of flow velocities and depths from depth frequency distributions at a given flow, changes in depth and width over the flow regime and average substrate size. Instead of one-dimensional HSI they used multivariate models to predict hydraulic habitat preference at the reach-scale from data observed at the macrohabitat scale. They compared fish community metrics computed from low flow conditions with long-term samples and found that relative abundance was primarily determined by zoogeographic factors but within geographic regions models explained up to 47% of the variance in relative abundance.

Another new approach to IFIM modeling uses a similar linked hydraulic and physical habitat modeling system but changes the scale to apply to larger river systems (Parasiewicz 2001). The methodology called MesoHABitat SIMulation (MesoHABSIM) collects habitat data at the mesohabitat
scale. The method apriori classifies the river into mesohabitat units (e.g. riffle, run, glide, backwater) then representative units are sampled for water column and bottom velocity, depth, and estimated substrate at seven locations for three to four flows across the flow regime range. Unsuitable, suitable, and optimal habitat area are determined by logistic regression of habitat characteristics with fish presence/absence data from unit samples or literature-based information. The hydraulic models within MesoHABSIM are limited to ratings curves developed from sampling thus habitat from unsampled flow regimes are interpolated from flow-habitat relationships. To date this method has been employed only on wadeable rivers using a combination of aerial photographs, laser range finder and field computer. Sampling is less field intensive than PHABSIM and less effort is spent to construct hydrodynamic models. MesoHABSIM is designed for large-scale, whole river assessments thus may be more applicable to large rivers where habitats on multiple riverine systems could be broadly classified and representative units measured in detail. Application of MesoHABSIM to larger rivers is in progress (Parasiewicz 2007). Large river methodological differences include increased reliance on remotely sensed images to map hydromorphic units and using an ADCP to collect depth and velocity data. Parasiewicz (2007) is currently using georeferenced sampled hydromorphic units to process high-resolution aerial photographs and map hydromorphic units throughout the river system, an approach that, if successful, could be used to map habitat in nonwadeable rivers of the Great Lakes.

A number of researchers are applying new technologies to instream habitat studies with the ultimate aim of increasing data quality and density and reducing the time and effort of collecting field data. In California, an ADCP, underwater video, handheld laser finder and GPS were used to collect habitat and flow data for IFIM of Chinook salmon (Gard and Ballard 2003). Gard and Ballard (2003) estimated that field effort decreased by a factor of 3.4, the number of sampled transects doubled, and discharge accuracy increased to 2.7% from 5%. Tomsic et al (2007) used new technology to develop HSI models for the Greater Redhorse and stoneflies species to assess the effects of dam removal in the Sandusky River, OH. Elevations and cross-section channel surveys were conducted using DGPS and a Sokkia Total Station. Hydraulic simulations models were constructed using 1-dimensional Mike-11 software calibrated to field deployed depth sondes and validated with an ADCP. Substrate was mapped manually from walked or boat transects. Substrate, velocity and depth suitability were defined for each HSI and modeled depth and velocity profiles were input from the hydraulic models to simulate future HIS following dam removal. Similarly, Scholten et al. (2003) used ADCP (> 150 cm) and AD velocimeter (<150 cm depth - shallow) to map bathymetry, slope and hydraulic parameters for the morpho-hydraulic module of an IFN model for fish habitat suitability in the Elbe River, Germany.

Instream flow methodologies that include one-dimensional computer models (PHABSIM) don’t describe the flow gradient patterns that influence stream habitat across spatial scales. Spatial velocity gradients or channel hydraulics create habitat through interaction of flow with river features such as bathymetry, boulders, woody debris, cross-section shape to create complex flow patterns including velocity shelters and wakes that are habitats for flora and fauna (Shields and Rigby 2005). Ghanem et al. (1996) evaluated the differences between one- and two-dimensional approaches to flow modeling for PHABSIM. PHABSIM typically incorporates a simplistic one-dimensional model to simulate water surface elevations in a channel reach over different flows, then computes velocity distributions for channel cross-sections from interpolation and regression analysis. One-dimensional hydraulic models require measurements of water depth and velocity to develop relationships between flow and suitable habitat. However, since field cross-sections are typically widely spaced, variation between cross-sections is not accounted for resulting in questionable accuracy. Ghanem et al. (1996) found that the two-dimensional hydraulic model could provide a good prediction of flows and better simulated complex flows based on less field data and less office work because the model only requires topographic and roughness input with field velocity measurements only used to validate the model.
Metrics of riverine habitat quality based on vertical hydraulic gradients were created from model simulations by Crowder and Diplas (2000). These metrics were indicators of flow heterogeneity based on either gradients of velocity magnitude or rotational flow in either the vertical or horizontal plane relative to flow direction. Two-dimensional explicit hydraulic models predict flow patterns around meso-scale structures such as boulders identified velocity gradients, shelters and transverse flows around boulder obstructions that were not identified in simple 1-dimensional models such as PHABSIM (Crowder and Diplas 2000). The 2-dimensional models were calibrated from velocity regimes measured by ADCP around physical habitat and across channel cross-sections which required over 200 hours of field work. They found that the metrics generated by numerical simulation models, current meter point measurements and ADCP sample data were of similar magnitude.

Currently, many of the approaches that assess riverine habitat relative to flow regimes use either summary hydrologic metrics such as a % of historical flow, or models such as PHABSIM that link habitat suitability to hydraulic models for target species. Anderson et al. (2006) propose a holistic framework for addressing instream flow needs for riverine systems that preserves the natural flow regime and links flow regime, habitat availability and population dynamics. Components of the framework include: 1) habitat preferences (vs. tolerances) based on individual bioenergetics or behavior; 2) inclusion of changes in population dynamics forced by environmental factors; and, 3) inclusion of both spatial and temporal variability. They review bioenergetically based population models using a Dynamic Energy Budget (DEB) approach that uses rate based equations that allow feedbacks among individuals, population and environment. They also suggest that models should include habitat geometries that incorporate landscape connectivity and dispersal distances into models as well as key process like system resilience to disturbance and inclusion of length scales from ecological rates (response, dispersal) as a method of quantifying spatial effects. They identify future needs as: 1) population bioenergetic models; 2) inclusion of landscape level persistence; 3) combined spatial and temporal effects; and, 4) understanding transient vs. long term responses to temporal variability.

CERC (USGS) has been modeling 2-dimensional hydrodynamics of habitat to assess the influence of changes to flow regimes from anthropogenic alteration of the channel or from climate change. In the Lower Missouri River, Elliot et al. (2004) used bathymetry, elevations and velocity profile data and USACE floodplain topography, to develop a 2-dimensional, depth-averaged hydrodynamic model (source River2Dv.0.90) of an 8 km reach near Boonville, MO. The model provided an inventory of depths and velocities over a 1-99% flow exceedence (validated from downstream stage discharge relationships). They then compared the modeled depth and velocity habitats with known locations of shovelnose sturgeon and found that adult surgeon select areas with high gradients of depth and velocity. The model suggests that the high gradient reaches are relatively insensitive to flow regime but that the shallow water habitat is highly sensitive to flow regime and flow alteration. The Ozarks group (USGS, CERC, Panfil et al. 1999) has used a 2-dimensional hydrodynamic model (RMA-2) and developed a method for habitat inventory using model output for hydrologic scenarios estimated from historical stream gage records. The 2-dimensional models were developed from interpolated bathymetry and topography and assigned Manning’s values calibrated from field measurements. Habitat was classified hydraulically based on Froude number (a ratio of the frictional vs. gravitational forces acting on flow) and a depth criterion of five classes (edgewaters, pools, glides, races, riffles). The Ozarks Group then analyzed the sensitivity of habitat to climate change. The models suggest that race and riffle habitat were the most sensitive to climate change with edgewater habitat increasing with increasingly dry years. They also noted that dry years have both lower magnitude and less variable flows.

Reuda and Cowen (2005) developed 3-dimensional hydraulic model simulations in combination with field data to show that exchange in the connecting channel between a Great Lakes freshwater embayment and Lake Erie resulted from multiple forces. They used acoustic Doppler profilers and a series of thermisters to measure temperature and velocity profiles during the spring and fall when
temperature differentials existed between lake and embayment. They found that oscillations in water levels (barotropic forces) were dominant.

The USACE has developed a hydraulic model, HEC-RAS, which is designed to work with HEC-HMS hydrologic input to produce hydraulic data and metrics for one-dimensional steady flow and unsteady flow (http://www.hec.usace.army.mil/software/hec-ras). Model components will also compute sediment transport and water temperature. HEC-RAS uses a geometric input file of river reaches that include elevations, bathymetric cross-sections, and roughness components. HEC-RAS also has a GIS extension, HEC-GeoRAS, that uses GIS to allow the user to create the HEC-RAS input file. HEC-RAS computes water surface profiles, water velocities that vary with depth and substrate, and hydraulic variables such as shear stress and Froude’s number that can be used to characterize the hydraulic components of physical habitat under multiple hydrologic conditions.

The MWRP Comprehensive Modeling system (Collaborative Approach to Understanding the Dynamics of the Muskegon Watershed: A Comprehensive Model, Risk Assessment and Tools for Use in Management, GLFT ongoing project) has used HEC-RAS and HEC-GeoRAS to model river hydraulics under a range of hydrologic conditions as input into simulations for weighted useable area habitat models and fish bioenergetic models for steelhead and chinook salmon. HEC-RAS input files were developed in Hec-GeoRAS from GIS habitat models of the entire Lower Muskegon River. The habitat models mapped channel units (riffle, run, edge, backwater), hydraulic characteristics from ADCP data, and substrate composition. These habitat maps were combined with topographic surfaces and bathymetric cross-sections spaced 20-30 m apart were digitized in GIS (Figure 1). Each cross-section was divided into 35 cells across the channel and 4 cells across each floodplain and each cell has associated channel unit and substrate data and roughness coefficients. Channel geomorphic data were then input into HEC-RAS along with modeled and gaged hydrologic data to estimate hydraulics for each cell in each cross section under daily flow conditions (Figure 1). HEC-RAS modeled hydrology and hydraulics can be input into individual-based fish models and models predicting useable habitat area to predict temporal and spatial variation in suitable habitat and fish productivity due to variations in river discharge. Figure 1 shows modeled adult walleye weighted useable habitat (HSI-based) in 2001 for one river reach in the Lower Muskegon River.

Individual Based Models (IBM), introduced above, use complex models to relate changes in river habitat to fish populations. IBM assess the changes in population dynamics of fish taxa (e.g. steelhead salmon, Coho salmon, and walleye) at various life stages through simulated changes in hydrology, hydraulics, temperature and prey densities (Tyler and Rutherford 2007). An IBM was developed for the Manistee River, MI, although the model was relatively generic. Model inputs were temperature, discharge, hours of daylight, prey densities, steelhead feeding stations and substrate characteristics. Habitat parameters such as temperature, discharge, light availability, and substrate were simulated from Manistee River or watershed data. IBM simulations of steelhead indicated that discharge and temperature may limit steelhead parr densities on the Manistee River and that restoration of the natural flow regime may increase the quality of steelhead habitat, but that steelhead populations may be limited by intrinsic density dependent factors at the fry and parr life stage. The model is currently being applied in the Muskegon River watershed to evaluate steelhead and Chinook salmon population dynamics with changes in land use scenarios. These IBM linked to dynamic habitat simulation models demonstrate the capability of data from new technologies combined with advanced modeling systems to predict how changes in environmental drivers will influence habitat characteristics and fish population dynamics.

**Summary**

Methods to sample and monitor the physical structure and flow regime of river channels vary from site-based field methods through remotely sensed spectral or radar data to hydrologic and hydraulic...
models. Field methods developed for large rivers typically evaluate river channel shape, depth, substrate, and macrohabitat at locations along transect on a sample reach and may combine the measurements into an assessment score. Local habitat measurements are important for relating local characteristics to biological samples and for validating other data and models, but alone they are not a cost-effective approach to sampling and monitoring large rivers across the Great Lakes region. Newer technologies and protocols include use of ADCP to measure velocity profiles, discharge, bed movement and stability, and channel morphometry and subsequently used to estimate stream power and channel shear and to classify flow regimes. Several large river programs use a suite of georeferenced boat-mounted sensors (ADCP, side-scan SONAR, DGPS, field computer, sub-bottom profiler, and underwater camera) to measure and validate channel bathymetry, substrate, velocity profiles, discharge, and substrate stability. This approach is less time-consuming and of higher resolution than manual measurements. Remotely sensed spectral and LIDAR data have been used to extract channel bathymetry and substrate distribution although mostly in clear water or shallow rivers. There is some evidence to support exploration of linking ADCP depth and velocity profiles to multi- or hyper-spectral data to classify hydraulic habitat in large rivers. These data could then be linked to hydrologic simulation models to assess change in channel and floodplain habitat with change in flow. Remotely sensed radar has also been useful for estimating stage-discharge relationships and validating hydrologic models. Radar data would be useful for regional or broad synoptic studies of hydrologic patterns. Numerous statistical hydrologic models that simulate flow from precipitation and channel and sub-surface routing have been developed. Applications that incorporate regional landscape and climate variables will be an important tool for examining effects of land use and local climate change on river flow and thus channel habitat. A number of hydraulic models have been used to estimate suitable fish habitat from depth, velocity, cover, substrate and temperature variables simulated over a range of flows. Dynamic individual-based models also incorporate hydraulic simulations to estimate the effect of varying habitat conditions on individual fish productivity.

**Substrate and Nearshore Topography**

The most basic definition of substrate describes material that forms the bottom of a lake or stream. Substrate topography, composition, and distribution are important determinants of the quality of spawning habitat and cover for many species of fishes. Substrate also influences benthic macroinvertebrate assemblages and production, which are important food sources for fish and have significant impacts on food-web energy interaction. Although the importance of substrate features in determining the reproduction success of many fishes in other aquatic environments has long been recognized, the linkages between the dynamic nature of the nearshore substrates and habitat utilization, biological communities, and ecosystem function are not well documented (Mackey and Liebenthal 2005).

Riverine substrate includes bedrock, clay, rock particles that vary in size from silt to boulder, large woody debris (LWD), and in-stream aquatic vegetation. In riverine ecosystems, substrate can influence fish habitat as in-stream microhabitat elements that provide spawning substrate, cover, foraging opportunities and refuge. Substrate size and variability are important determinants of habitat complexity and bed stability. Large substrates such as boulders and LWD are roughness elements that create hydraulic complexity, which subsequently influences fish habitat use. Large substrates also create diverse habitat types (pools, scour, depositional areas) resulting in foraging sites in areas with slower flows. Substrate complexity can result in interstitial crevices which may be heavily used by invertebrates and juvenile fish. Substrate also influences river channel and hydraulic characteristics through properties such as bed roughness, channel profile, and by deflecting or directing flow such as in a log debris jam (Clarke and Bryce 1997).

LWD is an important river substrate element and provides a major link between terrestrial and fluvial systems. River riparian zones control supply and type of wood to the channel while the geometry of the channel controls the mobility, and consequently the spatial distribution of the wood within the
channel. LWD is a source of nutrients in the riverine food web in part by its role in creating areas of sedimentation and accumulation of organic particles, and in part through the breakdown of the woody debris into coarse particulate organic matter (CPOM), fine particulate organic matter (FPOM), and dissolved organic matter (DOM) (Daniels 2006).

In both river and nearshore habitat evaluation, the most common focus of habitat measurement is to quantify the local percent composition of various substrate classes or cover to assess the habitat quality for the fish community. In other cases, substrate assessment focuses on individual fish species, such as the survival of salmon eggs or suitable trout spawning area, so measurements are more narrowly targeted to the vertical or horizontal distribution of substrate particles. Thus, the sampling methods used for assessing substrate depend on the overall intent of the study. Considering the amount of area associated with Great Lakes nearshore and large river habitats, this review will focus on mapping substrate composition classes and their distribution.

Direct observation or manual field methods are similar for large river and nearshore systems. Substrate composition is typically estimated visually by divers or underwater camera systems at systematically selected points, transects, or quadrats. For rivers or nearshore areas that are too deep or too turbid to be assessed visually, the substrate composition at the selected points or quadrates is estimated using core sampling approach. The commonly used substrate sampling methods include inserting a large diameter tube into stream bed, Ponar samples, visually assessing substrate composition using underwater camera or underwater scope, or using a frozen core method. For the frozen core method, a hollow tube is inserted into the substrate, liquid carbon dioxide is poured down the tube to freeze a core of sediment, the frozen core is then removed, and the composition is measured based on sieving sizes.

All of the established protocols for nonwadeable river habitat include manual identification, mapping and classification of substrate (USEPA EMAP, USGS NAWQA, MDNR SSTP, QHEI, NWHI). Substrate is commonly assessed at evenly spaced locations along established transects using visual assessment, sounding pole, underwater video or quantitative samples. LWD is typically visually tallied based on quantity and % cover of LWD above an established size (e.g. > 0.5 m long and > 0.3 m diameter).

The advantage of manual assessment methods is they provide relatively accurate substrate composition assessment for the interested areas. The disadvantages are they expensive, difficult to be applied to a large area like the Great Lakes nearshore and large river zones, and include observer biases. However, these methods are often employed as groundtruth data for other remote technologies.

Nearshore Systems

Side-Scan Sonar and Acoustic Substrate Mapping

Rukavina (1997) used RoxAnn surveys in Areas of Concern with the objective of mapping contaminated-sediment patterns. Work has also been done in open Lake Ontario at Toronto and Darlingtown in support of sampling surveys and monitoring of bottom changes. Calibration was based on bottom samples and diver observations and resulted in an 8-fold bottom classification ranging from mud to boulders and including weeds on hard or soft bottom. Survey results demonstrated RoxAnn’s capability for quick and detailed characterization of bottom type and bathymetry and its potential for time-series surveys to measure nearshore changes.

Minnesota Sea Grant program (http://www.seagrant.umn.edu/newsletter/2000/09/mapping_the_secret_spawning_grounds_of_lake_trout.html) conducted a project to map the “secret” spawning grounds of lake trout. The team used two boats to collect data in 1995, 1996, and 1998. They used GPS to record the exact location of the boats and side SONAR to collect bounced SONAR waves
from the boat to the lake’s bottom. They then translated the sound waves into bottom types and water depth. Using various colors to represent different bottom types, they created GIS maps that look like underwater topographical maps. The team used an underwater video camera to check the accuracy of the computer data. The camera helped identify eight categories of substrate: sand, sand and cobble, sand over bedrock, smooth bedrock, rough bedrock, conglomerate, cobble, and boulders. They mapped approximately 80 miles long nearshore areas between Duluth to Grand Marais for Lake Superior.

Edsall et al. (1989) mapped lake trout spawning habitat in Lake Michigan using side-scan SONAR technology. They conducted side-scan SONAR mapping in 1984 with an EG & G model SMS 960³ microprocessor, a model 272 100-kHz towfish, and a model 9000 magnetic tape deck. They used an EG & G model 260 microprocessor, a model 272-T 100-kHz towfish equipped with time-varied gain, and a model 360 digital tape deck. These systems directed acoustic beams from the towfish to the lake bed. The towfish received and magnified the returned acoustic signals from the lake bed. The system transmitted the returned signals to the microprocessor where they were converted into continuous strip-chart records on which surficial lake-bed features were shown on the planar view. With these systems, they were able to classify the substrate into nine categories, including sand, sand with scattered rubble, gravel with rubble, rubble with sand, rubble with scattered cobble, cobble piles on rubble, sand with rubble patched, rubble with cobble, and cobble with scattered boulders. They mapped a total area of 1758 hectares, which used 80 vessel-hours for performing the survey and collecting the ground truth data. An additional 240 person-hours were needed to produce the maps and a $5,000 contract for producing computer drawing maps. This study demonstrated that side-scan SONAR can be used for mapping Great Lakes nearshore substrate.

Edsall et al. (1992) and Edsall et al. (1995) also used the EG&G International side-scan SONAR systems to survey the Six Fathom Bank and Yankee Reef of Lake Huron and the Clay Banks Reef area of Lake Michigan to evaluate lake trout reproductive habitat. The methods they used were similar to Edsall et al. (1989). Additionally, they employed a Benthos, Inc. MiniRover MK II ROV equipped with a high-resolution, color video camera to view and videotape the lake bed in the survey area to assist the verification and interpretation of SONAR maps. For the Lake Huron study, substrate was classified into rubble with sand patches, cobble piles with sand patches, flat bedrock, bedrock ridge, broken bedrock on flat bedrock, sand, bedrock with cobble piles, rubble with cobble piles, rubble piles with scattered cobble, bedrock ridges with cobble piles, and bedrock with sand patches. For the Lake Michigan study, substrate was classified into rubble and sand, rubble and bedrock, sand and rubble, and sand. Using this method, 844 hectares were mapped along a 6 km shoreline of Lake Michigan. The depth surveyed was from 4-m depth contour to 20-m depth contour line. The 4-m depth was the safe operating depth of the survey vessel.

Mackey and Liebenthal (2005) mapped substrate spatial distribution and its change over time for nearshore area of Lake Erie. They employed the similar side-scan SONAR techniques that were used by Edsall et al. (1989, 1992, and 1995) to survey the substrates and produce continuous acoustic image of nearshore bottom. With the real-time GPS information, the acoustic images were processed and integrated into a single GIS data layer. They visually classified the substrates based on inferred grain size, composition, hardness, and observable surface features and digitized in GIS manually (pers. comm., Dr. Mackey, University of Windsor). The substrate types were verified using drop video or bottom grab samples. In addition to mapping and classifying substrates, they also compared the spatial changes in substrate surface area, pattern, distribution, and stability as measures of habitat availability and variability in time and space by comparing the classes and locations of substrate polygon boundaries that were measured at different times.

