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Aquatic Habitat Mapping in the St. Louis River Estuary

Submitted by:
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Cover Image Caption
Water lily shallow marsh community on the east shore of Clough Island on 14 August 2014. Photo by Carol Reschke.

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INTRODUCTION

The goal of this project has been to use data from recent aquatic vegetation sampling in the St. Louis River estuary to refine aquatic habitat maps for four restoration sites and four reference sites that can serve as models for restoration design and management. These aquatic habitat maps are designed for use by resource managers working to restore impaired habitats.

St. Louis River estuary restoration plans are part of the multi-agency St. Louis River Area of Concern Remedial Action Plan (RAP) to restore fish and wildlife habitats and remove impairments that led to listing the St. Louis River as a Great Lakes Area of Concern (MPCA and WDNR 2013). This 12,000-acre freshwater estuary was designated an Area of Concern in the 1980s because legacy contaminants and disturbances led to nine key impairments, including loss of fish and wildlife habitat.

Current restoration plans rely on aquatic habitat maps prepared for the 2002 Lower St. Louis River Habitat Plan (Appendix 1, Map 1); the original aquatic habitat polygons were drawn using minimal data on aquatic vegetation (SLRCAC 2002). The classification of aquatic habitats used in the 2002 Habitat Plan was qualitative, based primarily on the extensive expertise of local fisheries biologists. Since 2008, biologists in Minnesota and Wisconsin have conducted field surveys yielding over 3000 samples for aquatic and wetland vegetation in 23 key restoration and reference sites within the estuary.

The objectives of this project were to 1) identify restoration site mapping priorities and appropriate reference sites, and compile existing data on aquatic vegetation, water depths, and wind fetch as characterized by relative exposure index (REI) for the estuary; 2) run hydrodynamic models for at least four scenarios of river discharge and Lake Superior water levels and extract data on water velocities and temperatures at vegetation sample sites; 3) use multivariate analyses to classify aquatic habitats based on aquatic and wetland plant communities and associated environmental data, and prepare habitat maps and supporting data for four restoration sites and four reference sites; and 4) share progress on this project with estuary resource managers at least five times during the project period, at meetings of the St. Louis River Estuary Habitat Work Group.

<u>**Background on the St. Louis River Estuary**</u>

The St. Louis River is the largest tributary to Lake Superior on the U.S. side of the lake, and second largest tributary in the Lake Superior watershed. The lower 21 river miles of the St. Louis River include a large (12,000 acre) freshwater estuary where the river is at the same water level as Lake Superior, so river water mixes with Lake Superior water. Wetlands and aquatic habitats in the estuary are influenced by fluctuating water levels driven by both long term water level changes and lake seiche. A seiche (pronounced SAYSH) is a standing wave that oscillates in an enclosed body of water; in the Great Lakes, a seiche is often the result of a storm surge when sustained high winds from one direction push the water towards one end of the lake, and then the water sloshes back and forth in the lake's basin. In the St. Louis River estuary, the seiche can cause a subtle water level fluctuation of just a few inches on most days, but then the water levels can change several feet in a big storm. An incoming seiche can temporarily reverse the flow of the river, so the water flows upstream when the seiche flows in from the lake. River and lake water levels also fluctuate with precipitation patterns. At the lake end of the estuary, a large baymouth bar complex encloses the Duluth-Superior harbor, the largest harbor and busiest international port on the Great Lakes.

METHODS

Data compilation

Existing data on aquatic vegetation, water depths, Secchi depths, and relative exposure index (REI, an index of wind fetch and exposure to waves) were compiled for the estuary, along with NOAA's recently released hyperspectral imagery for the estuary. In addition, we obtained NOAA's shapefiles with classified hyperspectral imagery, which delineates patches of five aquatic plant cover types in the estuary: wild rice, bur-reed, cattail, water lilies, and other emergent vegetation.

The compiled vegetation sample points were reviewed to distinguish vegetated from unvegetated samples and to clarify which points planned for sampling weren't actually sampled. The compiled vegetation data set consisted of 4226 sampled points using multiple sampling methods. From this large data set, 3101 vegetation sample points were selected because they all use the same grid point intercept sampling method (Madsen 1999, MN DNR 2012). Many sample points weren't vegetated; these unvegetated points help us distinguish water depths and velocities that aren't suitable for aquatic vegetation, and they were very useful for mapping open water habitats lacking aquatic vegetation. In this data set of 3101 vegetation sample points, there were 870 points with vegetation present. Only the vegetated sample points were used for vegetation analyses, and this data set was reviewed for outliers and data errors. In a series of analyses, this data set was further reduced to remove samples in the harbor area due to data errors or outliers that were making for ambiguous results. The final data analyses were based on a smaller data set of 1937 sample points, of which 693 had vegetation present, including 47 plant taxa. After statistical outliers were removed and plant taxa present in fewer than 5 samples were removed, the final data set used consisted of 647 vegetation sample points and 39 plant taxa.

Refined bathymetry data ("Lidarbathyslre") were obtained from Jonathan Launspach at EPA's Great Lakes Toxicology and Ecology Division (GLTED). This bathymetry geodatabase included water depths interpolated in the estuary after the catastrophic 2012 flood; it was derived from a combination of 11 measured or scanned water depth data sets, including Minnesota and Wisconsin Lidar imagery that was used together to estimate slopes along the shoreline and provide digital elevation of either depth or height relative to Lake Superior water levels. Earlier bathymetry data had been measured before the 2012 flood caused catastrophic changes, and many shallow areas (less than 0.5m deep) were excluded from earlier bathymetry data sets. It was especially helpful for mapping to have the refined bathymetry that included shallow water depths. Relative exposure index data were also included in the geodatabase provided by EPA-GLTED.

Hyperspectral imagery is a new type of imagery consisting of 128 spectral bands; this hyperspectral imagery of the St. Louis River estuary was obtained from NOAA's website (downloaded from https://coast.noaa.gov/dataviewer/#/imagery/search/-10366823.605839167,5792184.54851289,-9897834.667809458,6064905.609800239). We obtained this imagery thanks to guidance from Brandon Krumwiede, a contractor with NOAA. Brandon also provided a link to shapefiles of interpreted hyperspectral imagery that showed distributions of five emergent and floating-leaf vegetation types (downloaded from ftp://ftp.coast.noaa.gov/pub/manoomin/geospatial/shapefiles/SLRE/). These shapefiles were very helpful for interpreting emergent marsh habitat polygons in areas where few or no vegetation samples had been collected.

Hydrodynamic modeling of water velocity and temperature

Model grid

The St. Louis River estuary hydrodynamic model currently uses a model domain grid generated from bathymetric data prior to the historic June 2012 flood. In 2019, the EPA provided an updated "mash-up" bathymetric dataset for the estuary; however, to date these data need incorporating into an updated model grid. In the existing grid, grid cells consist of horizontal triangular unstructured elements between grid vertices. The entire model (Lake Superior + SLRE Estuary) consists of 13,778 vertices that result in 24,118 triangular grid cells. Approximately 6000 of these vertices are densely located within the St. Louis River estuary. External forcing is generated from all rivers flowing into the estuary (n = 26, Fig. 1, small blue circles), with the focus being hydrodynamic changes resulting from low vs. high flows entering from the St. Louis River (Fig. 1, large red circle).

The bathymetric data from before the 2012 flood reveal depths range from 0.5m (SLRE model minimum) to approximately 12m approaching the Duluth entry canal (Fig. 2). Depths quickly increase to 20m+ once outside of the SLRE and into Lake Superior; however, this region is not the focus of this study, therefore the colorscale in Fig. 2 saturates at depths greater than 20m. Each surface element extends the full depth of the SLRE model and divides into 20 equal depth cells. Cell surface area in the SLRE model domain ranges from approximately 1000m^2 – 10,000m^2 (Fig. 3) and cell volumes range from approximately 100m^3 – 3000m^3 (Fig. 4). Cell surface area and volume increases exponentially in the larger Lake Superior domain. While the physics in the Lake Superior domain are solved during each model time step, analysis and representation of the model results outside of the SLRE domain are not of interest for this study.

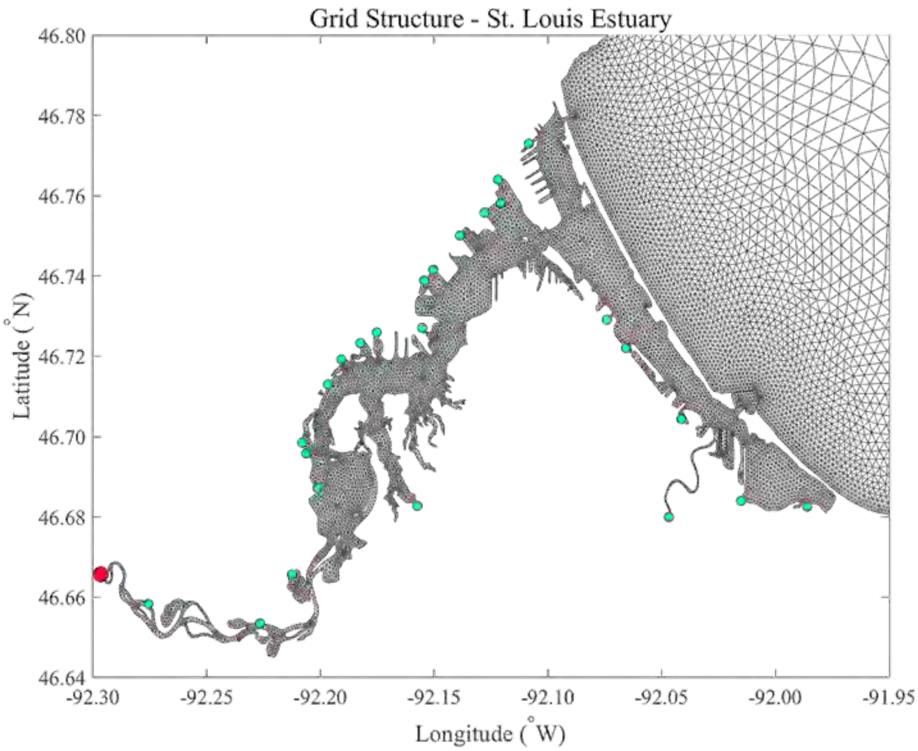

Figure 1. St. Louis River estuary model mesh (surface view). External forcing results from river/stream inflow with locations indicated by small blue circles. The St. Louis River inflow condition originates at the large red circle location and is the main parameter varied in this study.

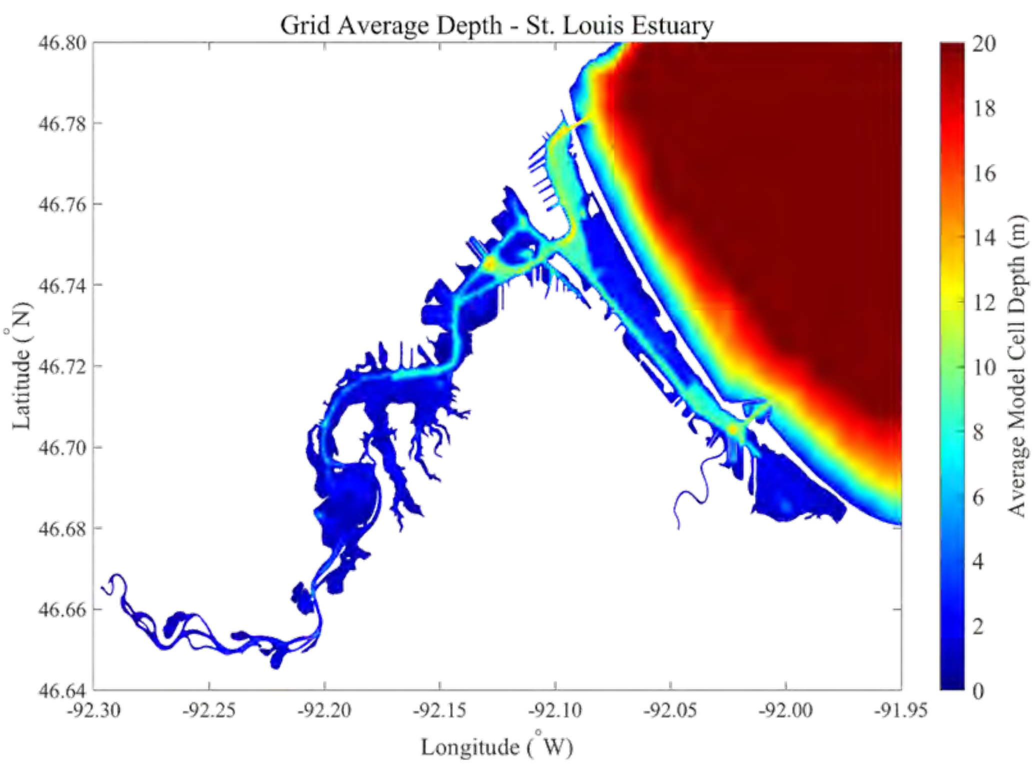

Figure 2: SLRE model depths. Model bathymetry from pre-2012 flood. Color scale saturates at 20m and deeper.

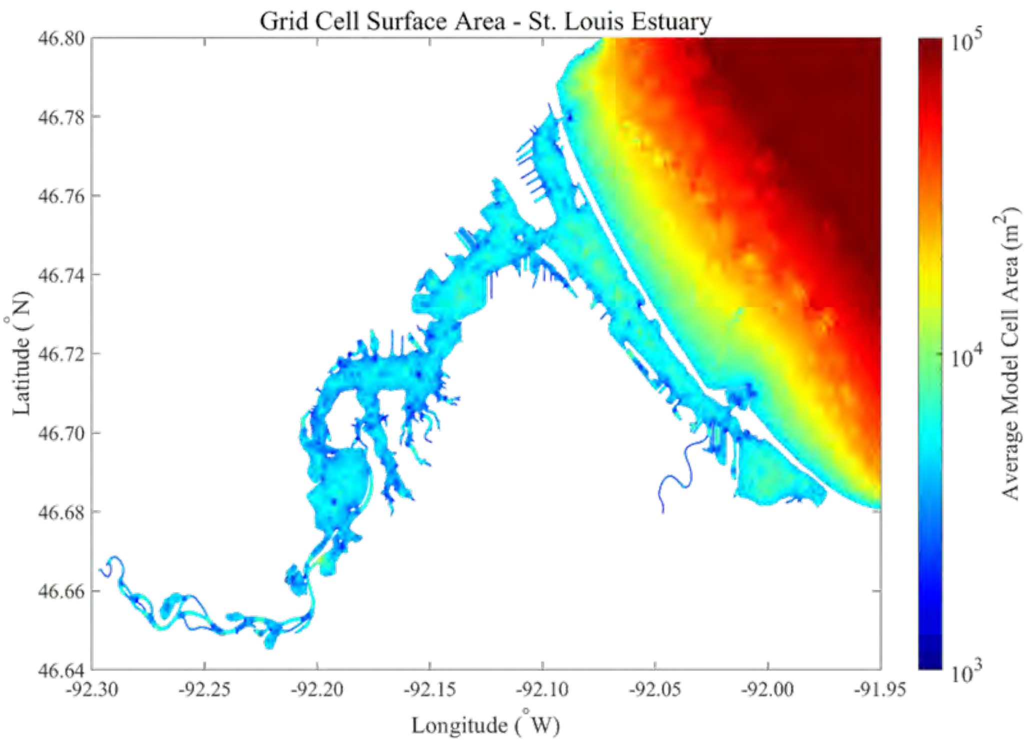

Figure 3: SLRE model grid cell surface area. Model bathymetry from pre-2012 flood.

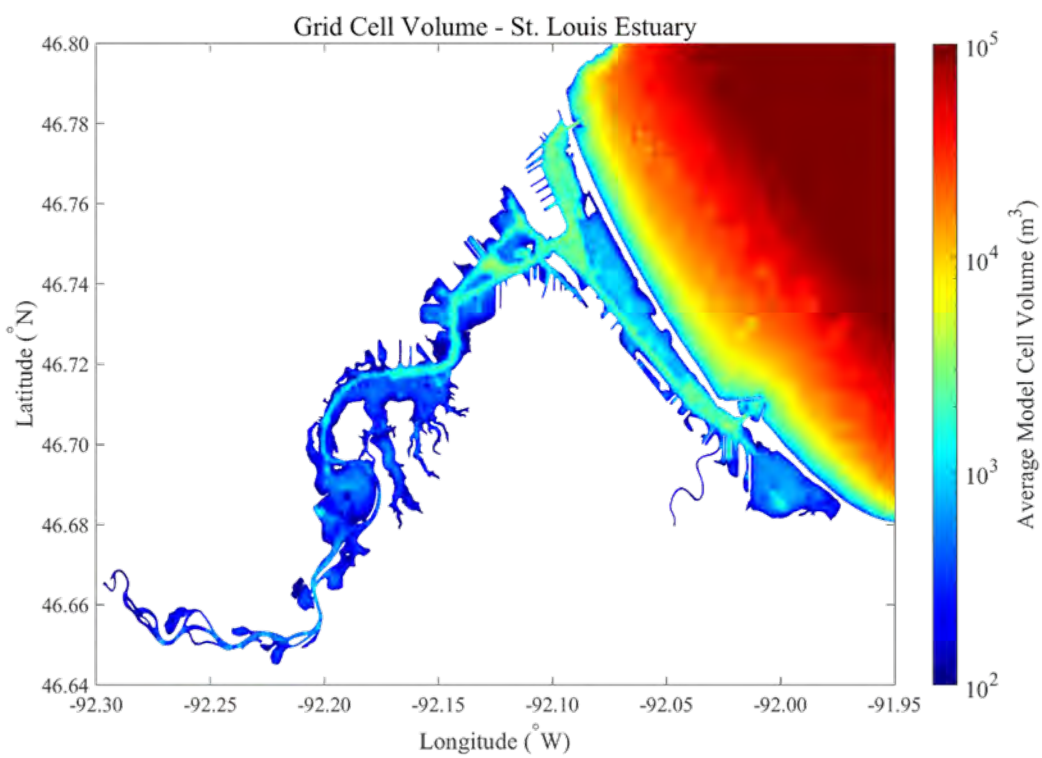

Figure 4: SLRE model grid cell volume. Model bathymetry from pre-2012 flood.

