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Assessment and Mapping of the Milwaukee Estuary Habitat

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ASSESSMENT AND MAPPING OF THE MILWAUKEE ESTUARY HABITAT

by

Brennan Dow

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ABSTRACT

ASSESSMENT AND MAPPING OF THE MILWAUKEE ESTUARY HABITAT

by

Brennan Dow

The University of Wisconsin-Milwaukee, 2018
Under the Supervision of Professor John Janssen

Rivermouth regions such as the Milwaukee Harbor, are the habitat interface between watersheds and the Great Lakes proper, and can host a large diversity of fishes. To facilitate an ecosystem approach management strategy, I developed a layered map that includes bathymetry, side scan sonar images, shoreline substrate classifications, and initial data of aquatic vegetation and centrarchid spawning locations. The 60 km perimeter of the study area consisted of 59% hardened shoreline. Ground truthing of substrate classifications via Ponar grabs or video had about 95% accuracy for fine and rocky boulder substrates. Rocky fine was the most inaccurate classification (35%), but with the introduction of a new classification “mussels fine,” it improved to 90.8%. The Milwaukee Estuary shoreline area was dominated by fine substrate particles (69.52%), with the next most common categories being rocky boulder (10.65%) and wood/steel pilings (9.51%). Six species of centrarchids were found to reproduce at various times in five locations. Macrophytes were sampled in 28 separate locations in four pre-determined areas. Eight different species of aquatic plants were collected and identified. Likely challenges for creating a more ecologically functional harbor for fishes will be to develop nursery habitats in a significantly altered environment and enhance habitat connectivity.

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INTRODUCTION

Estuaries in the Laurentian Great Lakes have deteriorated greatly since European settlement and urbanization along the shoreline of the world's most valuable resource, fresh water (Brazner 1997). In fact, the Great Lakes make up 21% of the world's surface fresh water (U.S. EPA 2017). Included in this immense basin are more than 30 million people, which make up roughly 10% of the U.S. and 30% of the Canadian population (U.S. EPA 2017). However, with the increase of urbanization development along this shoreline, the Great Lake's coastal areas have resulted in significant loss of valuable estuary habitat (Edsall and Charlton 1997). The extent of these losses throughout the entire region are not well documented, but it is estimated that about half of the 16 million hectares of wetland habitat along the Minnesota, Wisconsin, and Michigan shoreline had been destroyed by 1980, with the loss continuing at 8,000 hectares/year (Tiner 1984; Brazner 1997). Many of these impacts brought on by human shoreline modification and settlement have provided the need for extensive, localized environmental studies (Brazner 1997; Goforth and Carman 2009).

As a result, the Great Lakes Area of Concern was created under the Great Lakes Water Quality Agreement in 1987 (IJC 1987). The Great Lakes Area of Concern was formed by the International Joint Commission to designate beneficial use impairments (BUI) in many areas along the Great Lakes shoreline that were degraded through subsequent human activities. A few of these detrimental impacts include legacy toxic sediment contamination sites, point source and runoff pollution, and physical habitat alteration by dredging, creating hardened shorelines and building dam structures (Brazner 1997; Edsall and Charlton 1997; Levin 2005; Kaeser and Litts 2010). There are a total of 14 standardized use impairments that are assessed across all designated Area of Concern (AOC) locations (IJC 1987). The Milwaukee AOC was listed with 11 out of the 14 possible BUIs (WIDNR 2014). Two of which include the degradation of fish and wildlife populations and the loss of fish and wildlife habitat (WIDNR 2014).

Milwaukee, which historically was a glacial till, multi-stemmed estuary and wetland, has been on the Great Lakes Area of Concern list as of 1987 and is currently the fifth largest city in the midwestern United States (U.S. Census 2016). In the heart of the original wild rice wetland habitat (Lapham 1846), lies the reconstructed inner Milwaukee Harbor. The inner harbor and connecting tributaries are comprised of mostly sheet piling and other types of hardened shorelines for navigational purposes. Attached to the inner harbor is the outer Milwaukee Harbor, which plays a role in sediment and nutrient loading, as well as a buffer between the turbid river water confluence and Lake Michigan. A majority of the outer harbor and south shore areas are bordered with introduced “rip rap” (i.e. variation between rocks and boulders) to break apart wave action. At many locations in the outer harbor and south shore areas, these boulders are known as armor stone ($0.11\text{-}0.28 m^3$; $2803.23 kg\ m^{-3}$). All these areas in the Milwaukee Harbor provide a unique system that supports a diverse and surprising number of fauna. Therefore, can be classified as a ‘novel ecosystem’ (Hobbs et al. 2009; Wensink and Tiegs 2016), i.e. an ecosystem with man-made structure and a mix of native and invasive species. As a result, the Milwaukee Harbor may offer unexpected habitats of ecological value and allow potential for creating and enhancing ecosystem function.

Although ongoing studies have looked at fish populations and the physical features of the Milwaukee Harbor (Holey 1984; Hirethota et al. 2005; U.S. EPA 2011; Sullivan et al. 2014), there is minimal information on where native fishes are spawning and if they have enough nursery habitat for sustaining populations. Regions similar to Milwaukee Harbor have been known to be important for the life cycles of many Great Lake fish species (Jude and Pappas 1992; Larson et al. 2013). These coastal rivermouth regions strongly influence nearshore water quality, thermal regimes, and are normally involved in biogeochemical cycling of nitrogen and phosphorus (Steinman et al. 2009; Larson et al. 2013; Janetski and Ruetz III 2015). In contrast, while the pelagic zone of the Great Lakes is becoming less productive due to invasive quagga mussels (Fahnenstiel et al. 2010), improved production and diversity can remain higher in rivermouth systems (Larson et al. 2013; Janetski and Ruetz III 2015). Despite their ecological importance, these regions are rarely the focus of a holistic approach to system-scale research and management efforts (Larson et al. 2013). As a result, urbanized estuaries act as the habitat interface between upstream watersheds and the Great Lakes proper (Larson et al. 2013).

Habitat Mapping

Fish habitat can be considered a combination of multifaceted features on both the physical and chemical level to sustain individuals and even populations (Kaeser and Litts 2010). More specifically, fish relate to habitat across a variety of spatial and temporal scales (Muller et al. 1998), from different types and sizes of habitats (Fahrig 1989; Marcus 2002; Andrews 2003; Levin and Stunz 2005; Ogdahl et al. 2010; Persinger et al. 2010; Bhagat and Ruetz III 2011). Monitoring fish habitat in wadable riverine environments normally focuses on finer scales and generates more site-specific information (Wang et al. 1996; Muller et al. 1998; Quiñones and Mulligan 2005; Firkus 2013). However, in larger, deeper and more turbid systems, these approaches become costly and may not be feasible (Newton and Stefanon 1975; Edsall et al. 1989; Nack et al. 1993; Randall et al. 1996; Creque et al. 2010; Burguera 2016).

Towable side scan sonar, while expensive, involves an underwater sensor towed from a boat which limits its use in shallow waters and locations where obstacles might be present (Edsall et al. 1989; Anima et al. 2007; Manley and Singer 2008). Side scan sonar units with boat mounted transducers have proven effective for habitat and substrate mapping at very high resolution (Kaeser and Litts 2011; Richter et al. 2016; Snobl 2016). Although, while the use of side scan sonar is becoming more popular, the technology has not been thoroughly tested as a means to characterize aquatic habitat in a Great Lakes estuarine environment.

Habitat mapping work in marine environments is generally more common, but often utilize multi-beam echo sounders (MBES) to accomplish in-depth seabed habitat surveys (McGonigle et al. 2009; Brown et al. 2011). MBES can simultaneously collect seafloor bathymetry and backscatter data to provide a multi-dimensional image, but requires complex technical support (Brown et al. 2011). In some cases, data taken can be classified by the software for separate benthic types and classifications (McGonigle et al. 2009). MBES, while pragmatic for marine environments and site-specific surveys, are often much more expensive than a high-end side scan sonar unit.

Role of Macrophytes as Habitat

Submerged vegetation is an important environmental factor for fishes in the littoral zone of lakes (Albert and Minc 2004). Macrophytes provide structure, cover from predation, and offer a feeding environment for young of the year (YOY) fishes by containing a variety of small invertebrate prey (Randall et al. 1996; Randall and Minns 2002). They are increasingly being used worldwide for the assessment of aquatic ecological condition (Albert and Minc 2004;

Ogdahl and Steinman 2014). Macrophyte growth and presence is greatly influenced by physical habitat conditions (quality of sediments, shallow water gradient, water quality and turbidity). Macrophytes have also been used as coastal indicators of shoreline restoration efforts (Levin and Stunz 2005; Ogdahl and Steinman 2012; Ogdahl and Steinman 2014). Since no previous studies have been done in the Milwaukee Estuary (Wawrzyn 2013), a list and map of existing macrophyte species through baseline surveys should be completed to assess this aspect of habitat.

Unfortunately, with only minimal information about native fish spawning activity, bottom substrate composition and macrophyte coverage in the Milwaukee Estuary, this gap of knowledge between the upstream watersheds and the Great Lakes proper will continue to exist. This lack of information limits the harbor's ability to have comprehensive fishery or habitat plans, forcing regulatory agencies to protect or develop new habitat in a piecemeal fashion. The harbor needs to function and be managed as a unit with internal biological connectivity, fostering connectivity between Lake Michigan and its tributaries. Facilitation of this requires a baseline survey to understand what suitable habitat exists and to locate possible sites for habitat recruitment.

METHODS

Study Area

The Milwaukee Estuary (Figure 1) has a perimeter of roughly 60 km of shoreline (59% are hardened shorelines), including a breakwall interface with Lake Michigan and covering a total area of 7.5 km^2. There are three tributaries (Milwaukee, Menomonee and Kinnickinnic) whose combined flow connects to the outer harbor by an engineered channel (0.6 km). The study area includes downstream of North Avenue on the Milwaukee River; downstream of West Canal Street on the Menomonee River and its canal system (South Menomonee Canal and Burnham Canal); downstream of West Becher Street on the Kinnickinnic River. Some areas are dredged for shipping and tour boats. The estuary also includes a large, semi-sheltered, south shore area. A preliminary map was constructed of this area, but was not as comprehensive as the inner and outer harbors.

Fish community in the study area consists of approximately 50 species (WIDNR 2017) with some seasonal variability related to harbor hydrodynamics, temperature, and forage availability. The most common are: Lake Michigan salmonids, Largemouth Bass *Micropterus salmoides*, Smallmouth Bass *Micropterus dolomieu*, Rock Bass *Ambloplites rupestris*, Bluegill *Lepomis macrochirus*, several other *Lepomis spp.*, Yellow Perch *Perca flavescens*, Northern Pike *Esox lucius*, Freshwater Drum *Aplodinotus grunniens*, White Sucker *Catostomus commersonii*, several species of minnows (Cyprinidae), and many other fish forage species (Alewife *Alosa pseudoharengus,* Round Goby *Neogobius melanostomus*, Rainbow Smelt *Osmerus mordax*).

Mapping Assessment

Substrate composition and presence of fish habitat was preliminarily evaluated in spring 2015 using a 10.4” Lowrance™ HDS-Gen 2 Structure Scan® sonar unit and LSS-2 transducer (Navico, Tulsa, Oklahoma), borrowed from the Wisconsin Cooperative Fishery Research Unit at the University of Wisconsin-Stevens Point. During sampling, the boat moved < 50m parallel to the shoreline and at a speed of 5 to 6.5 km/hour. The transducer provided a transmit power of

500W (RMS) and was set at a frequency of 455 kHz. Other settings were set to 71% contrast, medium noise rejection, surface clarity off, and scroll speed at normal. Sampling in the early spring (2015) allowed a clear, unobstructed, visual representation of the study area due to limited interference from vegetation.