Waples et al. (2005) used high resolution bathymetry to study lakebed characteristics of the nearshore area of western Lake Michigan. The bathymetry of the survey area was mapped using a
SeaBeam 1180 multi-beam hydrographic survey SONAR. This survey system employed 126 acoustic beams operating at 180 kHz and a swath width of up to 153° resulting in bottom coverage that is fully real-time-compensated for roll, pitch, and yaw, which assures that each beam hits the lake floor independent of the motion of the ship and that the surveyed area does not oscillate with the role of the vessel. They surveyed about 300 km of survey lines over approximately 17.5 km² with water depth between 10-20 m. They classified the bottom of the survey area into mostly rock, cobble and sand, mostly sand, and clay outcrops and verified their classification results using direct observation with a ROV.

Eyles et al (2006) used side-scan SONAR in the Georgian Bay to identify, classify and map benthic substrates. They recommend side-scan SONAR as an effective and relatively inexpensive and accurate method for identifying substrate types. Merged with aerial photos and other existing datasets (bathymetry, land cover, base maps) in GIS, they created a seamless map of habitat from shoreline through near shore to off shore and a relational database with available georeferenced data about fisheries habitat. They were able to examine the geophysical properties of the near shore zone relative to the river influenced near shore zone. The rivers deposit sand and in combination with wind and currents are dynamic features of the lake bottom.

Cholwek et al. (2000) used a single beam echo sounder coupled with a RoxAnn classification sensor to measure depth and bottom substrate along 8 km of the nearshore area of Lake Superior and a lower portion of the Bad River. They identified 7 substrate size and type categories using a supervised classification (from field truth data) and multivariate statistics to define and isolate confidence limits of substrate types. The authors noted that very little bathymetric or substrate data were available and that to protect and restore lake trout habitat, depth and substrate data were needed for 350 km of the MN Lake Superior shoreline. Lake trout spawn from 5-35 m deep which typically extends about 0.5 km from shore, which would require surveying a coastal region of 120 km².

Remote Sensing for Substrate Mapping

Remote sensing offers a cost effective solution to mapping Great Lake nearshore substrates. Although several sensors such as Landsat, Hyperion and HyMap provide data at suitable spatial resolution for classification of substrate, this technique is still being tested.

Joshua et al. (http://gis.esri.com/library/userconf/proc04/docs/pap2006.pdf) mapped near-shore submerged substrate in Lake Tahoe, which has high water clarity. They determined the capability of IKONOS imagery for effectively discriminating different submerged substrate types and produced digital substrate maps. Mapping was based on an IKONOS satellite data mosaic of 9 individual scenes. The IKONOS data needed a high level of geometric and radiometric preprocessing to remove distortions resulting from atmospheric scattering and wind (waves on lake, etc.). Prior to image analysis the lake was stratified into different mapping regions that were analyzed individually. They inferred four substrate types (boulder, mixed, sand, aquatic plants) from the IKONOS imagery with of 86 %.

Werdell and Roessler (2005) used multispectral images (7 bands of visible to far red) of the water surface in turbid water of eastern Long Island Sound. They combined a radiative transfer equation model to extract the fraction reflected light from the benthic substrate (albedo) from the surface reflectance with a linear spectral mixing model that separated the resulting bottom spectrum into percent components of the unique substrate elements. The constraint of this method for large rivers is the spectral optical depth or the depth of light penetration which varies as a function of wavelength. In the turbid Long Island Sound this was 3-8 m. However, they were able to distinguish unique substrates such as clay and silt, sand, eel grass and kelp with a high degree of certainty. Plants exhibited the highest variance in spectral signatures due to variation in pigment concentration and composition and epiphytic growth. Another constraint was that the benthic substrate was not bright (<10% of whole surface reflectance) and the water
column was generally green confounding the plant substrate. However, they were able to remove the effects of the water column and water depth to yield unique spectra for benthic substrates. In contrast, photographic color imagery cannot be decomposed into a complex spectral signature. Also, they felt that the spectral model estimates of substrate cover were better estimates than visual observations because an observer often clumps visually similar areas into one substrate while decomposing the spectral image may identify more heterogeneity. This method could be improved by adding bands or using hyperspectral imagery.

Dr. Janssen at the University of Wisconsin, Milwaukee has used high resolution aerial orthophotographs of the Wisconsin Lake Michigan coast to map algal beds (Cladophora) on rocks (pers. comm.). The resolution was a few centimeters and penetrated to 8-10 m, but quality was dependent on calm conditions, correct sun angle, and cloud cover. Groundtruthing included Scuba, snorkeling, drop video, and ROV’s.

Barnes et al. (2003) used a high-resolution, airborne laser system SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) to map approximately 200 square kilometers of shallow lakebed morphology on a 4-m grid at decimeter resolution for six reef and coastal areas in Northern Lake Michigan. They provided geo-referenced lakebed measurements at 1-m horizontal and decimeter vertical resolution. They developed and applied new algorithms to extract spectral reflection and amplitude information from the laser data to allow additional classification of geologic substrate information. The SHOALS system decimeter elevation/location data were merged with coarser NOAA gridded bathymetry (Holcombe et al. 1996) and a 30m USGS digital elevation model (DEM) topography to generate the six map images. Three geologic regimes (bedrock, glacial and modern) were interpreted from the morphology, which formed the basis for substrate, habitat, and morphologic classification.

Toth and Grejner-Brzizinska (http://www.cfm.ohio-state.edu/research/AIMS/) reviewed methods used to integrate LIDAR imagery with high resolution digital aerial imagery to extract DEM. They developed a DEM reconstruction method using georeferenced, integrated LIDAR and digital aerial images automatically on a 5 m grid with no editing. The technique was able to use both images to differentiate between natural and anthropogenic surfaces. GPS/INS is an integrated GPS and Inertial Navigation System (INS) to improve direct georeferencing of aerial imagery (the Airborne Integrated Mapping System (AIMS); http://www.cfm.ohio-state.edu/research/AIMS/paper3.pdf). The INS is a self-contained, 3-dimensional positioning system with high short term accuracy that can be integrated with GPS for calibration and georeferencing corrections. GPS/INS was able to accommodate LIDAR and SAR images that were very complicated to indirectly georeference (using triangulated GPS). The GPS/INS system provided more accuracy and reliability than GPS alone, and the direct georeferencing systems represent cost reduction in photogrammetric processing and turn-around times when compared to the traditional triangulated GPS georeferencing system. They also suggest that LIDAR can process multiple returns to separate vegetation from terrain surfaces.

Li (2007) describes a project to integrate LIDAR data and 0.6 m panchromatic satellite QuickBird spectral imagery to map Lake Erie shorelines in 3-dimensional at 10-30 cm vertical and 30 cm horizontal accuracy. The purpose of the project is to improve the cost effectiveness, accuracy and efficiency of Great Lakes shoreline mapping by combining the vertical accuracy of LIDAR and horizontal accuracy of QuickBird. Combining the two types of images will produce higher quality images because LIDAR can delineate bluff line edges and anthropogenic structures while QuickBird imagery can help to discriminate shoreline segments in areas with minimal slopes. QuickBird is also an improvement over maps produced from IKONOS imagery which had 2-3 m resolution and will closely approximate shorelines identified from traditional aerial photography.
The USACE is currently surveying all the coastal regions of the U.S. including the Great Lakes coastal margins including river mouths and harbors using a combination of LIDAR and hyperspectral sensors as part of the national Coastal Mapping Program (pers. comm., J. Lillycrop, USACE). The flights survey 1,000 m lakeward and 500m landward from the shore. Over water they use a bathymetric LIDAR with 15 cm resolution and hyperspectral sensors with 36 bands and 1 m pixel resolution. The USACE is using a combination of LIDAR and hyperspectral imagery to classify substrate types into coarse classes. They have finished surveying Lakes Ontario, Erie, Huron and the Detroit and Niagara Rivers and expect to survey Lakes Michigan and Superior in 2008. The return time is expected to be every 5-6 years and the data will be publicly available from various sources including local USACE offices and NOAA coastal services following image processing.

Riverine Systems

SONAR and ADCP

Several large river studies have used side-scan SONAR to identify, quantify and map benthic substrate. The Hudson River Benthic Mapping Project in New York (Nitsche et al. 2007) used side-scan SONAR to characterize structure and hardness of bottom (accuracy 2 m pixels) and chirp sub-bottom profiler using ground penetrating radar to characterize sub-bottom sediment structure from 1998-2002. Nitsche et al. (2004) found that side-scan SONAR surveys of the Hudson River substrate indicated that variations of fine-grained substrate were small and could not be distinguished based on side-scan imagery alone. The authors integrated sub-bottom profiles, bathymetry and field samples to classify side-scan images based on depositional and erosional processes that produce differences in porosity, roughness and compaction that are visible on the side-scan SONAR. Processed images were loaded into GIS and integrated (Sediment Profile Imagery technology) to classify the river based on regional variation in channel morphology, bedrock type, sediment texture, and sediment dynamics. All data were Georeferenced using DGPS. Ground truth data were obtained from sediment cores, grab samples analyzed for grain size composition, and an underwater camera (Sediment Profile Imaging) lowered a few cm into the sediment water interface to show grain size, surface micro-topography, and biological features such as tubes and burrows. Shallow areas < 2 m were not able to be mapped and are underrepresented. (www.dec.state.ny.us/website/imsmaps/benthic/webpages/benthic data.html). Brenden et al. (2006b) reported similar difficulties in classifying substrate for shallow areas using single beam SONAR.

The USGS has conducted habitat surveys on the Missouri River using protocols developed by the Columbia Environmental Research Center (CERC). Bed material is classified using RoxAnn processing of transducer echoes to create grids of relative depth, roughness and hardness. These grids were then classified into substrate classes using multivariate unsupervised classification and known substrate classes for validation (how validation data was obtained was not clear). There were three areas of uncertain classifications related to mud and organic matter but the substrate data provided maps of substrate that could be related to discharge and used to evaluate distribution of erosional and depositional areas following flood flows. In 2002 the USGS characterized physical pallid sturgeon habitat variability from bathymetry, velocity and substrate parameters in the Missouri River at Fort Randall (Elliot et al. 2004). Similar to the above protocol they used DGPS for elevation, echo sounding for bathymetry and RoxAnn processing with multivariate unsupervised classification to classify sediments from the transducer echoes. In addition, limited side-scan SONAR imagery was used to validate substrate classifications. Side-scan SONAR provided high resolution images from medium-frequency SONAR (900 kHz) which provided a compromise between higher resolution (high-frequency) and turbid water which attenuates high frequency SONAR more quickly.

The USGS used side-scan SONAR images with underwater video to map sediment types and extent on the channel of the Colorado River following a dam release (Rubin 1994). They detected different types of substrate (boulders, cobble, gravel, sand) as well as distinctive patterns of sediment.
The side-scan SONAR images were consistently matched with the video images implying that side-scan SONAR could be used to map sediments in the channel. In turbid waters, downstream underwater video could not be used while side-scan SONAR could (http://walrus.r.usgs.gov/grandcan/twostudies.html).

Fine sediments on the Colorado River were mapped up and downstream of the Glen Canyon Dam using a combination of topographic mapping using total stations from river edge to 1 m depth and a hydrographic survey system that combined a shore based total station with boat-mounted SONAR transducer to record depth and position for mapping river bathymetry. These two maps were integrated in GIS to form a TIN surface model of river and floodplain topography. GIS was used to calculate changes in sediment areas and volume, and identify areas of deposition and erosion with changes in hydrology.

Large woody debris has been sampled in the Sulphur River, Texas, using a single-beam portable echo sounder from a boat using differentially corrected GPS for position location (White et al. 2006). The effective survey resolution was 16 cm which was close to the width of the large woody debris. They found that using the standard deviation of binned data effectively separated LWD from channel bathymetry signals. This method was used to both identify location and quantity of LWD and to develop background channel bathymetry for hydraulic models. The success of this method depended on the survey scale being fine enough to obtain one or more echoes from each LWD and constant boat speeds because echo signals vary with the speed of the boat carrying the equipment such that slower speeds over LWD would cause it to have relatively more echoes within the channel bathymetry.

Gaeuman and Jacobsson (2005) describe the use of an ADCP for describing the distribution of stable and unstable substrates, the degree of particle movement and near-bed water velocities. They used the bottom-tracking function of the ADCP with DGPS to measure features of the river bed by assessing the return velocity of acoustic pings to estimate the velocity of the bed materials relative to the velocity of the instrument. Comparison of ADCP estimates with traditionally sampled bedload suggested that the bedload transport rates are comparable. Data quality issues include random errors, velocity ambiguity errors that occur when the water velocity is large relative to the instrument velocity, bedload movement which can be corrected by using DGPS, and errors calibrating the compass of the ADCP unit.

A new technology that is being used in Crane Creek and estuary (Lake Erie basin) is a Dual-frequency Identification Sonar (DIDSON). DIDSON has been primarily used to assess fish populations or view fish behavior but also could be used to identify substrate and other bottom features. DIDSON can be employed from a boat or from shore and can be linked to a laptop for image control. The dynamic images are high quality video.

Remote Sensing
Aerial photos and airborne spectral imagery have been widely used to measure and map riverine substrate. Smikrud and Prakash (2006) used low-cost, high-resolution (0.6-0.8 m pixels) 3-band digital aerial photos taken over 2 years to map LWD on a 0.32 km² stretch of the floodplain of an Alaskan river. The camera collected blue, green and red (visible) spectral bands. LWD does not have a unique spectral signature in the visible range and ,even with hyperspectral images, LWD can be confused with gravel and sand so they used spatial and textural properties transformed using principal components and a filtering process to identify and classify LWD. Accuracies (User’s 82%, Producer’s 95%, overall 89%) were assessed from comparison to field data and from visual assessment of a representative sample of the classified image. Further research used weighted habitat indicators (channel, edge, pool and LWD) from hyperspectral imagery to map potential salmon habitat in GIS (Prakash 2006). They noted that previous researchers have had problems with LWD identification using multispectral (4-band, 1-m pixel) imagery because of insufficient spatial resolution, mixed pixel effects, and problems with coregistration of imagery and field maps so that supervised training using field maps could not identify LWD or other small objects. Use of hyperspectral imagery at 1 m pixel resolution with principal component

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transformation and matched-filter classification or 8-band CASI 0.8 m imagery were more accurate (79%). Problems in identifying LWD occurred when the LWD was obscured by shadow, glare, water or vegetation. It is possible that shadows and riparian vegetation would be limiting for using aerial photography on large rivers within the Great Lakes region. The exception would be for large rivers surrounded by large wetland complexes where channel images would not be obscured by overhanging vegetation.

The USGS used digital orthophotography from 1999 to identify geomorphic features of 150 mi of the Missouri River at the reach and segment scale (Elliot et al. 2006). Most of the characteristics measured for geomorphic classification related to channel and bank form and condition. They did include an estimate of LWD mapped from 1999 aerial photographs at resolutions of 1:1,000. They were able to identify LWD pieces with trunks greater than 1 m in diameter. LWD was considered a dependent variable and was not included in classification but they could characterize the LWD status of various segments of the river from aerial photos and GIS digitization.

Airborne multispectral and thermal imagery has been used to characterize hydraulic features, riparian composition, abundance of large instream woody debris, and stream temperatures in the Upper White River, WA (Black and Haggland 2003). Spatial resolution of the multispectral imagery was 0.5 m, while for thermal imagery the spatial resolution was 1.0 m. Aerial images were classified using supervised algorithms. Multi-spectral images could not accurately identify instream woody debris at resolution of 0.5 m or less. Shadows on the imagery (taken in September) and overhanging vegetation impacted imagery identification of woody debris, and wood elements smaller than the pixel resolution could not be identified. The benefits of using multispectral imagery to map stream habitats include collection of large amounts of unbiased data in a short time, digitally storage and known level of accuracy. Wright et al. (2000) also had very poor classification success for LWD using multispectral imagery in wadeable rivers in MT and WY. For that research, four-band multispectral digital imagery in conjunction with field data with unsupervised and supervised classification techniques were used to measure LWD. Classification accuracy for LWD was on the order of 0.0 to 11.2% per geomorphic unit. Overall, only 26% of LWD pixels were correctly classified.

Airborne hyperspectral imagery at 1-m resolution, 128-band was used to map in-stream habitats in 3rd-5th order western streams and identify LWD (Marcus 2002). Marcus (2002) used matched filter mapping of a principal component transformed image for woody debris with overall accuracies of 83%. Matched filter algorithms partially unmixed the spectral signature so that partial signatures such as LWD elements with known signatures can be recognized. Hyper-spectral imagery allows features with a spectral signature to be mapped even when they are a fraction of a pixel. Marcus (2002) noted that the use of hyperspectral imagery for rivers is limited by water clarity, riparian cover and availability of hyperspectral sensors.

LIDAR combined with hyperspectral imagery has also been used to map river bathymetry and classify substrate. LIDAR and hyperspectral sensors have been flown in four lower river mouths of southern Lake Michigan (Christenson and Gerczak 2003) and is currently being flown by the USACE for all Great Lakes nearshore areas, large river mouths, and harbors. However, these studies have shown that large rivers are generally too turbid for adequate penetration of laser and spectral sensor beams for full bathymetric surveys and substrate classification and mapping. Substrate classification and mapping in large rivers will likely need application of SONAR which can be linked to the nearshore topographic LIDAR and spectral imagery (pers. comm., J. Lillycrop, USACE).

In wadeable Ozark rivers, Panfil and Jacobsen (2001) studied the relationship between landscape physiography, land use, and stream habitat conditions. They measured habitat conditions at basin-wide scales using GIS. Additionally, they used the NAWQA sampling protocol to measure reach-scale
attributes. They used scanned and georectified aerial photos to map gravel bars to estimate gravel transport. They found that channel morphology, habitat distribution and substrate characteristics were more related to physiographic conditions but that within physiographic groups, land use disturbance (cleared land and pasture) had subtle influences on habitat conditions due to increased erosion and sediment supply including increase in finer particle sizes and decrease in pool depths. While this method is not directly applicable to nonwadeable rivers of the Great Lakes region, the approach has promise as a way to use field validated remote images to measure substrate conditions and then relate the measurements to land use, geology, and physiography for regional analysis.

Models

As part of the Upper Mississippi River LTRMP, a model was developed to predict the probability of occurrence of aquatic vegetation based on flow velocity, wind fetch, bathymetry, growing-season daily water level and light extinction coefficient in the river for pool 8 of the river system (Yin et al. 2007). The models were built and validated with aquatic vegetation transect data (see field methods section). These model predictions are available on line in a user-interactive mode allowing selection of year and type of vegetation distributions to display (http://umesc-ims01.er.usgs.gov/website/sub_veg_model/viewer.html).

Zorn et al (2006) used causal modeling (Covariance Structure Analysis) to describe relationships between landscape characteristics, local habitat variables, and fish biomass in streams of Lower Michigan. Model data included GIS summaries of land use/cover and geology, stream gradient, site scale habitat measurements (substrate, velocity, depth, total phosphorus, and temperature), exceedence flows, and fish biomass for each of 245 sites. Landscape variables that influenced local habitat included (in decreasing strength) catchment area, channel gradient, agricultural land use, coarse till, outwash deposits and low flow yield. Landscape variables explained 50-83% of the variance in low-flow yield, depth, velocity, total phosphorus and temperature but only 18-30 % of substrate variables. Local-scale variables of total phosphorus, depth and % cobble had significant effects on fish biomass. The sites for this model were primarily wadeable streams but the method of using landscape scale variables to predict local scale biological or habitat variables shows promise for large rivers and near shore areas. For example Weigel et al. (2006) used environmental data at the site, reach and basin scale to analyze how gradients of environmental variables related to fish assemblages (abundance, biomass and metrics) on 31 nonwadeable rivers in Wisconsin. They found that site and basin scale variables defined a gradient from high conductivity, fine substrate and agricultural land cover to forest land cover and rocky substrate. They also found that land cover alterations at the basin scale were most strongly related to fish assemblages across the region.

Summary

Presently, most of the Great Lakes nearshore substrate data are provided by the side-scan SONAR and acoustic substrate mapping. Three on-going Great Lakes habitat classification programs, including the multiagencies’ Integrated Habitat Classification and Map of the Lake Erie Basin, the Institute for Fisheries Research’s Great Lakes GIS Project, and the USGS Aquatic GAP’s Great Lakes Coastal Ecological Classification, are assembling the individual substrate databases collected by different agencies into a centralized database. Although side-scan SONAR and acoustic techniques have improved the efficiency of substrate sampling relative to direct observation approach and provided sufficient data for coarse level classification of Great Lakes nearshore habitat, it will be challenging to resample the entire nearshore area substrate with relatively finer resolution for habitat loss/gain and trend analyses. The remote sensing techniques for substrate mapping are still in the testing stage. Because of the immaturity of the efficient large scale sampling techniques, side-scan SONAR and acoustic techniques are still the best technology for sampling high priority areas, such as mapping fish spawning areas.
A variety of methods have been tested in large rivers including side-scan SONAR, spectral imagery, ADCP, LIDAR, and predictive causal models. Side-scan SONAR with automatic or manual processing is the most common and reliable method. Use of LIDAR and spectral imagery is likely limited to clear water, shallow rivers due to light penetration constraints. ADCP is a promising technology that can collect multiple data at one pass including benthos roughness, and substrate transport, and with more advanced processing could provide detailed substrate classification.

**Aquatic Vegetation**

Like substrate, the composition, distribution, and percentage cover of aquatic plants may determine the fish species composition, individual fish species production, access to fish stocks by fishermen, fishing gear and boat access. Aquatic macrophytes can also be efficient indicators of water quality, and their presence may enhance water quality due to their ability to absorb excessive loads of nutrients and to reduce wave formation that decreases sediment resuspension.

Aquatic macrophytes can influence lake and riverine ecosystems in a number of ways that fall into three main categories: 1) limnological effects related to changes in physical and chemical conditions in the water and sediments; 2) metabolic effects related to production and processing of organic matter and nutrient cycling; and, 3) effect on biotic interactions and community structure related to the role of macrophytes in providing a structured habitat (Gasith and Hoyer, 1998). The importance of macrophytes will decline with increasing size and depth of the water body.