June 2012 Flood

A historic flood inundated the St. Louis River and estuary during June of 2012. The USGS Gauge 04024000 on the St. Louis River near Scanlon, MN measured a discharge and approximately m^3/s (ft^3) (Fig. 5). As a comparison, the SLRE hydrodynamic model simulated this period to highlight differences between low flow and historic flood levels (Figs. 6 and 7).

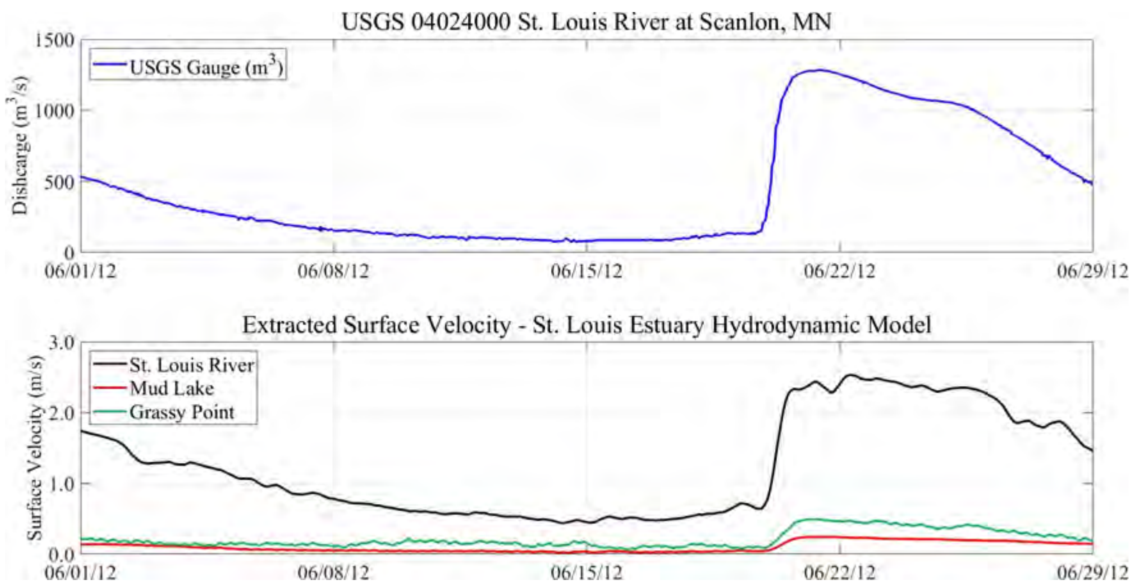

Figure 5: (top) Volumetric discharge from the USGS station on the St. Louis River for June 2012; (bottom) Extracted SLRE model surface velocities for three stations during the same time period.

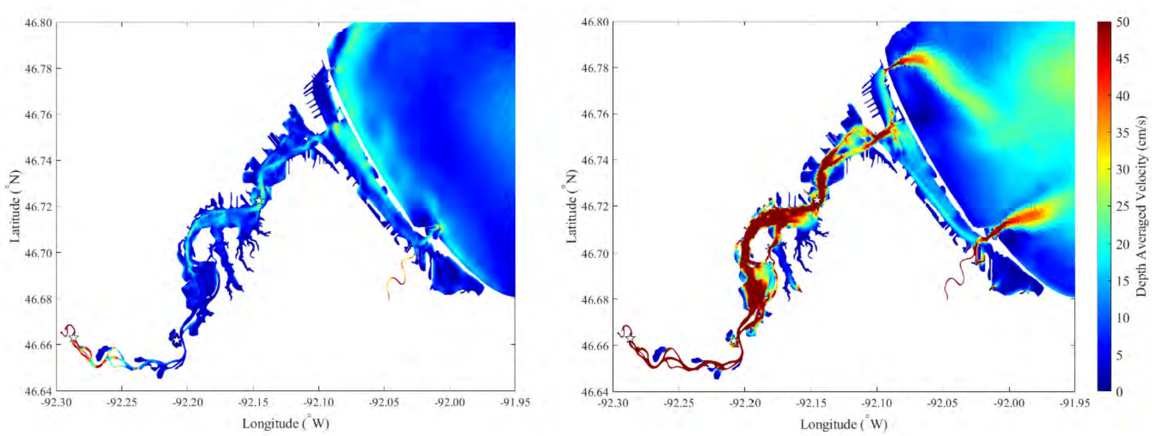

Figure 6: Depth averaged velocity from St. Louis River estuary hydrodynamic model output from (left) low flow conditions on June 15, 2012 and (right) flood conditions on June 21, 2012. Color scales kept equivalent between the two figures; however, velocities far exceeded 0.5m/s in the St. Louis River and Estuary during the June 21, 2012 flood, as illustrated in the previous Figure 5. Data in Figure 5 extracted from locations of white stars (St. Louis River upstream location, Mud Lake, and Grassy Point).

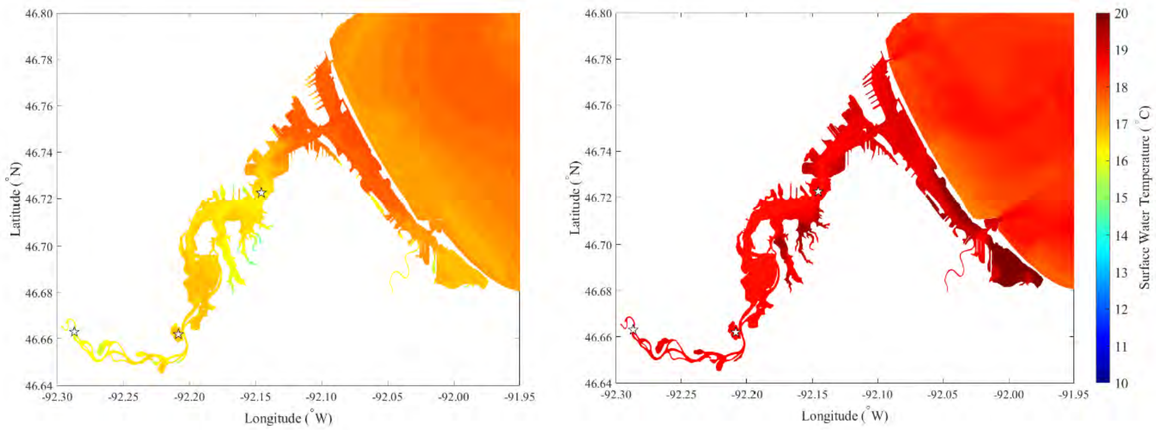

Figure 7: Surface water temperature from St. Louis River estuary hydrodynamic model output from (left) low flow conditions on June 15, 2012 and (right) flood conditions on June 21, 2012. Color scales are equivalent.

NRRI and WDNR Sampling Locations

There are 3101 locations within the St. Louis River estuary where NRRI and WDNR have collected environmental data and aquatic vegetation samples. The NRRI subset of these locations (1086 locations) is shown in Figure 8. Using GPS data from these sampling locations, we are able to extract model data to investigate relationships between hydrodynamics in the St. Louis River estuary and the sampled vegetation. An example of extracted model data was illustrated earlier in Figure 5, where timeseries data were extracted for three locations: near the St. Louis River model domain inlet, one from Mud Lake, and one from Grassy Point. Extracted data come from hydrodynamic modeling of the 2012 flood.

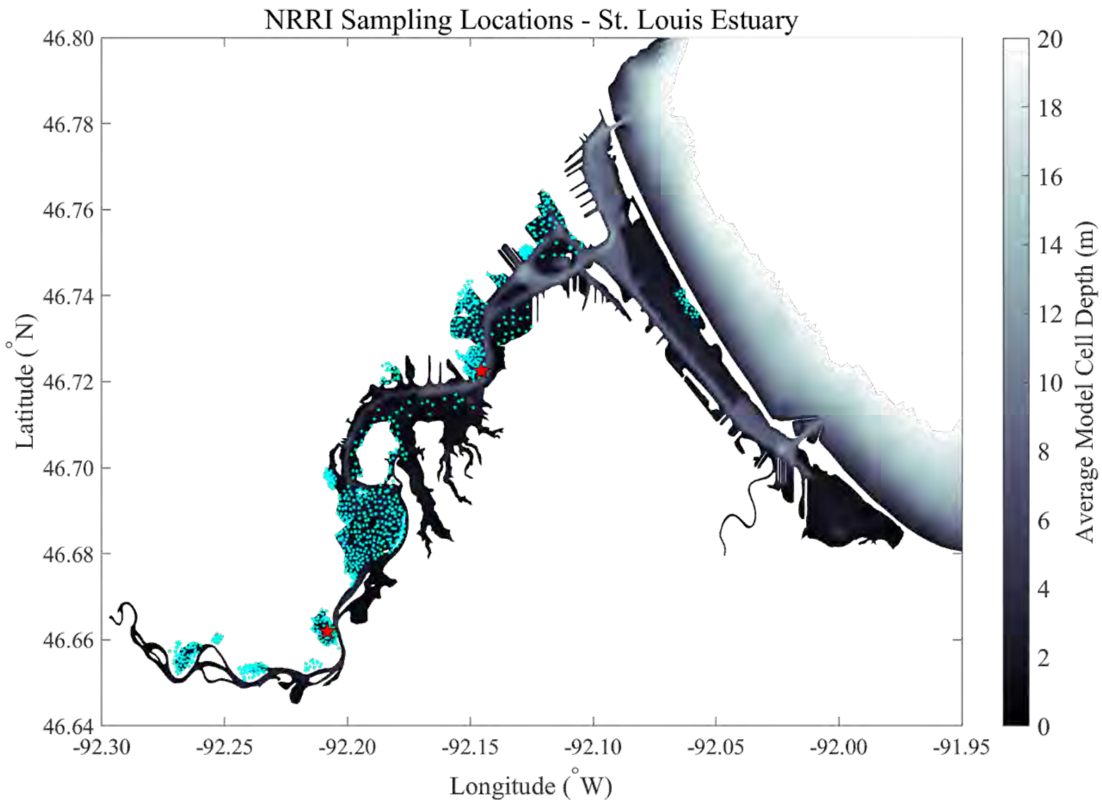

Figure 8: NRRI environmental and aquatic vegetation sampling locations throughout the St. Louis River Estuary, represented by the blue dots. Red stars show locations that SLRE model data were extracted and plotted in the previous Figure 5.

Modeling Scenarios

This project models hypothetical scenarios for the St. Louis River estuary, which is a different approach from how the hydrodynamic model is typically run. In order to generalize results for this project and minimize the number of external variables, all meteorological forcing (winds, solar radiation, precipitation, waves, etc.) were turned off in the model. The initial conditions for the SLRE hydrodynamic model were defined with zero velocity (U = 0 m/s, V = 0 m/s), a constant temperature and salinity across the full depth (T = 15C, S = 0). To determine low flow and high flow conditions to simulate, a flood frequency analysis was performed on data from the USGS Gauge 04024000 from the St. Louis River (Fig. 9, left). Similarly, the water levels in the Duluth-Superior harbor were analyzed to determine what is considered low water vs. high water elevations (Fig. 9, right). Using these results, a project modeling matrix was developed (Table 1). Low flow is considered to match bankfull discharge in the river (~12,741 ft^3/s), while high flow is considered to be the 100-year flood stage (~40,471 ft^3/s). Similarly, low water levels are considered to have an elevation of 183m, whereas high water levels are considered to be 183.6m, on average. Two more modeling scenarios were added later, one for moderate flows approximating a 10-year flood stage (~26,000 ft^3/s) and an extreme flow approximating a 500-year flood stage (~50,002 ft^3/s).

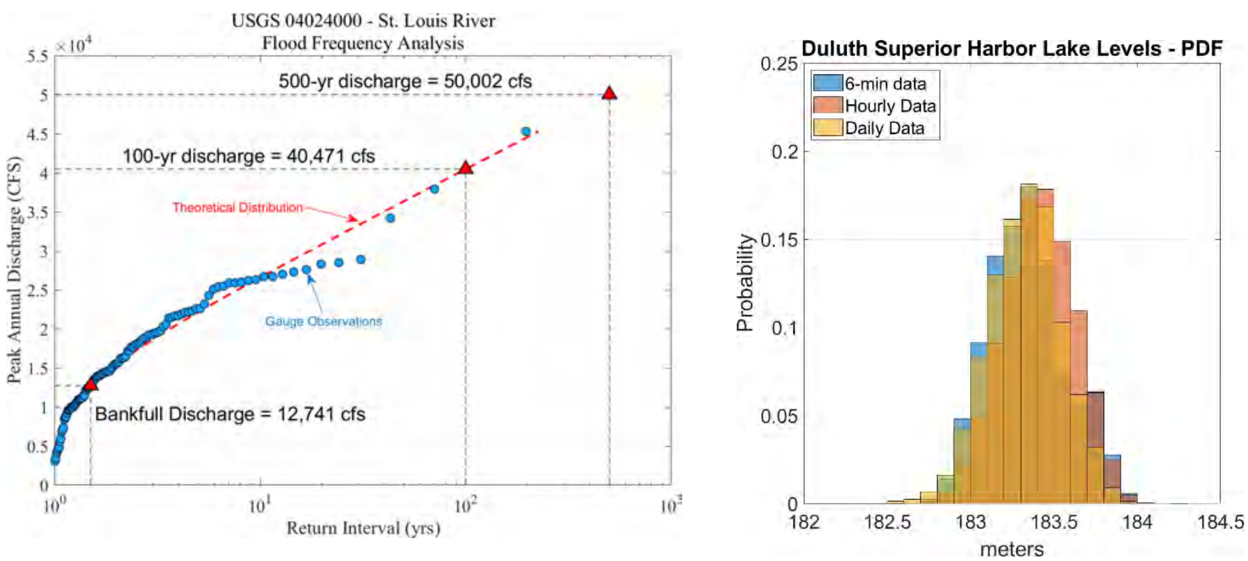

Figure 9: Flood frequency analysis from the St. Louis River (left) and water surface elevation data for the Duluth-Superior harbor (right).

Table 1: Project modeling matrix for low and high flows and water levels.

		Lake Superior Water Level (m)	
		Low	High
St. Louis River Discharge (cfs)	Low	Z = 183.0 m Q = 12,741 cfs	Z = 183.6 m Q = 12,741 cfs
	High	Z = 183.0 m Q = 40,471 cfs	Z = 183.6 m Q = 40,471 cfs

SLRE Model Results

Data from four hydrodynamic model scenarios (low discharge, medium discharge, high discharge, and extreme/flood discharge) were extracted data for 3101 sampling locations in the estuary. Data were extracted from all periods between 2008 to 2018 model runs, even after the physical aquatic vegetation samples were collected. Variables extracted for each scenario included minimum, average, and maximum bottom velocities; minimum, average, and maximum water surface velocities; minimum, average, and maximum depth-averaged velocities; minimum, average, and maximum bottom temperatures; minimum, average, and maximum water surface temperatures; and minimum, average, and maximum depth-averaged temperatures. The results extracted 18 variables for each of four discharge scenarios, for a total of 72 water velocity and temperature variables that were extracted from runs of the hydrodynamic model.

Vegetation classification and analysis

Iterative classification and ordination analyses were run to identify meaningful aquatic habitats and wetland plant communities. The best classification results relied on splitting the data set into two overlapping groups and running two separate classifications, and then comparing the classes for the whole data set using ordinations to evaluate the classes that best reflected environmental gradients.

The final data analyses were based on a data set of 1937 sample points after sample points from the harbor area had been omitted. For this data set of 1937 sample points, 693 had vegetation present, including 47 plant taxa. Analyses were run using PCORD 7 software (McCune and Grace 2002). After statistical outlier samples were removed and plant taxa present in fewer than 5 samples were removed, the final data set used consisted of 647 vegetation sample points, 39 plant taxa, and 99 environmental variables. Some of the outlier samples were from emergent marsh or floating mat vegetation samples. This final data set of presence/absence data was transformed with Beals smoothing (Beals 1984, McCune and Grace 2002). A flexible beta classification of the 647 vegetation samples x 39 plant taxa was run, and cluster membership was identified for the uppermost 8 groups in the classification dendrogram; percent chaining in the classification dendrogram was 2.50.

This data set was then run with Bray-Curtis ordination, overlaying the five group levels of the classification, and the results were good, but the ordinations showed no significant correlations with velocity data, which had been observed in previous analyses of a subset of this data set. The classification groups overlapped in the center of the Bray-Curtis ordination, so the data set into two overlapping subsets: one with primarily floating-leaf and submerged vegetation and a second with primarily emergent vegetation. Then, the best classification results from those two classification runs were combined into seven lumped classes, and these groups were evaluated in both Bray-Curtis and Fuzzy Set ordinations. As a result of this evaluation, two groups were combined: one from the emergent classification and one from the submerged and floating-leaf classification, and that yielded the final six plant community types that were used to map aquatic habitats. Four variations of Fuzzy Set ordination were run with different combinations of key environmental variables constraining the ordination. The best results were in the fourth variant, with five environmental variables constraining the ordination: water depth, relative exposure index, extreme discharge maximum depth-averaged water velocity, average night lights, and taxa richness. The ordination was rotated a few degrees to provide the clearest correlations with environmental variables, and the resulting ordination is shown in Figure 10.