Multiple programs were used to convert sonar files to representable data. The program SonarTRX© (Leraand Engineering Inc., Honolulu, Hawaii) was used to convert sonar files to keyhole markup language (KML) and eXtended Triton Format (XTF) files, both of which are compatible with ArcMap™ 10.4.1 (ESRI Inc., Redlands, California). These raster files were then processed as a geodatabase in ArcMap™ to generate a shoreline mosaic image of the study area; a closeup example shown in Figure 2. A bilinear interpolation resampling method and max default mosaic operator were chosen to best represent the data. ReefMaster© (ReefMaster Software Ltd., Birdham, West Sussex) was used to generate a bathymetric map of the entire study area using a newer Lowrance™ 12” HDS-Gen 3 Structure Scan© sonar unit. Attached to the unit were a transom-mounted XDCR LSS-2 side scan transducer and HST-WSBL Broadband transducer. Settings on the new sonar unit were set to the Lowrance™ HDS-Gen 2 for similar configurations. Data track lines imported on ReefMaster© generated minimum and maximum depths of 0.72m to 11.20m, respectively. Max interpolation between data points was set to 150m with a contour grid smoothing level of 20. Water depth was standardized and corrected based on a one hour resolution over the course of the study to correct for changes in lake level. Data were retrieved from the United States Geological Survey (USGS) water-stage recorder and acoustic velocity meter gage at the mouth of the Milwaukee River (Lat 43°01.467’, Long 87°53.900’). Map boundary was created and imported from Google Earth™ as a .kmz file to represent a closed loop shoreline of the study area (Figure 1). Final sonar files were uploaded to ArcMap™ 10.4.1 and MAPublisher/Adobe Illustrator to create a multi-layer “technical” and “non-technical” map for project stakeholders and the public.

Substrate Classification and Analysis

The shoreline mosaic image was layered over a basemap of aerial images taken in 2010 and obtained from wisconsinview.org. The shoreline mosaic image and aerial images were based on the Wisconsin Transverse Mercator coordinate system. Substrate classifications were grouped into seven categories based on a modified Wentworth (1922) scale (Kaeser and Litts 2010; Goclowski et al. 2013; Snobl 2016). Substrate particle size classes for five of the seven categories are as follows: fine (< 2mm), rocky fine (> 2mm and < 256mm diameter), mixed rocky (combination of two or more particle size classes > 2mm – at least one being rocky), rocky boulder (> 256mm), and woody fine (> 10 cm diameter). The remaining two categories include regions that were not boat accessible (unknown) and structures that are used for walkways and docking (wood/steel pilings). Substrate categories are further explained in Table 1. Shapefiles were manually created into color coded polygons for each category. A minimum map unit was determined to contain a 5m radius (78.54 m^2) and represented the smallest size of a polygon for any substrate category. Total shoreline area (km^2) sampled was quantified using GIS analysis and distributed into 22 different locations with a total of 496 separate polygons.

In order to evaluate accuracy of substrate allocations, 20 randomly selected polygons were chosen for each substrate particle size category. Each selected polygon was converted into compatible .gpx format through GPS Visualizer and imported into the sonar unit. A sample was then taken randomly in each polygon. Substrates were collected via micro (2.38L) Ponar grabs, measured and characterized based on substrate particle size classifications. In presence of larger particle size or shallow water, substrate was verified using an Aqua-Vu video camera or by visual inspection (boat). Two sites were unable to be sampled due to in-accessibility by private docks and shallow water; these sites were not included in the analysis. An error matrix was implemented to assess accuracy of the chosen substrate assignments by dividing total correct characterizations by the total sampling locations (Congalton 1991; Muller et al. 1998; Kaeser et al. 2013).

Temperature

Temperature loggers (HOBO Pendant Temperature 64K Data Logger) were deployed in June 2017 at six different locations: two (shallow and deep) on the inside of the breakwall near the North Gap of the Milwaukee Harbor, one on the NW side of McKinley Marina, one on the west side of Summerfest Lagoon, two (shallow and deep) at the Menomonee Canal Confluence, one in the Burnham Canal, and one near Barnacle Buds in the Grand Trunk location (Figure 4). Loggers recorded at one hour intervals to record general changes in water temperature brought on by upwelling or seiche events. Data was used in determining probable length of spawning events in different locations throughout the estuary.

Macrophyte Assessment

The aquatic plant survey of this project was conducted from July to September 2017. The initial goal of the survey was to locate and create a photographic record of large macrophyte stands throughout the study area. However, preliminary investigations noted the importance of habitat connectivity and warranted focus on specific locations. Sampling occurred in four separate areas (South Shore, Art Museum, Summerfest Lagoon and Discovery World; Figure 6) based on preliminary side scan data and observations through nursery habitat evaluations. The edges of large macrophyte stands in these areas were found with side scan sonar and sampled near the center of the stand. Rake rope surveys (Deppe and Lathrop 1992; Hauxwell et al. 2010) were conducted with a thatching rake to collect macrophytes at each location. The rake was 35.56 x 12.7 cm and had a double rake head with 19 teeth on each side. Lead weight (2.18 kg) was added to weigh down the rake with a majority of the weight coming from 1.36 kg attached to the center of the rake (Figure 3). At each sample location: four rake tosses were performed off the corners of the boat (Front Left – FR, Front Right – FR, Rear Left – RL, Rear Right – RR), boat orientation (degrees), location (decimal degrees), sediment (Muck – M, Rock – R) and water depth (meters) were recorded for every toss. After the rake was brought into the boat it was assigned a rake fullness rating from 0 to 5 and each plant was identified to species (Deppe and Lathrop 1992). Near the Art Museum, where vegetation stands were sparsely distributed, two person, 40m scuba transects were also completed to better quantify richness and abundance of plant stems. Aquatic vegetation was counted and identified one meter on both sides of the transect line and tallied on dive slates.

Fish Spawning and Nursery Habitat Evaluation

Locating fish spawning areas in such a large study area was hard to accomplish, but the preliminary side scan sonar maps facilitated locating potential spawning substrates. Originally, the goal of the project was to focus on the Milwaukee Area of Concern (AOC) four native fish indicator species: Greater Redhorse *Moxostoma valenciennesi*, Northern Pike *Esox lucius*, Walleye *Sander vitreus*, and Lake Sturgeon *Acipenser fulvescens*; however, none of which have been known to reproduce in the study area since colonization. Therefore, the project focused primarily on centrarchids, which includes a few of the fishes listed as subset AOC indicators for Beneficial Use Impairment (BUI) evaluation (Table 3). Fish that were found on nests or fish that displayed spawning behaviors were recorded with GoPro cameras from boat, scuba diving or snorkeling and generally monitored for any changes in reproductive status.

RESULTS

Mapping Assessment

Shoreline mapping via side scan took roughly 15 hours. Some sections had to be rescanned due to waves causing distortion and black striations across the image or track diversions caused by boat traffic. In some cases, a non-parallel orientation to the shoreline caused captured images to display only partial, distorted shoreline characteristics. All the data that was acquired through mapping and assessment surveys were displayed as different layers in ArcMap™ and MAPublisher/Adobe Illustrator. These layers varied between the “technical” and “non-technical” map for the selected audience (Figures 12, 13 and 14).

Substrate Classification and Analysis

Substrate composition mapped via side scan sonar was estimated to be 77.6% accurate based on ground truthing at 98 sampling locations (Table 2). The seven substrate categories worked well, however, with the addition of an eighth category that includes quagga mussels, the accuracy increased to 90.8%. Fine and rocky boulder substrates were classified with 95% and 94.7% accuracy (respectively), while mixed rocky (84.2%) and woody fine (80%) were identified with reasonable accuracy. The least accurate designations were rocky fine substrate particles (35%), which were generally misidentified clusters of quagga mussels. These were commonly located in areas where river discharge and/or seiche water flow is accelerated due to channel constrictions. Due to hardened shorelines and dredging in the lower reaches of the tributaries and harbor areas, the Milwaukee Estuary shoreline was dominated by fine substrate particles (69.52%), with the nearest categories being rocky boulder (10.65%, introduced rip rap) and wood/steel pilings (9.51%, docking and walkways) (Figure 5).

One important note is how rapidly the harbor and its tributaries can change as a consequence of large storm events. Due to these changes in the harbor hydrodynamics, large objects (i.e. trees, branches, boulders etc.) were found to move from previous locations. Therefore, we focused only on categorizing permanent substrates.

Temperature

Temperature fluctuations due to seasonal changes, and abrupt events (i.e. upwelling and seiche) in the harbor and the rest of the study area was a major driver for spawning events. Coastal upwelling affected temperatures at the outer harbor (Breakwall, McKinley Marina and Summerfest Lagoon) and inner harbor (Grand Trunk) (Figure 9). This reason for penetration as far as the Grand Trunk is most likely due to a deep channel (~10m) in the inner harbor leading up to the Kinnickinnic River where the water shallows to 7-8m. Temperature differences between these locations were typically no more than 3°C and followed similar trends from mid July 2017 to October 2017. Sporadic surface water temperature differences (10°C) at the Breakwall were due to more of an influence from lake intrusions and upwelling effects from

June 2017 to August 2017. The Burnham Canal surface water temperature logger recorded large fluctuations throughout the deployment most likely due to warm-water discharge from the WE Energies plant (Figure 11).

Macrophyte Assessment

The macrophyte rake survey was performed in 28 sampling locations in four pre-determined areas (Figure 6). Seventy-five percent (90) of the 120 rake tosses collected vegetation. The Art Museum made up sixty-three percent (19) of the 30 empty rake samples. The deepest at which submerged vegetation growth was found was 3.6m. Using the DNR substrate classification for aquatic plant surveys, muck was the dominant sediment type (68.3%), while rock (27.5%) and sand (4.2%) sediments were not as common. Eight different species of aquatic plants were collected and identified (Table 4). The most abundant species in the four areas, in order of relative abundance, were Eurasian watermilfoil (*Myriophyllum spicatum*), elodea (*Elodea canadensis*) and curly-leaf pondweed (*Potamogeton crispus*).

Because rake samples were mostly empty at the Art Museum, we conducted two 40m diving in ~3.4m of water with relatively low water visibility (2m). Four different species of aquatic plants were identified and counted (Table 4). Clasping-leaf pondweed (*Potamogeton perfoliatus*) was by far the most abundant at 36 separate stands (608 total vegetation stems), while *E. canadensis* (22 stands; 35 total vegetations stems), *P. crispus* (16 stands; 22 total vegetation stems) and narrow-leaf pondweed (*Potamogeton strictifolius*; 8 total vegetation stems) were also found.

Fish Spawning and Nursery Locations

Centrarchids were found to reproduce at various times in five locations (Table 5). Fish species that showed nesting behavior included: Rock Bass, Green Sunfish, Pumpkinseed*,* Bluegill*,* Smallmouth Bass and Largemouth Bass*.*

The Summerfest Lagoon and Discovery World locations were the most productive for observing fish spawning with active spawning as early as June 2017 and as late as middle of August 2017. Two spawning events were observed in the Summerfest Lagoon separated by drastic decreases in surface water temperatures (Figure 10). In the beginning of June 2017, over 100 Rock Bass were found on nests in the Summerfest Lagoon. Largemouth Bass and Rock Bass chose more sheltered locations as vegetation growth increased (Figure 7). Bluegill and Pumpkinseed were found on nests at the end of July 2017. Most fish preferred rocky substrate for spawning, while others used solely quagga mussels (alive and dead) and a combination of both as primary components for their nests (Figure 7). All nests were found in less than two meters of water.

Spawning activity was not expected in the Burnham Canal due to the overall depth of the canal (4-8m). However, Largemouth Bass*,* Bluegill and Green Sunfish were found on nests much earlier in the year (middle of May to middle of June) compared to other observed spawning locations. At the end of May 2017, one Largemouth Bass occupied a nest on a small collapsed dock wall on the north side of the canal, 95m from South 11th Street (Lat 43°01.594’, Long 87°55.595’). Nesting colonies of Bluegill and Green Sunfish were also found in the Burnham Canal at the same time (May to June 2017). They occupied a larger section (30m) of collapsed dock wall about 100m from the canal terminus, where preferred substrate, water depth and overhead cover existed. In the middle of June 2017, larval fish broods were found near the surface of the water next to both nesting locations. Temperatures reaching > 25°C for a consistent period over five times from June until November, signifies the importance of an early spawning period in the canal system (Figure 11).

The South Shore Terrace and Texas Rock locations were so large that without the use of side scan sonar, finding areas of spawning substrates and nesting locations would have been difficult. One long section of shoreline near Texas Rock was one of the main locations were spawning activity occurred (Figure 8). Smallmouth Bass and Rock Bass were observed on beds along the shoreline that were sheltered by surrounding vegetation in late July 2017. Both species occupied quagga mussels (alive and dead) or cobble for spawning substrates (Figure 8). Similar results were found in Edwards et al. (1983) where Smallmouth Bass were found to spawn later in the year on cobble and gravel substrates. Smallmouth Bass nests were monitored the following week and all were covered by siltation from strong south-east winds during the previous weekend. Egg mass on the nests was significantly diminished and survival of the eggs appeared unlikely.