Fish use aquatic macrophytes for shelter and refuge, as a direct or indirect food source in the form of epiphyton and associated invertebrates, and as spawning, nesting, and nursery sites. Fish species in densely vegetated margins of some water bodies are tolerant of low dissolved oxygen concentrations and high temperature. Sparse vegetation or isolated macrophyte patches also attract some fish which use them for shelter, food, or spawning habitat.

Aquatic macrophytes can contribute to an increase in fish abundance, particularly in areas once devoid of any substantial amount of cover. Borawa et al. (1979) reported that fish densities increased from approximately 1000 fish/ha to more than 15000 fish/ha after the invasive plant *Myriophyllum spicatum* became established in Currituck Sound, NC. Killgore et al. (1989), in their study in the Potomac River, MD, estimated fish densities ranging from 17000 to 98000 fish/ha in areas with plants, which was between two to seven times higher than densities observed in areas without aquatic vegetation.

Aquatic vegetation provides fish with foraging areas, spawning substrates, and refugia from predation (Casselman and Lewis 1996, Radomski 2006) and are important habitat for amphibians and waterfowl (Lindsay et al. 2002, Woodward and Meyer 2003). Many fish depend on vegetative habitat for part or most of their life (Becker 1983). Numerous fish species use protected embayments and vegetative cover disproportionately to their availability (Wei et al. 2004).

**Floating and Emergent Vegetation**

Extent and change in area of floating and emergent vegetation have been traditionally mapped using aerial photographs. For example, Radomski (2006) digitized aerial photographs for 100 Minnesota lakes and analyze those data using image analysis software to map and detect historical changes between 1939 and 2003. Sawaya et al. (2003) used satellite multispectral IKONOS sensor data from a shallow Minnesota lake and classified emergent vegetation into five classes: a) cattail and arrowhead, b) sedge, c) brush, d) water lily and floating-leaf pondweed, and e) mud flat with dead sedge or cattail. The grouping accuracy was about 80%.
Submerged Vegetation

Traditionally, mapping of submerged vegetation over large areas was performed using either aerial photography or medium resolution satellite data. Although sensors such as Landsat and SPOT have been used to detect submerged aquatic vegetation in relatively shallow water, diversity and heterogeneity of bottom reflective targets often lead to problems with mixed pixels, and fine-scale patterns among subsurface targets are not readily distinguishable.

One of the active research areas is to use higher spatial resolution data to classify submerged macrophytes. William et al. (2003) identified the distribution of two species of submerged plants in lower Potomac River, MD, using hyperspectral HyMap system airborne imagery. The flightline dimensions were 2.3 x 20 km and ground sampling distance of the imagery was 4 m. Sensor radiance data were converted to apparent reflectance using ACORN, an atmospheric correction code based on the MODTRAN 4 radiative transfer model. Field sample plots were located in the HyMap imagery and spectral signatures of submerged aquatic plants were extracted by averaging over a 200-m² pixel area for each plot. William et al. (2003) used a band centered at 640 nm to suppress optically active components such as chlorophyll and floating algae in the water column. The overall accuracy of the vegetation maps derived from hyperspectral imagery was determined by comparison to a product that combined aerial photography and field based sampling. They found that the method can reasonably separate the two targeted submerge aquatic plant beds.

Sawaya et al. (2003) used satellite multispectral IKONOS sensor data to classify submerged vegetation into four classes in small Minnesota lakes. They used high quality IKONOS and QuickBird images with only minor cloud cover. They applied a resolution enhancement of the multispectral bands using the panchromatic band. They first identified wetland boundaries using spectral-radiometric differences and spatial patterns visible on the images. They then stratified the wetlands into emergent and submergent vegetations by performing an unsupervised classification. They finally performed multiple unsupervised classification processes to identify lower level aquatic vegetation classes by excluding higher level classes. The four submersed classes were thick submerged vegetation at the surface, submerged vegetation at the surface, submerged vegetation below the surface, and thinner/deeper submerged vegetation below the surface. The five emerged aquatic vegetation classes were cattail and arrowhead, sedge, brush, water lily and floating-leaf pondweed, and mud flat with dead sedge or cattail.

Wolter et al. (2005) used unsupervised classification from orthorectified Quickbird satellite multispectral data to classify submerged vegetation at three sites within the U.S. portion of the Great Lakes. The QuickBird data were orthorectified by the vendor to 1:24,000 base maps and converted the eleven-bit digital counts to at-sensor radiance. They applied a glint-correction algorithm to images with obvious wave-related glint problems to improve visibility of bottom targets. They classified submerged aquatic vegetation by masking all non-water and cloud targets from the visible bands using the NIR band of the QuickBird imagery as a mask. Visible bands (centered at 485, 560, and 660 nm) were then classified into 200 classes, among which 76 were potential submerged aquatic vegetation classes. They used field data collected on different transects for water depth, Secchi depth, substrate type, and submerged vegetation class to verify the reliability of their classification. They concluded that QuickBird imagery is a useful tool for classifying submerged aquatic vegetation in the nearshore areas of the U.S. Great Lakes. Although single-date classifications produced good results, combination of a visible red difference image with visible red and green bands afforded a more accurate mapping.

Although considerable progress has been made in using satellite imagery to classify submerged aquatic vegetation for nearshore and wetland areas, additional efforts are needed to investigate the effects of plant shading on classifying submerged vegetation presence and density, as it appeared to be an important factor between prostrate and more upright growth forms in the Wolter et al. (2005) study.
Another significant area for continuing research is the fundamental understanding of the relationship between the volumetric reflectance, submergent vegetation density, water depth, and bottom reflectance parameters (Yang 2005). Regarding regional mapping effort, Wolter et al. (2005) are skeptical about the operational and economic feasibility of using QuickBird sensor data as a monitoring tool for the entire Great Lakes basin. Rigid satellite tasking constraints and data cost, coupled with unpredictable water clarity and surface condition may preclude reliable data flow and quality for regional submerged aquatic vegetation mapping (Wolter et al. 2005). Presently, an assembled database or effort to assemble a database of submerged aquatic vegetation for the nearshore Great Lakes area does not exist.

**Physicochemical Characteristics**

**Water Depth**

The side-scan SONAR and acoustic technology or the Scanning Hydrographic Operational Airborne Lidar Survey system described in the section on mapping substrate are commonly used techniques to measure bathymetry of lakes. Measuring lake depth is relatively easier than mapping substrate composition. During the past several decades, individual studies have collected bathymetric data for different parts of the Great Lakes. Relatively recently, several federal and research institutes have attempted to assemble these individual data into central databases and to make them available to users.

One of such attempts is the effort of the Great Lakes Environmental Research Laboratory (GLERL). Schwab and Sellers (1980, 1996) (ftp://ftp.glerl.noaa.gov/publications/tech_reports/glerl-016/dr-016.html) described bathymetric grid data and digitized shorelines compiled for the five Great Lakes and Lake St. Clair. The bathymetric grids consist of an array containing the average lake depths in 2-km squares (1.2-km squares for Lake St. Clair). The digitized shorelines are lists of latitudes and longitudes for closed loops describing lake and island shorelines. Conversion equations for map-to-geographical and geographical-to-map coordinate transformations are given for all the bathymetric grids. The reported dataset is a consolidation of the depth and shoreline data for Lakes Michigan and Ontario on a 2-minute grid that were compiled by Hughes et al. (1972) and the averaged depth in 2-km squares for Lakes Erie, Huron, and Superior that were compiled by Robertson and Jordan (unpublished). Additionally, GLERL’s work added Lake St. Clair bathymetric data and included shoreline digitizations for all the lakes in a single, well-documented, computer compatible depth and shoreline database. Presently, the bathymetry data for Lakes Erie, Huron, Michigan, and Ontario are available online.

A more recent effort is the project on lake-floor geomorphology of Great Lakes. The NOAA National Geophysical Data Center, GLERL, and other agencies have compiled bathymetric data collected from the Great Lakes in support of nautical charting for at least 150 years by the USACE, the NOAA National Ocean Service, and the Canadian Hydrographic Service. These projects generated new lake-floor bathymetry data, including water depth. The goal of the effort is to compile Great Lakes bathymetric data and make them readily available to the public, especially to the communities concerned with Great Lakes science, pollution, coastal erosion, response to climate changes, threats to lake ecosystems, and health of the fishing industry. This program is managed by the National Geophysical Data Center and relies on the cooperation of NOAA/GLERL, NOAA/National Ocean Service, the Canadian Hydrographic Service, other agencies, and academic laboratories. This new bathymetry provides a more detailed portrayal of lake-floor topography and lake-depth information.

The USACE is currently surveying all the coastal regions of the U.S. and the Great Lakes coastal margins, including their river mouths and harbors using a combination of LIDAR and hyperspectral sensors as part of the national Coastal Mapping Program (pers. comm., J. Lillycrop, USACE). The flights survey 1,000 m lakeward (or to the depth of light extinction) and 500m landward from the shore.
Over water they use a bathymetric LIDAR with 15 cm resolution with a 5 m spacing between elevation measurements over water and 1 m spacing over land. They also use hyperspectral sensors with 36 bands and 1 m pixel resolution. From these data the USACE is producing seamless topographic/bathymetric digital elevation model (DEM), shoreline vectors, bottom reflectance and type, building footprints and land use maps (supervised classification from hyperspectral imagery). They have finished surveying Lakes Ontario, Erie, Huron and the Detroit and Niagara Rivers and expect to fly Lakes Michigan and Superior in 2008. They plan to resurvey the coastal margins every 5-6 years and the data will be publicly available from various sources including local USACE offices and NOAA coastal services following image processing.

Water Temperature

Nearshore

Water temperature has a profound influence on the entire aquatic ecosystem, including fisheries. Because the Great Lakes has such a large surface area, the surface water temperature of Great Lakes influences regional weather patterns (Schwab et al. 1999). As a result, there is great interest in understanding the spatial and temporal patterns of Great Lakes surface water temperatures.

Traditionally, routine water temperature has been obtained at locations of opportunity, such as municipal water intakes or water level gauging stations. To obtain information on lakewide temperature distribution patterns, early investigators mounted ship-based synoptic surveys of lakes (Ayers 1965). Later, aircraft-mounted radiation thermometers were used to map surface temperature distribution (e.g., Noble and Wilkerson 1970, Webb 1974). Because the large size of the lakes and resources involved, neither ship- nor aircraft-based surveys are practical for routine mapping of lake surface temperature. NOAA National Data Buoy Center has operated a series of satellite-reporting weather buoys in Great Lakes during the ice-free season since 1979. The collected buoy data have been published by the National Data Buoy Center, which is readily available to users. Although this data source has good temporal coverage, it is available only for regions where the buoys are located which tend to be in open water, not near shore zones.

Satellite remote sensing with its wide-area synoptic and repetitive coverage provides information that is not readily available by other means. In an early effort, Lathrop et al. (1987) analyzed Landsat-5 Thematic Mapper thermal IR (Band 6) data for measuring and mapping surface water temperature of Great Lakes. They empirically calibrated the Thematic Mapper thermal IR using regression models of mapped surface temperature data over the entire coverage area of the Thematic Mapper thermal IR. The infrared imaging sensor on weather satellites is an excellent tool for obtaining both spatial and temporal distribution of surface water temperature. Satellite thermal sensors make lake-wide synoptic surface temperature data instantaneously for all the Laurentian Great Lakes several times a day (Bolgrien and Brooks 1992). Schneider et al. (1993, cited in Schwab et al. 1999) combined temperature maps derived from air-born and satellite-born radiometers with the ice cover climatology to produce a combined water temperature and ice climatology for the Great Lakes. They also produced a numerical model to estimate representative vertical temperature profiles for each lake.

Schwab et al. (1992) described the early effort that NOAA CoastWatch program used to measure Great Lakes surface water temperature. In 1990, the CoastWatch program chose GLERL as the CoastWatch regional site for Great Lakes. The CoastWatch program has provided digital images of lake surface temperature at resolutions of 1.3 and 2.6 km for the Great Lakes several times per week to GLERL since 1990. GLERL makes the Great Lakes CoastWatch products available to other federal agencies, state and local government agencies, academic institutions, and other organizations engaged in cooperative research programs with NOAA. The initial CoastWatch water surface temperature imagery was obtained from NOAA polar-orbiting weather satellites. NOAA had three polar-orbiting weather
satellites that carried the Advanced Very High Resolution Radiometers (AVHRR). Each satellite passed over a given area twice a day. The AVHRR scanned a swath of approximately 2,700 km on the surface of the earth beneath the satellite in five radiometric bands. The AVHRR data were processed at 4-km scale for Global Area Coverage and a 1.1-km scale for Local Area Coverage. The AVHRR data were also used to generate High Resolution Picture Transmission data that were used for the Great Lakes CoastWatch imagery. The CoastWatch program extracted four scans, one for all the Great Lakes (2.56-km resolution), one for Lake Superior (1.28-km resolution), one for Lake Michigan and Huron (1.28-km resolution), and one for Lakes Erie and Ontario (1.28-km resolution). The initial products of this program were surface water temperature maps produced on a routine basis of 2-3 images per week and are available within hours of acquisition. These satellite-derived temperatures were consistently 1-1.5°C cooler than the temperature measured at the NOAA weather buoys.

More recently, Schwab et al. (1999) provided a routine automated technique for using satellite imagery to derive a complete map of Great Lakes surface water temperature based on satellite imagery on a daily basis. The technique used near real-time sea surface temperature imagery and cloud mask maps for the Great Lakes from the NOAA CoastWatch program. The maps had a nominal resolution of 2.6 km and provided as complete as possible coverage of the Great Lakes by using previous imagery to estimate temperatures in cloud covered areas. These satellite-derived temperature estimates deviated from NOAA weather buoy temperatures by less than 0.5°C. One example of the potential applications of this product is a summary of the daily Great Lakes Surface Environmental Analysis temperature maps from 1992 to 1997. The data are presented as time series of lake-wide average surface water temperatures for each lake.

Presently, all the updated Great Lakes surface water temperature provided by the CoastWatch program are available at the NOAA CoastWatch Great Lakes Regional Node located at the NOAA Great Lakes Environmental Research Laboratory in Ann Arbor. The most recent data file is stored at http://coastwatch.glerl.noaa.gov/glsea/ncepetagl.dat, and contains surface temperature data extracted from the daily Great Lakes Environmental Analysis composite at National Centers for Environmental Prediction Eta model grid points. These data are available each day at about 06:30 LST as part of GLSEA production. Historical data files are stored at http://coastwatch.glerl.noaa.gov/cwdata/let/yyyy/, with names of form "gyyyyjjj00.let", where yyyy is the 4-digit year, and jjj day of year. The data are also available from an online reporting system (http://www.coastwatch.msu.edu/). The online reporting system is a cooperative project between the NOAA CoastWatch Great Lakes Regional Node located at the NOAA Great Lakes Environmental Research Laboratory in Ann Arbor and the Great Lakes Sea Grant Network. The online reporting system was created and maintained by Michigan Sea Grant and the Michigan State University Remote Sensing and GIS Research and Outreach Services.

**Riverine**

Thermal remote sensing has more recently been used across the northwest to estimate longitudinal temperature profile (± 0.5°C) (Torgenson et al. 2001), and to monitor regional river temperatures (Cherkauer et al. 2005). Other studies have explored the use of Forward Looking Infrared (FLIR) imagery as a monitoring tool to assess stream temperature and in combination with radio-telemetry observe use of thermal habitat selection by target fish species (Torgenson et al. 1996). FLIR is a small portable imaging system that can be employed from either air or ground platforms. Thermal imagery for small stream temperature requires substantial processing to remove biases due to subpixel mixing and radiance from riparian vegetation which would not be significant constraints for large river temperature extraction. Thermal infrared imagery could be incorporated in any remote multi- or hyperspectral survey of riverine habitat to document spatial patterns of temperature across river systems in the Great Lakes ecosystem.
In addition, a number of landscape and fish based models have been developed that predict temperature in riverine systems across Michigan, Wisconsin and Illinois (Seelbach and Wiley 1997, Brenden et al. 2006b). Predictive models of river mean July water temperature in rivers have been developed using landscape variables and a stream network framework. Another approach was used in Lower Michigan to classify river temperature based on observed changes in fish community composition, species richness, and species abundance (Wehrly et al. 1998a). Three temperature categories were identified (cold <19°C, cool 19 to <22°C, and warm >22°C) and three temperature fluctuation categories (stable < 5°C, moderate 5-10°C, and extreme >10°C) to create nine thermal regimes (3x3). They found overlap in distributions of fish thermal guilds as well as differences in fish species distributions within guilds but overall spatial patterns of thermal guild distributions were biologically meaningful.

Turbidity and Chlorophyll

Nearshore

Traditionally, chlorophyll and turbidity have been sampled from locations and depths that are believed to be representative of the general condition of a study region. This approach assesses the conditions of the targeted locations and provides insightful information on the relationship between chlorophyll or turbidity conditions and the other factors. An example is EMAP collected chlorophyll concentration data from thirty-nine sampling stations located in the nearshore region of Lake Michigan (http://www.epa.gov/emap/html/data/greatlak/data/mich94/water/lmchl94m.pdf). The chlorophyll analysis was conducted on water samples collected from the surface (i.e. approximately at the 1 meter depth). This chlorophyll data set is used to characterize the trophic status endpoint by providing estimates of phytoplankton biomass and serving as an indicator of aquatic productivity in the Great Lakes. Because of the large area and complexity of the Great Lakes, this approach can only provide information for very limited areas due to cost and time restrictions.

Using satellite image or airborne spectrometer data to measure chlorophyll and turbidity has a great potential for assessing Great Lakes conditions because of the potential cost effectiveness of covering large spatial areas like the extensive coastline of the Great Lakes (e.g., Dekker and Peters 1993, Mayo et al. 1995, Zilioli and Brivio 1997). Although a lake-wide chlorophyll and turbidity database has not been established for the Great Lakes, several efforts have been carried out in the Great Lakes region and on the Great Lakes.

Warrington et al. at Michigan Technological University (http://www.geo.mtu.edu/great_lakes/lakersi/cgi-bin/rsi_tak/tutorial/papers/ls_5-02.pdf) studied cross-margin transport processes in the coastal margins of Lake Superior using satellite-based chlorophyll and turbidity maps from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS). They obtained chlorophyll concentrations from an empirical algorithm that is a ratio of bands 3 (490 nm) and 5 (555 nm). Validation of SeaWiFS chlorophyll indicated a linear fit of the data with R² values of 0.90; but the satellite-based chlorophyll was overestimated by a factor of 3, indicating that regional chlorophyll algorithms are necessary for the Great Lakes. Similar efforts on Lake Michigan found a good relationship between measured and remotely sensed chlorophyll a (94%); however, seasonal changes in optical, nutrient, and turbidity properties of the water resulted in changes in phytoplankton physiology and composition which impacted remote sensing reflectance and could compromise the algorithms used to calculate chlorophyll a (Bergmann et al. 2004). River outflow and nearshore erosion and suspended sediment affect nearshore turbidity and light absorbing characteristics, which affect optical properties of nearshore water and the plankton community composition and thus the ability of simple algorithms to classify all waters of the Great Lakes including nearshore zones.

The NOAA CoastWatch program has been utilizing imagery from new satellite sensors such as SeaWiFS for assessing ocean color (chlorophyll) (G. A. Leshkevich,
http://www.glerl.noaa.gov/res/Task_rpts/ 1994/cmleshk03-2.html). Since 1999, NOAA has collected optical data (using Satlantic radiometer) and water samples (to obtain chlorophyll, TSM, DOC, POC) on Lakes Superior, Michigan, and Erie to calibrate ocean color algorithms using SeaWiFS satellite data. This would lead to a remote sensing method for mapping chlorophyll distribution in the Great Lakes. The field collected chlorophyll data were analyzed and compared with output of four ratioing chlorophyll retrieval algorithms (no atmospheric effects) and output from SeaDAS processed SeaWiFS satellite data (with atmospheric correction). Based on the analysis of the measured chlorophyll data compared with the processed output from SeaWiFS data (chlorophyll algorithms and SeaDAS processing), they found that returned chlorophyll values were highly variable in time and space. This could be due to what appears to be three coastal regimes in the Great Lakes: Case I (open ocean of second order), Case II (coastal), and Case III (highly turbid) and that chlorophyll is often not the major colorant. Although atmospheric correction algorithms have been improved, it appears that the chlorophyll ratioing algorithms themselves, and not the atmospheric correction are the cause of the variable chlorophyll values (as the input remote sensing reflectance values were measured in situ and had no atmospheric effects). In an attempt to solve this problem, NOAA is exploring the use of a neural network model based on a bio-optical model, which is being used to solve a similar problem found in European coastal waters. In 2004, the CoastWatch Research and Product Development initiated three research programs including acquisition of RADARSAT SWA calibration software, collaboration with researchers at the German Aerospace Center on testing a neural net algorithm for the Great Lakes, and collaboration with researchers at the University of Toledo to develop an improved turbidity product and data base. However, most of these efforts have been focusing on Great Lakes ice measurements.

There have been considerable efforts in the Great Lakes region to use satellite imagery to measure chlorophyll $a$ and Secchi disk transparency for inland lakes. The majority of this effort has occurred in the states of Michigan, Minnesota, and Wisconsin where the majority of inland glacial lakes of U.S. are distributed. Olmanson et al. (2002) described the methods used for three major studies in the three states. These studies include: a regional-scale lake water quality assessment funded by the Water Quality Initiative of the Twin Cities Metropolitan Council; a study of cumulative impacts of land development on lakes in the north-central hardwood forest ecoregion funded by the Minnesota Department of Natural Resources; and, a tri-state assessment of water clarity as part of the Upper Midwest Regional Earth Science Applications Center funded by NASA. The studies used Landsat Multi-spectral Scanner (MSS) or Thematic Mapper (TM) data and ground-truthed results with measures of chlorophyll $a$ and Secchi disk transparency. Olmanson et al. (2002) recommended that images selected should be high quality and cloud-free from late summer index period with preference for August.