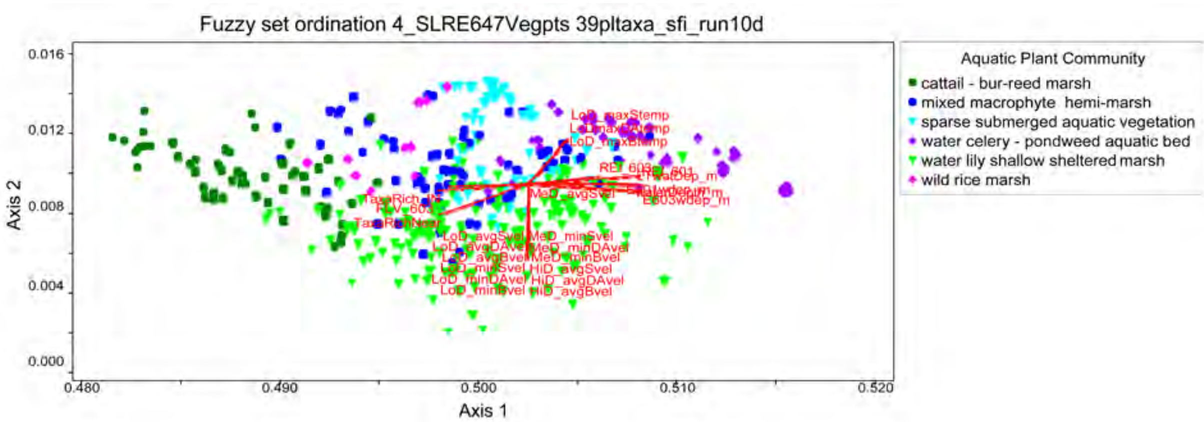

Figure 10: Fuzzy set ordination of 647 vegetation sample points and 39 plant taxa using Beal's smoothing transformation. Red vectors indicate significant correlations of ordination axes with environmental variables. Axis 1 is strongly correlated with water depths, relative exposure index, and taxa richness; Axis 2 is strongly correlated with minimum and average velocities in low, medium and high discharge scenarios, and with maximum temperatures in the low discharge scenario.

The final aquatic habitat classification included six plant community types and a seventh aquatic habitat for open water lacking any vegetation. The six plant community types are: cattail – bur-reed marsh (Photos 1 and 2), water lily shallow marsh (Photos 1, 3, and 4), mixed macrophyte hemi-marsh (Photos 5 and 6), wild rice marsh (Photo 7), water celery – pondweed aquatic bed, and sparse submerged aquatic vegetation. Of these, only five types consistently occurred in the eight sites to be mapped. Wild rice marsh was observed in Rask Bay in 2014 (Photo 7), but in most years rice is very sparse in Rask Bay due to overbrowsing by geese, and for this project that area in Rask Bay was mapped as mixed macrophyte hemi-marsh. All the wild rice marsh sample points in the classified data set were from Pokegama River wetlands, southeast of Clough Island, and therefore not included in the eight sites mapped for this project. The strongest environmental factors correlated with plant community composition were water depths, relative exposure index, taxa richness, water velocities, and water temperatures.

Mapping aquatic habitats and plant communities

After a suitable classification was refined, the outliers and omitted data were reviewed to assign those sample points to the closest of the six vegetation types, and a point shapefile was created to show the location of each of 1937 vegetation sample points and the habitat/plant community type assigned to that sample. This point shapefile was displayed in GIS (ArcMap 10.7) along with recent satellite imagery (Appendix 1, Map 4), NOAA's 2018 hyperspectral imagery, and maps of water depths (Appendix 1 Map 6), relative exposure index (Appendix 1, Map 7), water velocity (Appendix 1, Map 8) and water temperatures (Appendix 1, Map 9).

Aquatic vegetation tends to be patchy, so polygons were drawn to reflect the dominant vegetation type sampled within each polygon, as well as interpreted from imagery and environment maps. Emergent and floating leaf plant community polygon borders were drawn primarily from vegetation texture and color in the imagery that included fairly consistent vegetation types at sample points within the polygon. NOAA's classified hyperspectral imagery was especially helpful to identify emergent vegetation, but it was sometimes difficult to distinguish between coarse-textured cattail – bur-reed marsh and adjacent shrub swamps in the imagery. So some cattail – bur-reed marsh polygons may include patches of shrub swamp (mainly alders and willows).

Submerged aquatic vegetation and open water (lacking vegetation) were mapped primarily using water depths and vegetation sample data, with some checking REI and water velocities. The final polygons were digitized, attribute tables populated, and metadata completed. A set of maps was produced showing the locations of the eight sites in the estuary along with maps of key environmental factors used to classify and map polygons, so you can see the patterns of water depths, relative exposure index, water velocities and water temperatures throughout the study area (Appendix 1, Maps 2 – 10). Then, for each of the eight sites, two aquatic habitat maps were produced, one solid shaded map color-coded by habitat type and a second map showing only the boundaries of the polygons so the color and texture patterns in the imagery can be seen within each polygon (Appendix 1, Maps 11 – 18). Final polygon shapefiles and metadata have been uploaded to NRRI's Data Portal (https://data.nrri.umn.edu/data/). Most project goals were met, except that there was insufficient time to calculate vegetation quality metrics for plant communities at each site. However, current plans are to do that as part of another project funded by the U.S. Fish and Wildlife Service, and the attribute tables can be updated when those vegetation quality data are available. When we learned about the EPA-GLTED's updated bathymetry data, we hoped to refine the hydrodynamic model grid to reflect the updated water depth data; however, refining the model grid is a very time-consuming process that turned out to be beyond the scope of this project.

RESULTS

Resource managers are working to restore impaired aquatic habitats in the St. Louis River estuary, which has been designated a Great Lakes Area of Concern (AOC) due to nine Beneficial Use Impairments (BUIs) identified for this AOC. Project results provide resource managers with updated and refined aquatic habitat and wetland plant community maps for eight sites within the estuary. These maps are intended to assist with documentation of restoration efforts aimed at addressing BUI 9: Loss of Fish and Wildlife Habitat. This project focused on four reference sites (Rask Bay, Weasel Bay, North Bay, and Clough Island) and four restoration sites (Perch Lake, Mud Lake, Spirit Lake, and Kingsbury Bay) where restoration planning and/or activities are underway. These eight maps (Appendix 1, Maps 11 – 18) are examples of what can be produced for the entire estuary, in an effort to update maps from the 2002 Habitat Plan. The need for updated habitat maps has been discussed by the St. Louis River Habitat Work Group. For the restoration sites, these maps document conditions present before habitat restoration activities (e.g. construction, dredging, filling, planting, and management) were initiated. These maps document initial conditions prior to restoration efforts, and they can be compared to later maps to document changes in aquatic habitat and wetland plant community acreages and extent as restoration efforts proceed. They may also be useful in long-term monitoring of wetland and aquatic habitats in the estuary. Funding from MLSCP was essential to facilitate this mapping effort and illustrate to resource managers the usefulness of detailed aquatic habitat maps.

ACKNOWLEDGEMENTS

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Matching funds for preparation of this report were provided by the University of Minnesota Duluth, Natural Resources Research Institute (NRRI). The data discussed in this report were collected by staff of NRRI and Wisconsin DNR (WDNR) from 2009 through 2016 using a combination of Federal and State funds from the Minnesota Pollution Control Agency (MPCA); Krech, Ojard & Associates; the U.S. Fish and Wildlife Service (USFWS); and the Wisconsin Department of Natural Resources (WDNR).

Jay Austin and Dan Tietze contributed ideas on using their hydrodynamic model for the design of this project, and Craig Hill ran the hydrodynamic model and extracted data from the model for thousands of locations of vegetation samples. Carol Reschke ran vegetation analyses and digitized map polygons. Jonathan Launspach provided data developed by EPA-GLTED on bathymetry and relative exposure index. Brandon Krumwiede provided links to hyperspectral imagery developed by NOAA as part of the Lake Superior Manoomin Project. Kristi Nixon helped download and compile environmental data used in analyses. The aquatic habitat classification and mapping methods were refined following discussions with and/or comments from Brandon Krumwiede, Hannah Ramage, Daryl Peterson, Dave Warburton, Reena Bowman, Kristi Nixon, Annie Bracie, Katya Kovalenko, Val Brady, and George Host. Kristi Nixon and Kate Carlson, and Brandon Krumwiede provided assistance with use of ArcMap software. Cynthia Poyhonen provided essential support and patience throughout this project. The authors are grateful for the contributions, discussions, and comments provided; any errors or omissions in this report are the responsibility of the first author, who compiled this report.

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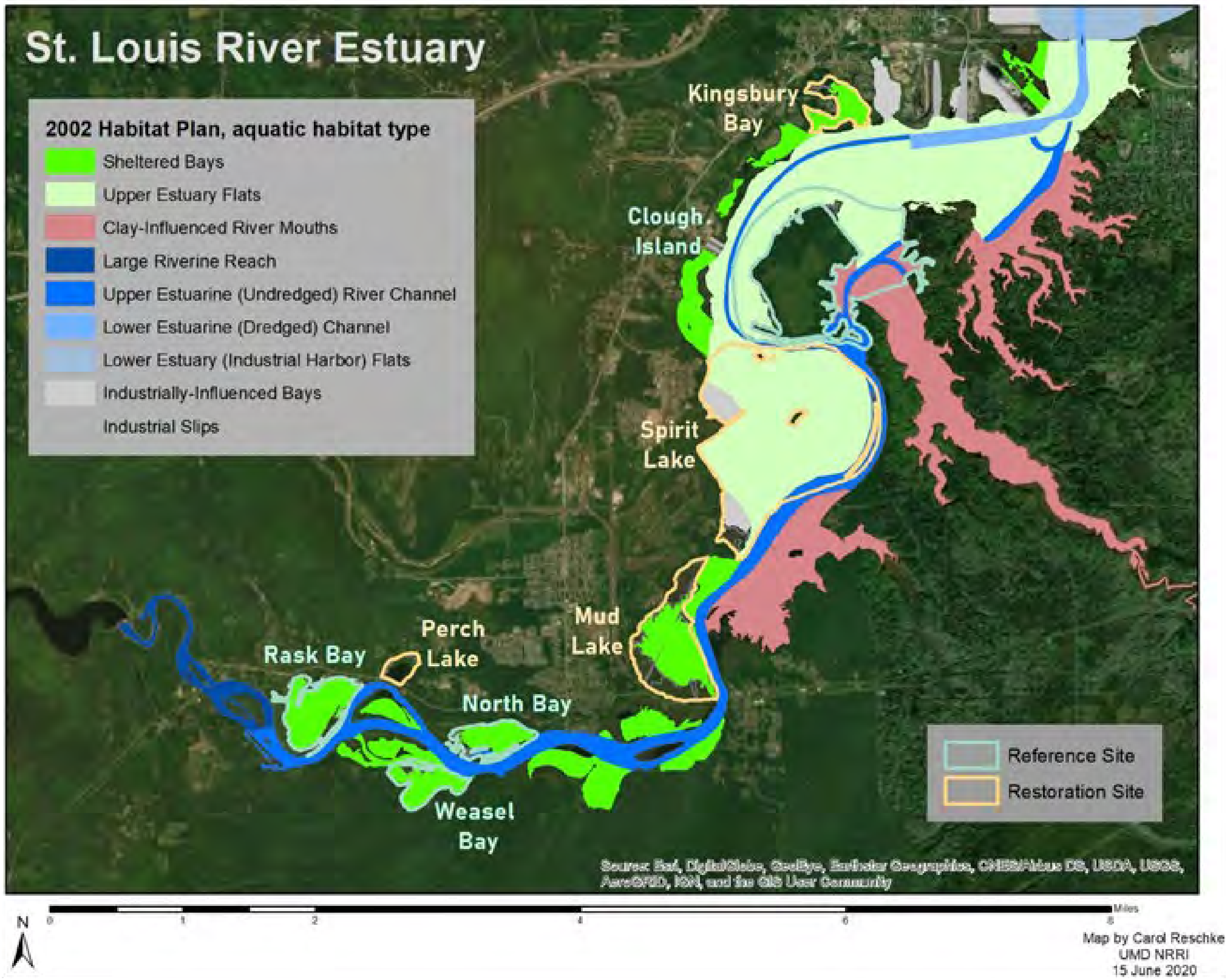
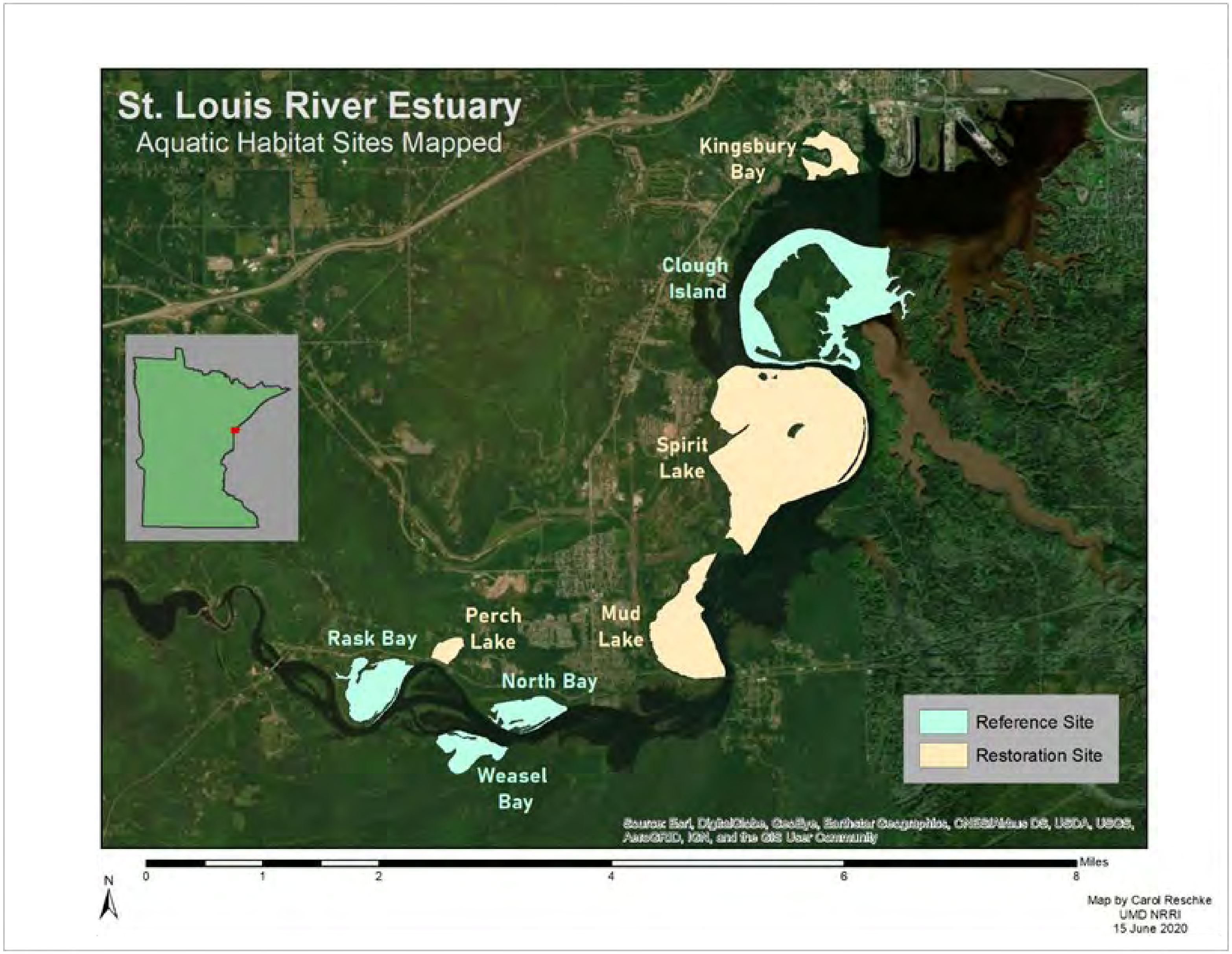
APPENDIX 1: Maps and Photos

This report was prepared by Carol Reschke and Craig Hill using Federal funds under award NA18NOS4190081, Project No. 18-306-12, from the Coastal Zone Management Act of 1972, as amended, administered by the Office for Coastal Management, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce provided to the Minnesota Department of Natural Resources (DNR) for Minnesota's Lake Superior Coastal Program. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of NOAA's Office of Coastal Management, the U.S. Department of Commerce, or the Minnesota DNR.