DISCUSSION

Mapping with side scan was useful for locating submerged vegetation, likely spawning areas and potential “biological deserts.” Through mapping and substrate classifications an additional category that includes mussel beds and even loose mussel shells on fine substrate, and henceforth “mussels fine,” should be used in future substrate classifications of Great Lakes rivermouths. Based on the results from this project, future methods and habitat work in different rivermouth regions will be better understood and surveying techniques will be easier to perform.

Substrate Classification and Analysis

Substrates along the shoreline of the Milwaukee Estuary were primarily fine particle material (69.52%; 1.23km^2). Around 47% of this fine particle material was found along the shoreline of the inner harbor and connected tributaries. This large amount is associated with the hardened, dredged shorelines of the lower reaches of the rivers and inner harbor. Substrate classification accuracy in the Milwaukee Estuary were similar to a few studies using side scan sonar techniques in riverine environments (Kaeser and Litts 2010, 77%, Kaeser et al. 2013, 84%). Issues with classification inconsistencies were due to misidentifying quagga mussels as “rocky fine” substrate particles sizes. Similar results were found in Kaeser and Litts 2010, where sandy riffles or dune-like patterns were misidentified as “rocky fine” substrates. Mussels along the shoreline in the harbor were often found to slough off rock structures from wave action and form beds and mounds along the bottom. In some instances, they can be broken apart by wave action and form ripples.

Future substrate classifications in the Great Lakes must include dreissenid mussels because they are habitat engineers that are home to important forage such as isopods and amphipods (Berkman et al. 1998; Bially and Macisaac 2000). This classification approach can be found in marine estuaries, where bivalves are included in habitat classifications (Stevens and Connolly 2005). The use of side scan sonar to classify substrates have been predominantly done in riverine systems, where quagga mussels are not present (Muller et al. 1998; Quiñones and

Mulligan 2005; Kaeser and Litts 2010; Firkus 2013). With the post-addition of “mussels fine,” the accuracy of the substrate ground truthing exceeds to 90.8%.

Temperature

At the outset of this project the general concept of the different estuary habitats was a split between the outer harbor and inner harbor separated by the river mouth channel. Geographically, the inner and outer harbor are divided by a connecting channel and distinguished as separate entities. This channel was developed as part of a “straight cut” project in 1857 to build a new entrance to the inner harbor (Harbor District 2015). It provides direct access from Lake Michigan to downtown Milwaukee, 0.08 kilometers north of its natural location (Harbor District 2015). Hydrodynamically, both bodies of water are influenced by one another. In the spring and summer months, large storms and upwelling events can cause major exchanges of warm and cold water between the outer and inner harbor (Figure 9). During flood events, river discharge can drive temperature in the inner and outer harbors, but during low discharge an upwelling event can push water into all three tributaries and fluctuate water temperatures significantly. In some cases, these events can last a few weeks.

Fish Spawning and Nursery Locations

There are multiple areas in the Milwaukee Estuary that centrarchids used for spawning habitat, but these locations were found to be separated by large distances. The distance of these locations varies, but the substrate in these ranges are comprised of mostly fine particle sizes (Table 6). As a result, potential “biological deserts” exist between spawning areas and potential nursery habitats.

Spawning activity in the Summerfest Lagoon occurred in two events separated by an upwelling event in mid July 2017. Nesting substrates for Rock Bass and Largemouth Bass were not as limited as other locations, but Rock Bass may interpret quagga mussels as fine rocky substrate. However, unlike Gross and Nowell (1980), Rock Bass were found to select nesting locations near large rocks or woody debris along the western shoreline of the Summerfest Lagoon. Rock Bass have been found in the Great Lakes basin on coarse substrate nests with an average of 1.7cm diameter (Gross and Nowell 1980). In a review of Great Lakes fish habitats by Lane et al. (1996), Rock Bass prefer a wide range of coarse substrates (cobble, rubble and gravel), but were not mentioned to nest on dreissenids.

In some instances, male Largemouth Bass were found to clean the periphyton off the surface of boulders to create nests. Lane et al. (1996) reported Largemouth Bass using boulders as spawning substrates, but others reported that Largemouth Bass select mostly gravel, rubble and sand. One reason Largemouth Bass in the Summerfest Lagoon were choosing boulders as nesting areas might be due to limited preferred habitat earlier in the spawning season. As the end of the summer approached, more Largemouth Bass were found nesting on gravel in sheltered vegetation locations.

The occurrence of spawning activity in the Burnham Canal is a good example of "accidental" spawning habitat as found in other industrialized Great Lake shorelines (Williams 1996; Edsall and Charlton 1997; Palta et al. 2017). Bluegill*,* Green Sunfish and Largemouth Bass that were found to display spawning characteristics, occupied small sections of dock walls with overhanging cover in early summer (middle of May to middle of June). One reason why shoreline canopy cover was an important factor for choosing bedding sites was due to the amount of bird predation back in the canal system. There are many birds of prey in the canal system, including a large Black-crowned Night-Heron *Nycticorax nycticorax* rookery in the west end of the South Menomonee Canal and the occasional Green Heron *Butorides virescens* or Great Blue Heron *Ardea herodias*.

Even though the areas created by the collapsed dock wall were small, they created an opportunity for fish reproduction in a location that was originally considered to have no fish spawning activity due to the canal's unfavorable characteristics (consistent high surface water temperature, silt bottom – not dredged since fall 1987, hardened shoreline, and sediment contamination; US EPA 2016). In 2018, the end of the Burnham Canal is to undergo a remediation and ecosystem restoration project by the U.S. Environmental Protection Agency (EPA) to clean up contaminated sediment and soil at the Superfund Site (Burzynski, Pers. Comm.). With the input from different agencies, an aquatic wetland will be developed on top of a sediment cap for a variety of fauna. These plans have not yet been finalized, but part of the project goal is to mimic what was observed and retain the knowledge gained from this study and apply it to areas throughout the remediation process.

The South Shore Terrace and Texas Rock site was the only spawning location that was not completely sheltered from wind and wave action. Spawning activity here was influenced by temperature and wind fluctuations. Anthropogenic alterations in the environment has also been found to be a major driver for Smallmouth Bass nest failure in northern Lake Michigan (Kaemingk et al. 2011). More prevailing winds begin to occur later in the year with less daily variability. During this time, the west shoreline of Lake Michigan has morning breezes generally out of the south and strengthen in the afternoon out of the NE through SE (NOAA 2017). These effects were detrimental to Smallmouth Bass and Rock Bass nesting in the south shore areas because the area has a long fetch from north to south, allowing large wave action and sediment transport.

Temperature fluctuations from river discharge and coastal upwelling by Lake Michigan can drastically impact spawning. Temperature in different parts of the estuary during these events depends upon some combination of both water masses. Since these events are idiosyncratic and have the potential to disrupt spawning events that were initiated before upwelling, a more complete monitoring term is required to understand recruitment success. This would also be able to help pinpoint spawning activity in different areas of the estuary, as these events can be influential in the reproduction process (Goodyear et al. 1982; Nack et al. 1993; Lane et al. 1996; Kaemingk et al. 2011; Larson et al. 2013). Placing temperature loggers throughout the estuary should also be more site-specific and include multiple locations in the south shore area to get a better idea of water currents and hydrodynamics. For the case of this study, temperature data was only collected during expected spawning period of fish. However, a portion of the spawning period in the Burnham Canal was missed due to unknown fish spawning activity.

Macrophyte Assessment

The two types of implemented surveys (scuba and rake rope) were moderately successful for the Milwaukee Estuary. The macrophyte assessment was not as widespread, as was originally planned due to the unknown extension of fish spawning events in the Summerfest Lagoon and South Shore Terrace locations. Thus, areas were chosen based on known locations of large macrophyte stands and selected areas of habitat connectivity significance. Future sampling in the study area should be completed towards the end of the summer (August and September), when vegetation growth is at its peak and fish are no longer found on nests. A widespread baseline survey of macrophyte abundance in the Milwaukee Harbor and residing tributaries was completed later in 2017 by The Nature Conservancy (Tucker, Pers. Comm.). Even though the side scan sonar was used to find the boundary of the macrophyte stands, the sparseness of the macrophyte stands at the Art Museum caused rake rope surveys to not be entirely inclusive of surrounding vegetation. In some instances, the anchor was full of vegetation after it was retrieved, but the rake tosses in that area did not acquire any vegetation and were given a fullness rating of zero. Therefore, establishing new sampling methods with transects perpendicular to the shoreline in known areas of vegetation growth and performing scuba, acoustic vegetation and rake rope surveys is warranted. These sampling techniques have been performed before in large lake systems (Capers 2000; Sabol et al. 2002; Zhu et al. 2007; Wagner and Mikulyuk 2012; Ogdahl and Steinman 2015).

Implementing the Map

While the Milwaukee Estuary is no longer what it once was prior to settlement and development along the shoreline of Lake Michigan, it can still be managed in a way where humans and the environment can co-exist. A lot of the issues that are being dealt with today in the Milwaukee Estuary AOC are a result from the inability to grasp the consequences our actions have on the surrounding environment. Today’s strategies of conservation biology either include reserving natural habitats or restoring them to their natural state (Rosenzweig 2003). However, to create new habitats in an environment such as this, we need to implement a new strategy called reconciliation ecology (Rosenzweig 2003), i.e. the science of inventing, establishing, and maintaining new habitats to conserve species diversity in places where people live, work or play. This strategy does not restore pre-settlement habitats, but modifies structures built for more ecosystem function, so that they are more ecologically suitable. To accomplish this, future studies and work in the Milwaukee Estuary are necessary to determine what ecological factors are crucial for each individual species and to provide them with the groundwork to flourish in a significantly altered environment.

Substrate

- There is a need to develop new types of spatial habitat along the shorelines of the inner harbor and lower reaches of the tributaries to bridge hardened shoreline gaps from the outer harbor to the upper sections of the rivers. Some of these efforts are currently underway in Milwaukee, where “habitat hotels” (similar to a hanging garden basket, but underwater - Harbor District Inc.) and floating islands (created with a blend of synthetic and natural floating media, from which plants grow) are being installed along the bulkhead walls to provide more surface area and habitat for not just fish species, but other aquatic wildlife. Young of the year fish (yellow perch, and largemouth bass) have been found near these structures. Ducks, muskrats, birds, and frogs have also taken advantage of these simulated shoreline habitats.
- The search for new additional areas of “mussels fine” is warranted to identify areas where mussels form beds across fine particle substrate. Using knowledge gathered from this study, additional locations can be found and provide insight about the biological significance that these beds have for small invertebrates.

Fish Spawning and Nursery Locations

- The original Milwaukee Estuary wetland most likely had minimal sand/gravel habitat for centrarchid spawning. Since this estuary underwent drastic ecosystem changes via shoreline and benthic modification, as well as the introduction of many invasive species, we found centrarchids flourishing at multiple locations on a large variety of substrates. Novel nesting habitat for centrarchids should be a focus of future research because live and dead dreissenids have created a new, and apparently acceptable substrate. Whether the habitat is beneficial is not yet known.
- Facilitating the movement of multiple fish species should be done in the Milwaukee Estuary to determine if fishes reproducing in the estuary venture to other spawning sites or are predominately found in a specific area. Past research has been successful on evaluating fish movement and monitoring habitat use from telemetry (Hirethota et al. 2005; Rogers and White 2007; Landsmen et al. 2011; Goclowski et al. 2013). This knowledge could help link together the proposed “biological deserts” and allow better understanding of fish movement and management practices.
- As seasonal water temperature fluctuates from year to year, native fish spawning locations will continue to be affected by the environment. Spawning events that occur early in the year (Burnham Canal) and later in the year (Summerfest Lagoon, South Shore Terrace) might have very different influences on recruitment. Future work should be done to determine the importance of habitat connectivity for survivability of larval and young of the year fish.

Table 1. Substrate Classification

Substrate classes were augmented from a Wentworth (1992) scale and derived from previous studies done on assessing fish habitat by use of side scan sonar in streams (Kaeser and Litts 2010; Goclowski et al. 2013; Snobl 2016). Substrates were appointed a classification in ArcMap™ 10.4.1 (ESRI Inc., Redlands, California). A minimum map unit was determined to contain a 5m radius (A ≈ 78.54 m^2) and represented the smallest size of a polygon for any substrate category.