Kloiber et al. (2002) analyzed ten Landsat TM images and four MSS images of the Twin Cities Area of Minnesota for a 25-year period (1973-1998). They found that the fit of regression models for satellite brightness data and measured Secchi disk transparency decreased with increasing time window between image collection and ground observation. Use of ground data collected with one day of the image date was recommended ($R^2 = 0.86$), but windows up to seven days provided reasonable results ($R^2 = 0.72$), especially in late summer when water clarity is relatively constant. Average brightness data from at least nine pixels in the deep open area of a lake should be used to predict lake clarity, but the accuracy of the prediction did not improve much with more than nine pixels in the area of interest. A three-coefficient regression model using the TM1/TM3 band ratio and TM1 band was a consistent and reliable predictor of water clarity ($R^2$ values of 0.7–0.8). A similar relationship involving the MSS1/MSS2 band ratio and MSS1 band was a reasonable predictor for MSS data. Efforts to produce a standard prediction equation applicable to images collected on different dates were not successful, but a simple regression procedure to account for differences in atmospheric conditions among image collection dates substantially decreased the range of coefficients in the regression model.
Bauer et al. from University of Minnesota and Chipman et al. from University of Wisconsin (http://resac.gis.umn.edu/water/regional_water_clarity/content/Publications) developed an image processing and classification protocol based on a strong relationship between Landsat TM bands 1 and 3 and Secchi disk transparency for lakes in Minnesota. They applied this protocol for classifying lake clarity in west-central Minnesota and eastern Wisconsin. As part of a NASA-sponsored Upper Great Lakes Regional Earth Science Applications Center, they applied the procedure to statewide assessments of the much larger number of lakes in Minnesota and Wisconsin.

Fuller et al. (2004) described such an effort in Michigan for inland lakes. They used imagery collected by the Landsat 7 ETM+ sensor that was launched in 1999 by NASA. The Landsat 7 ETM+ sensor collects information in nine bands from 0.4-1.0 µm, in the spectral and infrared portions of the electromagnetic spectrum, on a 16-day return cycle at 30 m pixel resolution. Stepwise regression predicted field Secchi disk transparency ($R^2$ of 0.61 to 0.80) and chlorophyll $a$ ($R^2$ of 0.81). Secchi depth transparency was predicted from bands 1, 2, and 3, while chlorophyll $a$ was predicted from bands 2, 3, and 7.

Another tri-state collaborative effort is ongoing to use NASA satellite imagery to monitor lake water clarity calibrated from field measurements already being collected by resource agencies and citizen monitoring efforts (http://resac.gis.umn.edu/water/regional_water_clarity/regional_water_clarity.htm). Although no detailed information is available, a 2000 regional census of the lake clarity conditions in Minnesota, Wisconsin, and Michigan was produced.

Airborne remote sensing has also been tested for measuring lake chlorophyll levels and water transparency. Pulliainen et al. (2001) developed and tested a semi-operational approach to retrieve chlorophyll $a$ concentration from airborne imaging spectrometer data for 11 inland lakes in Finland. All their airborne imaging spectrometer data were made using a flight altitude of approximately 1000 m. Their retrieval approach is empirical and requires nearly simultaneous in situ training data on water quality for determination of regression coefficients. Their results indicated that the relationship between in situ measurement and airborne remote sensing data could be applied for lakes where no in situ data were collected in the same region. Melack and Gastil (2001) developed a methodology using airborne imaging spectrometry to synoptically measure chlorophyll $a$ concentration for Mono Lake in California. They used NASA’s AVIRIS multispectral data atmospherically corrected by applying a version of the radiative transfer model. Using a predictive equation for calculation of chlorophyll based on a band ratio of reflectances, they determined spatial distribution of chlorophyll throughout Mono Lake. Thiemann and Kaufmann (2002) also developed a method using hyperspectral airborne data to assess chlorophyll $a$ concentration and Secchi disk transparency for inland lakes in Germany. They used algorithms developed based on in situ water sampling and reflectance measurements. For Secchi disk transparency, they calculated the area between base line and the spectrum from 400-700 nm and correlated it to the Secchi disk transparency measured in situ. The chlorophyll $a$ concentration was quantified using the existing reflectance ratio at 705 and 678 nm, which had a linear relationship to chlorophyll $a$ concentration for laboratory spectrophotometric measurements. They reported that these remote estimates had mean standard errors of 1.2-1.3 m for Secchi disk transparency and of 10.2-10.9 μg/l for chlorophyll $a$ concentration.

Presently, field collected chlorophyll and turbidity data have been collected locally and are widely scattered. A Great Lakes wide database for values of chlorophyll or turbidity has not been assembled because such large scale datasets do not exist. The use of satellite image or airborne spectrometer data to measure chlorophyll and turbidity is still in the testing stage.
Riverine

Turbidity and chlorophyll \(a\) concentrations were estimated in an 80 km reach of a large river in Ohio using hyperspectral imagery (Senay et al. 2001). Using field spectral measurements to calibrate analysis, they found that a ratio of narrow bands was highly correlated with both chlorophyll \(a\) and turbidity. For water chemistry factors like turbidity, chlorophyll \(a\) and the related total suspended solids, spectral imagery is a very promising method for remotely measuring river water chemistry; however, nutrients are not directly observable in spectral imagery requiring a different approach such as modeling. Landscape modeling of nutrients has proven more effective and explained spatial variation in nutrient concentrations and loads across Michigan and Wisconsin streams. Other water quality models include the USEPA QUAL2K model that can estimate river reach nutrient concentrations, biological oxygen demand, pH, pathogens and anoxia from a one-dimensional, steady state model (http://www.epa.gov/athens/wwqtsc/QUAL2K), or the simulation model Aquatox that predicts the fate of nutrients and organic chemicals (http://www.epa.gov/athens/wwqtsc/html/aquatox.html).

Nutrients

Nitrogen and phosphorus are the most commonly measured nutrients for lakes because of their direct influences on lake trophic status. Increased nutrient concentrations is often associated with anthropogenic activities and eutrophication. Presently, nutrient concentrations are measured through field sampling and analyzed in situ or in laboratories. Although many local government agencies have monitoring programs on Great Lakes, they generally provide only local information.

Two broad-scale programs have conducted field sampling for the purpose of monitoring nutrient status and trends across the Great Lakes. One of the programs was established under the Canada-United States Great Lakes Water Quality Agreement that was first ratified in 1972 and then renewed in 1978 (http://www.on.ec.gc.ca/greatlakes/default.asp?lang=En&n=FD65DFE5-1). Under this agreement, the U.S. established a long term sampling program through the USEPA Great Lakes National Program Office (GLNPO). This program started annual monitoring of the Great Lakes in 1983 for Lakes Michigan, Huron, and Erie; in 1986 for Lake Ontario; and in 1992 for Lake Superior. This program sampled nutrient concentrations twice a year at particular depths within each of the Great Lakes. The number of stations that are sampled varies among lakes (Lake Superior = 19 stations; Lake Michigan = 11stations; Lake Huron = 14 stations; Lake Erie = 20 stations; Lake Ontario = 8 stations) (http://www.epa.gov/glnpo/monitoring/limnology/Station_Maps/stations.html). Also under this agreement, Environmental Canada has conducted open lake cruises on the Great Lakes to ensure compliance with the water quality objectives, to evaluate trends, and to identify emerging issues. Since 1974, this program has sampled 98 stations on Lake Ontario, 53 stations on Lake Erie, 94 sample on Lake Huron and Georgian Bay, and 94 stations on Lake Superior (http://www.on.ec.gc.ca/monitoring/water-quality/greatlakes-e.html). All of these stations are open water sites and are unlikely to reflect local nearshore conditions.

The other broad-scale program that has been conducted is the Environmental Monitoring and Assessment Program-Great Lakes (EMAP-GL) that was initiated in 1990. EMAP-GL was designed to periodically estimate the status and trends of the ecological resources. It provides a strategy to identify and bound the extent, magnitude and location of environmental degradation and improvement on a regional scale based on stations randomly located in the Great Lakes. A probability-based sampling design has been used in the EMAP-GL region so that the Great Lakes resources and characteristics are sampled in proportion to their areal distribution. This sampling design makes it possible to estimate, with known confidence, the proportion or amount of area having defined environmental characteristics (http://www.epa.gov/emap/html/data/greatlak/data/ sup94/station/lssta94m.pdf). Based on the limited information available, this program is carried out only at a pilot scale.
Warren and Horvan (2003) compared the data collected by the GLNPO and EMAP-GL programs from off shore Lake Michigan. They found that both programs appear to give a reasonable assessment of Lake Michigan. The differences in average values of chemical parameters between the programs are small in absolute value, although sometimes statistically significant. They recommended that for expansion of the EMAP-GL program, additional comparison between the GLNPO and EMAP-GL programs should be conducted.

Water Current Circulation

The Great Lakes internal water currents and seiches, in conjunction with water density, have important effects on planktons, fish larvae, and nutrient distribution. Although the major water movement occurs in off shore areas, such effects strongly impact nearshore habitat composition and dynamics. Long term current measurements have been made in many areas of the Great Lakes during the last several decades. The earliest direct open-lake measurements of Eulerian currents were performed by the Federal Water Pollution Control Administration in the early 1960s in Lake Michigan and later extended to other lakes. Arrays of vector-averaging current meters were first used extensively in Lake Ontario to measure open water currents. The moorings consisted of a series of current meters placed on a taut line suspended in the water column beneath subsurface floats to minimize the vertical movements of the current meters. The whole-basin current measurement program using this new technology was conducted in Lake Ontario by the International Field Year for the Great Lakes (Saylor et al. 1981). The efforts to measure whole-basin circulation were also expanded to other Great Lakes, such as Lakes Huron (Csanady 1970), Erie (Saylor and Miller 1987), and Lake Superior (Lam 1978). However, those measures are fragmented with specific local area focus and the databases are maintained by individual programs.

The most complete lake current information available is for Lake Michigan. Gottlieb et al. (1989a) placed 15 moorings in Lake Michigan from June 1982 to July 1983. The mooring were placed at the 75-m circumferential isopleth of the lake and along the transecting southern mid and northern portion of the lake. Monthly-averaged currents were measured and determined to be weakly anticyclonic during June and July, cyclonic during the rest of the year, and most intense during March. Temperatures and bidaily-averaged currents both show the effects of the vortex-mode oscillation. Gottlieb et al. (1989a) also placed an array of four instrumented moorings covering an area of 150 km² approximately 40 km offshore at depths of 5, 10, 20, 30, 50, and 100 m in eastern central Lake Michigan during May-October 1984. The current velocity data were used to compute the divergence and curl across the array area at each depth level. Two or three events of large southeastward currents, north-south alternating wind bursts, upwelled thermocline, and increased positive divergence and negative curl were observed from mid-August to early September. Gottlieb et al. (1990) deployed 8 current meter moorings in Green Bay and in the passages separating the bay and Lake Michigan, from September 1988 to April 1989 and 21 moorings from May to September 1989. Each mooring held two or three current meters, usually placed at 12 and 20 m depth and 5 m above the bottom. They found that winter monthly-averaged currents reveal a very weak and poorly defined mean circulation pattern in the bay. Monthly-averaged summer currents showed a somewhat anticyclonic circulation pattern in the southern half of the bay, and a persistent inflow below 20 m depth through all four major passages. Comparison of bidaily-averaged currents and observed wind patterns indicates that north to northeast winds create a single cyclonic circulation cell in the bay, and south to southwest winds create a two-celled pattern that has an anticyclonic cell in the south half of the bay and a cyclonic cell in the north. Low-pass-filtered currents and temperatures during July and August reveal a strong, persistent, well-defined, 8-day-long oscillation associated with seiching of the thermocline in Green Bay.

Miller (1997) characterized the currents in the nearshore region of western Lake Michigan using measurements recorded at 4 mooring sites near Milwaukee Harbor, Lake Michigan during 1993-94. They
reported that the current patterns were strongly dependent on wind direction and speed during all seasons with the most effective winds corresponding to directions with the greatest fetch. Flow was generally constrained to shore-parallel directions interspersed by periods of very weak currents. Maximal current magnitudes were generally less than 30 cm/s. Upwelling and downwelling events, a consequence of alongshore wind stress, were a regular feature, though the intensity was less than that generally observed on the eastern shore of Lake Michigan. Current magnitudes were markedly reduced when ice cover was present in the region. Cross-shore transport at the measurement sites off Milwaukee was minimal when the water mass was vertically homogenous as indicated by the lack of onshore-offshore flow. In winter, any cross-shore transport that occurred was primarily associated with flow over bathymetric features and the coastline geometry.

Presently, an integrated current database for nearshore water does not exist. Beletsky et al. (1999) modeled mean circulation maps for the Great Lakes using long-term current observations from about 100 Great Lakes moorings during the 1960s to 1980s. Based on the availability of data, they generated summer circulation patterns in all of the Great Lakes, winter circulation patterns in all of the Great Lakes except Lake Superior, and annual circulation patterns in Lakes Erie, Michigan, and Ontario. More recently, D. Schwab at GLERL has been collaborating with D. Beletsky at Cooperative Institute of Limnology and Ecosystems Research to develop and implement a Great Lakes circulation and coastal forecast system that can simulate and predict the three-dimensional structure of currents, temperatures, water level fluctuations, wind waves, ice, and sediments in the Great Lakes. They are integrating the models with the required observational data systems into a real-time coastal prediction system. The project will make the information developed from this system available in a useful format and in a timely fashion to coastal users and resource managers (http://www.glerl.noaa.gov/res/Task_rpts/1997/ppschwab01-1.html).

**Physical Habitat Complexity**

Habitat complexity can be defined by the amount and diversity of physical habitat, such as macrophytes, shoreline complexity, substrate topography (rugosity and substrate size), water depth, current velocities, and other habitat features that influence fish communities. The amount and diversity, as well as the integrity, of habitats have a direct influence on fish community composition, dynamics, and diversity (Gormann and Karr 1978). The coastal region of the Great Lakes is an interlinked shallow water system of diverse habitat types that is influenced by river flow and by Great Lakes water levels, wave and circulation.

Most studies on the relationship between habitat complexity and fish communities have been conducted in marine environments (e.g., Risk 1972, Roberts and Ormond 1987, McClanahan 1994, Beuker and Jones 1997, Ferreira et al. 2001; Johnson 2006); only limited study of the effect of habitat complexity on fish communities has been done in freshwater systems (e.g., Gorman and Karr 1978, Horan et al. 2000). Often studies only examined one or several variables out of the many components of habitat complexity and a variety of different methodologies are used in these studies. The majority of these studies only examined selected fish taxa in one habitat type. As defined in the Oxford English Dictionary, complexity “consists of many different and connected parts”. Therefore, assessing habitat complexity is a multivariate issue and many different aspects of habitat structure and composition need to be taken into account when addressing it (Gratwicke and Speight 2005). Currently, methodologies that integrate all habitat aspects into a holistic measure of habitat complexity are generally lacking for the Great Lakes nearshore system. Fisheries managers clearly need a simple, inexpensive approach that can be used to quantify habitat complexity in a range of different habitats that can be used to assess and predict how environmental change might affect fish communities.
Approaches to Measuring Riverine Complexity

Since methodologies that integrate all habitat aspects into a holistic measure of habitat complexity are lacking for the Great Lakes nearshore system, the approaches of habitat assessment systems developed for rivers may be considered when conducting assessment of Great Lakes nearshore habitat complexity. Physical habitat evaluation has been widely used as a tool for monitoring river habitat improvement or restoration, predicting potential fish presence and abundance, and identifying limiting factors. Physical habitat measurements are also used to classify rivers into similar groups for management purposes and to detect the impacts of human activities.

Many approaches have been used to summarize and evaluate river conditions after habitat data have been collected. One increasingly common and useful approach is to compute a single value that represents the condition or quality of habitat for a given river segment. Such a value facilitates spatial and temporal comparisons and communication of assessment status, and is usually generated from a habitat model or index. Those models, such as the USEPA Rapid Bioassessment Protocols (Plafkin et al. 1989), Ohio’s Qualitative Habitat Evaluation Index (QHEI; Rankin 1989), and Wisconsin’s fish habitat rating system (Simonson et al. 1994, Wang et al. 1998), are general and assess the suitability of a river segment for an entire biotic assemblage. This approach could be modified and used to integrate the many habitat components in the nearshore area of Great Lakes into a habitat complexity index to meet the management and research needs.

A number of riverine assessment protocols produce a multivariate index score that incorporates numerous habitat metrics, and thus represents overall habitat complexity. Many examples exist for wadeable rivers. The following are a select set of examples for large rivers.

The Index of Stream Condition scores habitat based on five sub-indices of hydrology, physical form, streamside zone, water quality and aquatic life measured by a macroinvertebrate indicator (Ladson et al. 1999). The index score is a sum of sub-index scores based on comparison with natural conditions using best profession judgment. Visual assessment is used for all but water quality and discharge measurements. The study reach is 5 km and stream is scored based on widths of over or under 15 m wide so this index is potentially applicable to large rivers.

The EMAP nonwadeable sampling protocol has used to conduct regional river assessments in pilot studies (Stoddard et al. 2005) using a selected and modified version of the wadeable condition indicators (Kaufmann 1999). Indicators are in two general categories: indicator of condition and indicator of stress. Specifically, data are collected for water quality, physical habitat, periphyton, macroinvertebrate and aquatic vertebrate assemblages, sediment quality and fish tissue contaminants. Habitat condition is characterized by seven physical attributes: channel dimensions, channel gradient, channel substrate size and type, habitat complexity and cover, riparian vegetation cover and structure, anthropogenic alterations and channel riparian interactions. Habitat complexity is a metric that combines measures of proportion of undercut banks, boulders, LWD, brush, and cover from riparian vegetation. These metrics are then compared to a set of reference conditions established regionally.

The Ohio EPA’s QHEI, updated in 2006, sums scores of six metrics for a final index score of stream habitat quality. The metrics include substrate type and quality, instream cover, channel morphology, riparian zone and bank erosion, pool/glide and riffle/run quality, and map gradient which sum to a multimetric index score indicating the relative quality of the stream. This apparently can be used with large rivers as boat methods and streams >30.6 m wide are listed. However, large streams of GL region are unlikely to score high since quality seems to be based on smaller, high gradient reference streams although specific reference streams are not indicated and no landscape-scale perspective is
Michigan’s Nonwadeable Habitat Index (NWHI) was developed from a statistical analysis of a wide range of habitat characteristics measured in the field and from aerial photographs. They used principal component analysis and correlation to reduce the set of measures to spatially independent metrics (Wilhelm et al. 2005). From regression analysis with stressor indicators, they chose seven final metrics that were scaled and summed to form the final index of large river habitat quality. This index is not based on a reference condition, which is difficult to define or identify in large rivers, rather it is based on primarily quantitative field measures and relationships with anthropogenic disturbance.

**Fish Habitat Classification**

Classification of ecosystems and biological communities provides a framework for grouping and simplifying systems and for increasing our understanding of complex ecosystem structure and function. Classification helps describe ecological patterns and address the causes of pattern formation, thus it must incorporate bio-physical and spatio-temporal scales.

**Riverine Habitat Classification**

No specific large river classification framework has been developed for the Great Lakes region although a number of frameworks have been developed for watersheds and stream networks for the region (Seelbach and Wiley 1997, Brenden et al. 2006b). It is widely accepted that riverine systems are hierarchical (Frissell et al. 1986, Hawkins et al 1993, Maxwell et al. 1995) and that broad-scale higher level features influence smaller local-scale features. Maxwell et al. (1995) describe the river ecosystem as a nested hierarchy in which the larger unit constrains the nested unit (e.g. watershed-valley segment-stream reach-channel unit). Geology, climate and physiography are forces organizing larger units while variations in hydrology and channel geomorphology constrain the lower levels. Other ecological theory has classified rivers on a longitudinal gradient. Classification systems like the River Continuum Theory (Vannote et al.1980) or simply stream order describe river structure and function changing from headwater to lower river in a systematic pattern that varies with physiographic region (Wiley et al. 1990). Longitudinal patterns may not help to classify large river habitat because much of the habitat variation in large rivers is lateral (Hudson et al. 1992). Lateral patterns on large rivers have been addressed by the Flood Pulse theory that addresses the importance of seasonal flood events in shaping river ecology (Junk et al. 1989, Tockner et al. 2000).

A number of hierarchical classification schemes have been developed for spatial scales from watershed through valley segment to microhabitat (Frissell 1986, Rosgen 1994, Higgins et al. 1998). Classification schemes have also been developed based on different variables or combinations of variables such as ecoregion (Clarke and Bryce 1997), hydraulics (Panfil et al. 2001), or fish (Beechie et al. 2005). Many have extensive data requirements (Seelbach et al. 1997) often from a combination of field and map evaluations across an extensive geographic range. We present below some of the classic and newer methods for riverine classification that use hydrogeomorphology, multi-scale landscape variables, ecoregion, biota, temperature and hydraulics to classify river systems. These stream network classifications may not include some key variables that influence large river habitat structure and function such as effect of Great Lakes water levels and floodplain structure and connectivity.