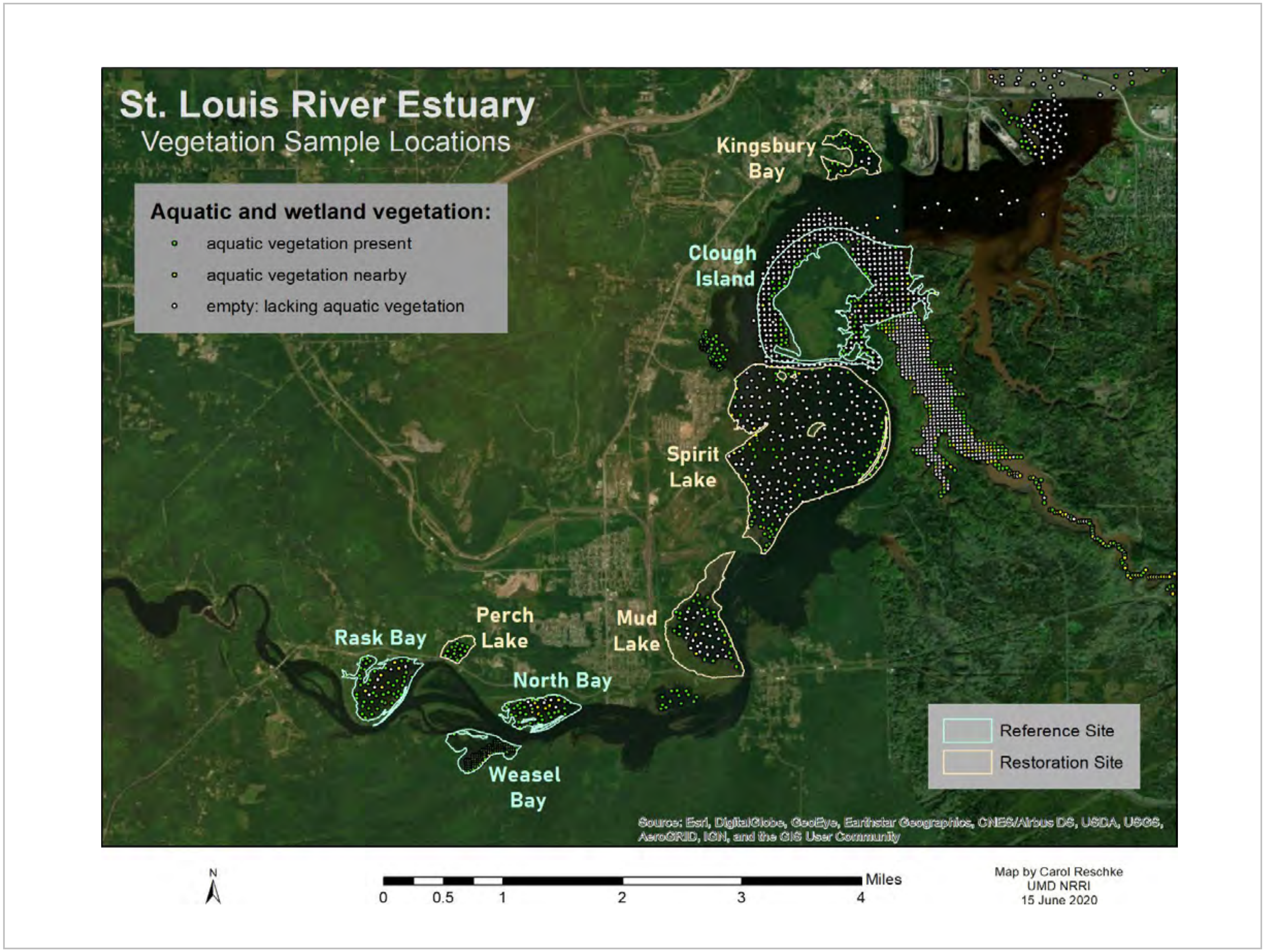
Map 1: Aquatic habitat types mapped in the 2002 Habitat Plan, with outlines of eight sites mapped for this project. Most of the eight sites fall within only one of the 2002 Habitat Plan aquatic habitat types; one site (Perch Lake) wasn't included in the 2002 map.



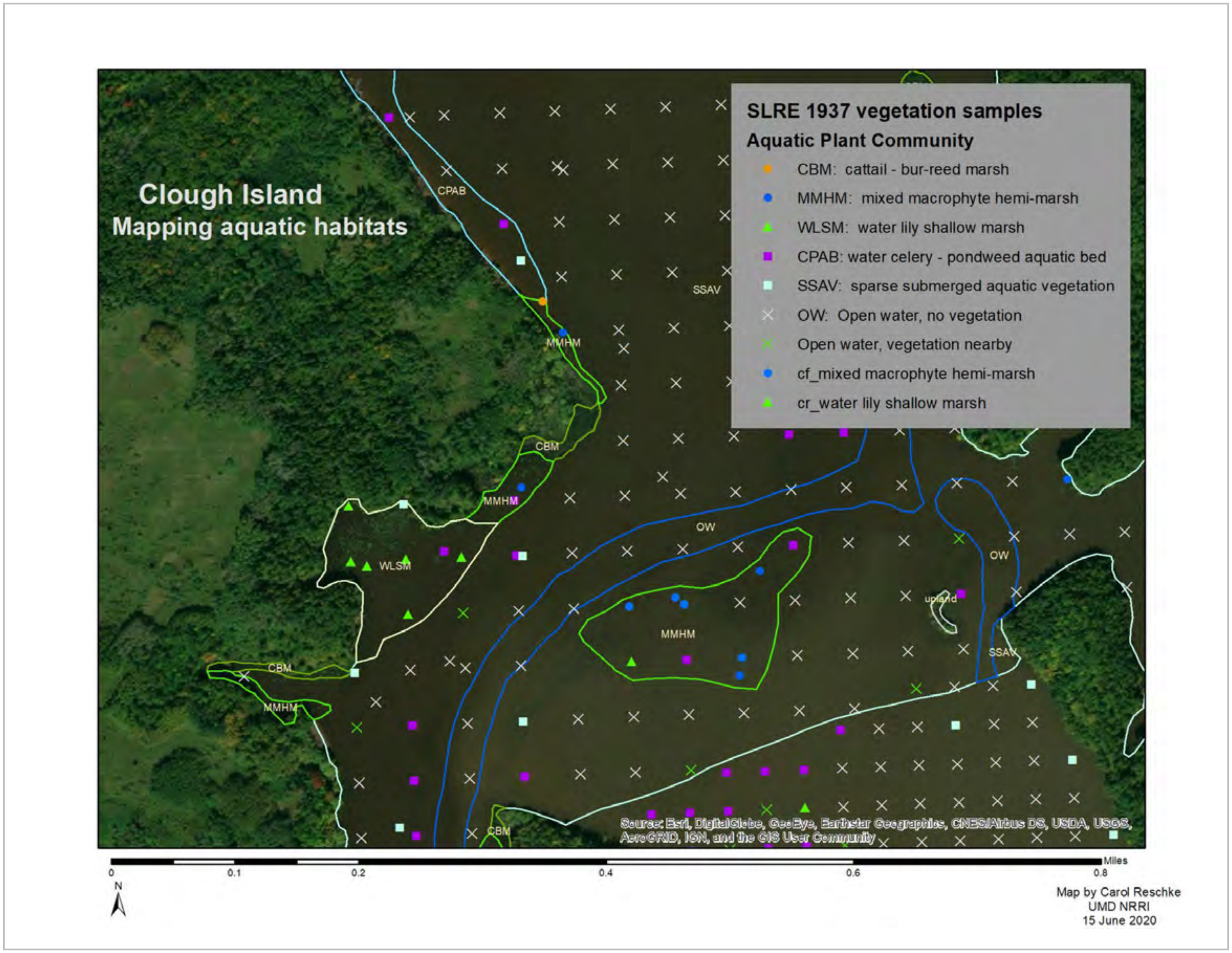
Map 2: Location of eight sites mapped, four reference and four restoration sites.



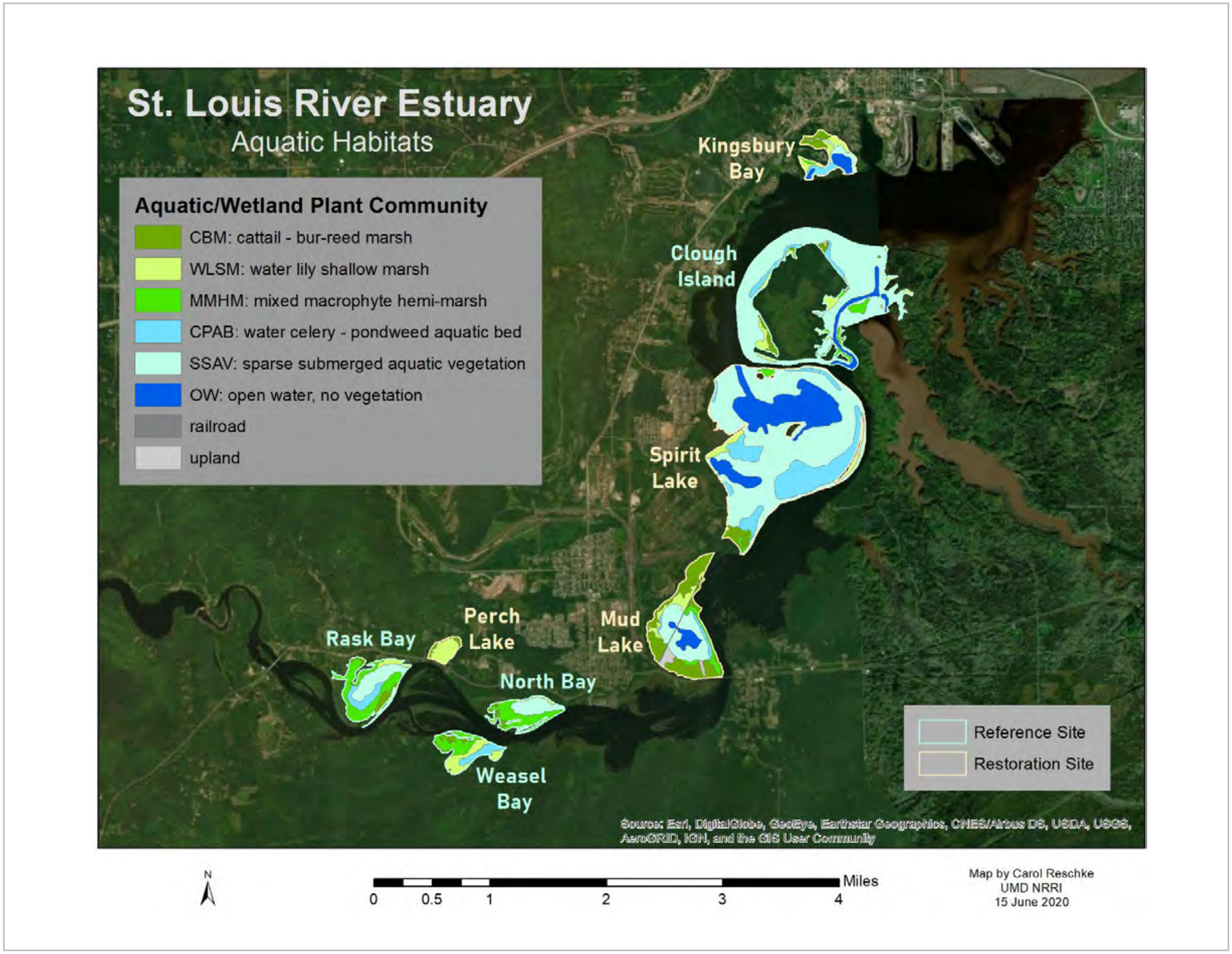
Map 3: Location of vegetation sample points used to classify aquatic habitats and wetland plant communities at eight sites. Green dots indicate vegetated sample points, yellow dots had vegetation nearby, and white dots indicate lack of any vegetation.



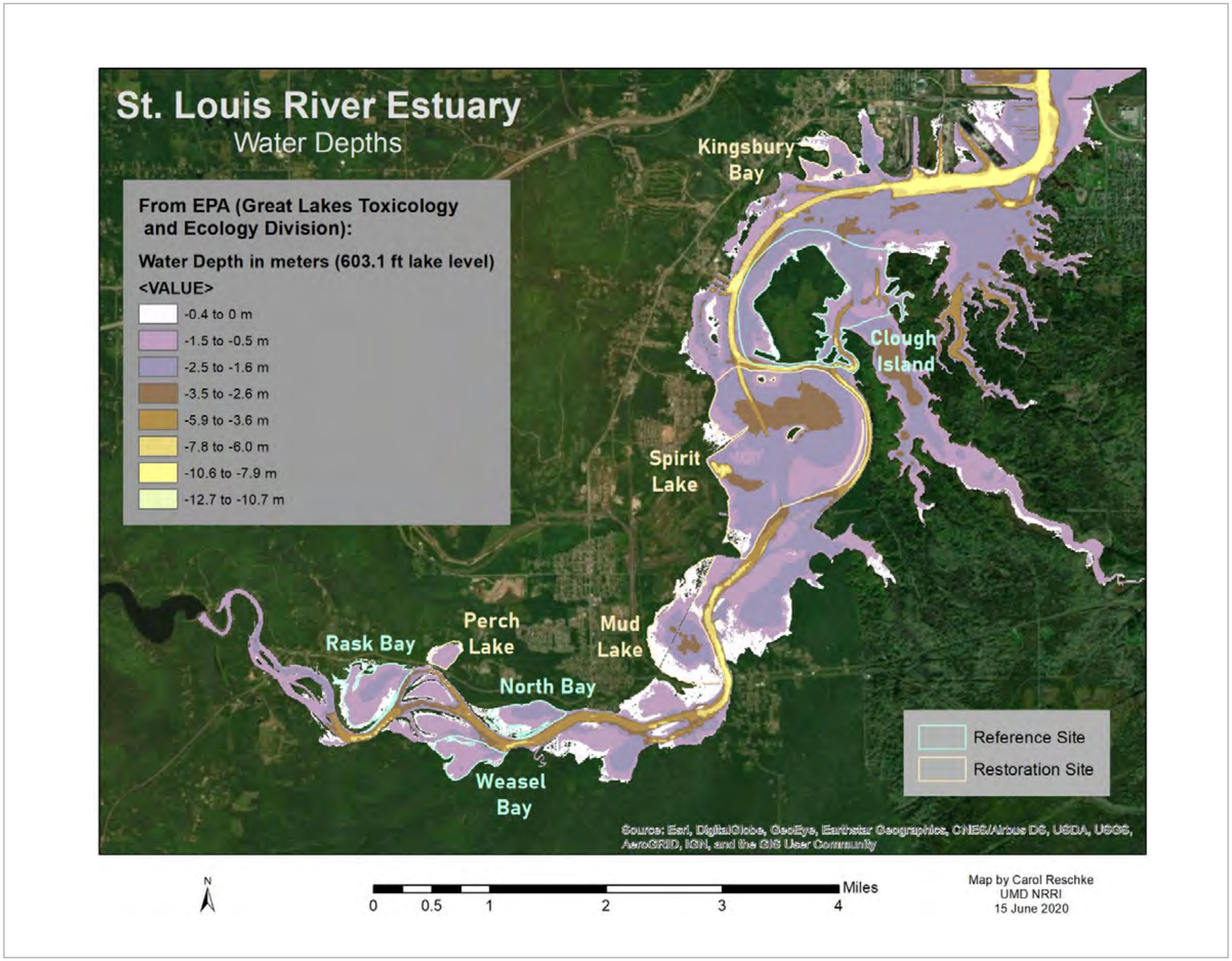
Map 4: Close-up of northeast shore of Clough Island imagery showing locations of classified vegetation sample points used to assist in interpreting aquatic habitat and plant community polygons.



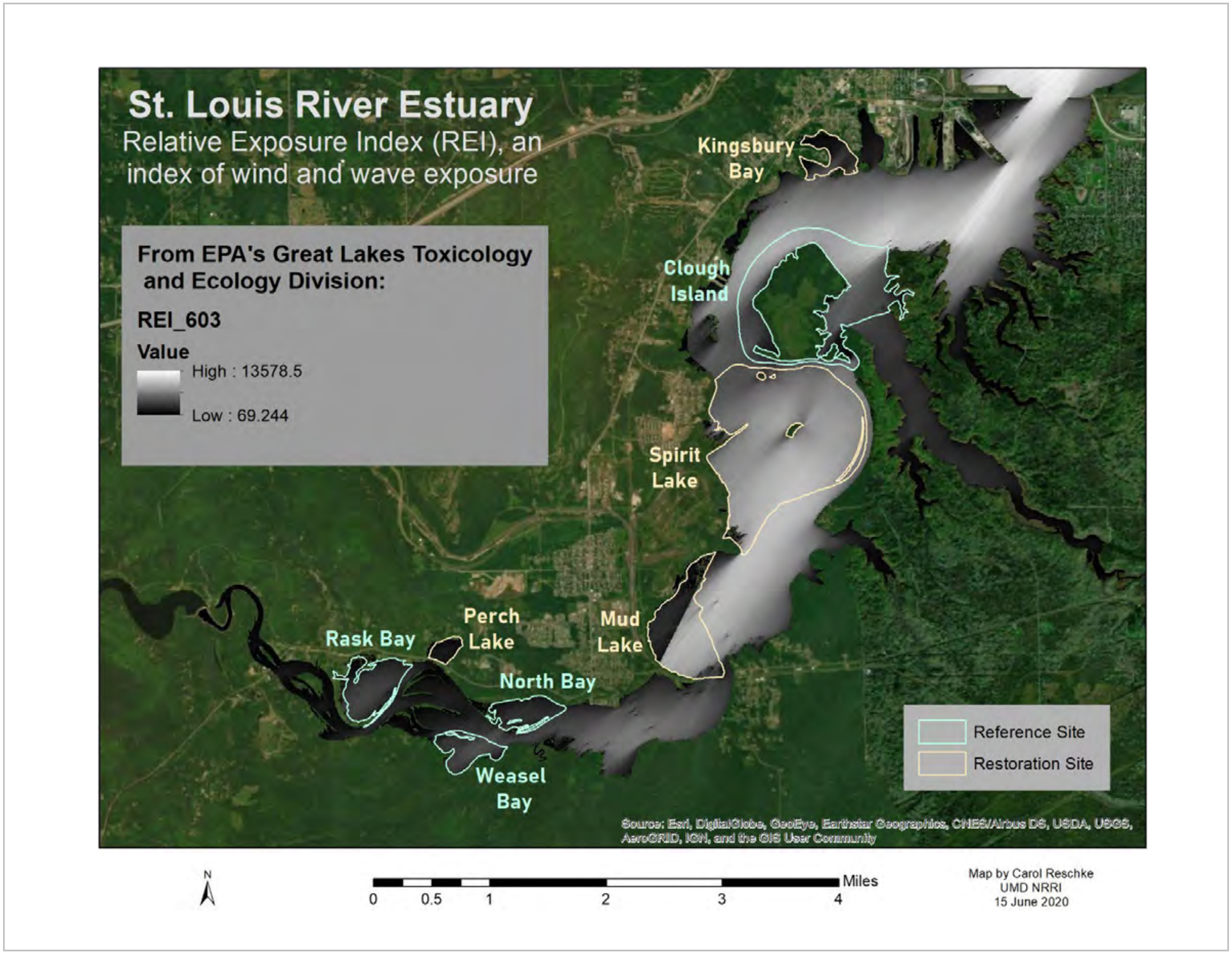
Map 5: Aquatic habitats and wetland plant communities mapped at eight sites.