Substrate Class	Definition
Fine	≥75% of area composed of particles <2 mm in diameter (sand, silt, clay or fine organic detritus)
Rocky Fine	>25% of area composed of rocks >2 mm, but <256 mm diameter across axis
Rocky Boulder	An area that includes > 3 boulders, each >256 mm diameter across longest axis, each boulder within 1.5 m of the next adjacent boulder. Any area that meets criteria counts, regardless of underlying substrate.
Mixed Rocky	An area comprising two or more substrate classes (at least one being rocky) arranged such that no homogenous portion is >10 m^2
Woody Fine	>25% of area comprised of wood debris/sunken logs/old wooden structures
Wood/Steel Piling(s)	> 25% of area comprised of wood or steel dock piling(s)
Unknown	An area beyond the sonar range but within the boundaries of the boat and shoreline.

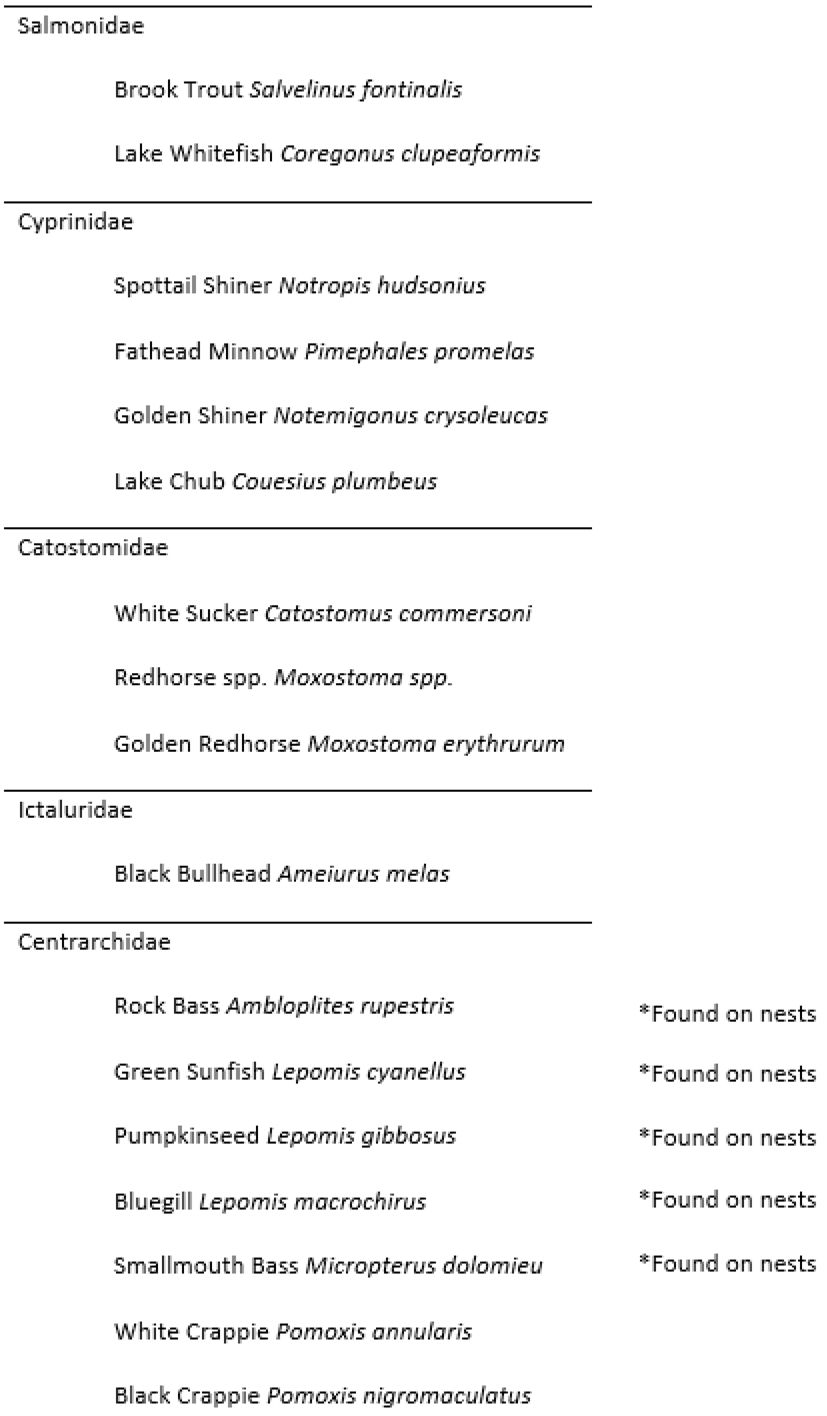
Table 2. Substrate Classification Error Matrix

An error matrix generated to evaluate the accuracy of substrate allocations (Congalton, 1991). Twenty randomly selected polygons from each substrate particle size were chosen and characterized using micro (2.38L) Ponar grabs. In areas where large particle sizes or shallow water was present, substrate was verified with an Aqua-Vu camera or visual inspection. Substrate was unable to be determined at two field sites and was not used in analysis (1 rocky boulder site and 1 mixed rocky site). Overall Accuracy represents total **correct** substrate classifications divided by total sampling locations.

	Reference Site Data (Ground Truth)							
Substrate Classifications	Fine	Rocky Fine	Mixed Rocky	Rocky Boulder	Woody Fine	Mussels Fine*	Row Total	Accuracy
Fine	**19**	0	1	0	0	0	20	95%
Rocky Fine	0	**7**	0	0	0	13	20	35%
Mixed Rocky	0	1	**16**	0	0	2	19	84.2%
Rocky Boulder	0	0	1	**18**	0	0	19	94.7%
Woody Fine	2	0	2	0	**16**	0	20	80%
Mussels Fine*	N/A	N/A	N/A	N/A	N/A	**N/A**	N/A	N/A
Column Total	21	8	20	18	16	15	**98**	
							Overall Accuracy	77.6%

Table 3. Sub-set of Milwaukee AOC Fish Indicator Species

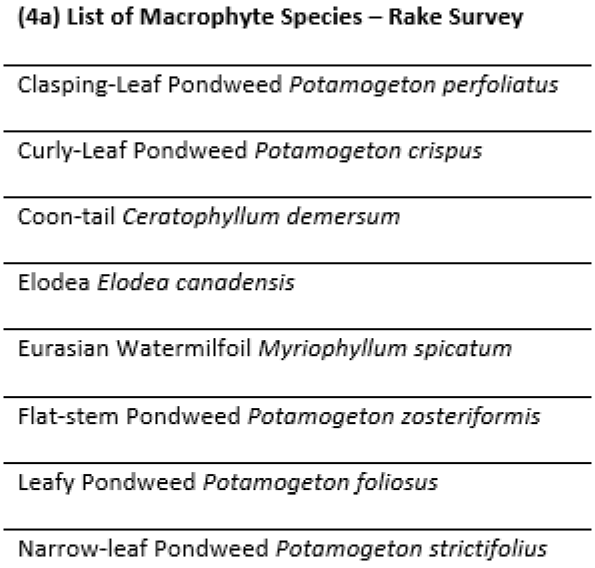
All fish listed were proposed to be used in BUI evaluation by a fish population assessment completed in 2014 in the Milwaukee Estuary Area of Concern (Sullivan and Fayram, 2014). Indicator species found on nests or fish that displayed spawning behaviors were recorded with GoPro cameras from boat, scuba diving or snorkeling and generally monitored for any changes in reproductive success.



Salmonidae		
	Brook Trout *Salvelinus fontinalis*	
	Lake Whitefish *Coregonus clupeaformis*	
Cyprinidae		
	Spottail Shiner *Notropis hudsonius*	
	Fathead Minnow *Pimephales promelas*	
	Golden Shiner *Notemigonus crysoleucas*	
	Lake Chub *Couesius plumbeus*	
Catostomidae		
	White Sucker *Catostomus commersoni*	
	Redhorse spp. *Moxostoma spp.*	
	Golden Redhorse *Moxostoma erythrurum*	
Ictaluridae		
	Black Bullhead *Ameiurus melas*	
Centrarchidae		
	Rock Bass *Ambloplites rupestris*	*Found on nests
	Green Sunfish *Lepomis cyanellus*	*Found on nests
	Pumpkinseed *Lepomis gibbosus*	*Found on nests
	Bluegill *Lepomis macrochirus*	*Found on nests
	Smallmouth Bass *Micropterus dolomieu*	*Found on nests
	White Crappie *Pomoxis annularis*	
	Black Crappie *Pomoxis nigromaculatus*	

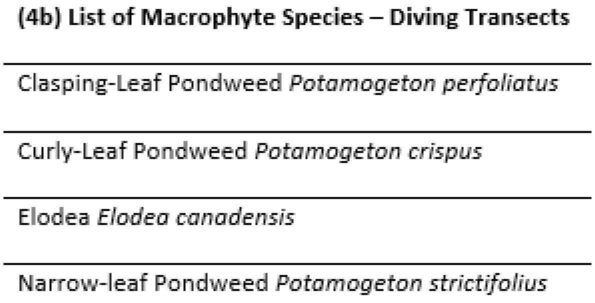
Table 4. Macrophyte Species Identified

The macrophyte rake survey protocol was performed in 28 different sampling locations in four pre-determined areas (4a). Eurasian watermilfoil and elodea were the most prevalent in all 120 rake tosses. Two 40m diving transects at the Art Museum were conducted in ~3.4m of water with relatively low water visibility (4b). Clasping-leaf pondweed was the most abundant at the Art Museum with 36 separate stands (608 total vegetation stems).



(4a) List of Macrophyte Species – Rake Survey

Clasping-Leaf Pondweed *Potamogeton perfoliatus*
Curly-Leaf Pondweed *Potamogeton crispus*
Coon-tail *Ceratophyllum demersum*
Elodea *Elodea canadensis*
Eurasian Watermilfoil *Myriophyllum spicatum*
Flat-stem Pondweed *Potamogeton zosteriformis*
Leafy Pondweed *Potamogeton foliosus*
Narrow-leaf Pondweed *Potamogeton strictifolius*



(4b) List of Macrophyte Species – Diving Transects

Clasping-Leaf Pondweed *Potamogeton perfoliatus*
Curly-Leaf Pondweed *Potamogeton crispus*
Elodea *Elodea canadensis*
Narrow-leaf Pondweed *Potamogeton strictifolius*

Table 5. Centrarchid Spawning in the Milwaukee Estuary

Possible locations of fish spawning areas were found with visual surveys and the application of side scan sonar. The Summerfest Lagoon and Discovery World locations were the most productive for observing fish spawning via scuba and snorkeling from the beginning of June 2017 to middle of August 2017. Rock Bass made up a large percentage of fish found on nests in these locations. Spawning activity found in the Burnham Canal was very site specific. Spawning beds required shallow water (on collapsed dock walls), gravel/cobble substrate and overhang cover from bird predation (trees, logs, etc.). A large colony of Bluegill dominated these few ledges used for spawning.

	Burnham Canal				**Grand Trunk**				**Summerfest Lagoon and Discovery World**				**McKinley Marina**				**South Shore Terrace and Texas Rock**			
Species	May	Jun	Jul	Aug	May	Jun	Jul	Aug	May	Jun	Jul	Aug	May	Jun	Jul	Aug	May	Jun	Jul	Aug
Bluegill *Lepomis macrochirus*	**X**	**X**				**X**	**X**				**X**	**X**	**X**	**X**	**X**					
Green sunfish *Lepomis cyanellus*	**X**	**X**				**X**	**X**													
Pumpkinseed *Lepomis gibbosus*											**X**	**X**								
Rock bass *Ambloplites rupestris*										**X**	**X**		**X**	**X**	**X**				**X**	**X**
Largemouth bass *Micropterus salmoides*	**X**	**X**								**X**	**X**	**X**								
Smallmouth bass *Micropterus dolomieu*										**X**	**X**	**X**							**X**	**X**

Table 6. Distance of Shoreline (km) between Spawning Sites in Milwaukee Estuary

All distances between spawn locations were measured using Google Earth™ and ArcMap™ 10.4.1. Movement between spawning locations are unknown, but distance of shoreline (km) and locations of “biological deserts” might be a major factor in limiting fish to spawn in one area.