Several classification methods take a hierarchical watershed-valley segment-stream reach-channel unit approach to stream classification. Frissel et al. (1986) developed a nested, hierarchical classification framework to understand spatial and temporal variability in stream systems. The hierarchical system starts with stream system (watershed), the segment, reach, pool/riffle system and finally microhabitat.
They provided detailed description of the features, spatial and temporal scale and controlling variables for each hierarchical level and the variables that could be measured to identify and classify at each level. The method is aimed at 3rd order or smaller streams but they suggest that physical processes forming habitat units will be similar in large rivers but the frequencies and magnitude of events will increase. The U.S. Forest Service (USFS) describes similarly structured three-tiered riverine classification consisting of valley segments (channel hydrogeomorphology), stream reaches (uniform morphology and flow) and channel units (specific habitat and microhabitat units) (Maxwell et al. 1995). The scale of mapping is also hierarchical and ranges from identification of valley segments at map scales ranging from 1:63,000 to 1:24,000, to stream reaches delineated at 1:24,000 to 1:12,000 map scale, to channel units delineated in the field at < 10m scale.

Geomorphic patterns and processes are part of most river classification systems. Rosgen (1994) developed a geomorphic stream classification system using four variables (entrenchment, gradient, width/depth ratio, and sinuosity) to classify streams into seven categories. Within these major categories he used six substrate classifications to further classify streams into 42 major steam types. Classification variables were derived from maps (gradient, sinuosity) and field measures (entrenchment ratio, W/D ration and substrate class) with more detailed field measurements necessary for further classification. Geomorphology was the basis for Hawkins et al. (1993) 3-tiered classification system defined by observable gradients in flow and depth. This scheme was based on consensus among experienced professionals. The classification is generally for smaller rivers (< 4th order) and how this scheme would apply to large rivers is not clear since channel units in large rivers can be large and have less distinct boundaries for flow and depth gradients. Rabeni et al (2002) tested a hierarchical channel unit classification system similar to Hawkins et al. (1993), but with adaptations for low gradient rivers of the Midwest U.S. (Rabeni and Jacobsen 1993). The classification system identifies 11 types of channel units in a two-tiered hierarchy based on field observations of general flow conditions and local morphology: slow water (bluff pool, later pool, obstruction pool, and glide); slack water (forewater, nonvegetated edgewater, vegetated edgewater, and backwater); fast water (race, low-gradient riffle, high-gradient riffle). They suggest that classification systems should be specific to the region, stream types (e.g. low-gradient Midwestern streams), and organisms studied.

More recently, a hierarchical geomorphic classification was developed for 150 mi of the Missouri River using digital orthophotography (1:12,000 to 1:40,000), NED with a spatial resolution of 30 m, and supplemental geology and soils data to identify geomorphic features at the reach and segment scale (Elliot and Jacobson 2006). Geomorphic characters were digitized from map data at the 1:1,000 scale, incorporated into a GIS database, and reaches classified using cluster analysis on a key set of variables (channel width, sand bar and vegetated bare area, and number of channels). Cluster classifications were validated by examining persistence of the units over time from multiple aerial photographs. The classes generally clustered into simple and more complex, braided channels, three width classes and varying proportions of sand and vegetated bars. They identified dominant physical processes (flow types, sediment transport, erosion, accretion, and disturbance) associated with each of the four geomorphic classes. This method used a combination of deductive analysis to select river segments and statistical, inductive analysis to classify river reaches. Data were obtained from remote sensing or existing data sources, thus the method could be applicable to other large river systems.

A number of recent studies have made extensive use of multi-scale landscape databases in GIS to classify riverine systems. The approach is congruous with the hierarchical, geomorphic methods described above but provides a regional framework for examining spatial and temporal patterns of river structure. In Canada, the Blueprint for Aquatic Biodiversity project developed by a partnership of the Nature Conservancy of Canada and OMNR identified 129 types of Aquatic Ecological Units (AEC) using landscape and sample data from the Canadian Great Lakes basin (Wichert et al. 2005). They first characterized systems using coarse scale GIS data to delineate flow and estimate drainage area, stream
order, geology, land cover, gradient, and the number of dams to identify aggregation of stream segments that have common properties. These aggregations are AECs that are represented by polygons in the GIS database (1,000-10,000 km²). The TNC has developed a hierarchical spatial classification framework for freshwater habitats first conducted in the Great Lakes region but has been modified and adapted for broader application (Columbia River & Paraguay River; Higgins et al. 2005). The framework has four levels: zoogeographic (drainage boundaries: 10,000-100,000 km²), ecological drainage unit (landform, geology, and climate: 1,000-10,000 km²), aquatic ecological system (geomorphical patterns: 100-1,000 km²), and macrohabitat unit (1-10 km length). Zoogeographic units have already been mapped and the remaining units can be mapped using GIS data such as gradient, elevation, size, connectivity, geology and hydrologic regime. The choice of data and classes were based on literature review and expert analysis. In regions where GIS data are adequate, TNC has developed an automated, unsupervised bottom-up classification algorithm; where GIS data are inadequate they use a map-based, expert driven, top-down approach.

In Michigan, researchers assembled maps and relational georeferenced databases with biological data for over 675 sites into a GIS database called the Michigan Rivers Inventory (MRI; Seelbach and Wiley 1997). The MRI has been used to develop an ecological valley reach (VSEC) classification for streams in Lower Michigan using a top-down, map-based approach (termed regionalization). Seelbach et al. (2006) interpreted map data including network junctions, slope breaks, major physiographic units, change in sinuosity, local groundwater inputs, extent of riparian wetlands or valley shape to create homogeneous VSECs that were related to a set of data attributes on catchment size, hydrology, chemistry, thermal regime, valley character, channel character, and fish assemblages. The MI-VSEC system can be used as a sampling frame and for ecological assessments. A similar regional GIS framework for multi-scale landscape features in the Midwest states of Michigan, Illinois and Wisconsin has been developed as part of the Aquatic GAP program (USGS and USEPA; Brenden et al. 2006b). The GIS framework is structured around the 1:100,000 National Hydrographic Dataset (NHD) for river channels and data are organized at three spatial levels: stream reach (confluence to confluence), riparian buffer (60m) and watershed. Landscape variables occurred in preexisting datasets and included land use, climate, geology, channel characteristics, and groundwater delivery and calculated attributes such as drainage area, slope, sinuosity connectivity, and water temperature. The framework has been used to develop predictive modes for mean July water temperature and flow exceedence curves. The framework has also been used along with georeferenced biological data to conduct statewide river assessments (Riseng et al. 2004).

Several stream classification projects have used ecoregion as a basis for classification (Bryce and Clarke 1996, Clark and Bryce 1997). Landscape-level ecoregions based on landscape features expected to influence stream habitat processes in northeast OR and southeast WA were created to address habitat issues for anadromous fish. They used a multivariate, top-down approach by combining data from topography, soil, vegetation and geology to create Level V ecoregions at 1:100,000 scale. They combined hand drawn boundaries of each landscape map to develop ecoregions which were field validated and digitized into GIS. The boundaries had good correspondence with fish assemblages and a concurrent project is testing an adjacent ecoregion using fish habitat data.

Meixler and Bains (1999) present a methodology and accuracy analysis of two non-hierarchical landscape-based models of aquatic habitat classification to predict stream biodiversity. They constructed GIS databases for the Allegheny River, Fall Cr and French Cr, NY at 1:100,000 and 1:24,000 scale and developed an automated and a calibrated classification protocol. In the automatic model, riverine habitat was classified into 18 types based on combinations of 5 landscape attributes: habitat quality (3 levels of channel alteration from digital maps of land use and GIS algorithms), stream gradient (3 classes from DEM data), riparian forest cover (2 classes from land use maps and GIS algorithms), water quality (2 classes from IGS landscape model), stream size (3 classes from drainage areas). Habitat types were matched with known fish and macroinvertebrate habitat preferences. They also developed a calibrated
model that used additional GIS data (geology, PS pollution & priority waters) and data from fish collections. Automatic and calibrated models had equivalent results and correlated well with macroinvertebrate diversity but predictions at 1:24,000 scale were less accurate than at 1:100,000 scale for fish diversity.

Minns and Weichart (2006) proposed a framework for habitat classification using process driven, dynamic variables (temperature, light, motion) that will link with process based fish models (e.g. bioenergetic models). They used light, temperature and water movement as the key variables identifying critical habitat domain and provide illustrations of lake (walleye) and river (salmonids) habitat-fish linkages. They also provide illustrations of linkages between fish guilds (taxonomy, thermal, spawning, adult size) and habitat domain classifications and suggest using habitat domains to frame monitoring programs.

Nearshore Habitat Classification

Habitat classification provides a framework that integrates all dominant habitat components and links them with locations where there are distinct differences in habitat characteristics from the other locations. Nearshore habitat classification requires assembling all habitat components that are potentially important to the nearshore ecosystem. Presently, there are several on-going efforts to classify habitat in nearshore Great Lakes zone or all zones into ecological or fish habitat classes.

One of the efforts is the USGS Great Lakes Aquatic Gap Program (http://www.gap.uidaho.edu/bulletins/13/mckenna.htm). J. McKenna and his associates started with developing and testing methods on selected pilot study sites in the Great Lakes basin. Pilot sites were chosen based on the availability, extent, and quality of databases containing the required abiotic and biotic data. Initial pilot studies began in Eastern Lake Ontario and Western Lake Erie. Other potential sites will include the Les Cheneaux Islands, Saginaw Bay, and Central Lake Erie as data become available. The analysis framework is to establish a relationship between the location of biological species and the characteristics of the habitat at that location before grouping similar habitat types. This approach is different from traditional methods that classify habitats and then relate species information to these classifications. This project has begun the process of identifying candidate variables that best characterize and distinguish the coastal habitat types. These variables represent conditions in a hierarchy of spatial scales and are presumed to have significant influence on the fish assemblages found in a particular habitat. At the top-tier of the hierarchy are the individual basins of Lake Ontario, Lake Erie, Lake Huron, Lake Michigan, and Lake Superior. The division by basin allows for an ecologically significant distribution of the habitat characteristics and the standardization of processing units for subsequent data. The coastal zone has been defined using thermal regime or depth of water as the boundary between nearshore and open water. With the limited amount of temperature data available and the varying characteristics of each basin, they defined the coastal zone based on the effect of energy on the coastal sediment. For their project, the coastal zone is defined as the area from the mean lake water line to the depth of water at which prevailing wave conditions no longer rework sediment or 10 meters of water, whichever is larger. The habitat characteristics used for this project include submerged aquatic vegetation, geomorphology, geologic formations, submerged substratum, submerged slope and aspect, and circulation and currents. These are the habitat characteristics that have significant influences on the location and distribution of aquatic species. The final stages of gathering basic habitat data are being completed. Fish databases have been compiled and modeling fish-habitat linkages for each species will begin shortly. Predicted distributions and identification of distinct habitat types will follow. The resulting geographic information system will then be available for conservation analyses (http://www.gap.uidaho.edu/bulletins/13/mckenna.htm).

Another effort is the Geographic Information System for Great Lakes Aquatic Habitat by the Institute for Fisheries Research (http://www.glfc.org/glgis/glgis_user_guide.htm; Rutherford 2004).
primary objective of the project is to integrate data from each Great Lakes basin into a common database to provide an inventory of basin-wide aquatic resources. The major tasks taken include: compiling existing digital base maps and ecological classifications of Great Lakes habitats; coordinating multiple, related, ongoing initiatives to track progress; assisting where possible to remove redundancies; inventorying available data; and, performing work needed to more fully develop the overall Great Lakes aquatic habitat GIS. Rutherford and his associates assembled GIS-based habitats and classifications of aquatic ecological units to facilitate sharing of data and holistic management of the Great Lakes basin. This database and classification include map-delineated spatial units and associated habitat and biological attribute data for terrestrial, tributary rivers, nearshore, and offshore ecosystems. This system is intended to serve as a fundamental base map for landscape-scale inventory of Great Lakes Basin aquatic resources. They developed ecological units through a cluster analysis of lake-wide, geo-referenced data on relevant physical habitat variables, such as surface temperature, substrate, bathymetry, and gradient. They then conducted ecological classifications to provide a framework for investigating natural phenomena and to establish reference conditions against which change can be measured. Classifications of open-water habitats were generated for Lakes Huron and Erie (a classification of habitat in Lake Michigan was generated previously). Using physical habitat variables (i.e., substrate, surface temperature, bathymetry, slope, and circulation), ecoregions (classes) were defined using a two-step cluster algorithm and tested with discriminant analysis and biological data. Presently, the Lake Erie classification has been completed and tested with hydroacoustic estimates of fish biomass from the NOAA Great Lakes Environmental Research Laboratory. In Lake Erie, six clusters of unique fish habitat were derived. An ANOVA analysis revealed that ecoregion classes explained significant variation in the index of fish biomass. They also compared their open-water classification of Lake Erie with classifications developed by J. McKenna of USGS Aquatic Gap project for western Lake Erie, which includes the shoreline and nearshore areas, and extends out through most of the western basin. The classification results for the nearshore area are similar for both projects, suggesting that the major variables used were important in their analyses.

A third effort is the An Integrated Habitat Classification and Map of the Lake Erie Basin (http://www.glc.org/eriehabitat/description) by a team consisting of Natural Resources Research Institute (NRRI) of University of Minnesota, University of Windsor, Great Lakes Commission, and USGS. This project is developing an integrated habitat classification and map for the Lake Erie basin that can be used to assist the development of a bi-national inventory of the status and trends in the quantity and quality of habitats in the Lake Erie basin. The integrated habitat map can be used to track improvements in habitat quantity and quality resulting from preservation, conservation, and restoration efforts and to guard against further loss or degradation from land use alterations. With the assistance from a group of regional experts, the project team has identified the existing geospatial datasets within the Lake Erie basin and assessed habitat classification schemes currently in use within the basin. The classification system developed by this team is a dynamic habitat classification scheme, which is developed based on multiple integrated geospatial data layers that contain information on physical, chemical, and biological attributes within each of the natural environmental zones. This approach allows grouping of a range of physical, chemical, and biological attributes to meet the needs of a specific organism or community for a given life stage. Areas where all of these environmental characteristics intersect can be used to identify and delineate potential habitat. The project team is collaborating with ongoing habitat assessment projects in the basin, including the ongoing projects of the MDNR Institute for Fisheries Research and the USGS Aquatic GAP. The project team is developing a strategy to apply the comprehensive classification scheme to the entire Lake Erie basin, and will develop a binational habitat map data exchange website to include links to geospatial metadata and habitat coverages in the basin. One constraint of the integrated map products was that landscape classifications such as land use or wetland types were not consistent between Canada and the U.S. so the final classification was at a coarse level (pers. comm., L. Johnson, NRRI)
Integrated Fish Habitat Assessment Using Landscape Approach

The quantity, quality, and integrity of fish habitat in the Great Lakes nearshore and large river systems are determined not only by the natural landscape settings and human activities within each of the systems, but also are strongly influenced by the natural and human modified characteristics of catchments, water course network structure, and their connectivity of the systems. Additionally, the fish habitat components of the Great Lakes nearshore and large rivers are not only interdependent within the systems, but also strongly interlinked between the two systems and the other systems in their catchments, such as inland lakes, wetlands, instream and landscape characteristics. Hence, many studies have been conducted to assess multiple fish habitat components and to develop assessment strategies using water course network and watershed landscape approaches. Some of these approaches have been addressed in the section on classification so will be briefly summarized here.

Linking Nearshore Habitats with Shoreline Land Uses

The USACE has been surveying the Great Lakes nearshore areas since 2006. They have surveyed Lake Ontario, Lake Erie, Lake Huron, and part of Lake Superior in 2006, and are going to survey Lake Michigan in 2008. They are using airborne LIDAR to cover spatial areas from the water line seaward 1,000 m or to the depth of extinction of the bathymetric LIDAR with a 5-m spacing between depth measurements and from the water line landward 500 m with a 1-m spacing between elevation measurements. In addition to the LIDAR, they collect RGB imagery at 20-cm pixel resolution and hyperspectral imagery at 1-m pixel resolution over the spectral range of 380 nm to 1050 nm. From these data they will produce a number of products, including, seamless topographic/bathymetric digital elevation model, shoreline vector, bottom reflectance, bottom type, building footprints, and land use maps. These survey products will produce a database that characterizes a coarse level status of multiple physical habitats for nearshore and shoreline zones (http://shoals.sam.usace.army.mil/).

Wei et al. (2004) linked fish distributions and their associated habitats with shoreline information. They assembled data from various sources to determine the biodiversity value of stretches of Great Lakes shoreline. The fish spawning atlas was georeferenced to ecoreach (coastlines stretches with concentrations of important wetlands) and substrate type to evaluate classification of fish into habitat taxocenes. Substrate composition was from medium resolution NOAA vector shoreline data. They found that fish distribution correlated with wetland type and that coastal wetlands were preferred habitat for a majority of Great Lakes fishes.

Linking Nearshore Habitats with Watershed Characteristics

Previously discussed nearshore fish habitat classification projects have synthesized multiple nearshore habitat components based on relatively homogenous spatial units. For example, the Habitat Classification and Map of the Lake Erie Basin (http://www.gle.org/eriehabitat/description) has identified geospatial zone boundaries and linkages between those zone coverages and compiled a list of critical attributes based on physical, chemical, and biological components for each of the six environmental zones. The six habitat zones include Terrestrial (forests, woodlots, grasslands, palustrine wetlands, and agricultural fields by watershed); Coastal Margin (shoreline, water column and substrate in embayments - water depths 3 m or less); Inland Lakes and Tributaries (streams, rivers, palustrine wetlands, and inland lakes); Nearshore Open-Water (water column and substrate - water depths 3 m to 15 m); Wetlands (coastal, riparian, and palustrine wetlands); and Offshore (water column and substrate - water depths 15 m and greater). They delineated detailed watersheds for Lake Erie for both the Canadian and US sides of Lake Erie basin using elevation data and ESRI's ArcHydro data model. A total of 1,075 watersheds were delineated for streams and interfluves draining directly to Lake Erie and Lake St. Clair. These watersheds were ordered from west to east allowing them to be agglomerated to represent larger drainage areas. Lakeward habitat zones and associated habitat components were analyzed and classified.
Wichert et al. (2005) identified 129 types of Aquatic Ecological Units using GIS and samples data from the Canadian Great Lakes basin. They first characterized the systems using coarse scale GIS data to delineate flow and estimate drainage area, stream order, geology, land cover, gradient, number of dams to identify Aquatic Ecological Units (1,000-10,000 km²) that represent polygons of Great Lakes coastal areas, inland lakes, wetlands or aggregation of stream segments that have common properties. Each unit was defined by levels of coarse scale classes. Biodiversity targets were identified using biological species and distributional data.

**Linking Components of River Network**

Fausch et al. (2002) developed a riverscapes model that incorporates the complex relationships between lotic habitat and fish life histories by including the spawning, feeding, rearing and refuge habitat in the spatial design of river study. They defined three elements for the new approach: 1) spatially explicit and georeferenced studies; 2) intermediate scales of habitat evaluation that encompass fish life history habitats (walking or low-altitude flights of 1-100 km segments); and, 3) top-down hierarchical approach. They concluded that collecting continuous data at coarse spatial scales is necessary to understand fish habitat use at different life stages and their distribution patterns. They related their approach to research on the patchy nature of stream habitat and on fish dispersal to those habitat patches. They recommend multi-scale, nested sampling design and trading off between high-resolution spatial and temporal scales to balance coarse, spatially extensive data with higher resolution continuous site-based data. Methods used for intermediate spatial extent include aerial infrared videography for temperature, side-scan SONAR for fish distributions, and GIS for visualizing data at multiple scales, as well as labor intensive field techniques such as walking or snorkeling the stream length. Coarse scale data is essential for understanding which scales are of interest and important to fish. They also note that methods that predict local fish abundance from microhabitat studies may miss important processes at the scale at which fish use habitat.

**Linking River Habitat with Watershed Characteristics**

Molnar et al. (2002) proposed a framework for an integrated modeling system based on linked models of hydrology, hydraulics, sedimentology, and ecology in a catchment framework. The modeling system included: 1) hydrologic models which were physically based distributed runoff models to estimate the spatially and temporally variable runoff production driven by landscape variables such as climate, topography and land use; 2) hydrodynamic stream flow routing models that routes the runoff into channels through the system; 3) a sediment transport model that estimates the spatial and temporal flux of sediment; and 4) an ecosystem dynamic component for assessing river quality such as models that map hydraulic habitat suitability. The main obstacle of this study was that component models at catchment spatial and temporal scales have rarely been developed and the authors did not define clearly ecosystem dynamics components.

Panfil and Jacobsen (2001) studied the relationship between landscape physiography, land use, and stream habitat conditions on the Buffalo and Current River ecosystems in the Ozark ecoregion. They measured habitat conditions basin-wide using GIS, NAWQA protocol for reach scale measurements, and georectified aerial photos to map gravel bars to estimate gravel transport. They found that channel morphology, habitat distribution and substrate characteristics were more related to physiographic conditions but that within physiographic groups, land use disturbance (cleared land and pasture) had subtle influences on habitat conditions due to increased erosion and sediment supply, including increase in finer particle sizes and decrease in pool depths.

The Michigan Rivers Inventory used a top-down, map-based approach to classify ecological stream segments (Seelbach et al. 2006). This system has been used to develop a suite of landscape-based
statistical models of storm flow, thermal regime, fish assemblage targets and ecological status. Brenden et al. (2006b) further improved this database by including all rivers and streams in Michigan, Illinois, and Wisconsin. They developed a regional framework for multi-scale landscape features. The GIS framework is structured around 3 spatial levels: stream reach (confluence to confluence), riparian buffer (75 m on each side of the stream), and watershed. Landscape variables were captured from preexisting datasets, which included land use, climate, geology, channel characteristics, groundwater delivery. They calculated river network attributes such as drainage area, slope, sinuosity connectivity, and stream order. They also modeled July mean water temperature and annual flow exceedence for all the streams. Landscape attributes were also used to classify riverine habitat on the Allegheny River, Fall Cr and French Cr, NY and used to predict stream biodiversity (Meixler and Bain 1999).