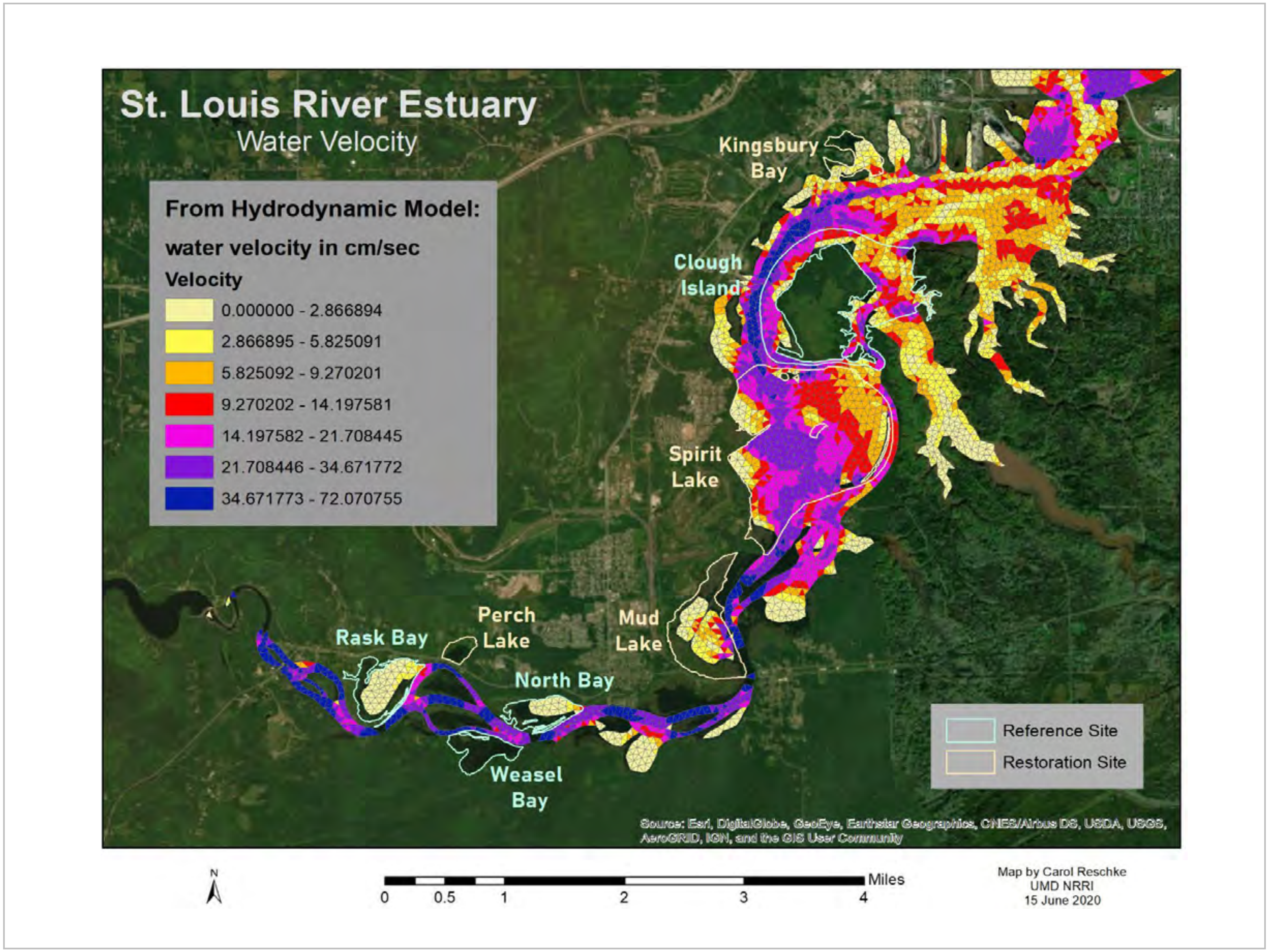
Map 6: Water depths (m) assuming high Lake Superior water levels at 603.1 ft elevation, from a geodatabase developed by EPA's Great Lakes Toxicology and Ecology Division in Duluth, Minnesota.



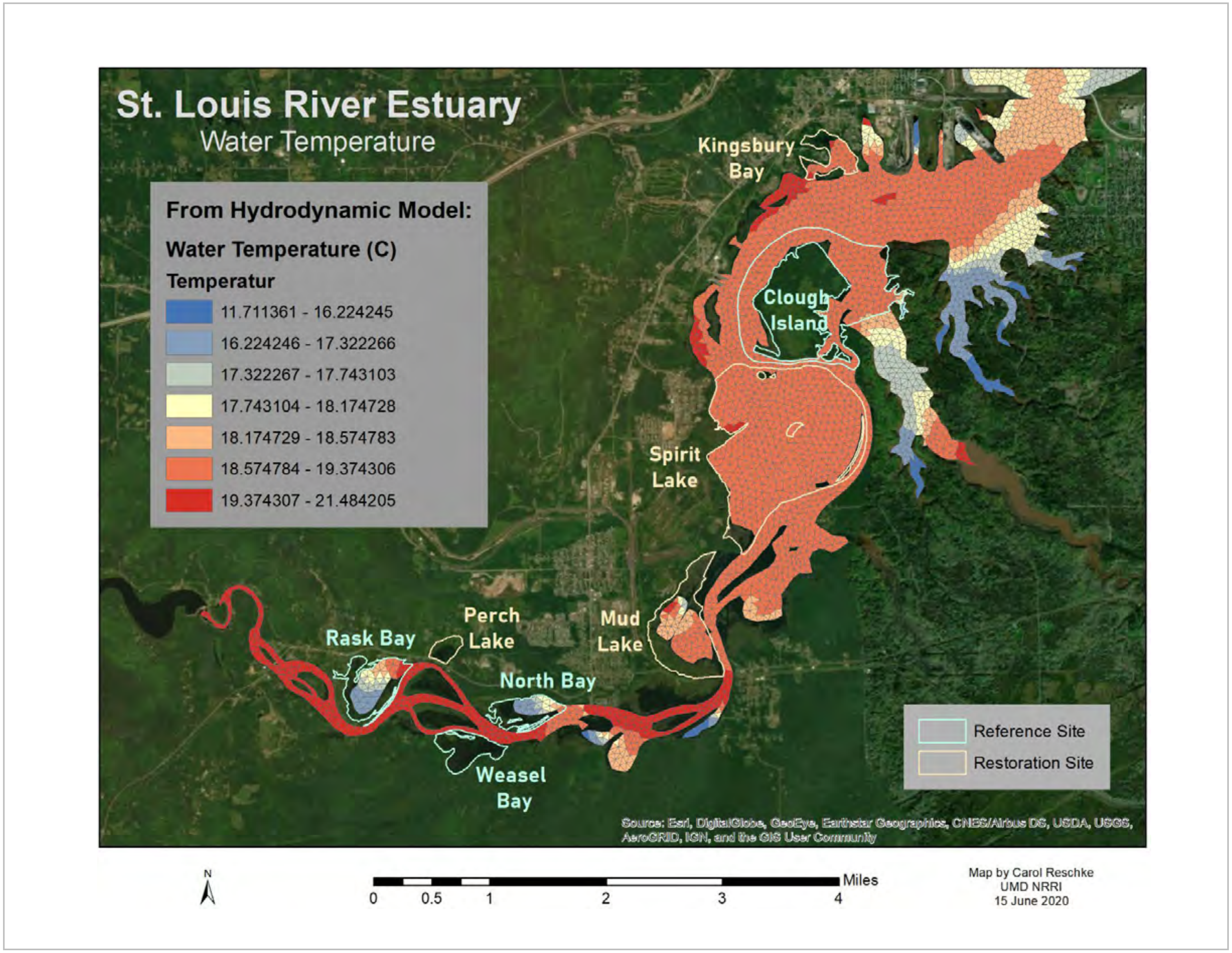
Map 7: Relative Exposure Index (REI) assuming high Lake Superior water levels at 603.1 ft elevation, from a geodatabase developed by EPA's Great Lakes Toxicology and Ecology Division in Duluth, Minnesota. REI is an index of wind fetch and exposure to waves.



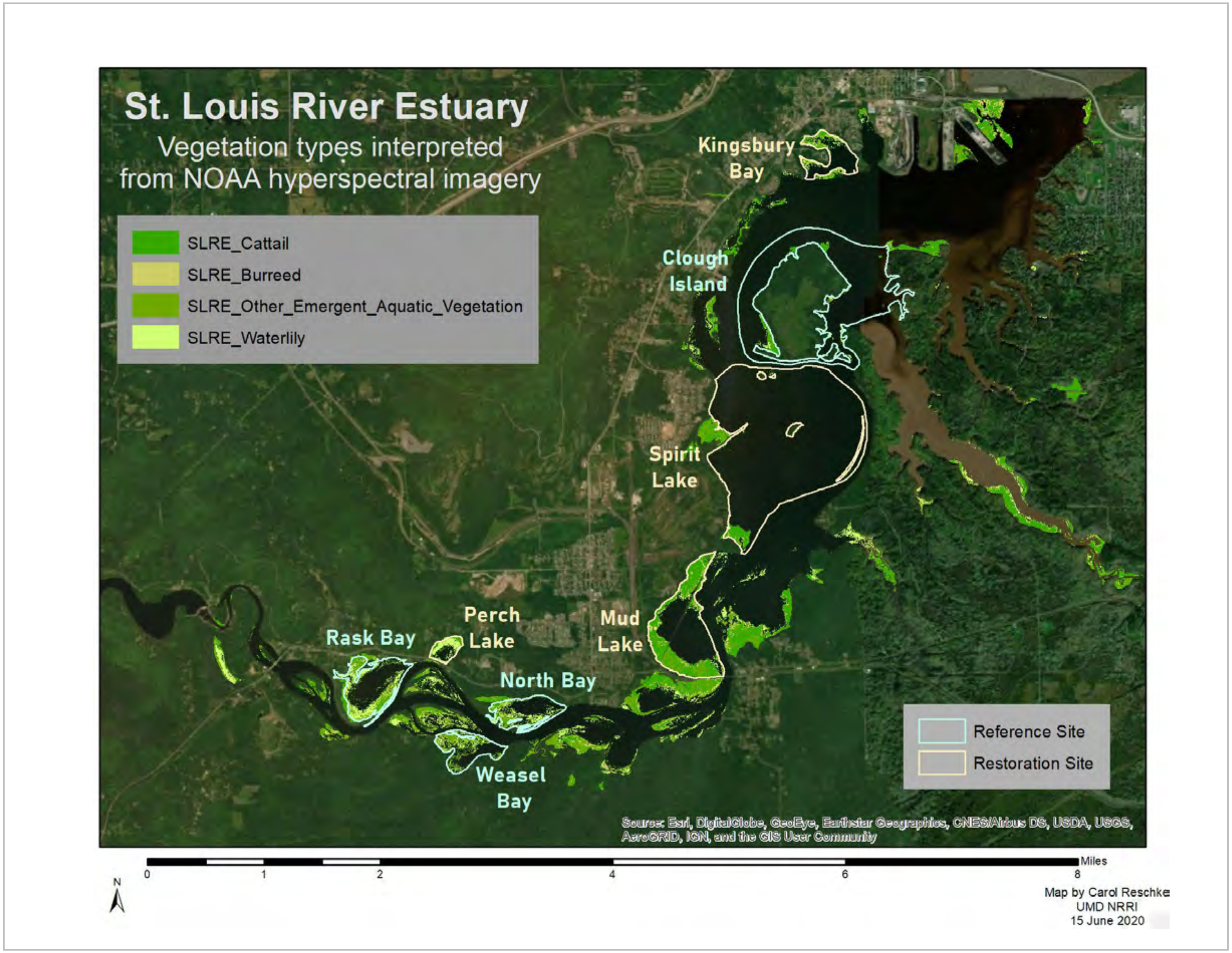
Map 8: Water velocity (cm/sec) from one scenario run with the hydrodynamic model produced by UMD's Large Lakes Observatory.



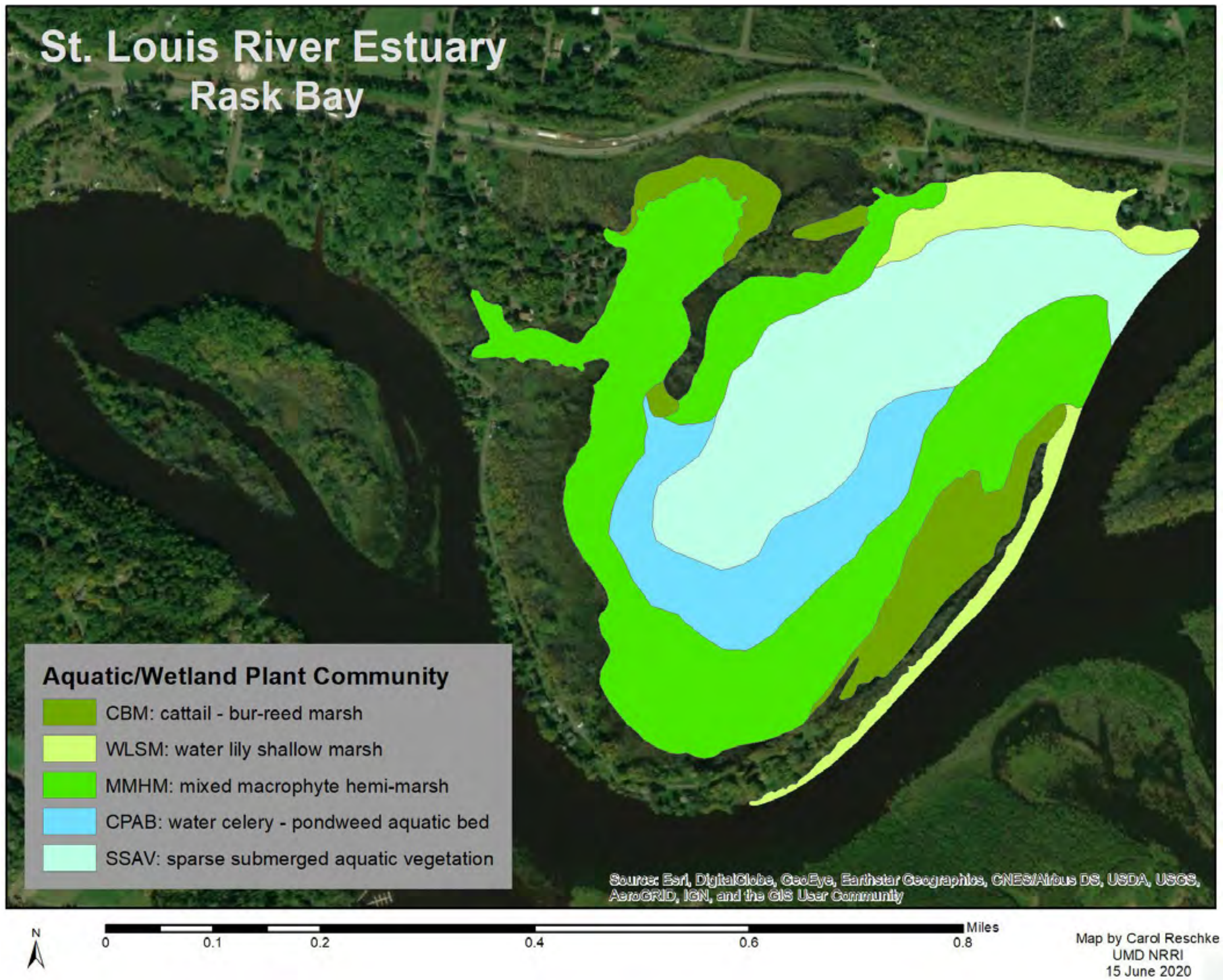
Map 9: Water temperature (°C) from one scenario run with the hydrodynamic model produced by UMD's Large Lakes Observatory.