	Distance of Shoreline (km)						
Spawning Location	Burnham Canal	Grand Trunk	Summerfest Lagoon	Discovery World	McKinley Marina	South Shore Terrace	Texas Rock
Burnham Canal	---	4.82	4.98	4.75	7.11	10	10.58
Grand Trunk	---	---	3.98	3.72	6.08	8.95	9.53
Summerfest Lagoon	---	---	---	0.037	2.73	7.76	8.34
Discovery World	---	---	---	---	2.69	7.72	8.30
McKinley Marina	---	---	---	---	---	10.41	10.99
South Shore Terrace	---	---	---	---	---	---	0.58
Texas Rock	---	---	---	---	---	---	---

Figure 1. Milwaukee Estuary Study Area

The study area has a perimeter of roughly 60.4km of shoreline and breakwall, as well as covers a total area of 7.49km^2. It contains three tributaries (Milwaukee, Menomonee and Kinnickinnic River) that connect and flow into the Milwaukee Harbor and eventually Lake Michigan. Referenced locations are found labeled on the image.

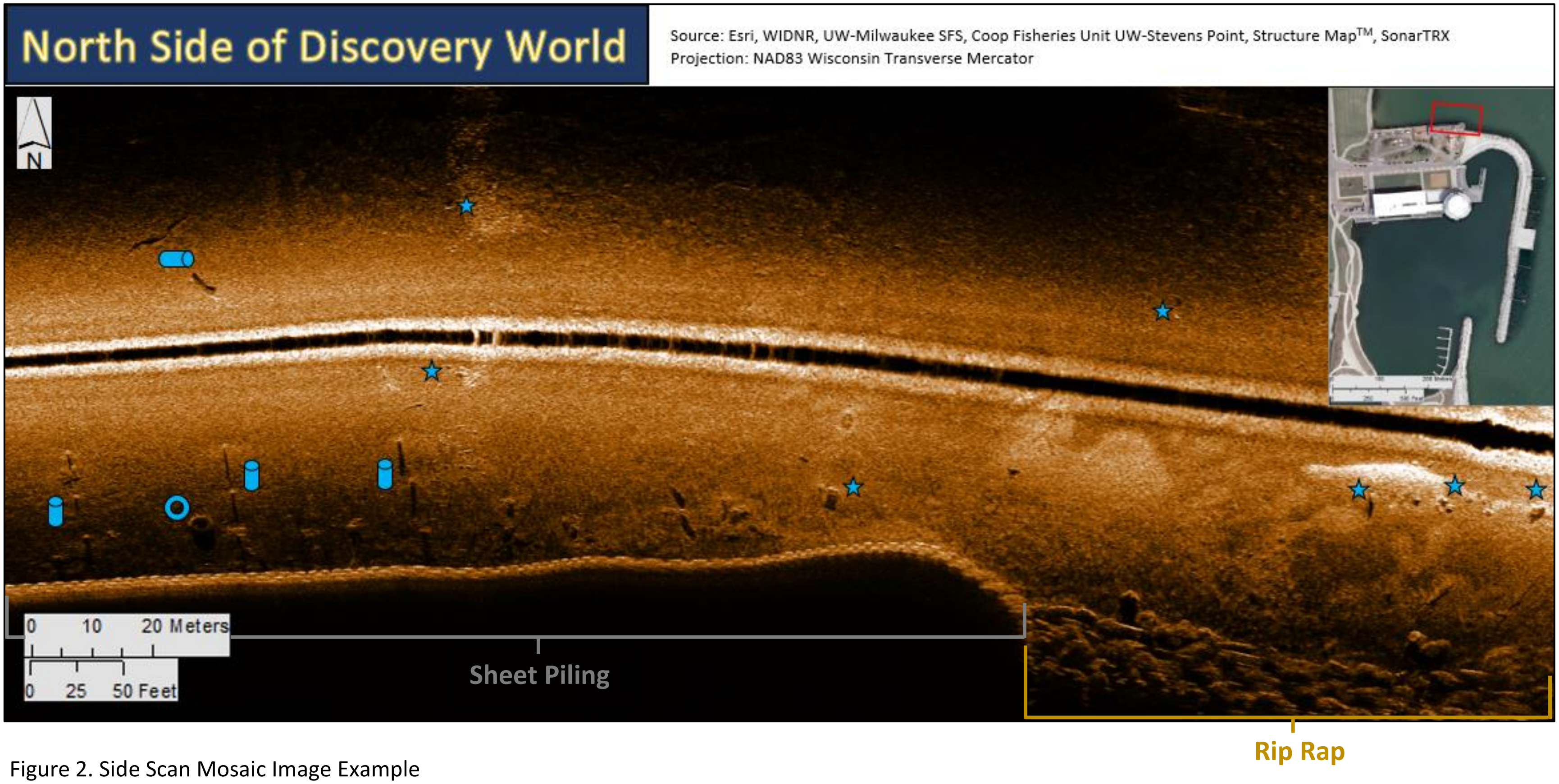


Figure 2. Side Scan Mosaic Image Example

This mosaic image displays a good representation of the change in shoreline habitat and physical structure between sheet piling and introduced "rip rap," which is also known as a variation between rocks and boulders. It also includes different types of features that can be identified because of the high amount of resolution. In the image, there is a tire (◎), multiple fish (★), submerged logs (⬭), old dock pilings with overcasting shadows (▯), and a lot of variation in benthic structure. The black line across the center of the image is the blanking distance by the side scan sonar device and represents the boat location.

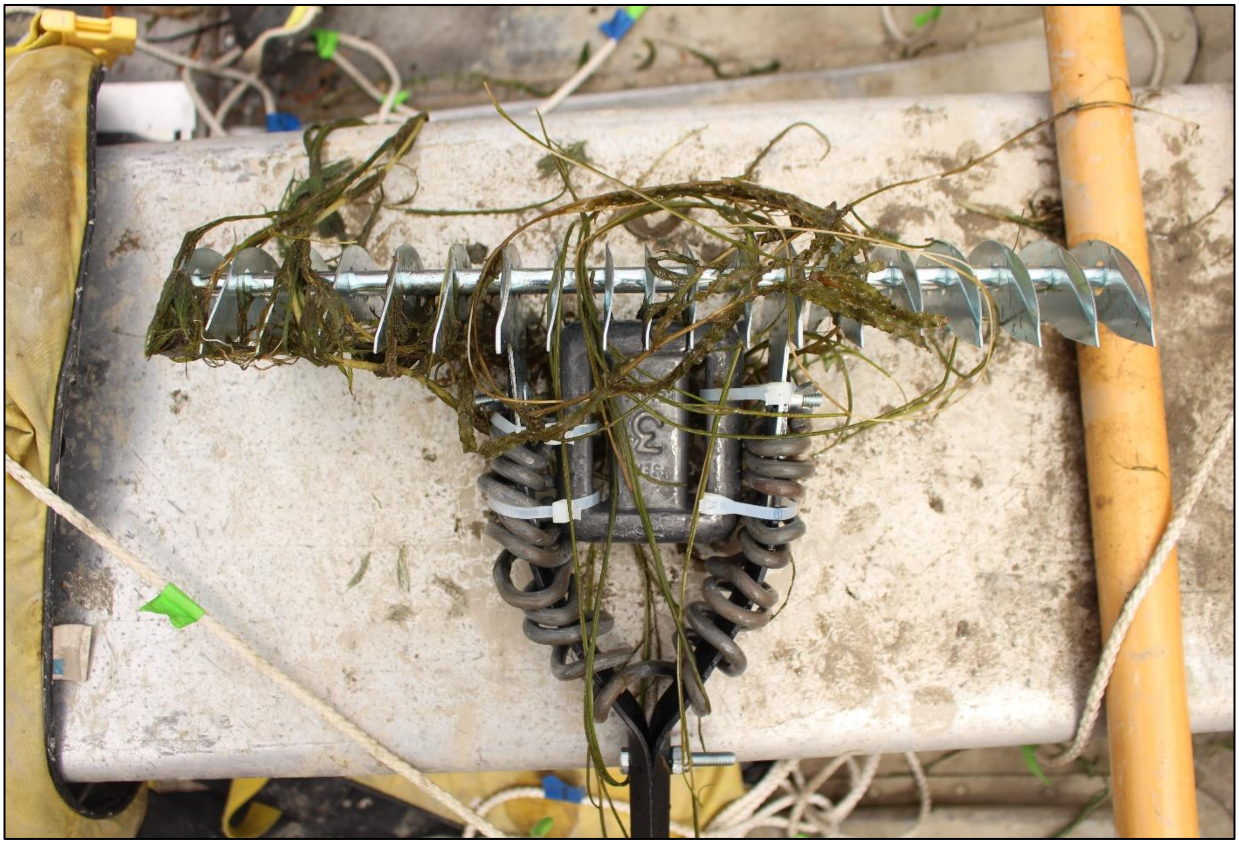


Figure 3. Macrophyte Rake Rope Surveys

Rake rope surveys were performed with a thatching rake to collect macrophytes. After the rake was brought into the boat it was assigned a fullness rating from 0 to 5 and each plant was identified to species. Picture above is a rake toss from the South Shore Terrace area. Curly-leaf pondweed*,* narrow-leaf pondweed and Eurasian watermilfoil are found in the picture above – given a fullness rating of two.

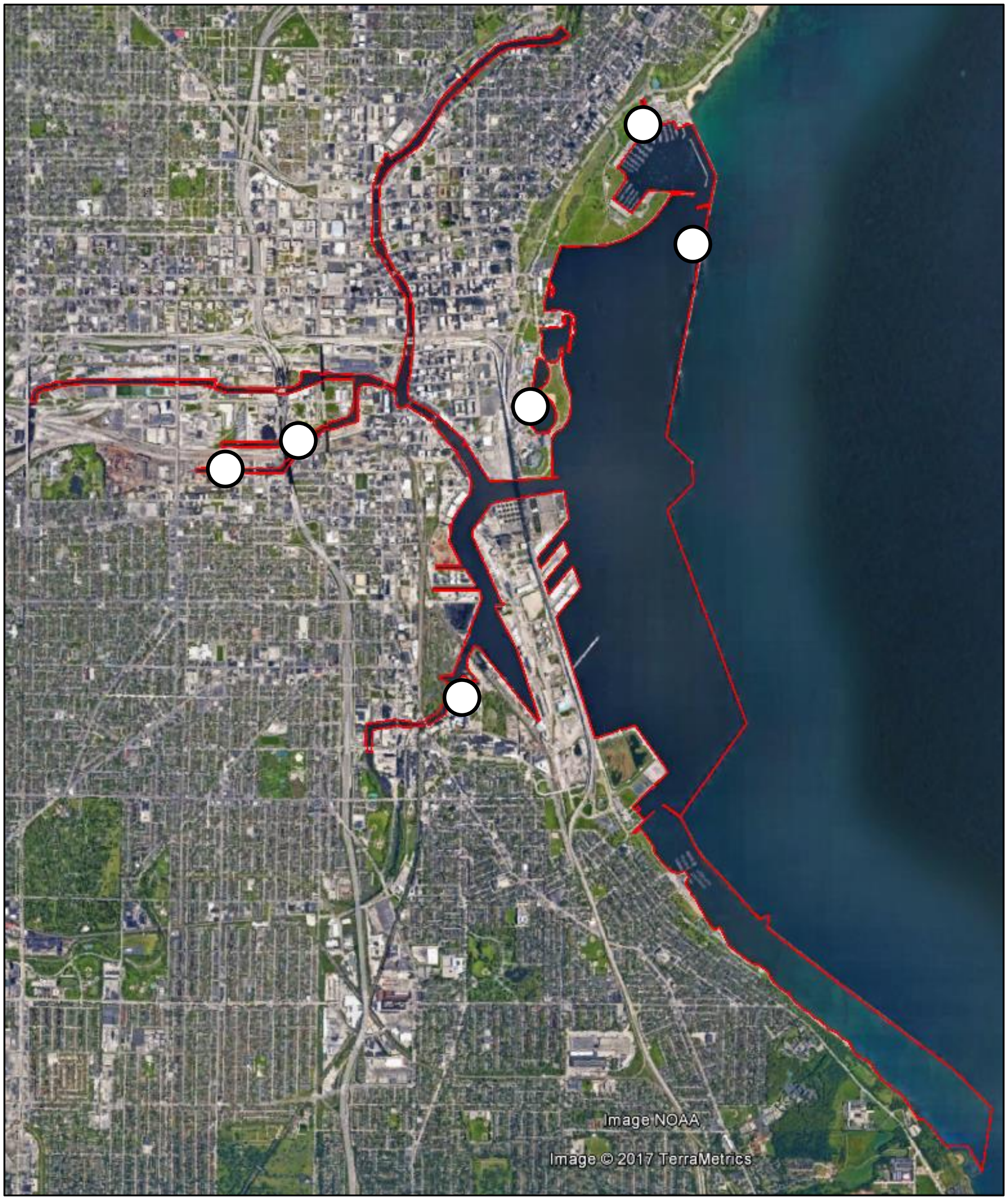


Figure 4. Temperature Logger Locations

Temperature loggers (HOBO Pendant Temperature 64K Data Logger) were deployed in June 2017 at six different locations in the study area. Loggers recorded at one hour intervals to observe changes in water temperature brought on by upwelling or seiche events. Data was used in determining probable length of spawning events in different locations throughout the Estuary.