Gergel et al. (2002) reviewed existing methods that have been used to assess riverine habitat and compared them to GIS-based landscape indicators of riverine quality. Traditional habitat methods included instream flow methods (historic flow, hydraulic methods and instream habitat assessment) and physical habitat measures (River Habitat survey, USEPA Rapid Bioassessment Protocol, Index of Stream Condition). The physical habitat methods involved field and map measures including channel morphology, substrate, gradient, banks, in-stream cover and typically resulted in classes of habitat quality. While physical habitat measures can provide long-term assessment of geomorphic changes they are labor intensive due to the many spatial scales of interest and the measures may not be biologically relevant. Landscape indicators can be linked to other indicators via GIS, provide a direct measure of human use, and can be used across large areas; however, landscape-based approaches are limited to the map resolution and the most useful scale of interest has not been established.

**SUMMARY OF HABITAT METHODS REVIEW**

We reviewed 305 studies and interviewed 44 researchers at 25 organizations (agencies, universities or businesses) by telephone or email about work efforts that pertained to fisheries habitat assessment in nearshore or large river habitats. Of those, 171 pertained to rivers, 141 to large rivers and 126 were nearshore studies or protocols. Of the total 282 studies, 115 were focused on the Great Lakes ecosystem; 37 of those pertained to large rivers, 84 to nearshore and 6 to both nearshore and large river studies or protocols (Figure 2). We also conducted numerous web-based database searches and visited over 200 web sites pertaining to riverine, nearshore, and coastal wetland habitat assessment. A digital database detailing the reviews and interviews accompanies this report (Appendix). While our review of methods could not be considered exhaustive and there are likely biases in the survey, it seems clear that relative to areas outside the Great Lakes, large rivers in the Great Lakes region are understudied. Noticeably there were fewer classification, mapping, inventory and monitoring studies for large rivers than for nearshore zones and only one large river restoration study compared to 13 for the nearshore (Figure 3). In the following sections we identify those protocols and technologies that show most promise for habitat studies in the coastal rivers and nearshore zones of the Great Lakes. We also identify areas where there are substantial gaps in our data and knowledge of Great Lakes coastal systems. We focus first on applications for river systems followed by nearshore systems.

**Large River Methods: Summary and Evaluation**

We reviewed 37 Great Lakes large river systems studies (Figure 2). These included studies of the St Mary’s, Detroit River, and St. Lawrence Seaway connecting channels. Ten of the studies primarily employed primarily field survey protocols with GIS to identify sites or map field data: four of these were large river sampling protocols from state or federal agencies; two were studies of sampling design, and two were studies of specific reaches. The remaining studies involved a combination of field-based
methods, GIS, aerial photos, airborne spectral imagery, SONAR, ADCP, and model approaches. Approximately 90% of the studies used GIS to aid in mapping, to summarize multi-scale landscape characteristics, and to georeference datasets. Nearly all recent studies include GPS to georeference data. The most common habitat variables measured in these large river studies were substrate (15), velocity or discharge (14), depth or bathymetry (15), temperature (11) and landscape indicators (13). Temperature was most commonly measured as surface water temperature. Most commonly measured landscape indicators were watershed scale variables such as land use/land cover, geology, slope or elevation.

Field survey protocols typically measured common habitat variables: channel depth, discharge or velocity, relative abundance of substrate, aquatic vegetation coverage, and amount of LWD. Habitat variables were measured using a variety of standard field equipment such as current meters, underwater cameras, depth sounders, laser distance finders, and visual assessment. Collection methods were very time and effort intensive and provided limited spatial coverage. However, these surveys are an integral part of state and federal agencies’ monitoring programs accompanying biological sampling and provide data that could be used to calibrate and validate other studies. Unfortunately these established field habitat protocols lack consistency in terms of variables measured, analytical procedures used, and reported metrics. Such differences limit the integration of data from various sources and prevent the use of meta-analyses for studying large regional patterns. Another issue is the relatively poor coverage of Great Lakes rivers by federal programs. Since large river protocols are in their infancy in the Great Lakes region, we suggest a standard set of variables, measurement protocols and metrics be identified to encourage broad scale analysis and utility of the field measurements in calibrating and validating other methodologies. To date, the most mature large river field method is the MDNR SSTP protocol, which could serve as a model for other Great Lakes state agencies.

There are a number of technologies that can be used to map, inventory, classify and assess riverine habitat. These include SONAR with supervised classification or visual interpretation, ADCP, aerial photography, airborne multi- and hyper-spectral imaging, airborne LIDAR, satellite spectral and radar imaging, and various modeling approaches.

Side-scan SONAR has been used successfully to collect bathymetry and substrate data in large rivers of the Great Lakes. Sonar data can be processed manually or using automatic supervised classification algorithms such as RoxAnn and then interpolated across the study reach to provide complete attribute coverage. Side-scan SONAR is a proven, cost and time efficient technology for mapping river depths and classifying substrate and may be the best method in large rivers where moderate turbidity limits the use of spectral or laser imagery for bathymetry and substrate data collection. A high quality side scan sonar system could cost between $60,000 and $100,000 and a seabed classification could cost around $60,000 (1997 figures).

ADCP is a new technology that has been effective in measuring discharge and hydraulic variability in rivers although it has not been used extensively in Great Lakes riverine ecosystems. This technology is promising because it can be used to simultaneously measure flow velocity gradients, bathymetry, substrate roughness, bed movement, and discharge during one field visit to multiple locations. ADCP can be used for real-time current monitoring, current and river surveys, and long-term autonomous deployment. The main disadvantage is the initial capital investment for purchasing the equipment, training, and maintenance. An ADCP unit costs around $30,000 but would require additional accessories to be field ready for a total final cost of $50,000 for a field ready unit. For shallow water, boundary layer measurements a Pulse Coherent ACDP would be needed for an additional $30,000.

LIDAR in combination with hyperspectral and multispectral imagery has been used in the Great Lakes region to measure depths and classify substrate in the clear waters of the nearshore zone. LIDAR and spectral light wave penetration is limited by water clarity and large river turbidity would limit the
application of this technology to clear water rivers. LIDAR is a promising technology for surveying riverine floodplains using the infrared beam of LIDAR to map elevations at low flow and identify side channels, backwater, and other water features. The benefits of using LIDAR include broad coverage, cost effectiveness, and high resolution elevation data. One approach would be to leverage the current USACE Coastal Mapping Program of nearshore zones to include some riverine floodplain areas.

Airborne multispectral including infrared imagery has successfully been used to map groundwater intrusion, surface water temperature, chlorophyll \( a \) and turbidity, and water depths in rivers. Benefits of multispectral imagery include broad spatial and temporal coverage, concomitant reduction in field work, and standardized and comparable data. Disadvantages include cost of imagery, inability to penetrate riparian vegetation, inability to penetrate cloud cover and atmospheric precipitation, and difficulty in penetrating turbid water. An attractive new application is the combination of multispectral data with velocity measurements collected concurrently using an ADCP and high resolution DEM to map velocity-depth classes over a range of hydrologic conditions. A preliminary examination of the hyperspectral imagery of the lower Muskegon River from 2004 suggests that both depths and velocities could be obtained for much of the river within the image (Figure 5; pers. comm. Dr. R. Hauer, University of Montana). For fine resolution classification (5-10 cm), airborne multi- or hyper-spectral imagery would be needed, but for more coarse-grained classification (8-9 m\(^2\) e.g. shallow/slow, deep/fast) satellite multispectral imagery such as QuickBird could be used. An advantage of QuickBird imagery is that it is supplied georectified and stitched. Both QuickBird and hyperspectral airborne imagery costs are relatively expensive.

Satellite SAR interferometric radar, which uses the Doppler effect and the dielectric constant of materials to estimate change in elevation and water levels, has been used to map floodplains, measure flood extent, assess change in channel morphology and floodplain topography following a flood event, and to remotely measures discharge in hard to access rivers. SAR radar could be a valuable tool for studying inundation patterns and habitat types in large rivers and floodplains which in turn provides information on connectivity, complexity, and the availability, accessibility, and suitability of floodplain habitat for fish with changes in river hydrology and Great Lakes water levels. SAR data is generally relatively coarse (30 m pixels) but could be combined with LIDAR surveys to provide high resolution elevation data.

Models that can provide high resolution simulations of hydraulic conditions across a range of flows are critical to understanding the spatial and temporal variability of depth and velocity gradients, key components of riverine fish habitat. Linking models that predict habitat variability to fish energetic and population models is essential for understanding how riverine habitat influences the productivity and diversity of the Great Lakes fishery. Currently the MWRP has developed a prototype of a linked hydrologic-hydraulic-habitat-fish energetics modeling system. Application of this type of modeling system across Great Lakes coastal rivers is limited by the current lack of essential data.

One very promising approach to collection of high resolution data for multiple parameters is the use of multiple sensors on either boat-mounted or stationary systems. A boat-mounted system could be used to make periodic measurements of channel habitat parameters at multiple locations. Boat-mounted systems could include side-scan sonar, ADCP, sub-bottom profiler, DGPS and on-board computers for collection of georeferenced and synchronous data on channel bathymetry, substrate, sub-surface profiles, velocity profiles thus detailed hydraulics, discharge, and substrate stability. Stationary systems could collect real-time monitoring data from multiple sensors including pressure transducers to measure water levels, multi-parameter YSI meter to measure water quality and temperature, an ADCP to measure water velocities and direction of flow, and a DIDSON to monitor fish movement all linked to a land-based computer. Simultaneous dynamic habitat measures could be related to fish movement and the Great Lakes water levels. Incorporating a multiple measure stationary system in a representative set of large
rivers would provide detailed data for comparison between river systems and to explore factors that influence fish movement and habitat use. Advantages of multi-sensor systems include broad spatial coverage of locally intensive, detailed data. The stationary systems also provide real-time monitoring data that is critically needed in coastal systems. Another advantage of boat-mounted systems is adoption of an established protocol thus potential collaboration with state and federal agencies for protocols and classification algorithms. Disadvantages include investment costs of equipment, training, and maintenance.

**Gaps in Large River Habitat Study**

Given the limited number of studies in large rivers in the Great Lakes region, gaps in data and knowledge are substantial. The estuary zones of most coastal rivers are not included in the USGS gaging program. These are the areas where river stage, dissolved oxygen and temperature are most critical yet we have almost no automated monitoring in place because historically backwater effects precluded straightforward flow gauging. Improving our understanding of dynamic conditions in these coastal river habitats is critical. Both monitoring and modeling of dynamic habitat conditions in key river systems across the Great Lakes would be an important first step forward. Three areas, in particular, should receive focused attention:

1) There is a serious lack of real-time monitoring of flow and chemistry in large coastal rivers and estuaries across the Great Lakes. These data could be collected at fixed monitoring stations with multiple sensors analogous to the current real-time gauging stations. Gaging by fixed ADCP does not require stable relationships between stage and discharge. Even though backwater effects complicate discharge estimation, more traditionally equipped stations could collect stage, velocity, conductivity, temperature and even fish movement data.

2) A related but separate need is for detailed local channel habitat data including channel bathymetry, velocity profiles, and substrate composition. Data of this kind could be routinely collected using boat-mounted sensors on a set of benchmark rivers, or on rivers prioritized by the fishery value. Both types of data are necessary to inventory, map, and model river habitat access in the coastal zone ecosystem.

3) Although floodplain dynamics have been rigorously studied in tropical regions, studies of connected floodplains have rarely been conducted in the Great Lakes region. Development of better understanding as to how large river floodplains are structured, how they function in terms of Great Lakes fishes, and how off-channel diversity relates to main channel diversity may yield important information regarding fisheries management and conservation. Coastal river floodplains can be relatively inaccessible and are therefore good candidates for remote sensing and modeling. Satellite SAR radar and multispectral data could be used to monitor flood inundation and map off-channel habitat types at a coarse scale across the range of flows. For finer scale data detailing habitat types and elevations a combination of LIDAR and either high resolution satellite multispectral data (E.G. IKONOS) or airborne hyperspectral data could be collected during key discharge stages.

**Nearshore Systems Methods Summary and Evaluation**

For this report, we reviewed 84 Great Lakes nearshore studies (Figure 2). Ten of the studies employed primarily site-based field methods, including scuba, underwater video, and visual assessment, for measuring habitat. Seventeen of the studies utilized GIS either for classification, assessment of land use cover, or web-based decision system support. Eleven studies used aerial photography for the purpose of identifying vegetation, land cover, and to validate spectral-based vegetation classification. Eleven
studies used satellite-spectral imagery and six studies used airborne-spectral imagery primarily for vegetation classification and mapping. Satellite imagery used largely multispectral sensors with spatial resolution ranging from 1-4 m (IKONOS, Quickbird) to 30 m (LANDSAT). Airborne imagery largely used hyperspectral sensors with 1-10 m spatial resolution and high spectral resolution (128-228 bands). In eleven studies, LIDAR was used to measure nearshore bathymetry often in conjunction with hyper-or multispectral imagery for bottom classification. Thirteen studies used SONAR for mapping nearshore bathymetry, aquatic macrophyte, and substrate typing. ACDP was used in four studies to measure flow dynamics and gradients between nearshore and large river systems. We also reviewed a number of model-based studies ranging from theoretical/conceptual statistical models to hydraulic models for assessing physical habitat and biota. As with riverine studies, nearly all recent studies relied on GPS for georeferencing data. The most common habitat variables measured in these studies were bathymetry (44), substrate (39), macrophyte structure (35), cover (27), temperature (23), chemistry (22), landscape indicators (17), and circulation/wave action (16). Forty-four of the studies were focused on nearshore or coastal wetlands.

Many wetland inventory methods have been applied to coastal wetlands and nearshore areas of the Great Lakes. One approach has been to develop a GIS-based coastal wetland inventory and database, a bi-national effort by the Great Lakes Coastal Wetland Consortium. The database is a collection of all known data for coastal wetlands from multiple sources thus is the most complete assemblage of current data regarding coastal wetlands. However the inventory is unevenly distributed and incomplete spatially and data are of inconsistent scale, methodology and represent different frameworks. This is an important contribution to regional inventory and assessment but substantial effort is needed to update and complete the existing inventory and to address mapping, inventory, and classification of other coastal habitat areas.

We reviewed numerous examples of using new technologies in remote sensing and SONAR to map, inventory, and classify coastal wetlands. A number of approaches have been successful and are promising approaches for the Great Lakes region. High resolution satellite multispectral data (IKONOS, 1-4m pixels) with supervised and unsupervised classification algorithms has been used to map and classify coastal wetland vegetation at fine spatial scales although vegetation classes were relatively coarse due to the limited spectral bands. Both satellite (Hyperion) and airborne (Probe-1) hyperspectral data have been used more recently for high spatial and spectral resolution classification and mapping of coastal wetland vegetation, even plant species identification. The airborne hyperspectral data has higher spatial and spectral resolution and accuracy than the satellite multispectral data but is likely too expensive to use at a broad scale. Recent work has identified key bands in hyperspectral data needed for classification of coastal wetlands that will help with data volume and cost. The drawbacks to spectral imagery, especially hyperspectral imagery, are the large volume of data, cost of the imagery, geometric and radiometric processing needed before the imagery can be used, unpredictable cloud cover and water clarity, and difficulty in identifying flooded forests from spectral data. There are trade-offs between spectral and spatial resolution, cost, and spatial coverage that need to be resolved before initiating large scale mapping and inventory of Great Lakes coastal wetlands.

In addition a variety of wetland and vegetation classification algorithms have been developed for both hyperspectral and multispectral imagery. Both supervised and unsupervised maximum likelihood algorithms are commonly used. More recently algorithms like the Spectral Angle Mapper and techniques such as derivative spectral transformation and matching and mixed pixel analytical procedures have been developed to classify features. Identification of the optimal remote data and classification procedures for broad-scale mapping and classification of coastal wetlands is an important next step.

Methods developed recently in the Great Lakes region have combined satellite radar SAR and multispectral data to map and classify coastal wetlands with good accuracy and moderately coarse resolution (30 m pixels). Bourgeau-Chavez et al. (2004) developed a set of three methods using JERS-1
SAR, Landsat, and land cover maps to map coastal wetland units with higher level of precision. They used a combination of multitemporal Landsat images and land cover map to develop change detection techniques that would be a cost-effective method of inventorying wetlands depending on that availability and resolution of land cover maps. They combined radiometric and categorical detection techniques to reduce errors due to noise or improper cover type labeling. This method could be used in combination with higher resolution hyperspectral or field data to further evaluate targeted areas that have changed. They also developed methods to map inundation in coastal wetlands using multitemporal SAR images and threshold algorithms. The ability to detect flood inundation would be an asset to both coastal wetlands and floodplain mapping, especially flooded forests. And finally, they combined classified maps from multiple SAR sensors (L-band and C-band) and multispectral Landsat data to provide finer resolution and wider range of wetland mapping and classification and delineation of inundation boundaries. These methods are very promising and have the potential to provide the broad spatial coverage needed for Great Lakes nearshore and coastal wetland inventory and identification of critical habitats. Satellite data may be limited due to rigid satellite tasking but radar and Landsat data are less expensive than higher spatial resolution data and the methods above are efficient, taking between 9 and 26 hours per scene (80-100 km) to process, classify and validate.

Sonar, most commonly side-scan SONAR, is a proven technology for mapping nearshore bathymetry, substrate, and macrophyte vegetation and has been used at multiple locations in Great Lakes nearshore regions. Both manual and classification algorithms such as RoxAnn have been used to classify and map substrate with good accuracy. More recent applications have incorporated real-time GPS with SONAR and integrated the data into GIS. Sonar is also largely unaffected by moderate turbidity but can be limited by dense submergent vegetation for bathymetry and substrate mapping. Multiple beam SONAR has also been used for high resolution bathymetry and substrate classification although it is less cost-effective due to the high initial cost of the multiple-beam sensor. Although side-scan SONAR and related acoustic techniques have improved the resolution and efficiency of collecting bathymetry and substrate mapping relative to direct observation, this technology would not be cost-effective for inventory and monitoring across the entire Great Lakes nearshore zone.

The most recent efforts to collect bathymetric and substrate data have combined LIDAR and hyper- or multispectral surveys of coastal regions as part of the Coastal Mapping Project (CMP; USACE). These data will provide accurate bathymetry and bottom classification and mapping up to 1 km lakeward at 5-6 year return intervals. The products from these surveys will include nearshore bathymetry at 5 m intervals, bottom classification, shoreline boundaries, and land use classification up to 500 m inland. All the data will be available free to the public either as raw data or already processed and classified. These maps of nearshore bathymetry and substrate with repeated coverage have been identified as a need by many researchers in the field and will be important for identifying critical habitat and evaluating change in nearshore habitat. Drawbacks of the CMP are that only U.S. coasts are being surveyed and the surveys only extend 500 m inland. Many coastal wetland systems that provide complex and critical fisheries habitat to Great Lakes fish occur in embayments and large wetland complexes that are connected to the Great Lakes whether continually or periodically. Regular LIDAR and hyperspectral surveys of Great Lakes coastal wetlands would provide the needed resources that could be used to inventory, classify and assess coastal wetlands with a high level of accuracy. Negotiations with the USACE could identify key areas for more complete coverage of coastal wetland that extend landward from the shoreline. In addition, negotiation and coordination between U.S. and Canadian agencies to provide similar coverage of Canadian nearshore zones would provide coverage for a complete inventory and assessment of available fish habitat in coastal zones. The Canadian Georgian Bay of northern Lake Huron and northern Lake Superior are primarily pristine nearshore habitats. Inventory and assessment of these pristine habitats will help tease apart the effects of water levels changes and global climate change from other anthropogenic impacts.
Using satellite or airborne spectral images to measure chlorophyll and turbidity has great potential for assessing nearshore Great Lakes productivity and water quality due to the cost effectiveness of large spatial coverage. Satellite based Sea-Viewing Wide Field of View Sensor (SeaWiFS) imagery has been used at scattered locations in the Great Lakes to develop relationships between water color and chlorophyll a (measure of productivity) with limited success. Processing images for the Great Lakes is more challenging because different coastal regimes require unique processing algorithms. Efforts to improve this technique are in progress and should be encouraged.

Another area of importance is the effect of lake circulation patterns, seiches, waves, and water levels on nearshore zones. Currently a collaborative effort has been initiated to develop a Great Lakes circulation and coastal forecast system to simulate and predict the three-dimensional structure of water currents, wave action, water level fluctuations, and temperature (USGS GLERL, NOAA/UM CILER, and MDNR IFR). This database will be an important contribution to the understanding of how the dynamic patterns of water current and levels might affect near shore habitats. In addition NOAA currently operates a Great Lakes Observing System which is a series of stationary instruments that measures water currents, velocities, levels, and water temperature. These instruments are primarily located off-shore. Installation of additional stationary instruments in nearshore zones to measure circulation patterns and water levels would provide data needed to describe complex dynamics of waves, seiches, currents, and water level changes in nearshore zones. These data will become even more critical as we attempt to understand, predict, and adjust to the effects of global climate change on the Great Lakes and particularly on fish habitats. Certainly, one of the most susceptible areas of the Great Lakes will be the nearshore zones where changes in water levels will impact habitat structure, temperature, and effects of waves and currents.

Gaps in Great Lakes Nearshore Habitat Study

While many more studies have been conducted in the Great Lakes nearshore zones than large rivers, because the nearshore zone is so large, existing data coverage is scarce and geographically scattered. No comprehensive survey of bathymetry, substrate and vegetation within the Great Lakes has been conducted. Many tools have been developed by a number of researchers, but application of these tools has been limited primarily due to lack of institutional and financial support. Technology and methodology to conduct a systematic program to map, assess, and classify nearshore zones and coastal wetlands are currently available. What is lacking is a consistent approach to large-scale mapping and inventory. We have identified four areas where substantial data gaps exist.