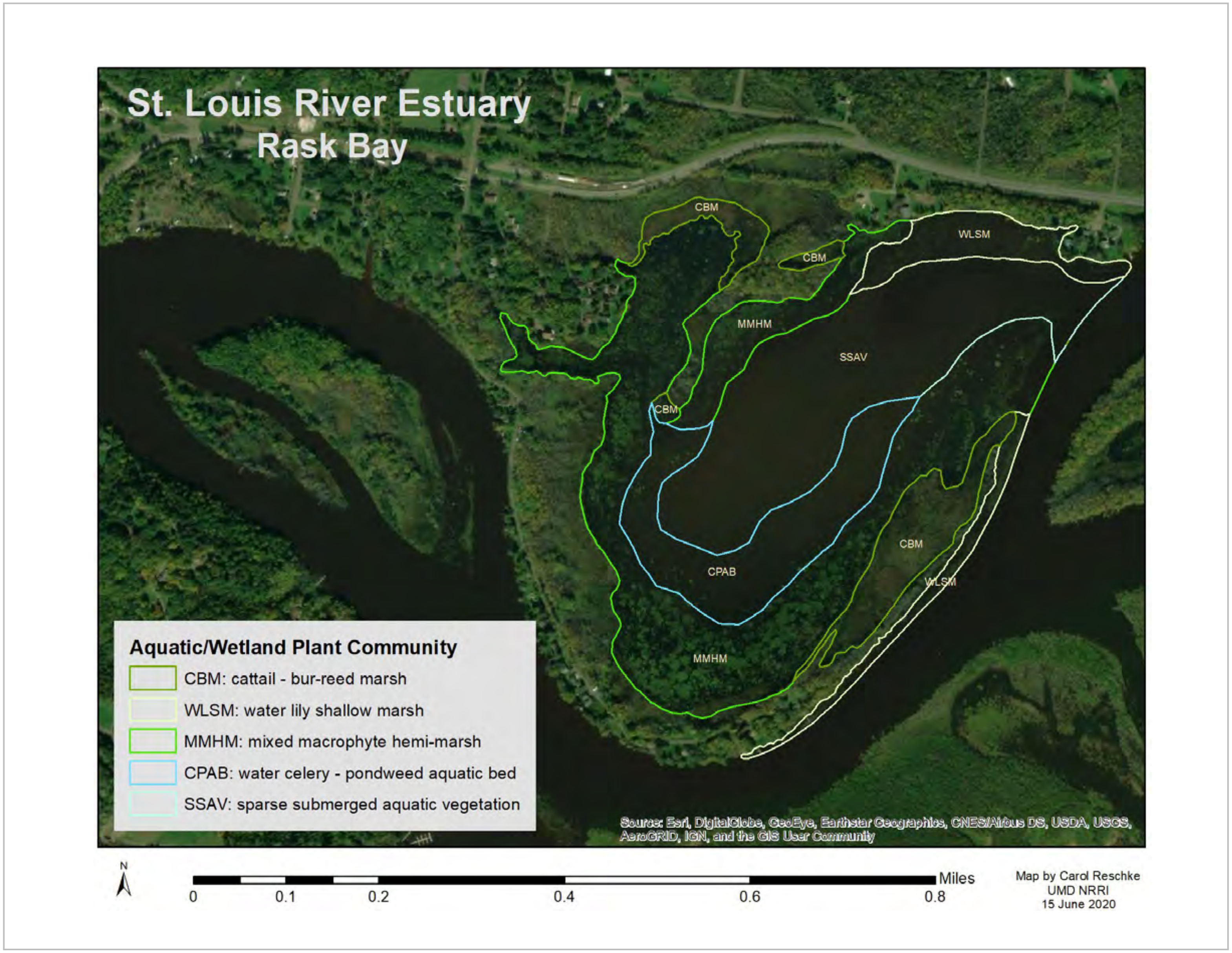
Map 10: Vegetation types interpreted from NOAA hyperspectral imagery.



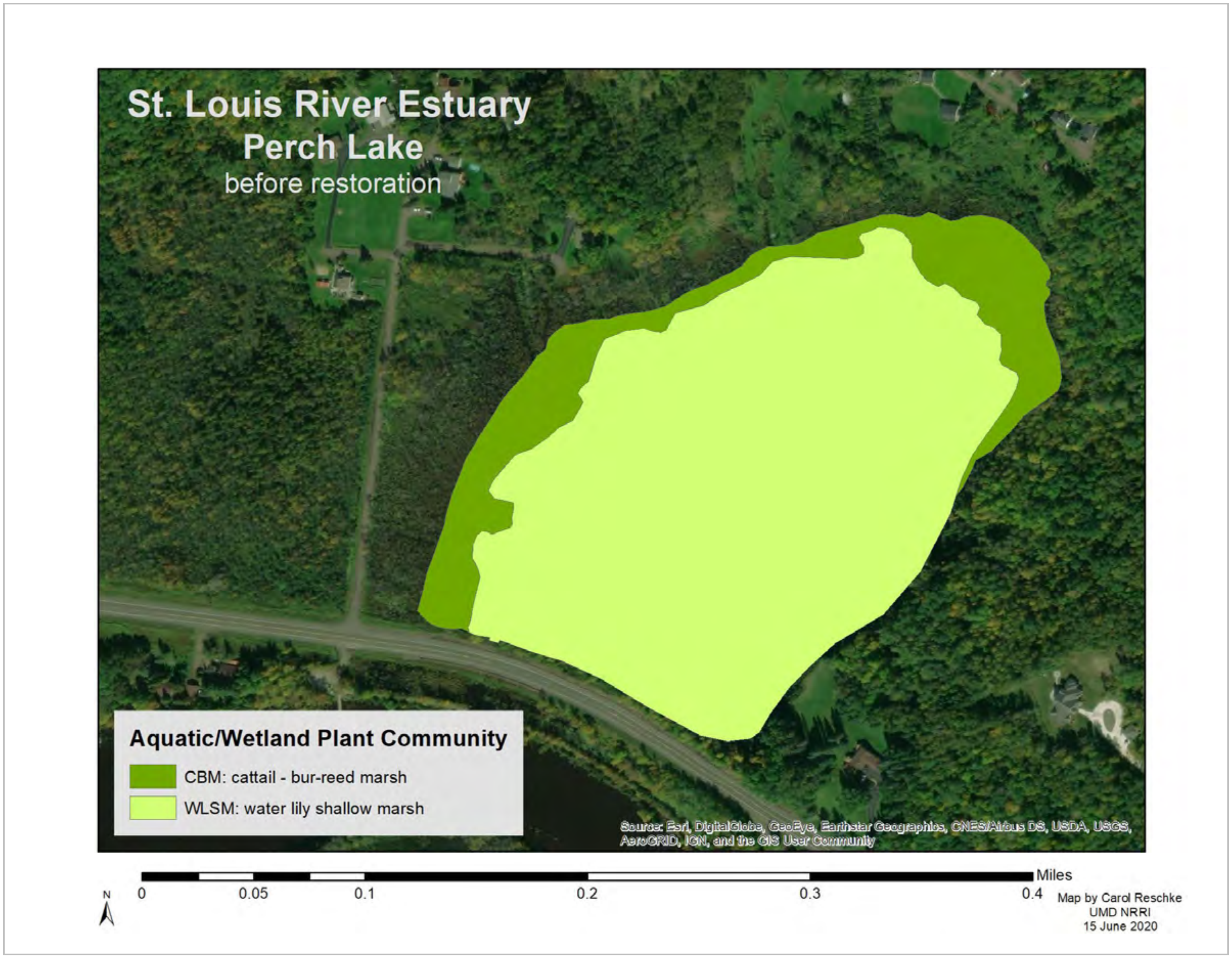
Map 11a: Aquatic habitats and wetland plant communities at Rask Bay, a reference site.



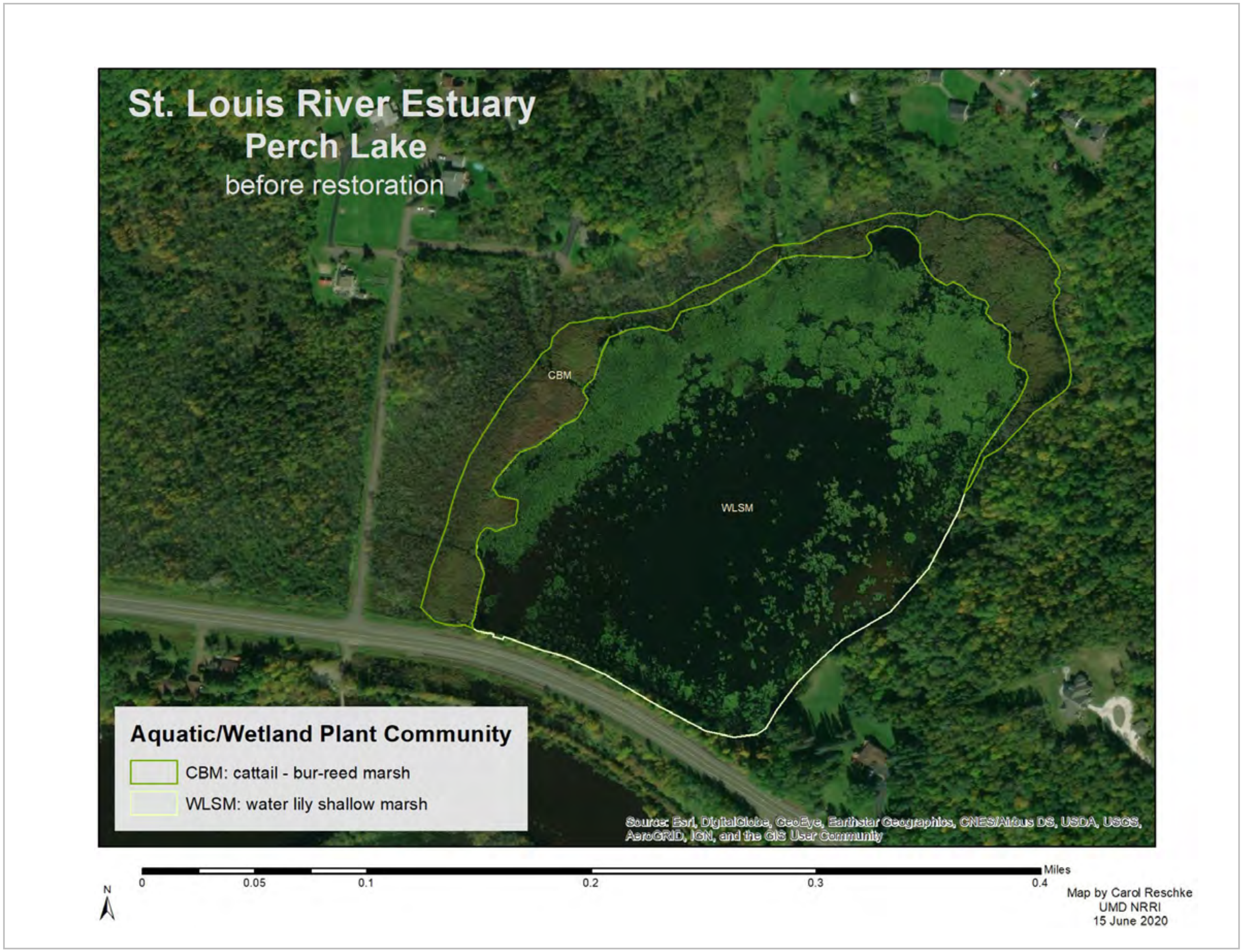
Map 11b: Aquatic habitats and wetland plant communities at Rask Bay, a reference site.



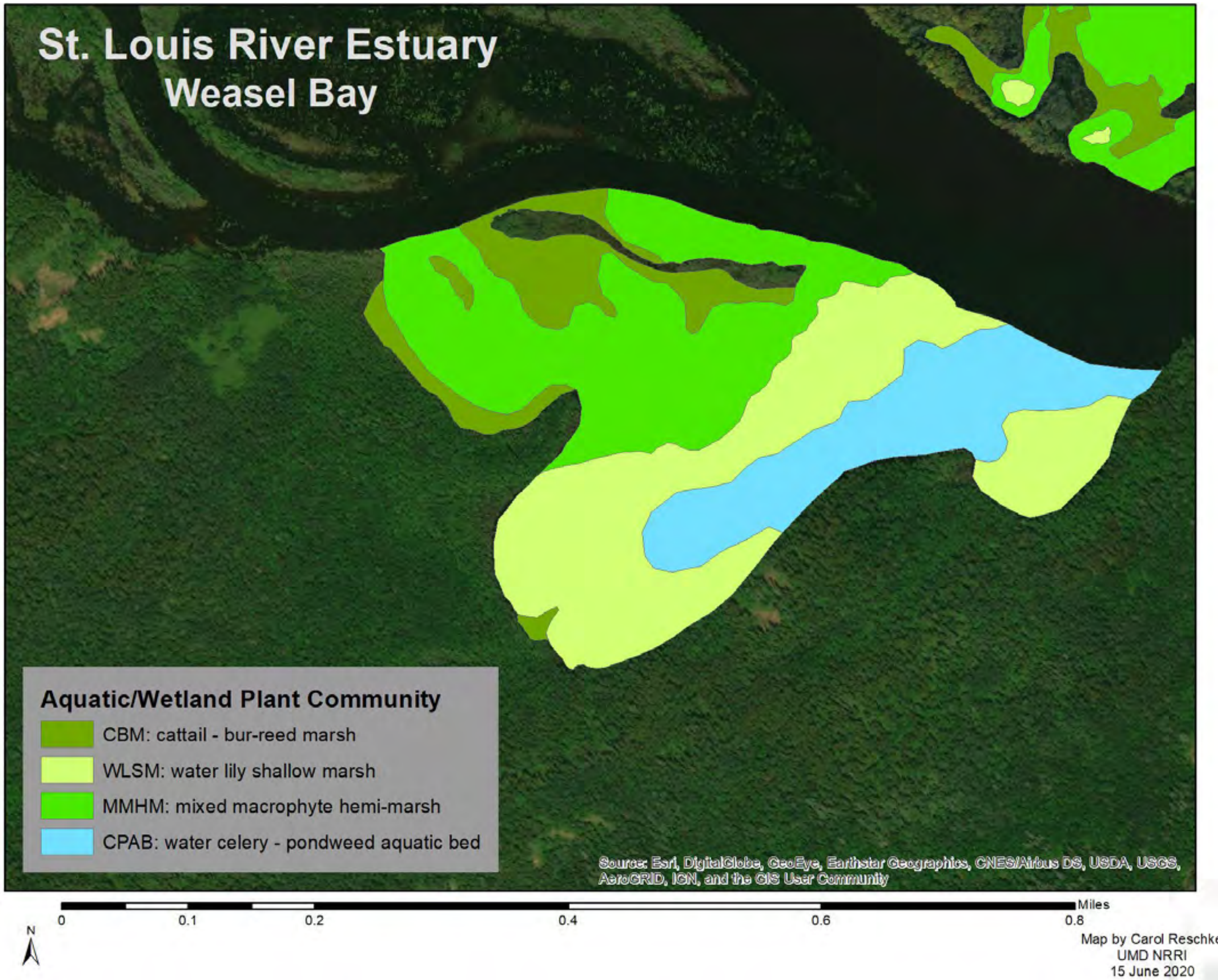
Map 12a: Aquatic habitats and wetland plant communities at Perch Lake, a restoration site. Perch Lake is connected to the St. Louis River by a culvert that runs underneath Highway 23.



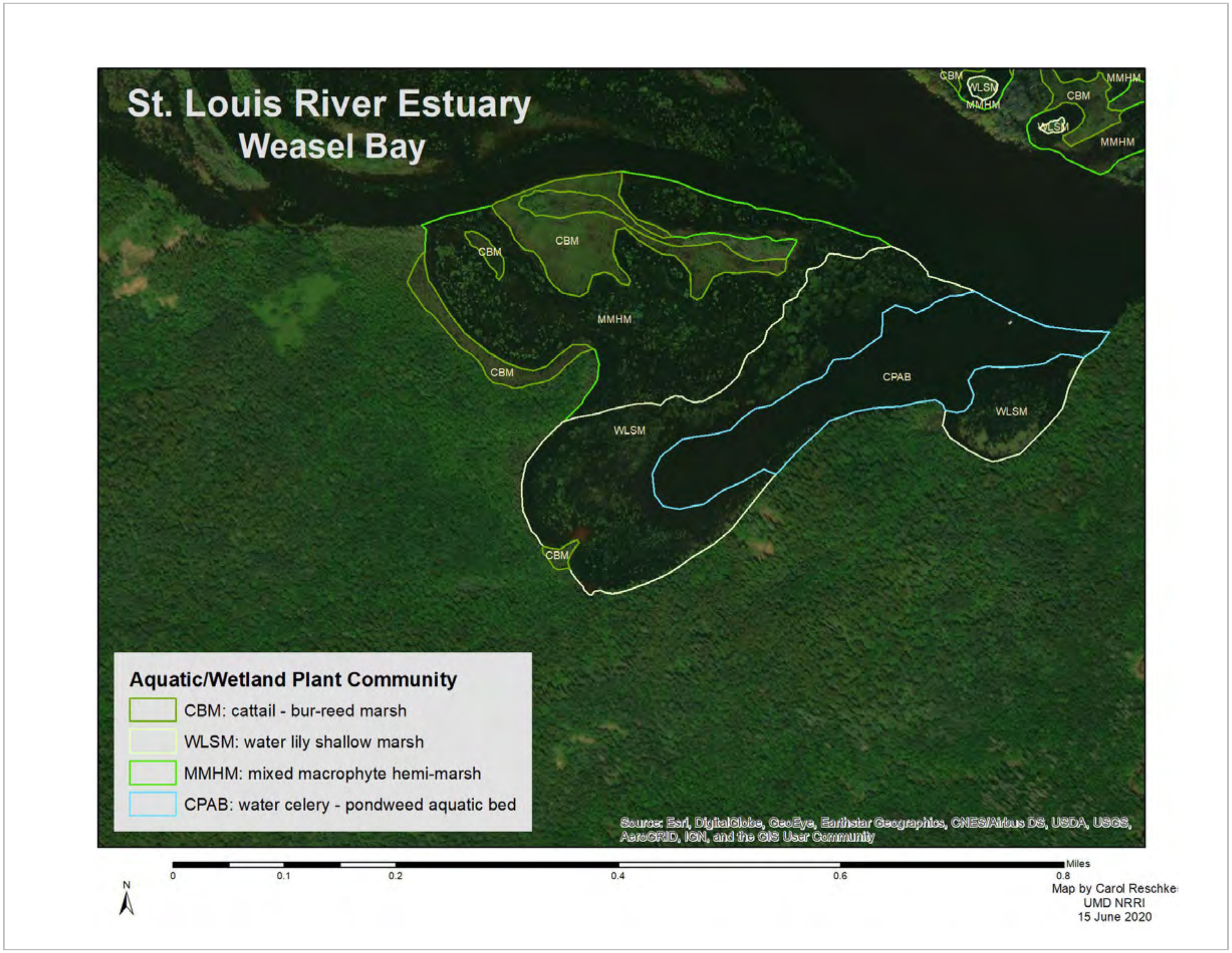
Map 12b: Aquatic habitats and wetland plant communities at Perch Lake, a restoration site. Perch Lake is connected to the St. Louis River by a culvert that runs underneath Highway 23.