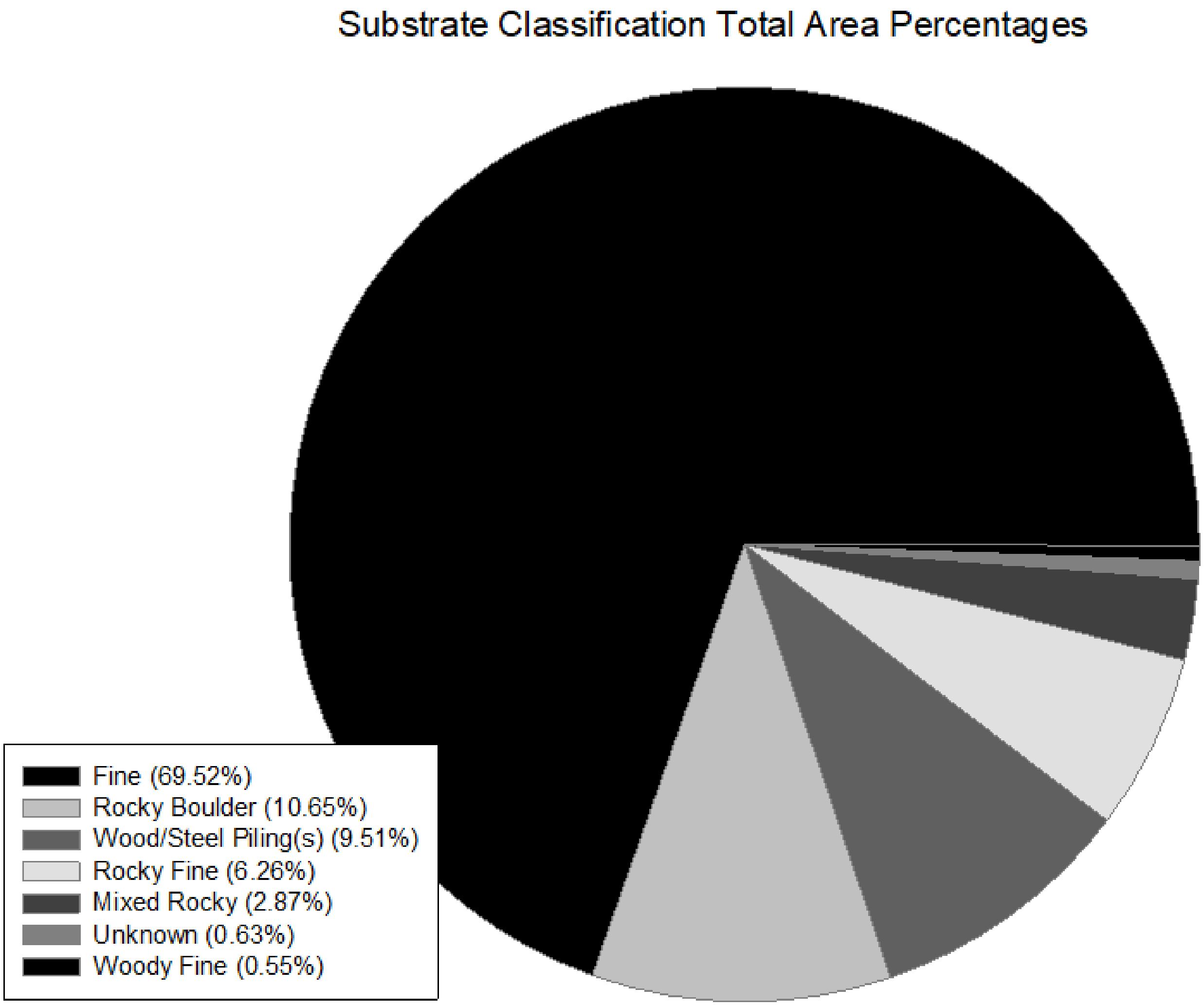


Figure 5. Shoreline Substrate Composition

Substrate classifications were grouped into seven different categories based on a modified Wentworth (1922) scale. Substrate particle size classes for five of the seven categories are as follows: fine (< 2mm), rocky fine (> 2mm and < 256mm diameter), mixed rocky (combination of two or more particle size classes > 2mm – at least one being rocky), rocky boulder (> 256mm), and woody fine (> 10 cm diameter). The remaining two categories include regions that were not boat accessible (unknown) and structures that are used for walkways and docking (wood/steel pilings).

Figure 6. Macrophyte Rake Survey Locations

Macrophyte rake survey protocol was performed in 28 different sampling locations in four areas (Art Museum – AM, Discovery World – DW, Summerfest Lagoon – SL, South Shore – SS). Eight different species of aquatic plants were collected and identified. Deepest depth at which submerged vegetation growth was found was 3.6m. The most abundant in the four areas were Eurasian watermilfoil, elodea*,* and curly-leaf pondweed, respectively.

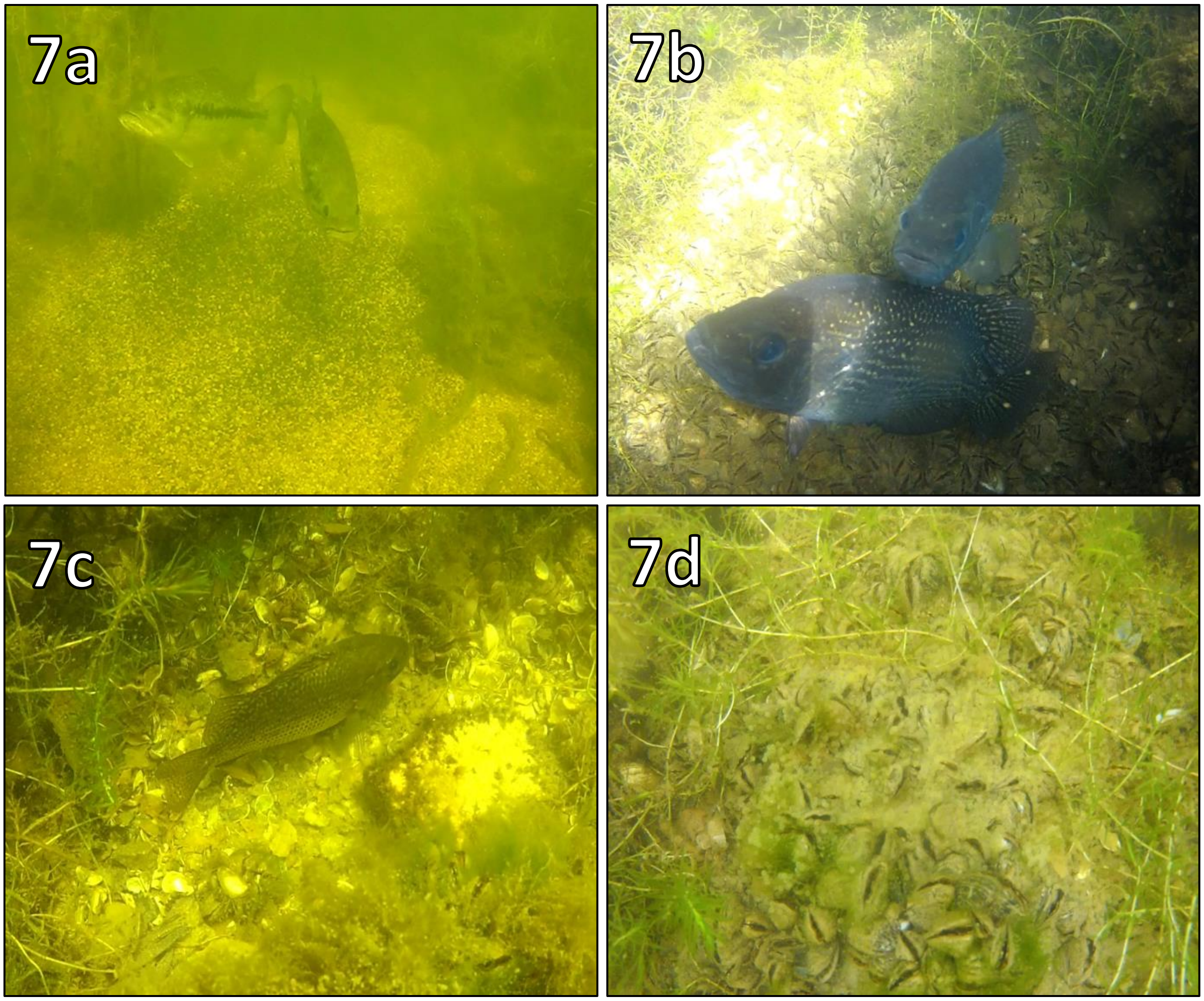


Figure 7. Summerfest Lagoon Centrarchid Nesting Selection

Largemouth Bass (7a) were found to spawn on mostly rocky fine particle sizes and selecting more sheltered locations as vegetation growth increased in the Summerfest Lagoon. Rock Bass (7b) were also found to select more sheltered locations as vegetation growth increased, but were found to spawn on a variety of substrates (7c), including live quagga mussels (7d).

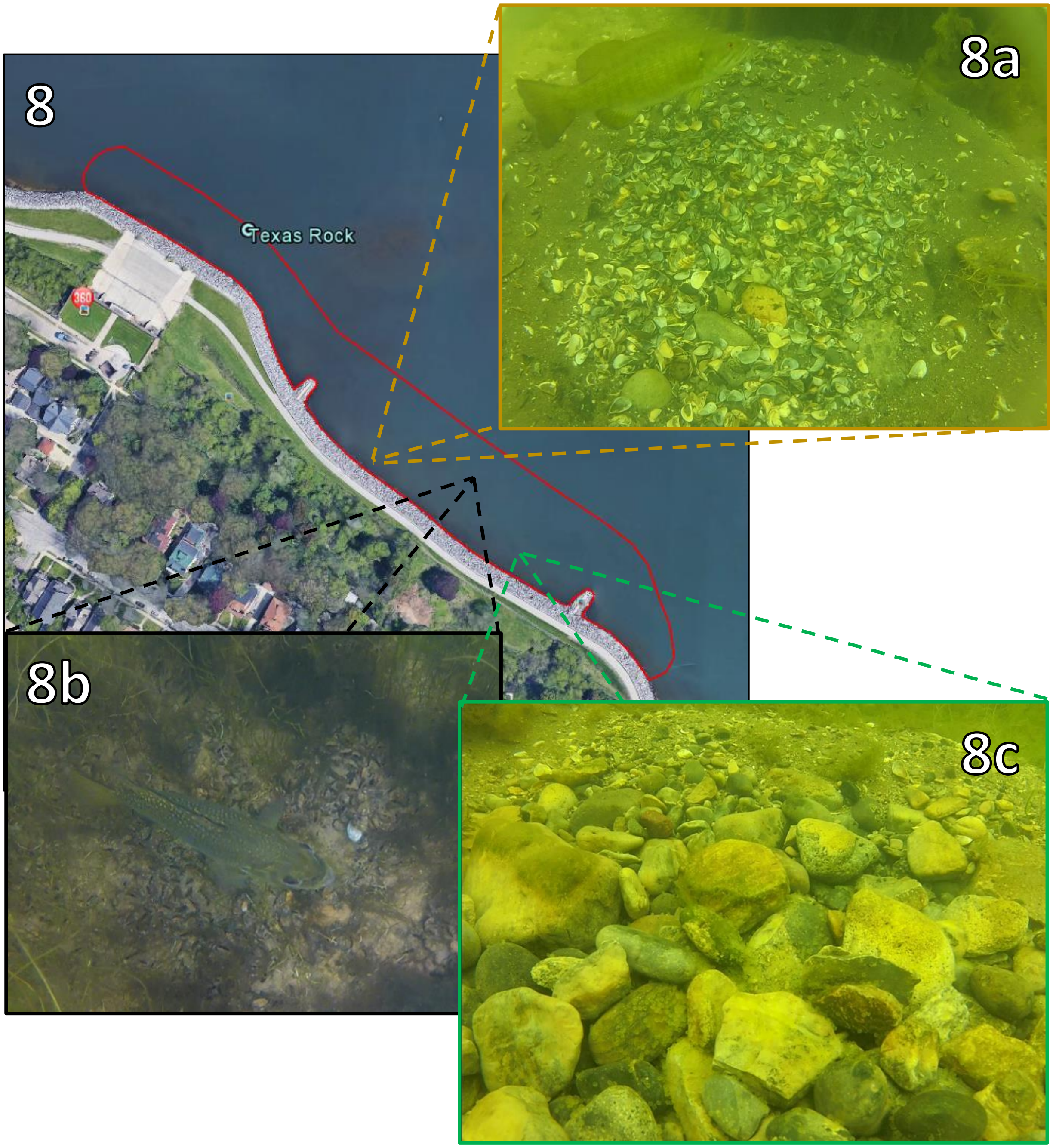


Figure 8. South Shore Terrace/Texas Rock Centrarchid Nesting Selection

Smallmouth Bass were found to spawn closer to the shoreline on a variety of substrates, including gravel/cobble (8c) and even mussel shells (8a). Rock Bass were found on nests further away from the shoreline and on substrates comparable to those in the Summerfest Lagoon (8b).