1) High resolution bathymetry and substrate mapping are needed for assessment and protection of critical fisheries habitat in the nearshore zones of the Great Lakes. Existing bathymetry and substrate data are available for the entire Great Lakes but at very coarse resolution and for isolated locations at a fine scale. The current Coastal Mapping Program (USACE) will provide the bathymetry and bottom classification that is needed for the U.S. nearshore Great Lakes and will be free to researchers and agencies. Coverage of the Canadian nearshore zones, however, is very limited. This is a critical gap given that large segments of the Canadian shoreline contain pristine nearshore and coastal wetland habitat.

2) Spectral and radar imagery, both satellite and airborne, is being used to classify and map coastal wetlands and wetland vegetation in the Great Lakes but spatial coverage has been relatively sparse. Exploratory methods that combine SAR and multispectral satellite data have successfully been used to map and classify a broad range of wetland types and water levels in coastal systems. These methods provide broad spatial and temporal coverage, both seasonally and annually, which is lacking in current coastal inventories. This data would also provide an opportunity to evaluate connectivity between nearshore zones, coastal wetlands and large river mouths which is substantial gap in our study and approach to Great Lakes coastal systems. Finer scale mapping and classification of coastal wetlands has
been successful using satellite multispectral data (1-4 m pixels). While spectral imagery is limited by cloud cover, cost, satellite schedules and tasking, and preprocessing, it can provide the finer scale analysis of the structure of targeted systems and is likely the scale of data needed for process-based models used to predict habitat responses to changes in regional or global level climate, water levels and development. Analyses that evaluate seasonal connectivity in conjunction with remote estimates of productivity could help identify critical habitat for spawning and nursery, evaluate the relative constraints faced by adfluvial fish, and help identify the reasons for reproductive constraints.

3) Further research is also needed to develop methodology to use imagery such as SeaWiFS to estimate productivity, turbidity and water quality of the coastal zones. This technology has been very useful in marine systems and for smaller inland lakes. Efforts to develop this technology should be supported and applied seasonally across the Great Lakes near shore and open water zones to better understand the flux of nutrients and materials between open water, nearshore and riverine systems.

4) A uniform approach to classifying and mapping coastal habitats needs to be developed. An operation GIS-based classification system would allow researchers and managers to conduct systematic stratified surveys and select representative systems for further, detailed study. We suggest (below) a Great Lakes Coastal Habitat Assessment Framework that links nearshore, coastal wetlands and riverine systems based on functionally connectivity and material flux. This framework would be supported by a GIS database attributed with geologic, hydrologic, connectivity and physiographic factors needed for unit description and classification.

GREAT LAKES NEARSHORE AND RIVERINE HABITAT ASSESSMENT FRAMEWORK

The Great Lakes system consists of offshore areas, nearshore areas, connecting channels, large rivers, inland watercourse networks and their contributing basins. The nearshore zones of the five Great Lakes can be viewed as five hollow donuts comprising the periphery of the lakes (Figure 4). The connecting channels, including the St. Marys River, St. Clair River, Detroit River, Niagara River, Welland Canal, and St. Lawrence River, link the doughnuts into a single shallow water system. The large rivers of the Great Lakes can be depicted functionally as the trunks of trees that deliver nutrients to the shallow near shore zone from roots embedded in terrestrial landscapes. They supply coastal systems with water, sediment, and other organic and inorganic materials. The branching inland river networks of riparian and floodplain zones, connected inland wetlands, and lakes are linked to the nearshore zones and coastal wetlands by the rivers and their hydrologic, biologic, and material flux, forming a large interlinked ecosystem.

Within the Great Lakes regions, total nearshore surface area has been estimated to range from 20,000 km² (assuming that the late summer thermocline intersects the lake bed at 9 m) or 67,000 km² (assuming that the late summer thermocline intersects the lake bed at 27 m). Total surface area of coastal wetlands is estimated at 1,700 km². Total surface area for contributing basins is estimated at approximate 522,000 km². Additionally, the system has 430 km of connecting channels, 23,104 km of large rivers, and 414,267 km of tributaries. All the components of this system are relatively shallow and easily traversed by fishes and other organisms, and therefore, comprise a kind of ecological corridor through the Great Lakes system. The speed of penetration by zebra mussels and other invasive species from lake to river and vice versa demonstrate the connectivity and influence of these interlinked components.
Traditionally, inventory and assessment of Great Lakes nearshore and large river habitats have been driven by local issues and have focused on a single system component often because of resource and technical limitations. The result has been a set of local datasets largely collected using inconsistent methods across the Great Lakes system and mostly unavailable or unknown to all but those who collected the data. Although these data provide the most detailed site-specific habitat information and are still the predominant data available today, these data are not being used for conducting lake-wide or basin-wide analyses, especially for assessing habitat losses and gains.

More recently, several efforts have been made to assemble and assess a single component of the system at the Great Lakes basin-wide scale or integrated multiple system components at one or multiple Great Lakes scales. One example is the bi-national Great Lakes Wetland Consortium. This inventory was built upon the most comprehensive coastal wetland data available at the time. This database includes both point and polygon coverages with associated attributes, which provides a standard reference for the coastal wetland communities and a temporal snapshot of wetland distribution by types (http://www.glc.org/wetlands). However, as previously stated, even this dataset is unevenly distributed and incomplete spatially and the data are at different scales and were collected using different frameworks and methodologies.

Examples of integrating multiple system components at one or multiple scales in the Great Lakes basin include: 1) the Great Lakes Aquatic GAP program initiated by the USGS (http://www.gap.uidaho.edu/bulletins/13/mckenna.htm); 2) the Geographic Information System for Great Lakes Aquatic Habitat by the Institute for Fisheries Research (http://www.glfc.org/ggis/ggis_user_guide.html); and, 3) the Integrated Habitat Classification and Map of the Lake Erie Basin by a team consisting of Natural Resources Research Institute of University of Minnesota, University of Windsor, Great Lakes Commission, and USGS (http://www.glc.org/eriehabitat/description). These programs have assembled available bathymetry, substrate, geology, topography, water quality, and biological community data to conduct ecological spatial classification. Such assembled databases provide multiple integrated geospatial data layers that contain information on physical, chemical, and biological attributes. Those databases assembled from individually distributed databases have common coarser level elements that are consistent across large regional scales, which allow integrated lake-wide or basin-wide analyses using the same standard and reference criteria but lack consistent detailed data. The project teams are developing strategies to develop bi-national habitat databases, and are working toward applying their comprehensive classification schemes to the entire Great Lakes basin.

Although considerable progress has been made to inventory Great Lakes fish habitat and integrate multiple components of the system at lake-wide or basin-wide scales, lake-wide databases are still in the early phases of development. Some of the essential data are available only from limited locations, while the others are incomplete at both spatial and temporal scales. Additionally, some of the available data were collected as point data, which then could represent variously size habitat areas. In contrast, some of the other available data are gathered as polygons. The sizes of the polygons, the number of data points, or the resolution of the data representing each polygon vary considerably depending upon goals of the projects, sampling locations, and the types of sampled habitat. Such discrepancies in data spatial units and data representativeness make the merging of such databases difficult, and hence hinder the integrated analyses at lake-wide or basin-wide scales.

Based on our review of the available methods for fish habitat sampling and synthesizing databases for the Great Lakes nearshore and their associated large river tributaries, it becomes clear that we need not only to identify fish habitat sampling gaps in inventory technology and database development, but we also need to develop a database framework and classification system for fish habitat data collection, synthesis, assessment, and reporting losses and gains. The technology and database gaps have been reported in the previous sections. Below we provide an example of steps for developing such a
database framework that has been used in riverine environment. We modified the steps used in riverine environment to meet the needs of fish habitat assessment for the Great Lakes nearshore and large river systems.

**Description of a Potential Coastal Habitat Framework**

**Identify Basic Coastal Habitat (CHab) Waterbody Unit** – A basic Coastal Habitat (CHab) waterbody unit should be a spatially delimited area that is relatively homogenous in physicochemical and biological function. For example, a river valley segment was used as such a unit by the Michigan Aquatic Assessment Partnership (MAAP, Brenden et al. in 2006b) and the Missouri River Aquatic Gap Project (Sowa et al. 2004). The river valley segment boundaries for large rivers of Great Lakes in Michigan, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, and New York have already been delineated by the MAAP, which is a collaborative group led by the Institute for Fisheries Research of Michigan DNR, University of Michigan, and the Great Lakes Aquatic Gap program of USGS. For Great Lakes nearshore habitat, the unit could be a small piece of the donut of each lake defined by hydrogeomorphic properties and material flux as well as the functional scale of management decisions.

**Delineate Catchment Boundaries of each CHab Unit** – Catchment boundaries for CHab units have not been defined presently. One approach is to define the boundary of a nearshore CHab unit along the lakeshore by dividing the shoreline into segments using the previously mentioned “tree” metaphor. The “tree trunk” represents the large river segment with branching “roots” in its associated catchment. The “branches” represent the coastal area where the influences of a large river segment and its associated catchment are measurable. Such influences may be detected as lake-ward gradients in water current, sediment, nutrient, turbidity, color, water temperature, plankton composition, substrate size, bottom topography, and human footprint from the catchment. Geomorphic and climatic properties of the nearshore zone such as water depth, bottom slope and topography, groundwater influence, and amount of connected wetlands will contribute to CHab delineation as will open water lake effects such as wind and waves. By combining all these factors, it is feasible to have distinct nearshore CHab units that are different in physicochemical and biological characteristics from their neighboring units.

**Inventory, Map, and Attribute Essential CHab Elements** – Once defined and delineated, each CHab unit should be attributed with the essential habitat elements including habitat measures within the boundary of a CHab unit, factors external to the boundary of the unit that have strong influences on the habitat characteristics within the unit, and factors that measure the connectivity among factors inside and outside of the units.

The essential habitat measures within the CHab unit are the parameters that we measure traditionally, such as substrate size, bottom topography, slope, bathometry, water temperature, current, turbidity, nutrients, toxicants, dissolved metal and gases, turbidity, macrophytes, plankton, mussels, fishes, benthos, occurrence and abundance of invasive species, nearshore shoreline condition, river bank condition, river flow regime, and others. All habitat measures from a specific location whether polygon, transects, or points could be attributed to a specific CHab unit so that measured parameters are linked and their relations with measures of outside the unit can be analyzed. An important consideration in future sampling design is that the data collected from a CHab unit is representative of the unit.

The external and connectivity factors that influence habitat in the CHab unit have not been measured traditionally. External factors may include measures of local and global climate, open water conditions such as waves and circulation patterns and characteristics of river catchments such as flow discharge, thermal and hydrological regimes, sediment and nutrient regimes, human activities, and social/economic conditions. Measures of connectivity among habitats inside and outside of the units may include: type of connection to the Great Lakes; lateral connectivity between coastal floodplain and
wetland systems; distance to different types of lakes, dams, ocean, and anthropogenic connections with non-Great Lakes watercourses; measures describing riverine fish habitats, such as distance to, types, quality, quantity, and connectivity of riverine fish spawning, nursing, and over-wintering habitats; and, measures describing the distance to the major fish spawning, nursing, and over-wintering habitats within nearshore and offshore zones.

**Develop a CHab Unit Classification Framework** – Classifying CHab units into classes with relatively minimal intra-class and maximum inter-class differences in physicochemical and biological characteristics can assist effective statistical sampling design, data collection, data extrapolation, status assessment, and reporting. For example, representative data from one or several sampling points, transects, or polygons of a CHab unit can represent the condition of the entire unit; data representing a CHab unit can arguably represent other CHab units within the same class of the same Lake or large river. Therefore CHab units can be used to aggregate data or assessments at multiple scales from individual lake basin to Great Lake ecosystem.

As previously mentioned, several ongoing efforts are conducting Great Lakes nearshore and river habitat classification, and several preliminary classification schemes have been proposed. However, only the river classification schemes have been developed based on ecologically defined river segments and these schemes do not explicitly include factors such as dynamic floodplain interactions nor Great Lakes water circulation and water level fluctuations. The Great Lakes nearshore classification schemes have been developed based on equal-sized arbitrary polygon cells that do not have distinct habitat characteristics between neighboring cells, hence do not represent ecological CHab units. Because of the difference in project objectives, the proposed classification schemes are different from the on-going individual projects.

Classification schemes are often goal specific and their resolution is restricted by the availability, detail, spatial scale, and resolution of the databases. Because of the large spatial extent and the complexity of the Great Lakes nearshore and large river system, gathering high resolution fish habitat data at the individual lake or the entire Great Lakes basin scales will be extremely challenging. Therefore, the classification of Great Lakes nearshore and large rivers should initially be based on the data type and resolution obtainable from currently available data, with additional data collection to fill essential temporal and spatial data gaps. Such a classification should focus on establishing standards, criteria, and references for further data collection and synthesis at lake-wide or basin-wide scales so that status and trends of habitats at nearshore and large rivers can be assessed, losses and gains can be reported, and management activities can be evaluated. Sub-classification schemes at finer resolution can be further developed to address local or specific issues at regions where such fine-scale data are available.

**Benefits of the proposed database framework and classification system** – The proposed database framework and classification system has several major benefits: 1) the proposed database framework assigns all Great Lake nearshore and large river tributary areas into a unique CHab unit. Such a unit provides a spatial framework for assembling existing data, identifying spatial data gaps, and facilitating future statistical sampling design; 2) attributed habitat data attributed will enable description of physicochemical and biological characteristics of the unit and assessment of interrelationships among all units in the coastal ecosystem; 3) the proposed classification system characterizes similar spatial CHab units into classes that potentially represent other units within the same class. Such a classification system provides meaningful data interpretations and extrapolations; and, 4) adjacent CHab units of the same class can be aggregated into larger functional units that have distinct physicochemical and biological properties and may require unique management strategies.

The benefits of the proposed database framework and classification system have several management implications. First, using the CHab units, all agencies with Great Lakes jurisdictions can
establish common data collection standards. For example, minimum data resolution can be established at the minimum size of the unique CHab unit, and reference conditions for each class can be identified and used across political boundaries. Second, all past and present individual projects can be linked to the database framework. Research and management projects conducted in the nearshore and large river tributaries are largely fragmented and currently there is no mechanism to link them together. The proposed CHab units can be used to link such fragmented data into an integrated database at lake-wide or basin-wide scales. Third, high priority CHab units with unique or critical habitats can be identified and protected, enhanced, or restored across political boundaries. Fourth, changes in quality and quantity of critical fish habitats at a specific location can be quantitatively assessed. For example, decrease in lake level as a result of climate change will lead to alterations of nearshore habitat. The proposed CHab units can be used not only to assess total habitat loss and change, but also to identify the locations and types of habitat lost or altered. Last, the proposed database framework and classification system could provide a mechanism for linking nearshore, coastal rivers, and the dynamic land-water interface. Such a mechanism would allow the evaluation how of management activities in the upland catchment effect land-water interfaces.

POTENTIAL PILOT PROJECTS

The RFP for this research requested an evaluation of the existing technologies, methods, and protocols used to sample, measure, and monitor habitat in large rivers and the nearshore zones of the Great Lakes and to make suggestions for potential pilot projects that could be initiated to begin to address the data gaps that exist for Great Lake coastal systems. We believe the following pilot projects could significantly accelerate the development of coastal habitat inventories, assessment, and science in the Great Lakes region.

1) Methods Development and Functional Assessment Projects

Linked Radar and Multi-Spectral Sampling for Coarse-Scale Mapping and Inventory

Methods have been developed combining satellite radar and multispectral imagery to map and classify nearshore and coastal wetlands and simultaneously assess hydrologic status. We propose application of this method at a basin scale to provide needed coastal habitat inventory, and help move us towards basin-wide data acquisitions. Recent work in the Great Lakes region has identified methods that combine satellite SAR radar and Landsat multispectral data at a medium resolution (30 m pixel) to classify wetland and nearshore habitat, map the extent of inundation in coastal habitat, including riverine floodplain areas, and using multitemporal images conduct radiometric change detection analyses. This level of resolution can merge with existing land use/cover map (e.g. IFMAP) and provide an inventory of nearshore and coastal wetland boundaries, types, and seasonal water levels, as well as and the ability to track changes in land use with changes in coastal habitat units. This type of coarse inventory could also be used to help link potential changes to coastal habitat units with changes in Great Lakes water levels due to global climate change and other effects.

Leveraging USACE LIDAR Flights

Currently the nearshore zone of the Great Lakes is being flown by the USACE using high resolution LIDAR and hyperspectral imagery. We suggest a pilot demonstration project to integrate that data with additional hyperspectral data from coastal wetland and riverine floodplains to provide spatially detailed bathymetry, morphology, vegetation type, and hydrologic patterns for coastal units. The results of this effort could lead to a consensus on a classification methodology for acquisition of fine-scale hyperspectral data. Given that LIDAR is only being flown in the U.S., the pilot project needs to occur on the U.S. shore. However, we suggest that coordination with the USACE and other U.S. and Canadian
federal agencies could result in LIDAR flights of the Canadian side of the Great Lakes that include some of the most pristine sections of Great Lakes coastal system along the northern shore of Lake Huron and Lake Superior. This scale of information is essential to understand and to model the dynamic linkages between systems.

2) Detailed Analysis of Representative Complex Coastal Units

Freshwater estuaries in the Great Lakes provide a link between riverine and nearshore and offshore but are not well understood. Some current thinking suggests that some of the drowned river mouth freshwater estuaries might be bottlenecks for Great Lakes fish recruitment for fish that use the tributaries to spawn. We suggest a pilot project that combines multiple remote sensor data, on-board boat sensors, and fixed station monitoring to collect data needed to understand the functional links between physical processes, primary productivity, biological interactions (particularly predation) and their influences on adfluvial fish recruitment. On-board and fixed station data could be linked temporally and spatially with satellite sensor data to track productivity and integrate with nearshore bathymetry, substrate and lake wide circulation modeled data.

River mouth estuaries vary widely across the Great Lakes dependent upon geomorphology, climate, riverine hydrology, and development in the watershed. It is this link between the Great Lakes coastal habitat and riverine habitat that defines the Coastal Habitat (CHab) unit described above. Different types of CHab units provide different kinds of habitat to Great Lakes adfluvial fish and different habitat conditions that could inhibit or enhance fish recruitment. Therefore, we suggest several separate pilot studies conducted in different systems but all aimed to assess the dynamic habitat variability in Great Lakes freshwater estuary. An example of different types of rivers that provide important walleye reproductive habitat could include: Muskegon River (drowned river mouth wetland and lake systems, nearshore urban development), Laughing Whitefish River (freshwater estuary, pristine system), Maumee River (large river, highly developed and altered).

3) Development of Great Lakes coastal habitat database and classification framework

Fish habitat inventory and assessment in the Great Lakes region have traditionally been location and issue driven. Lake-wide and basin-wide efforts have been recently initiated, but still are narrowly focused on parts of the complex coastal habitat system. The challenge is to provide a holistic framework for assessing Great Lakes coastal habitat that can be used across multiple spatial and temporal scales. We believe it is important that those who direct and fund Great Lakes habitat inventory and assessment projects have both a conceptual model and operational GIS framework to integrate investigations focusing on various aspects of nearshore, coastal wetland and large river estuary systems of the Great Lakes. Because we will never have enough time and resources to inventory and assess such a large system for a complete picture of habitat within a relatively short time frame, we believe the development of a database framework and classification system, applied to mappable functional units is likely the most effective way to address lake-wide and basin-wide habitat issues. The database framework will allow the integration of all key habitat components for addressing lake-wide or basin-wide visionary issues, as well as provide the flexibility to incorporate additional multidisciplinary habitat components for addressing local and emerging issues. The classification system will allow the integration of spatial units in the database into larger functional units that have distinct physicochemical and biological properties where the unique management policies can be developed, the effectiveness of management activities can be evaluated, and responsibilities of different jurisdictions can be identified. We propose a pilot project to begin developing a Great Lakes Coastal Habitat (CHab) mapping and classification framework. Ultimately we envision a large-scale, long-term effort to provide a framework for future research,
management, and restoration work in across the Great Lakes coastal system. To develop such a system we can identify several key tasks:

**Delineate Coastal Habitat units**

A Coastal Habitat (CHab) unit is a spatial area linking large river, freshwater estuary, coastal wetlands, and nearshore zone into a functional unit that is relatively homogenous in terms of physicochemical, geomorphological, and biological pattern and process. Delineation of CHab units should meet the following criteria: 1) units should have relatively small intra-unit and maximum inter-unit variation in physicochemical and biological characteristics; 2) key habitat features at different spatial scales can be quantified; and, 3) the size of the units would be variable and reflect variation in scale of processes involved, but should be sufficiently large enough to constitute a rational management and planning unit. Although there are many potential ways of delineating CHab units, the pilot project should focus on developing a repeatable method that is acceptable to key users (see also pages 89-93 for more discussion).

**Integrate Available Databases, Link Sampling Locations with CHab Units, and Display the Databases Using GIS Tools**

Valuable habitat data have been collected by many agencies and research institutes over the years, and these could serve as the backbone of a Great Lakes coastal habitat database. Some of these data have already been partially assembled into lake-wide or basin-wide databases. Many of them are still in the hands of local agencies or research institutes. Once CHab river units are delineated, the next priority would be to identify, assemble, and link existing habitat data into lake-wide georeferenced databases. The critical components of such projects may include: 1) database structure that allows integration of individual lake-wide databases into regional Great Lakes basin-wide database; 2) identification of critical habitat factors predictive of overall habitat quality with an implicit capacity for quality assessment; 3) attribution of all the data assembled to the CHab units; and, 4) development of GIS tools that can display, analyze, and report on the condition of the assembled data for users.