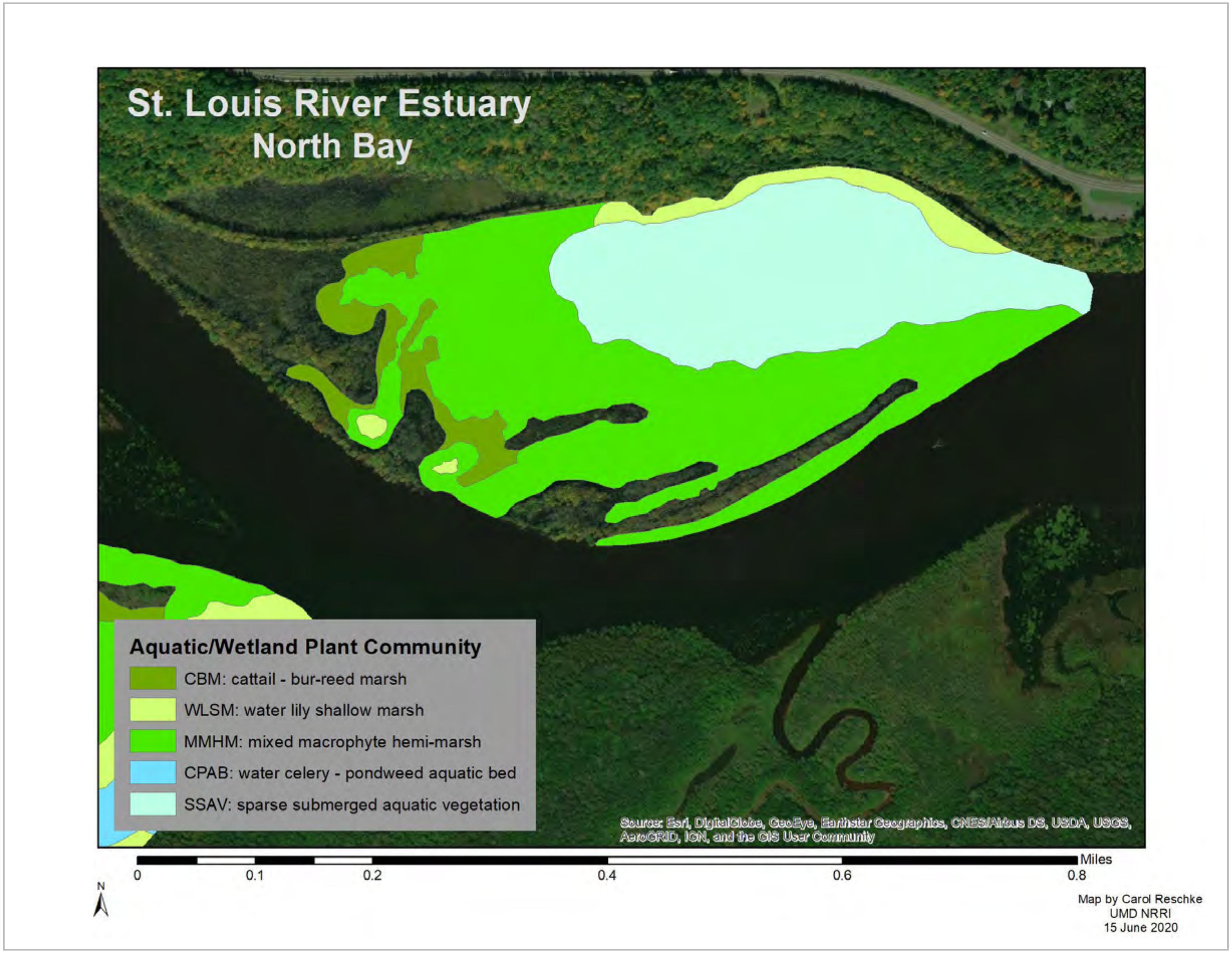
Map 13a: Aquatic habitats and wetland plant communities at Weasel Bay (also known as Duck Hunter Bay South), a reference site.



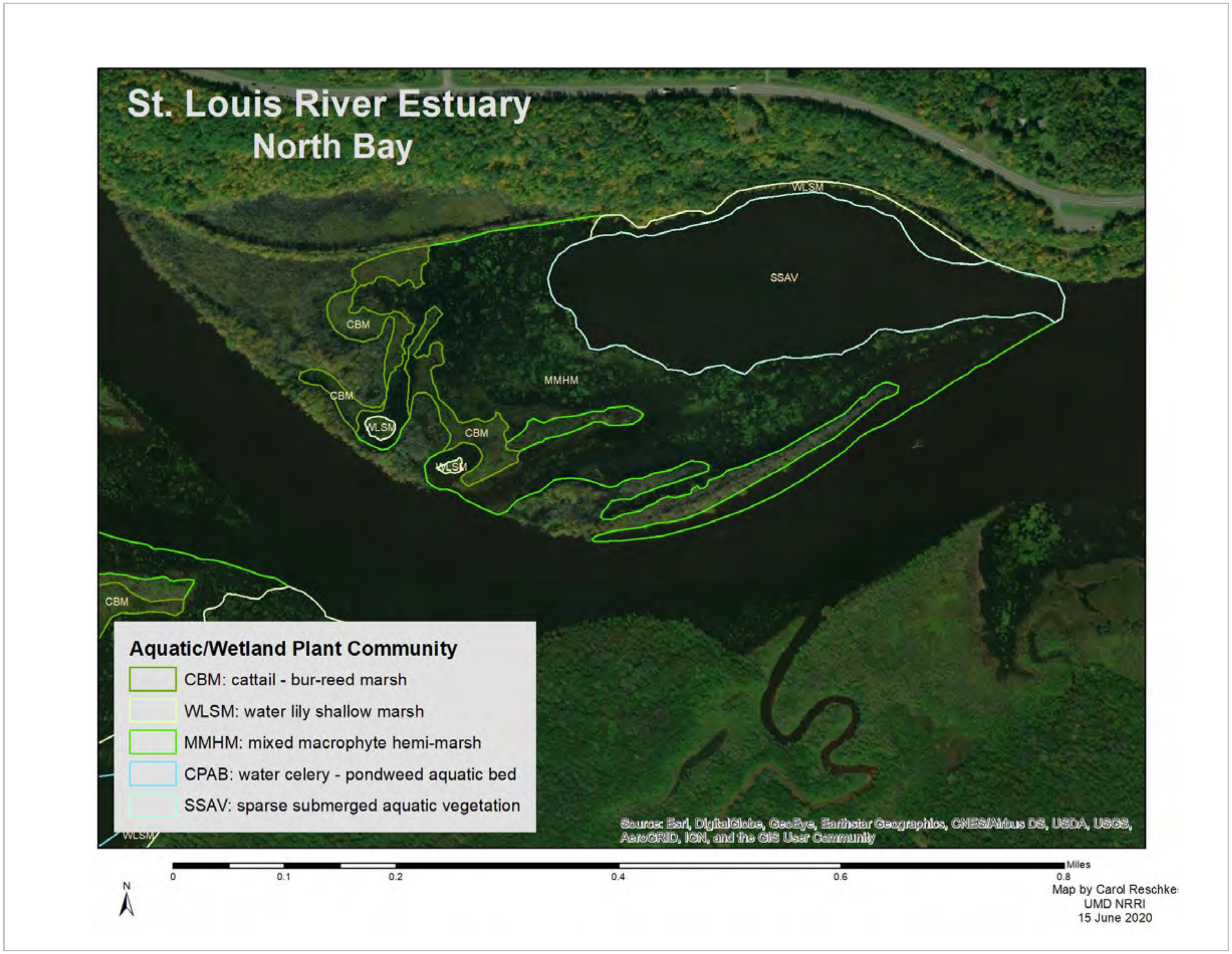
Map 13b: Aquatic habitats and wetland plant communities at Weasel Bay (also known as Duck Hunter Bay South), a reference site.



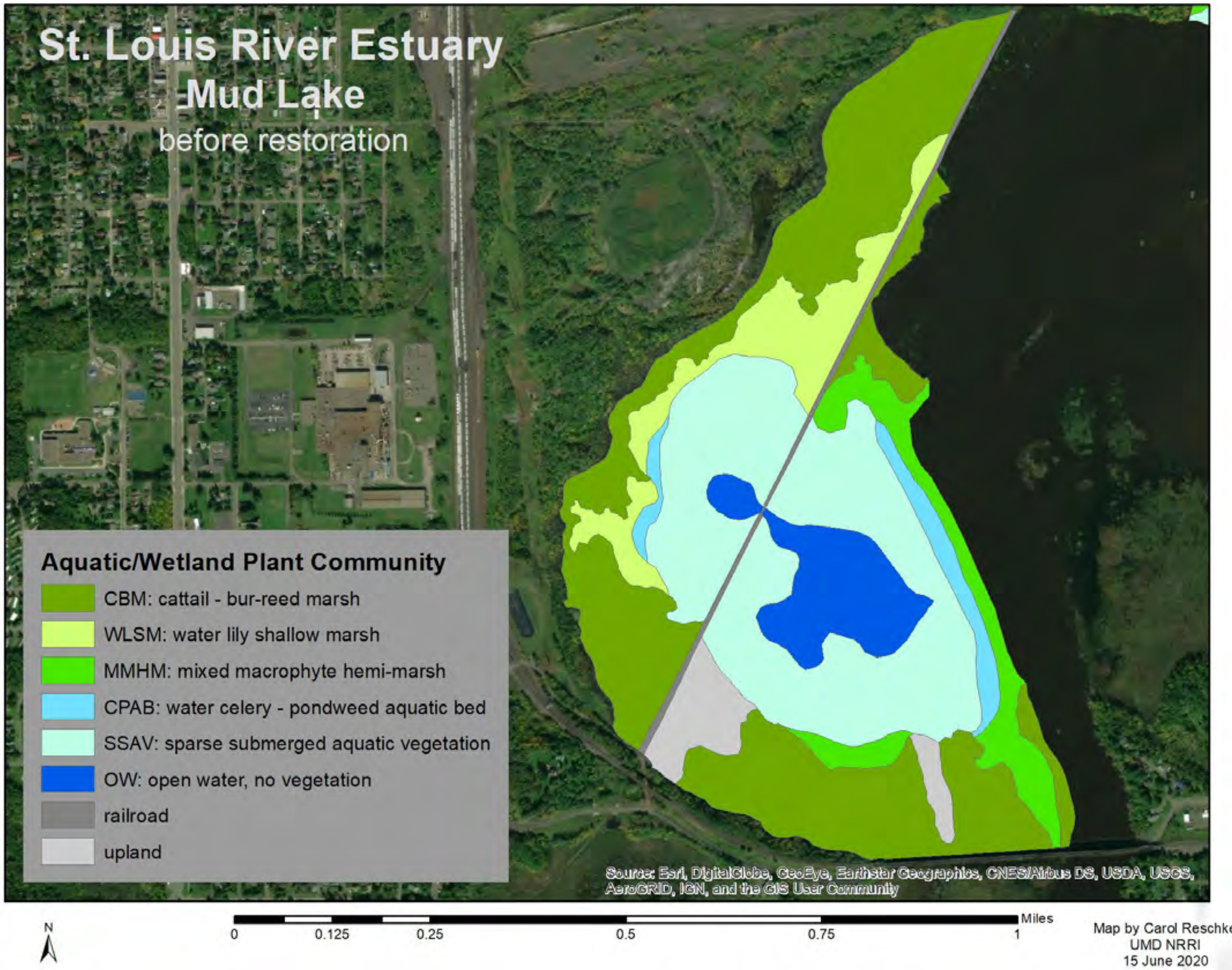
Map 14a: Aquatic habitats and wetland plant communities at North Bay, a reference site.



Map 14b: Aquatic habitats and wetland plant communities at North Bay, a reference site.

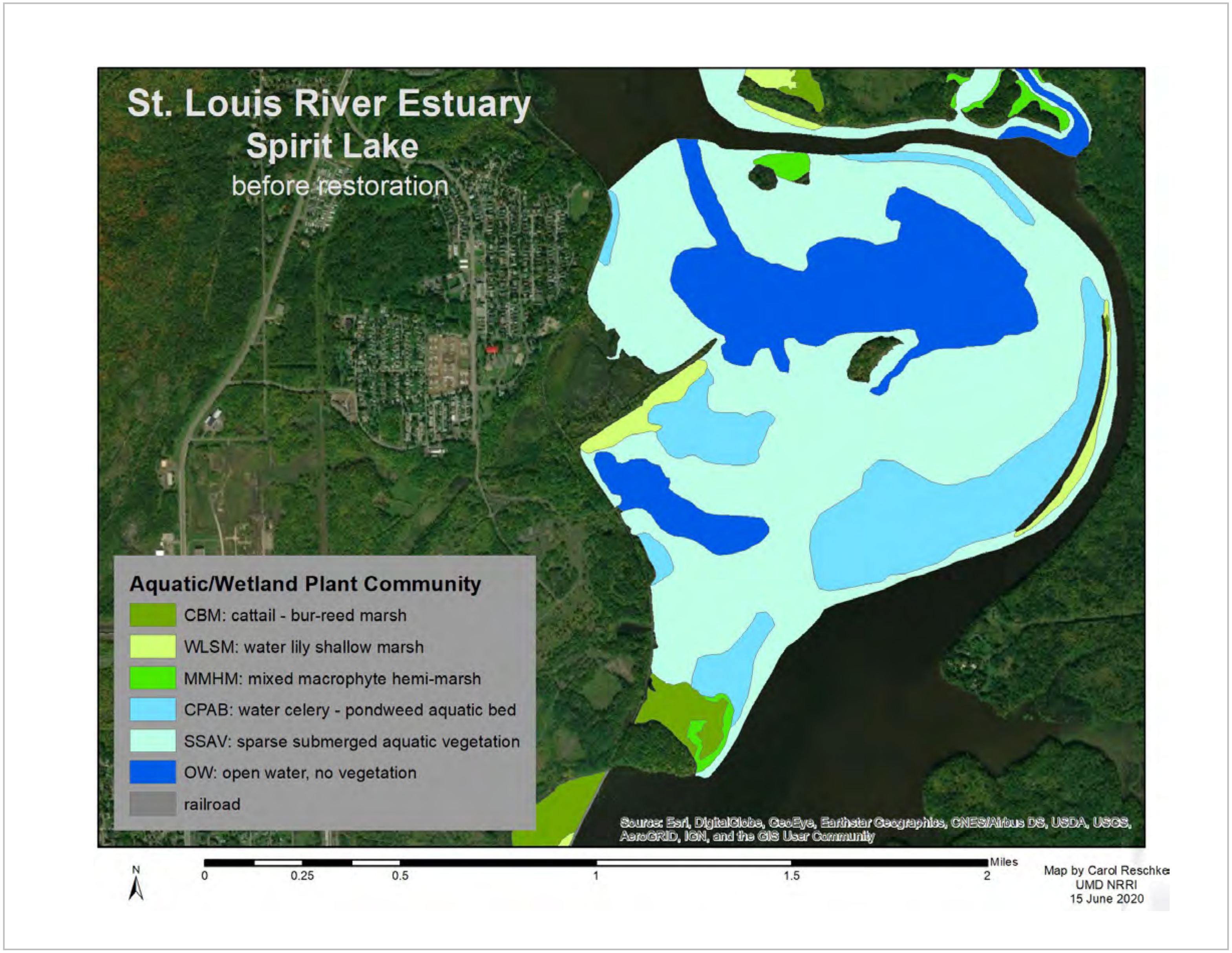


Map 15a: Aquatic habitats and wetland plant communities at Mud Lake, a restoration site.