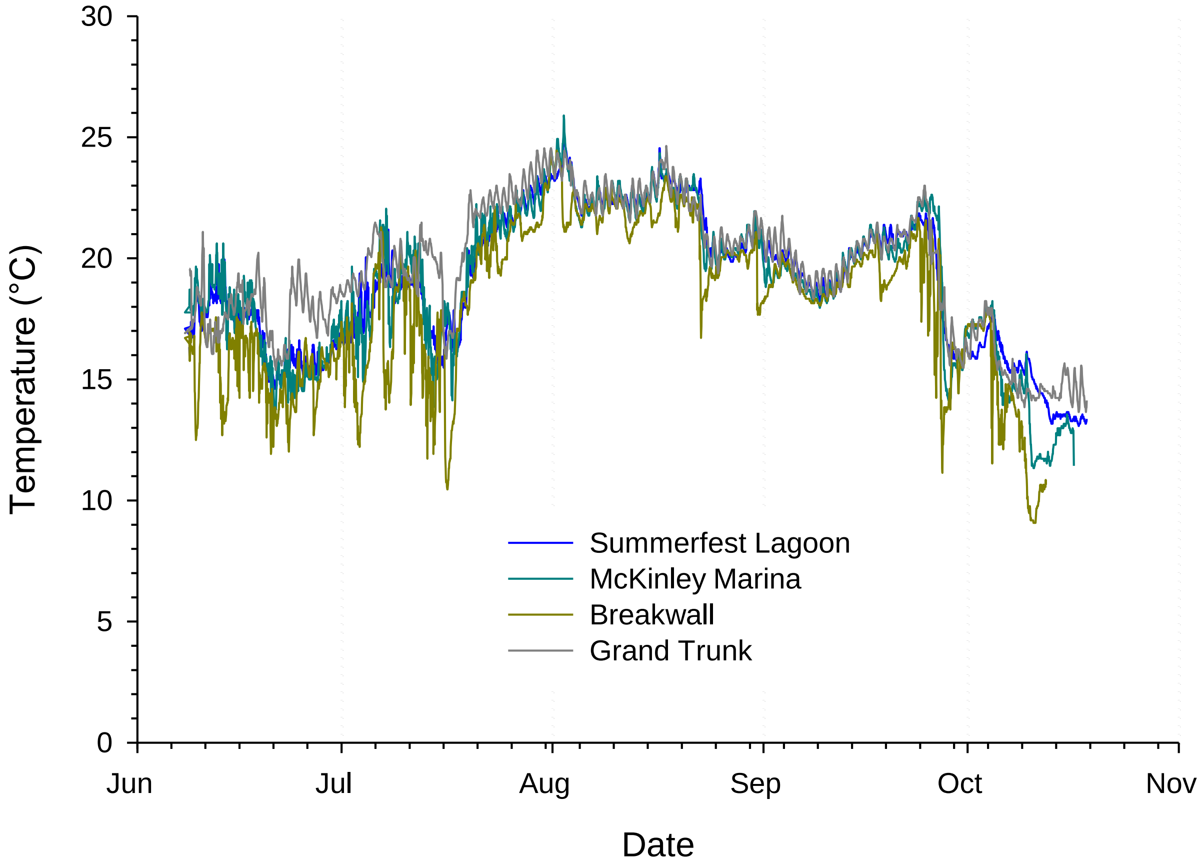


Figure 9. Surface Water Temperatures

Summerfest Lagoon, McKinley Marina, Grand Trunk, and Breakwall sites all followed the same trend in surface water temperatures. Temperature differences were no more than 10°C from June 2017 to October 2017. Sporadic surface water temperature differences at the Breakwall were due to more of an influence of lake intrusions and upwelling effects from June 2017 to middle of July 2017. Temperatures were recorded with HOBO Pendant Temperature 64k Data Loggers.

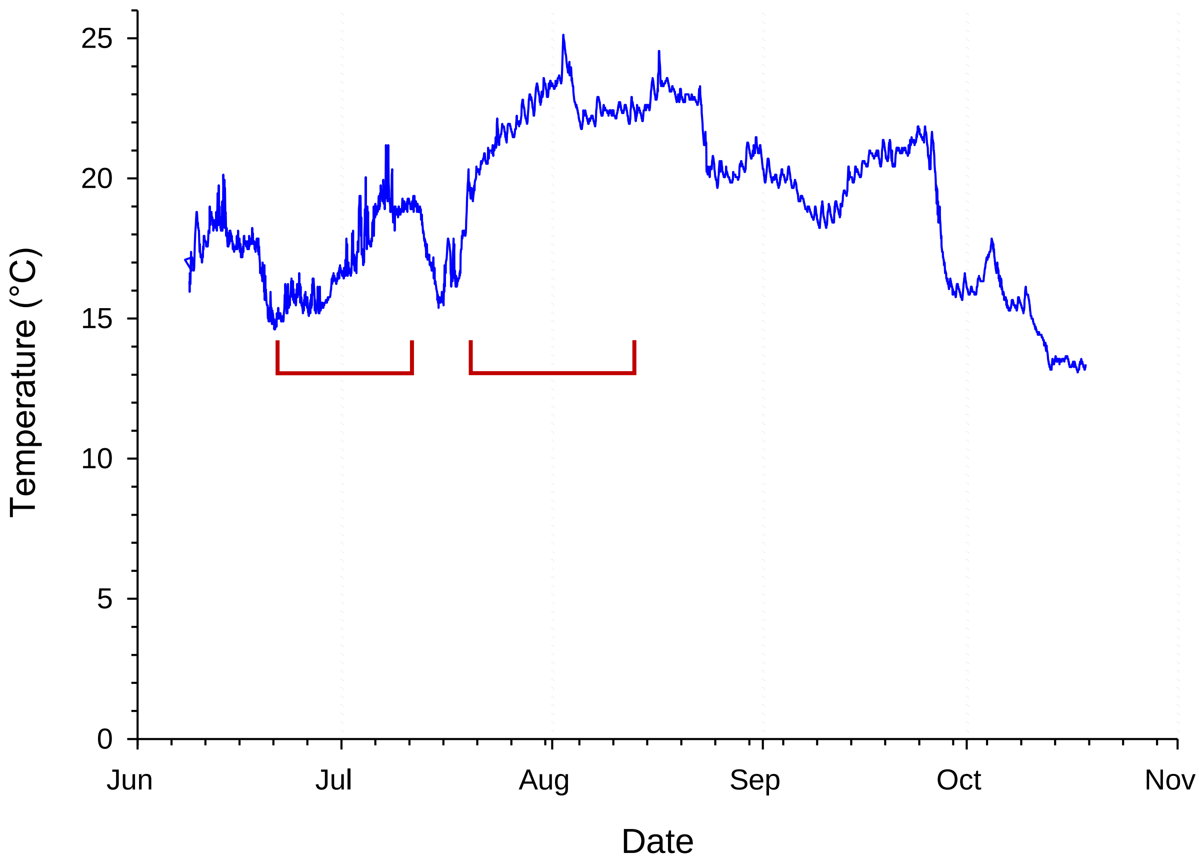


Figure 10. Summerfest Lagoon Surface Water Temperature

Two spawning events were observed in the Summerfest Lagoon. One in the middle of June until the beginning of July* and the other from late July to middle of August*. The initial spawning event consisted mostly of Rock Bass with few Largemouth Bass. The second event included mostly Largemouth Bass with the addition of Bluegill and Pumpkinseed. All nests were found in less than two meters of water. Temperatures were recorded with HOBO Pendant Temperature 64k Data Loggers.

**Spawning events marked with brackets*

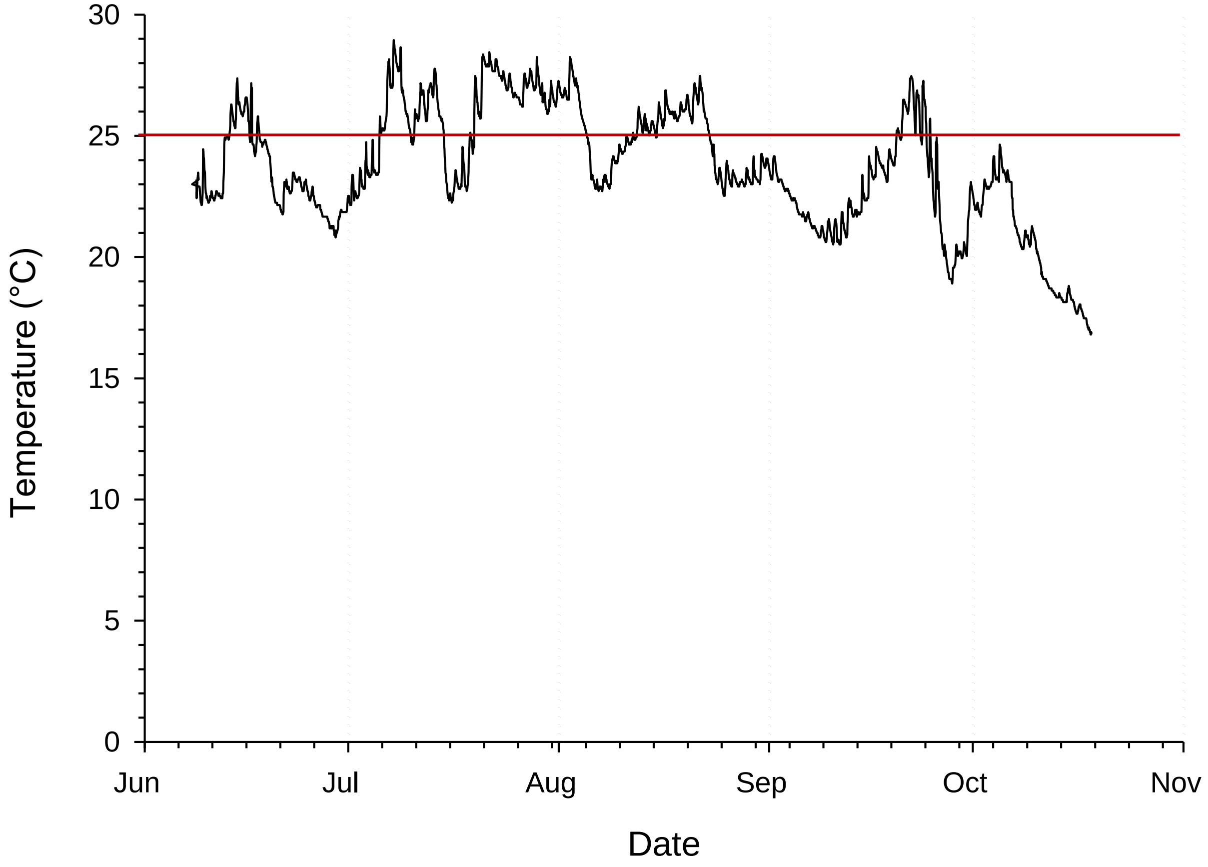


Figure 11. Burnham Canal Surface Water Temperature

The Burnham Canal surface water temperature fluctuated many times during deployment, most likely due to warm-water discharge from the WE Energies power plant. Temperatures reaching >25°C for a consistent period over five times from June until November, signifies the importance of an early spawning period in the canal system. All fish were on nests in less than 1.5 meters of water and occupying overhead cover from the middle of May to middle of June. Temperatures were recorded with HOBO Pendant Temperature 64k Data Loggers.