**Conduct Coastal Habitat Unit Classification(s)**

Although many classification systems have been developed for inland lakes and rivers, very limited efforts have made for ecologically classifying integrated nearshore and large river estuary systems. In this task, we envision developing a functional classification for these coastal environments. Existing Great Lakes nearshore classification projects do not classify coastal units into distinct ecological types reflecting influences of river network, catchment, shoreline, and direct catchment conditions. Furthermore, classifications of large river units have not taken into account influences of Great Lakes water level changes, their connection with riparian and floodplain characteristics, and their importance to key migratory fishes. Because classification is often goal specific, here we suggest development of a classification framework focusing on natural factors that are not generally influenced by human activities. The key factors characterizing the classification system should include the following: 1) flexibility with respect to the kinds of fish habitat that can be summarized; 2) ability to account for the interaction among CHab units and other key environmental variables; 3) ability to represent critical habitat for both fish communities as well as to key individual species; and, 4) ability to assess habitat losses and gains.

**Establish Standards, Criteria, and References for Guiding Data Collection, Database Building, and Assessment**

Once CHab units have been delineated, data from different spatial scales have been attributed, essential habitat factors have been identified, and a fundamental classification framework has been developed, the final task would be to establish criteria-based standards to guide further data collection and database development. One important result of criteria-based standards is the ability to establish reference conditions that can be used as a standard to assess the status of other habitat in other CHab units and identify potential management actions. This part of the project would likely include: 1) determination
of the essential factors necessary for assessing the status of Great Lakes coastal habitats; 2) identification of adequate sampling techniques and data resolutions to meet the assessment needs; 3) establish expected natural habitat conditions (reference) for each habitat class; and, 4) provide a habitat status assessment for a given time period for coastal habitats, from which the trends of habitat conditions can be evaluated and habitat losses and gains can assessed.
REFERENCES


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Ostazeski, J.J. and D.R. Schreiner. 2004. Identification of groundwater intrusion areas on the Lake Superior shoreline and selected tributaries in Minnesota. Minnesota Department of Natural Resources, Department of Fisheries. files.dnr.state.mn.us/areas/fisheries/lakesuperior/groundwaterintrusion.pdf


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Rankin, E. T. 1989. The qualitative habitat evaluation index (QHEI): rationale, methods, and application. Ohio Environmental Protection Agency, Division of Water Quality Planning and Assessment, Ecological Assessment Section, Columbus, OH.


TABLES AND FIGURES

Table 1: List of examples of airborne spectral sensors including type (MS = multispectral, HS = hyperspectral, PAN = panchromatic), spatial resolution, spectral resolution, swath size, cost (where available), and a source of information about that sensor.

Table 2: List of examples of satellite sensors including type (MS = multispectral, HS = hyperspectral, PAN = panchromatic, RM = radar), spatial resolution, spectral resolution, swath size, cost (where available), and a source of information about that sensor.

Table 3: Summary of our review of large river methods by habitat variable measured. N=none, R=rare, O=occasional, C=common, M=many.

Table 4: Summary of our review of nearshore methods by habitat variable measured. N=none, R=rare, O=occasional, C=common, M=many.

Figure 1: Demonstration of linked modeling system used to predict suitable habitat for fish species in the lower Muskegon River. These components are also used in the fish bioenergetics component of the modeling system.

Figure 2: Comparison of the numbers of habitat method studies we reviewed for large rivers and nearshore zones for all regions and for the Great Lakes region.

Figure 3: Comparison of the general purpose of habitat method studies we reviewed for large rivers and nearshore zones for the Great Lakes region. Note that some studies had multiple purposes.

Figure 4: Illustration of the conceptual framework for the Great Lakes nearshore and large river linked database. The upper graphic shows a conceptual map of the linked nearshore and large river units surrounding the U.S. Great Lakes (hydrography maps not available for Canadian side). The middle graphic is an enlargement of a large river-nearshore water body unit defined by brown lines. The lower graphic is a LIDAR flight of the near shore region of this large river-nearshore unit on Lake Huron (2007) illustrating the influence of the river on the near shore structure.

Figure 5: Hyperspectral image of the Muskegon River near US 131 illustrating the potential for mapping habitat from spectral imagery coupled with concurrent velocity profiles and substrate validation.
Table 1

<table>
<thead>
<tr>
<th>Airborne Optical</th>
<th>Sensor type</th>
<th>Purpose</th>
<th>Organization</th>
<th>wavelength range</th>
<th># bands</th>
<th>ground resolution</th>
<th>Cost</th>
<th>Temporal resolution</th>
<th>Swath width</th>
<th>Source</th>
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<td>AVIRIS: hyperspectral sensor</td>
<td>HS</td>
<td>monitor and map terrestrial and coastal environments</td>
<td>NOAA</td>
<td>0.40 – 2.5 μm</td>
<td>224</td>
<td>4-20 m (depending on flight height)</td>
<td>NA</td>
<td>Flexible</td>
<td>614 pixels</td>
<td><a href="http://www.csc.noaa.gov/crs/rs_apps/sensors/hyperspec.htm">http://www.csc.noaa.gov/crs/rs_apps/sensors/hyperspec.htm</a></td>
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<td>CASI: hyperspectral sensor</td>
<td>HS</td>
<td>monitor and map terrestrial and coastal environments</td>
<td>NOAA</td>
<td>0.4-1.0 μm</td>
<td>228</td>
<td>1-10m</td>
<td>NA</td>
<td>Flexible</td>
<td>1523 pixels</td>
<td><a href="http://www.csc.noaa.gov/crs/rs_apps/sensors/hyperspec.htm">http://www.csc.noaa.gov/crs/rs_apps/sensors/hyperspec.htm</a></td>
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<td>Probe 1: hyperspectral sensor</td>
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<td>128</td>
<td>1-10m</td>
<td>NA</td>
<td>Flexible</td>
<td>512 pixels</td>
<td><a href="http://www.csc.noaa.gov/crs/rs_apps/sensors/hyperspec.htm">http://www.csc.noaa.gov/crs/rs_apps/sensors/hyperspec.htm</a></td>
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<td>Deadalus - Airborne Thematic Mapper</td>
<td>MS</td>
<td>detailed studies widely used</td>
<td>widely used</td>
<td>0.4 - 2.35 μm &amp; 8.5-13.0 μm</td>
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<td>1-2 m at 1,000 m flight ht</td>
<td>NA</td>
<td>Flexible</td>
<td>938 pixels</td>
<td><a href="http://arsf.nerc.uk/instruments/atm.asp">http://arsf.nerc.uk/instruments/atm.asp</a></td>
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<td>LiDAR: laser altimeter</td>
<td>Laser</td>
<td>topography, elevation, bathymetry</td>
<td>NOAA, ACOE</td>
<td>520 nm &amp; 1064 nm</td>
<td>2</td>
<td>3 m horiz; 0.15 m vertical</td>
<td>free for GL nearshore</td>
<td>5-6 year return cycle-Great Lakes depends on aircraft ht</td>
<td>J. Lillycrop, ACOE</td>
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<td>Aerial photography</td>
<td>MS</td>
<td>land cover, historical</td>
<td>USGS</td>
<td>3</td>
<td>1m</td>
<td>$3-30/quad file</td>
<td>varies</td>
<td>varies</td>
<td><a href="http://eros.usgs.gov/products/aerial.html">http://eros.usgs.gov/products/aerial.html</a></td>
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<td>Table 2</td>
<td>List of examples of satellite optical and radar sensors including type (MS = multispectral, HS = hyperspectral, PAN = panchromatic, RM = radar), spatial resolution, spectral resolution, swath size, cost (where available), and a source of information about that sensor.</td>
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<th>Optical</th>
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<th>wavelength range</th>
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<th>Cost</th>
<th>Temporal resolution</th>
<th>Swath width</th>
<th>Source</th>
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<td><strong>HRVIR: High Resolution Visible InfraRed camera</strong></td>
<td>MS &amp; Pan</td>
<td>topography, ecosystem monitoring</td>
<td>France: SPOT-4 satellite</td>
<td>0.61-1.75</td>
<td>2 PAN; 4 MS</td>
<td>10 PAN; 20m MS</td>
<td>60 km</td>
<td>2002</td>
<td><a href="http://landsat.gsfc.nasa.gov/about/">http://landsat.gsfc.nasa.gov/about/</a></td>
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<td><strong>Landsat MSS</strong></td>
<td>MS &amp; Pan</td>
<td>mapping land cover, water and shore boundaries</td>
<td>NASA &amp; USGS</td>
<td>0.5-1.1 µm</td>
<td>4</td>
<td>80 m</td>
<td>18 days</td>
<td>185 km</td>
<td><a href="http://en.wikipedia.org/wiki/Thematic_Mapper">http://en.wikipedia.org/wiki/Thematic_Mapper</a></td>
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<td><strong>Landsat TM: Thematic Mapper</strong></td>
<td>MS &amp; Pan</td>
<td>mapping land cover, water and shore boundaries</td>
<td>NASA &amp; USGS</td>
<td>0.45-12.5 µm</td>
<td>3 MS, 4 IFR</td>
<td>30m</td>
<td>16 days</td>
<td>185 km</td>
<td><a href="http://en.wikipedia.org/wiki/Thematic_Mapper">http://en.wikipedia.org/wiki/Thematic_Mapper</a></td>
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<tr>
<td><strong>Landsat ETM+: Enhanced Thematic Mapper</strong></td>
<td>MS &amp; Pan</td>
<td>mapping land cover, water and shore boundaries</td>
<td>NASA &amp; USGS</td>
<td>0.45-12.5 µm</td>
<td>1PAN; 6 MS; 1 Thermal</td>
<td>16 m PAN; 30 m MS; 60 m thermal infrared</td>
<td>$720/image</td>
<td>17 days</td>
<td>186 km</td>
<td><a href="http://en.wikipedia.org/wiki/Enhanced_Thematic_Mapper_Plus">http://en.wikipedia.org/wiki/Enhanced_Thematic_Mapper_Plus</a></td>
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<td><strong>MOS-1 MESSR</strong></td>
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<td>NASA (Japan)</td>
<td>0.5-1.1 µm</td>
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<td>50 m</td>
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<td><strong>MODIS: Moderate Resolution Imaging Spectroradiometer</strong></td>
<td>MS</td>
<td>meteorology, surface temperature, land properties</td>
<td>NASA</td>
<td>0.41-14.2 um</td>
<td>36</td>
<td>250-1000m available at no charge</td>
<td>1 day</td>
<td>2330 km</td>
<td>Mukhamedyarov et al. 2002; <a href="http://eros.usgs.gov/products/satellites/modis.html">http://eros.usgs.gov/products/satellites/modis.html</a></td>
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<td><strong>ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer</strong></td>
<td>MS</td>
<td>geomorphological mapping, temperature, mineral composition</td>
<td>NASA</td>
<td>2.145-2.43um spectral; 8.125-11.65 um thermal</td>
<td>5 spectral; 5 thermal</td>
<td>15m</td>
<td>60 km</td>
<td>Mukhamedyarov et al. 2002</td>
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<td><strong>AVHRR: Advanced Very High Resolution Radiometer</strong></td>
<td>MS</td>
<td>meteorology, surface temperature</td>
<td>NOAA-KLM</td>
<td>0.58-12.5 µm</td>
<td>4-6 bands</td>
<td>1.1 km</td>
<td>no charge - $190/geo registered scene</td>
<td>bi-weekly</td>
<td>2400 x 6400 km</td>
<td><a href="http://eros.usgs.gov/products/satellites/avhrr.html">http://eros.usgs.gov/products/satellites/avhrr.html</a></td>
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<td><strong>SeaWiFS: Sea-viewing Wide Field-of-View</strong></td>
<td>MS</td>
<td>monitor bio-optical properties of water bodies</td>
<td>NASA</td>
<td>0.4-8.9 um</td>
<td>8</td>
<td>1.1-4.5 km</td>
<td>1 day</td>
<td>1,500-2,800 km km</td>
<td><a href="http://oceancolor.gsfc.nasa.gov/eaWiFS/">http://oceancolor.gsfc.nasa.gov/eaWiFS/</a></td>
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<td><strong>IKONOS</strong></td>
<td>MS &amp; Pan</td>
<td>land cover mapping, habitat mapping</td>
<td>Space Imaging, Inc.</td>
<td>0.45-0.9 PAN; 0.445-0.853 MS</td>
<td>1 PAN; 4 MS</td>
<td>1m PAN &amp; 4 m MS</td>
<td>3 days</td>
<td>11 km</td>
<td><a href="http://www.eosdis.nasa.gov/crs/ps/sensors/ikonos.htm">www.eosdis.nasa.gov/crs/ps/sensors/ikonos.htm</a></td>
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<td><strong>QuickBird</strong></td>
<td>MS &amp; Pan</td>
<td>high resolution digital</td>
<td>Digital globe, Inc.</td>
<td>0.45-0.9 PAN; 0.450-0.900 MS</td>
<td>1 PAN; 4 MS</td>
<td>0.6 m PAN; 2.4 m MS</td>
<td>1-3.5 days</td>
<td>16.5 km</td>
<td><a href="http://www.digitalglobe.com/">http://www.digitalglobe.com/</a></td>
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<td><strong>ALI</strong></td>
<td>MS &amp; Pan</td>
<td>mapping terrestrial and coastal environments</td>
<td>Natural Resources Canada: EO-1 satellite</td>
<td>0.4 - 2.5 um</td>
<td>1 PAN; 9 MS</td>
<td>10 m PAN; 30 m MS</td>
<td>$250-750 per 42-185 km strip</td>
<td>16 days</td>
<td>37 km</td>
<td><a href="http://www.ga.gov.au/acs/reports/rod_ser/eo1price.jsp">http://www.ga.gov.au/acs/reports/rod_ser/eo1price.jsp</a></td>
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<td><strong>Hyperion</strong></td>
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<td>mapping terrestrial and coastal environments</td>
<td>Natural Resources Canada: EO-1 satellite</td>
<td>0.4 - 2.5 um</td>
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<td>30 m</td>
<td>$250-750 per 42-185 km strip</td>
<td>16 days</td>
<td>7.7 km</td>
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<td>JERS-1 SAR (1992)</td>
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<td>land survey, coastal monitoring, topography</td>
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<td>1 band</td>
<td>18.5 m</td>
<td>free</td>
<td>44 days</td>
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<td><a href="http://www.eorc.jaxa.jp/JERS-1/GFMP/index.html">http://www.eorc.jaxa.jp/JERS-1/GFMP/index.html</a></td>
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<td>ERS-1 SAR</td>
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<td>observe ocean, waves, ice</td>
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<td>C-band (5.7cm)</td>
<td>1 band</td>
<td>30 m</td>
<td>$525/image</td>
<td>3 days</td>
<td>80 km</td>
<td><a href="http://southport.jpl.nasa.gov/ers1desc.html">http://southport.jpl.nasa.gov/ers1desc.html</a></td>
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<td>RADARSAT</td>
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<td>C-Band (5.6 cm)</td>
<td>1 band</td>
<td>8-50 m</td>
<td>$3,600/image</td>
<td>2-5 days</td>
<td><a href="http://gs.mdacorporation.com/">http://gs.mdacorporation.com/</a></td>
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<td>RADARSAT2</td>
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<td>3-100 m</td>
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<td><a href="http://www.radarsat2.info/about/v2-6pager_marketing_6pg-web.pdf">http://www.radarsat2.info/about/v2-6pager_marketing_6pg-web.pdf</a></td>
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<td>Vegetation: radiometer</td>
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<td>wide angle vegetation monitoring</td>
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<td>X-band &amp; L-band</td>
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<td>1,150 m</td>
<td>NA</td>
<td>2,250 km</td>
<td>Mukhamedyarov et al. 2003</td>
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### Table 3


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<th>Channel Morphology</th>
<th>Substrate</th>
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**Figure 1**

**Figure 1:** Demonstration of linked modeling system used to predict suitable habitat for fish species in the lower Muskegon River. These components are also used in the fish bioenergetics component of the modeling system.
Figure 2

Figure 2: Comparison of the numbers of habitat method studies we reviewed for rivers (black), large rivers (dark gray) and nearshore zones (light gray) for all regions and for the Great Lakes region.
Figure 3: Comparison of the general purpose of habitat method studies we reviewed for large rivers and nearshore zones for the Great Lakes region. Note that some studies had multiple purposes.
**Figure 4**: Illustration of the conceptual framework for the Great Lakes nearshore and large river linked database. The upper graphic shows a conceptual map of the linked nearshore and large river units surrounding the U.S. Great Lakes (hydrography maps not available for Canadian side). The middle Graphic is an enlargement of a large river-nearshore water body unit unit defined by brown lines. The lower graphic is a LIDAR flight of the near shore region of this large river-nearshore unit on Lake Huron (2007) illustrating the influence of the river on the near shore structure.
Figure 5

Figure 5: Hyperspectral image of the Muskegon River near US 131 illustrating the potential for mapping habitat from spectral imagery coupled with concurrent velocity profiles and substrate validation.
APPENDIX

Digital Database Description

We constructed a digital database of the literature and web-based information that we reviewed and study investigators and agency personnel who we interviewed. The database includes information about the reference, the type and scale of habitat, the habitat variables measured, the methods used, the location and resolution if available, how the study related to fish habitat specifically, and finally a short summary of the reference. The database was constructed as a workbook in MS Excel with specific topic areas covered on different worksheets. Each reference has a unique ID number that links the individual references among worksheets. The Excel worksheets were imported into a MS Access database program using the unique ID to link individual references. The MS Access database can be used to select studies of a particular habitat type or method and create a spreadsheet that includes selected references and accompanying data. We have supplied both the MS Excel spreadsheets and the MS Access database with this report. Following is a more detailed description of the structure of the spreadsheets.

The database has five components linked by unique identification numbers (ID): Reference, Habitat, Method, Fish, and Method Assessment. The Habitat, Fish, and Method components are primarily a set of indicator variables to facilitate sorting and selection of particular types of studies, methods, habitats, and variables, while the Method Assessment component includes a short description of the habitat method(s) used. The Reference component (spreadsheet) includes information about the Contact Person (also first author or interviewee), the role of the contact person in the reference, co-authors, the year of the study or interview, the title and journal reference information, title of white literature, chapter, title, editors, publishers, and pages of book references, agency, web site, full reference and key words. There are also several indicator variables that can be used to select specific types of references including: peer-reviewed, journal, book, web/gray, conference proceedings, agency, interview, and review.

The second component describes aspects of habitat that were studied or measured. The first variable is an indicator variable indicating whether the study took place in the Great Lakes region. The next two variables describe the spatial and temporal extent of the study, if available. The next twelve variables are indicators variables indicating the type of habitat under study. These include large/lower river (nonwadeable), floodplain, riparian, stream (wadeable systems), lake, nearshore, open water, embayment, harbors, wetlands, terrestrial, and other. More than one habitat type may be indicated. The second set of variables includes ten indicators of habitat scales including: macrohabitat, microhabitat, mesohabitat, river reach, river valley, discrete nearshore units, Great Lakes basin, watershed, open water, and other. This part of the database was the most challenging as the scale was often not specified and the definition of various habitat scales differ between studies. Again, studies could include more than one scale. The final set of variables included 15 descriptors of the physical habitat that were measured or modeled. The set of variables include: cover, substrate, large woody debris, depth/channel survey (large rivers), bathymetry (nearshore), velocity/discharge, flooding/floodplain, channel morphology/macrohabitat, hydraulics, circulation/waves (nearshore), temperature, chemistry, vegetation structure, landscape indicators, and other. The final variable lists the physical variables that were measured or modeled in the study or methodology.

The third component of the database includes descriptors of the methods used in the study or by the interviewee. The first set of indicators describes whether the method was used or could be used for rivers or nearshore regions. For example, a number of inland or marine coastal wetland assessment methods would apply to Great Lakes nearshore surveys. The next two variables are a short descriptor of the type of method or technology that was used (e.g. GIS, SAR radar, Hyperspectral) and a descriptor of the type(s) of models used. The next two variables indicate whether the study was georeferenced and the
resolution (spectral, spatial) if that information was available. The next 17 variables are indicator
variables that describe the method or technology: field only, field component (field work was a part of the
effort), GIS component (GIS was used but not exclusively or primarily), GIS based (GIs was the primary
or exclusive method used), aerial photography, airborne spectral, satellite spectral satellite radar, LIDAR,
Sonar (includes single beam, side-scan and multibeam), acoustic Doppler sonar, ground penetrating radar,
underwater video, model-based (models were the primary method of identifying or assessing habitat),
classification algorithms (mathematical equations used to classify remote sensing or GIS data), theory
(primarily theoretical discussions, no application), and other. The next seven variables describe the utility
of the method although there was often more than one use. These categories include: mapping
(delineation of local habitat types), inventory (broad reconnaissance and mapping of habitat),
classification (assignment of habitat classes), attribution/assessment (description and measurement of
habitat characteristics and assessment of habitat quality), monitoring (measurement of change in habitat
over time or space), restoration (efforts to restore habitat to higher quality or original condition), and
other. The next four variables are short descriptors of various aspects of the methodology: purpose of
method (the overall purpose for using the method in the study), classification methods (methods used to
classify habitats), statistical methods (list of statistical methods used from simple descriptors to complex
analysis), and method validation (evidence of analysis used or data collected to validate the method).

The fourth component describes the relevance of the project to specific aspects of fisheries habitat. We
noted whether the study or method identified critical habitat or used target taxa and specific fish metrics.
We also added a column for any details describing fish-habitat linkages.

The fifth and final component is a summary of the study, method, or interview. The reviewer assessment
is a short paragraph that describes the habitat method or protocol including information on accuracy and
precision, technical descriptions of methods or tools, location and habitat information, key relevant
findings, and finally a critique of the method or technique if applicable or possible.

We have included a graphic of the structure of the database showing the various components, variables,
and overall structure of the MS Access database. The MS Access database can be used to perform
queries and select a subset of studies or interviews that are of interest, along with a select number of
descriptive variables. We have created a few queries that select large river and nearshore studies done in
the Great Lakes region.
Graphical depiction of the structure and relationships within the digital habitat database.