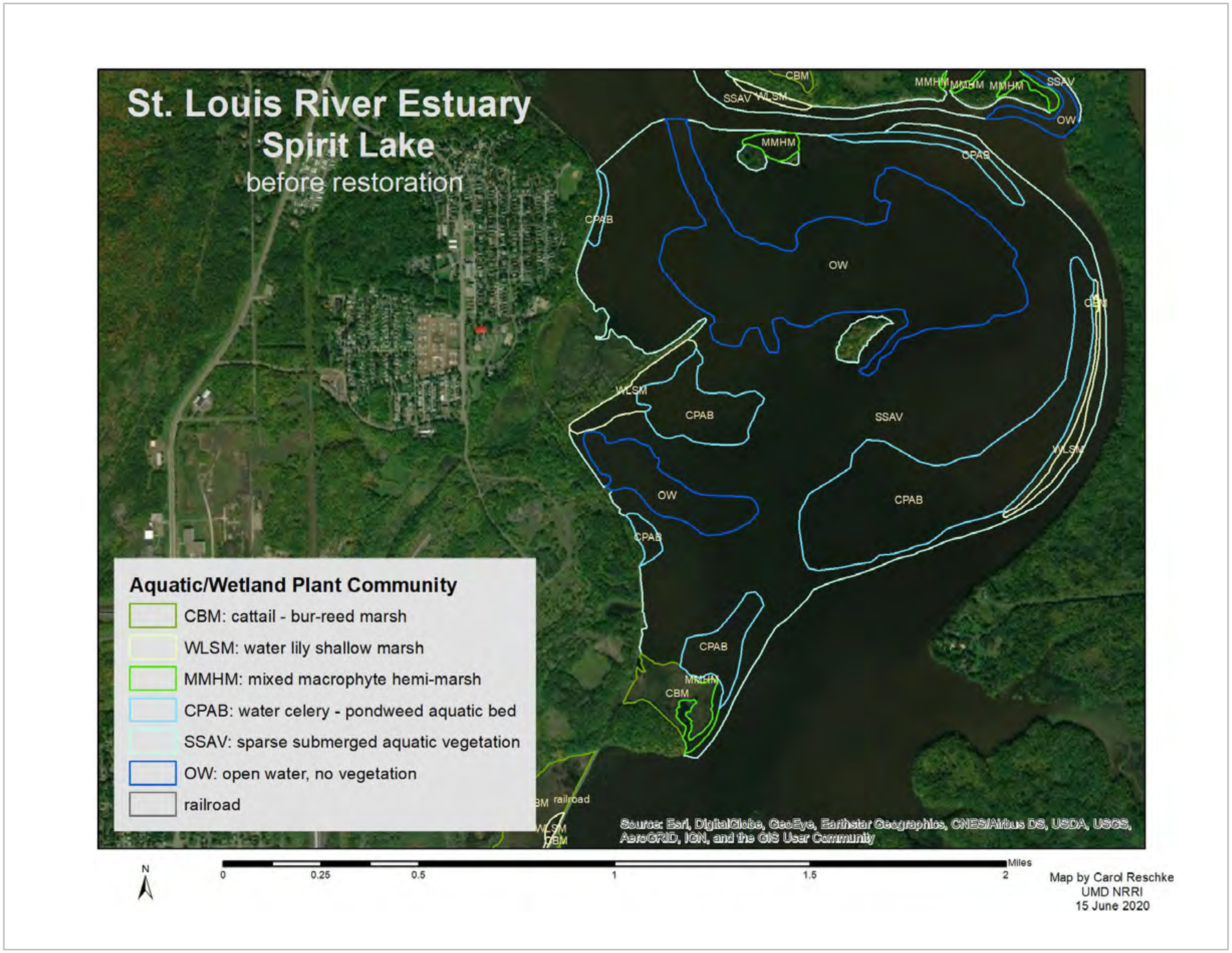


Map 15b: Aquatic habitats and wetland plant communities at Mud Lake, a restoration site.

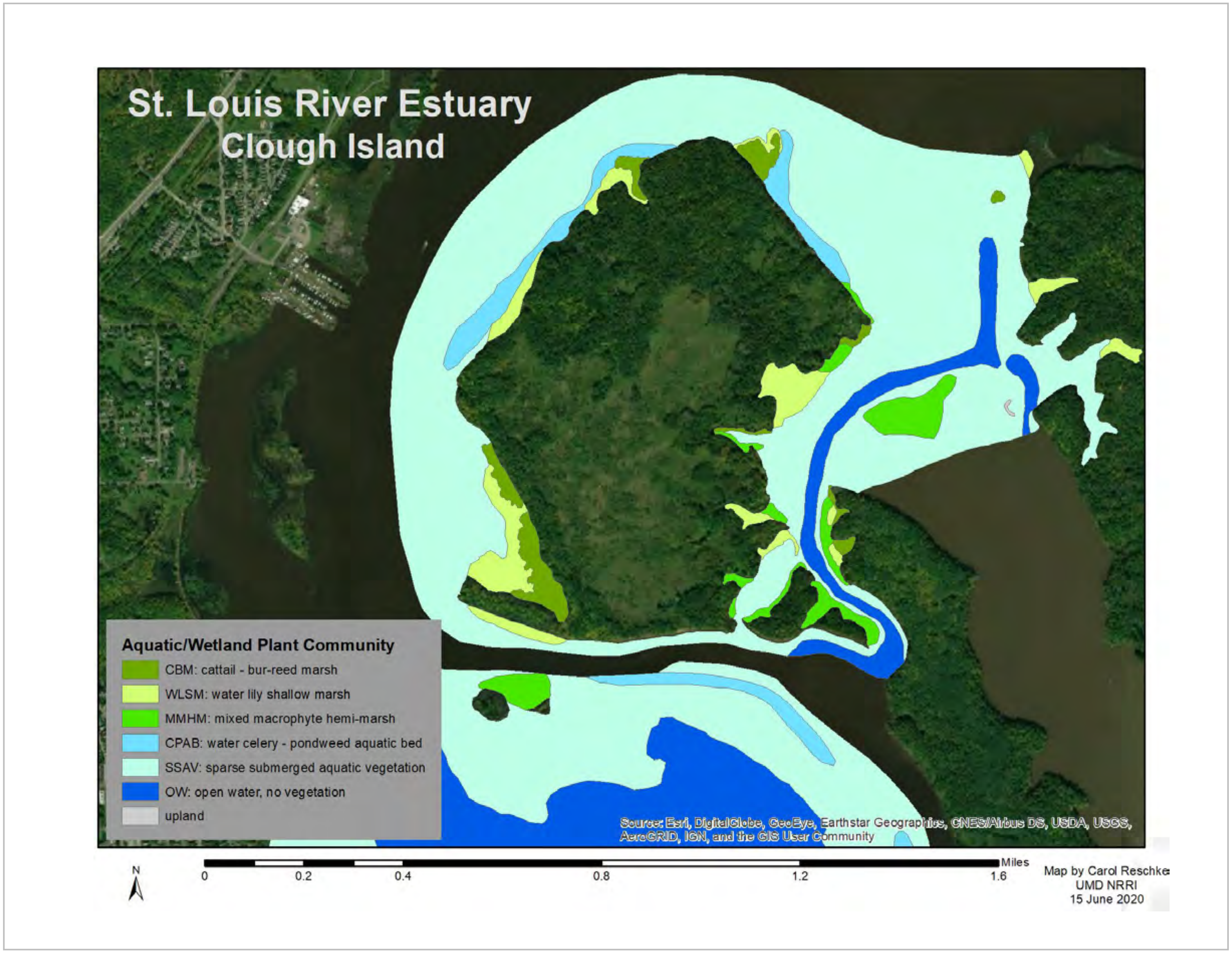
Map 16a: Aquatic habitats and wetland plant communities at Spirit Lake, a restoration site.



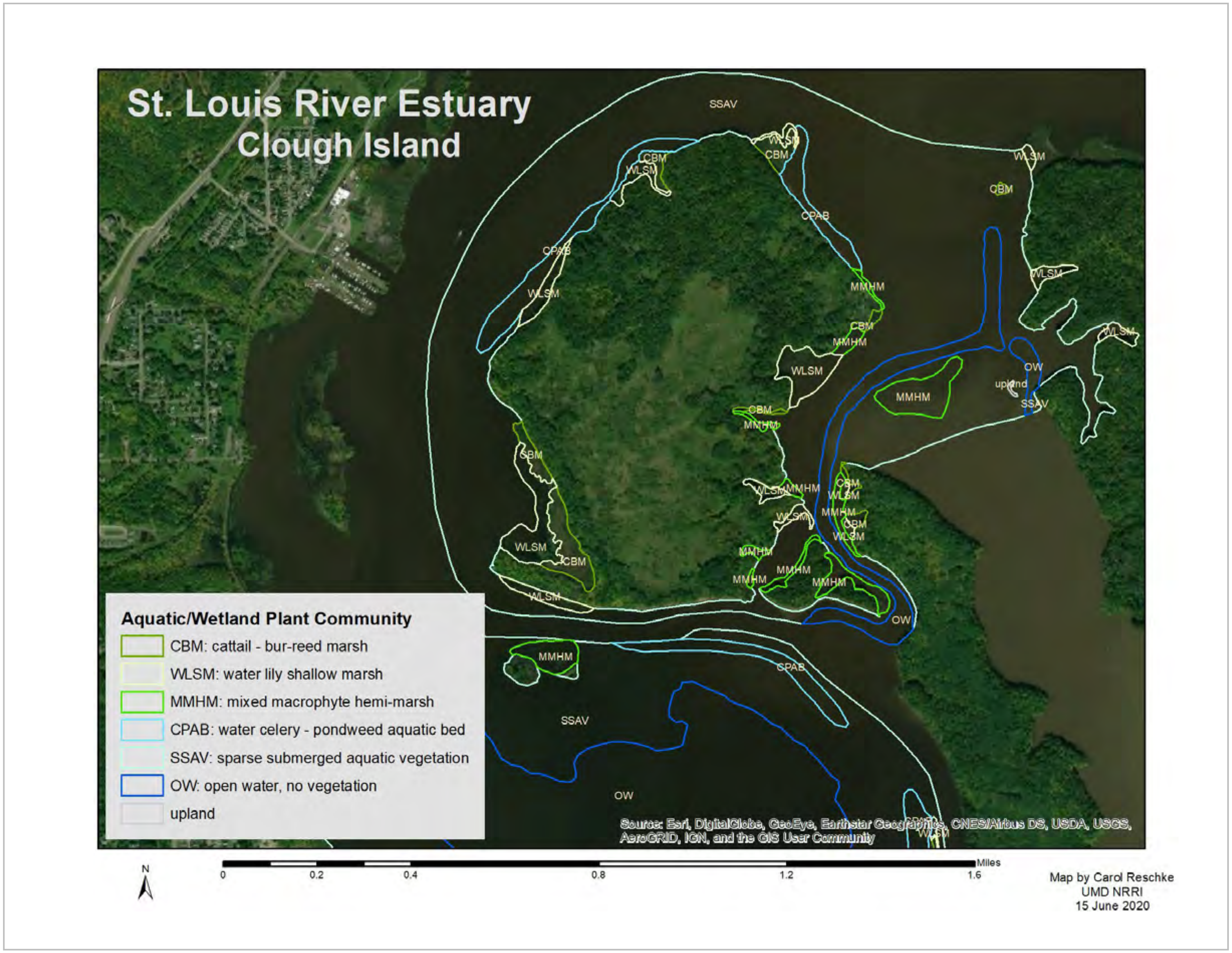
Map 16b: Aquatic habitats and wetland plant communities at Spirit Lake, a restoration site.



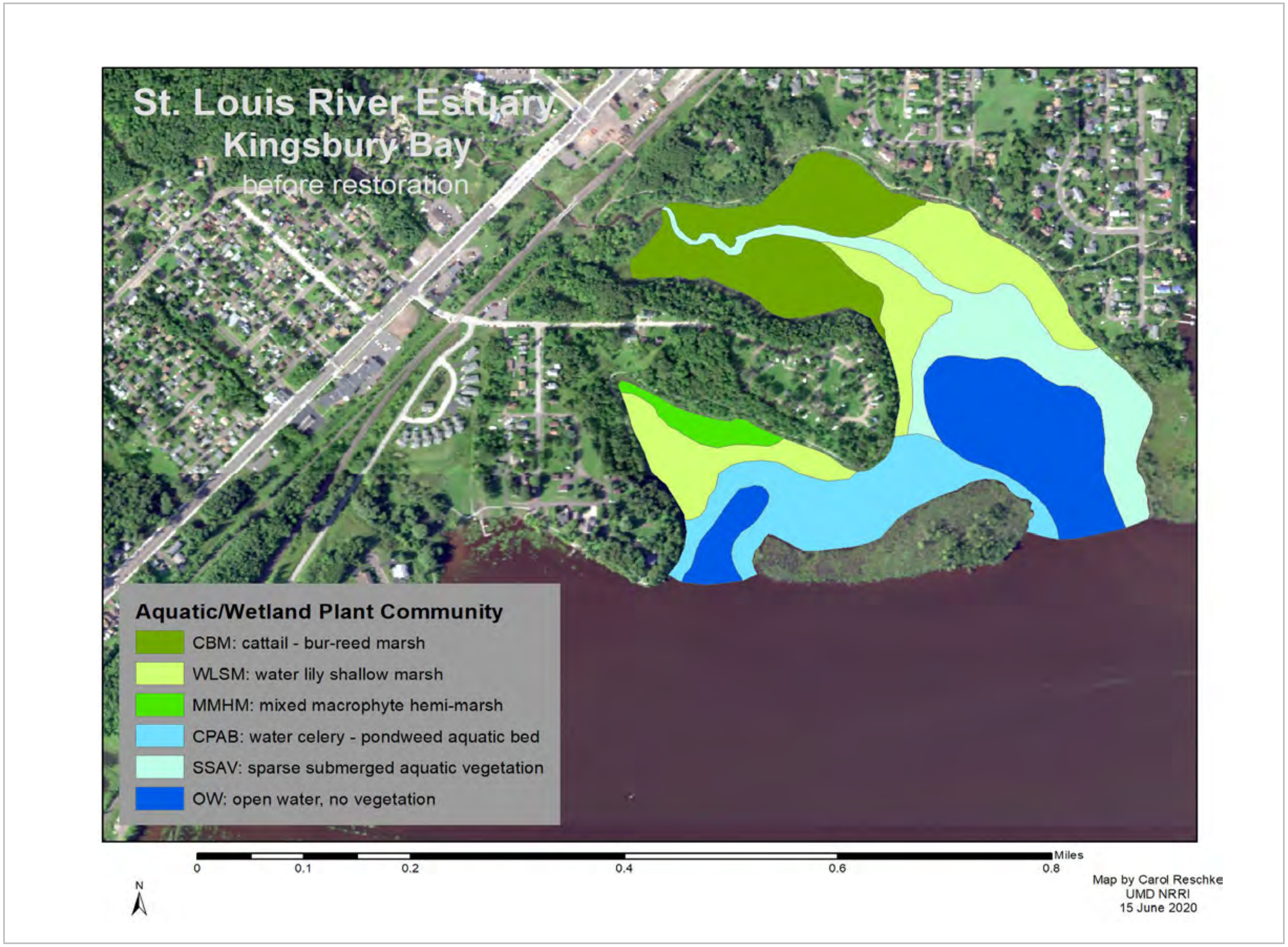
Map 17a: Aquatic habitats and wetland plant communities at Clough Island, a reference site.



Map 17b: Aquatic habitats and wetland plant communities at Clough Island, a reference site.



Map 18a: Aquatic habitats and wetland plant communities at Kingsbury Bay, a restoration site.



Map 18b: Aquatic habitats and wetland plant communities at Kingsbury Bay, a restoration site.

Photo 1: Water lily shallow marsh in foreground, and edge of cattail – bur-reed marsh at Rask Bay on 23 July 2015. Photo by Carol Reschke.

Photo 2: Cattail – bur-reed marsh at Kingsbury Bay on 23 August 2017. Photo by Carol Reschke.

Photo 3: Water lily shallow marsh at Weasel Bay on 29 August 2019. This habitat has a patchy mosaic of floating-leaf plants including water lilies, bur-reed (in the foreground), and pondweeds, usually with a lot of submerged aquatic vegetation as well. Photo by Carol Reschke.

Photo 4: Closer view of Water lily shallow marsh at Weasel Bay on 29 August 2019, showing oval floating leaves of *Potamogeton nodosus*, submerged leaves of *Vallisneria americana* in lower left, and linear floating leaves of *Sparganium emersum* on the far right. Photo by Carol Reschke.

Photo 5: Mixed macrophyte hemi-marsh at Weasel Bay on 29 August 2019. Note that this habitat includes a mix of emergent, floating-leaf, and submerged aquatic plants in a patchy mosaic. Photo by Carol Reschke.

Photo 6: Mixed macrophyte hemi-marsh at North Bay on 23 July 2015, showing a denser mosaic of emergent bulrush (*Schoenoplectus tabernaemontanae*), bur-reed (*Sparganium eurycarpum*), and arrowhead (*Sagittaria rigida*), floating-leaf water lilies and pondweeds, and open water patches with submerged aquatic vegetation. Photo by Carol Reschke.

Photo 7: Wild rice marsh at Rask Bay on 27 Aug 2014, an unusually good year for wild rice at this site. Most years this area is mixed macrophyte hemi-marsh, but in 2014 rice was dense enough to be wild rice marsh. The best examples of wild rice marsh in the estuary are along the Pokegama Rver. Photo by Carol Reschke.

MINNESOTA'S LAKE SUPERIOR COASTAL PROGRAM