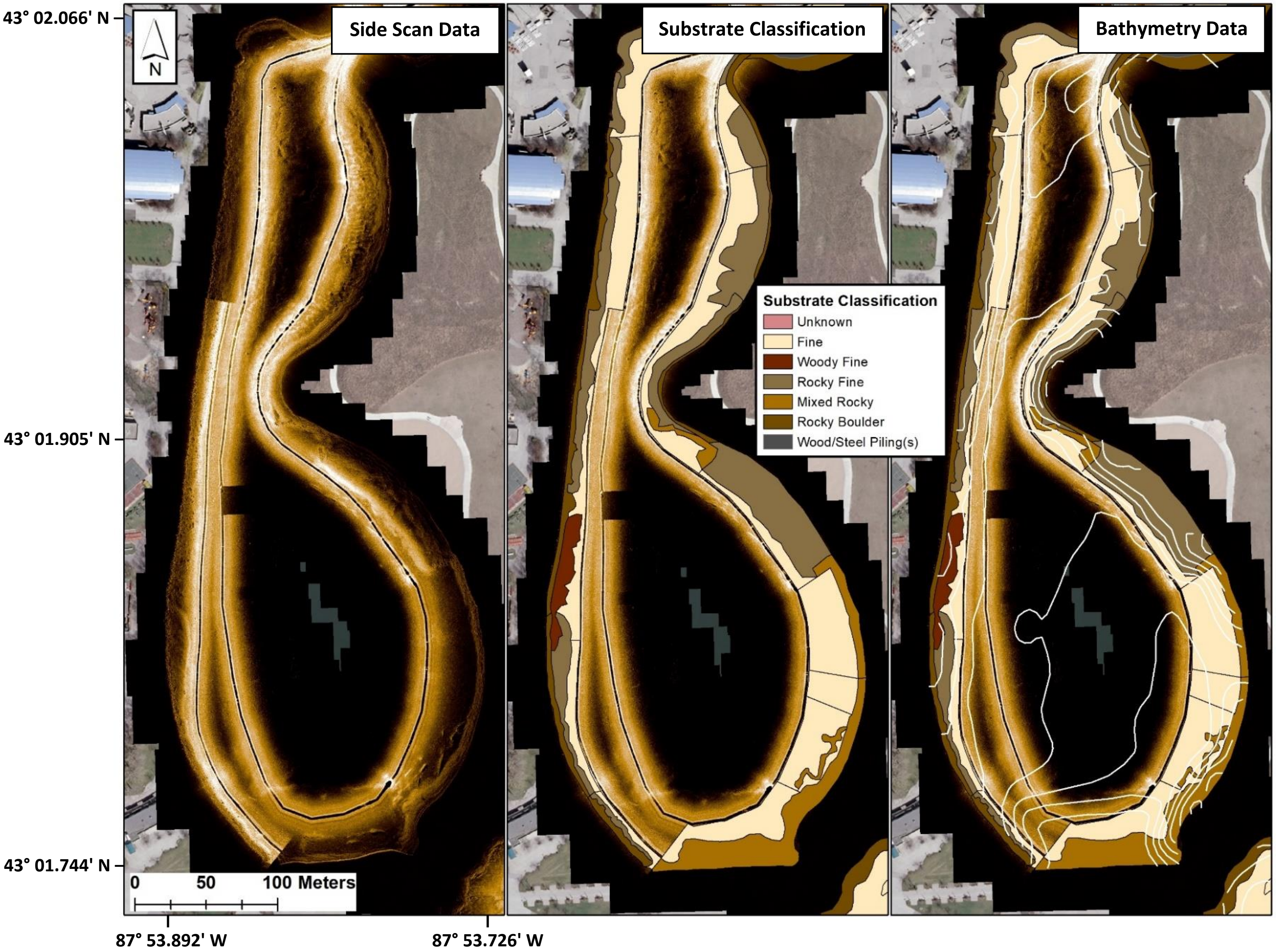


Figure 12. Summerfest Lagoon Multiple ArcMap™ Layers

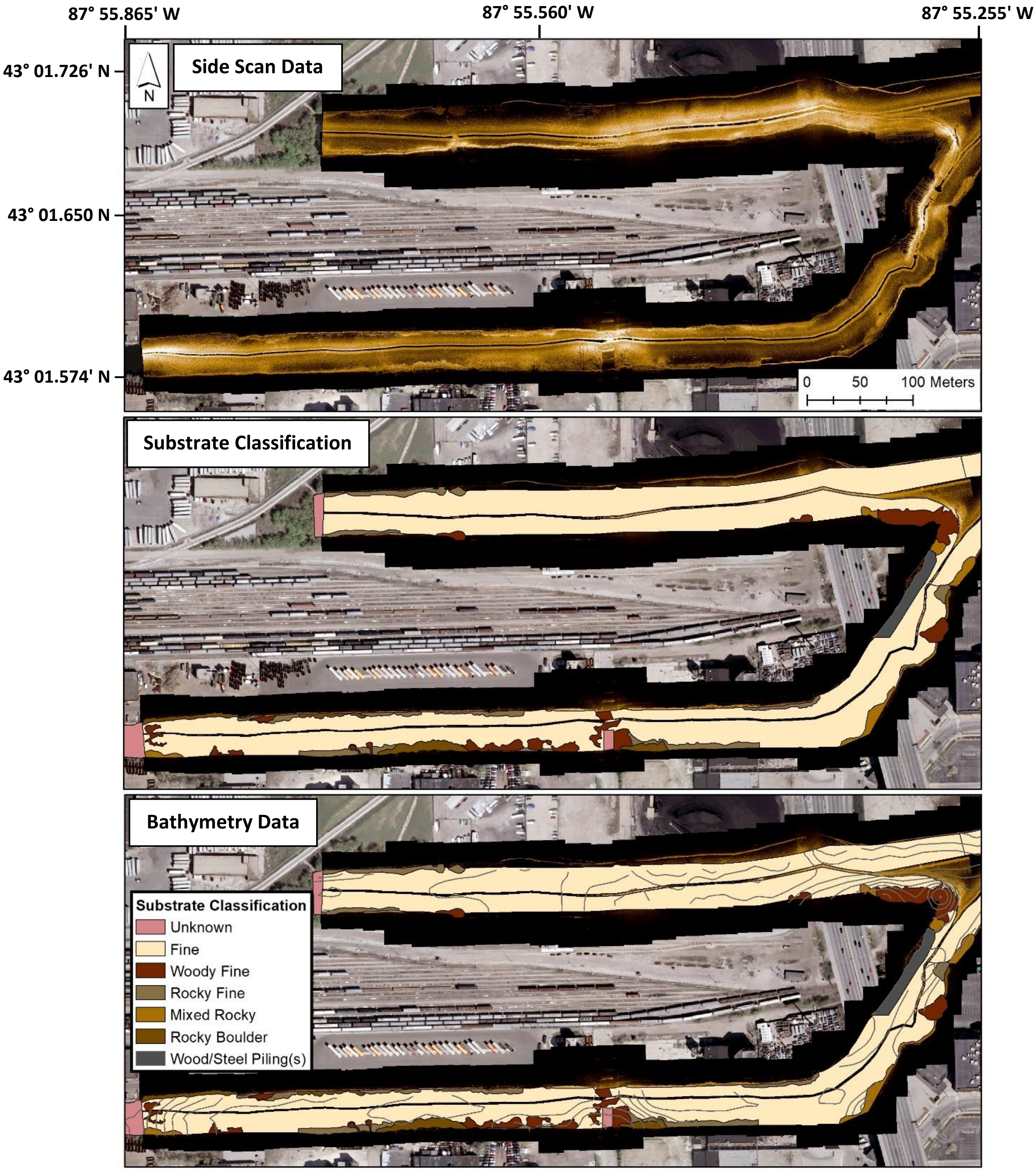


Figure 13. Burnham Canal Multiple ArcMap™ Layers

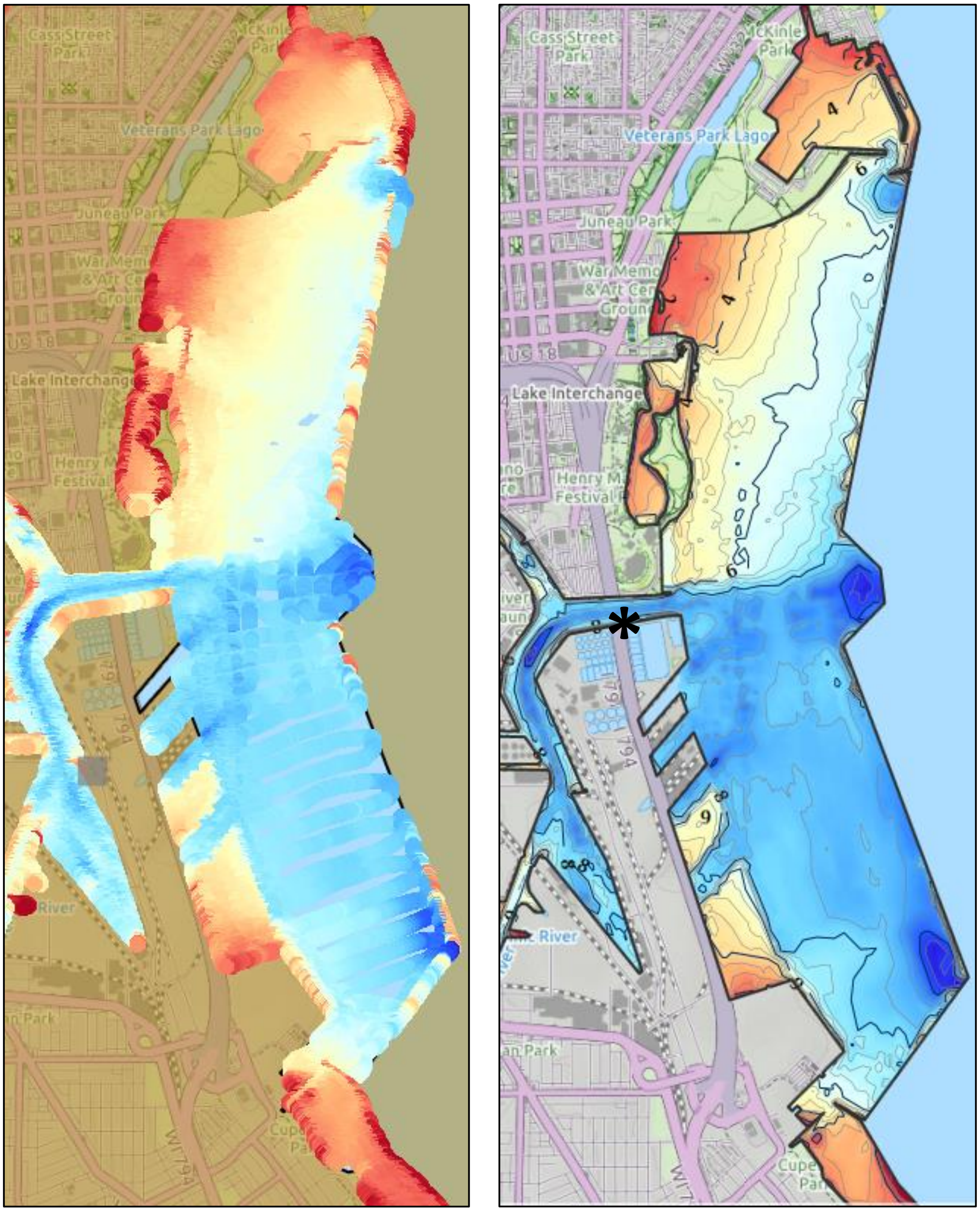


Figure 14. Bathymetry Data ReefMaster© Data

Water depth data (meters) was collected from a Lowrance™ HDS-Gen 3 sonar unit. Data track lines imported on ReefMaster© generated minimum and maximum depths of 0.72m to 11.20m, respectively. Max interpolation was set to 150m with a contour grid smoothing level of 20. Water depth was standardized and corrected based on a one hour resolution to correct for changes in lake level. Data was retrieved from the USGS water-stage recorder and velocity meter at the mouth of the Milwaukee River*.

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