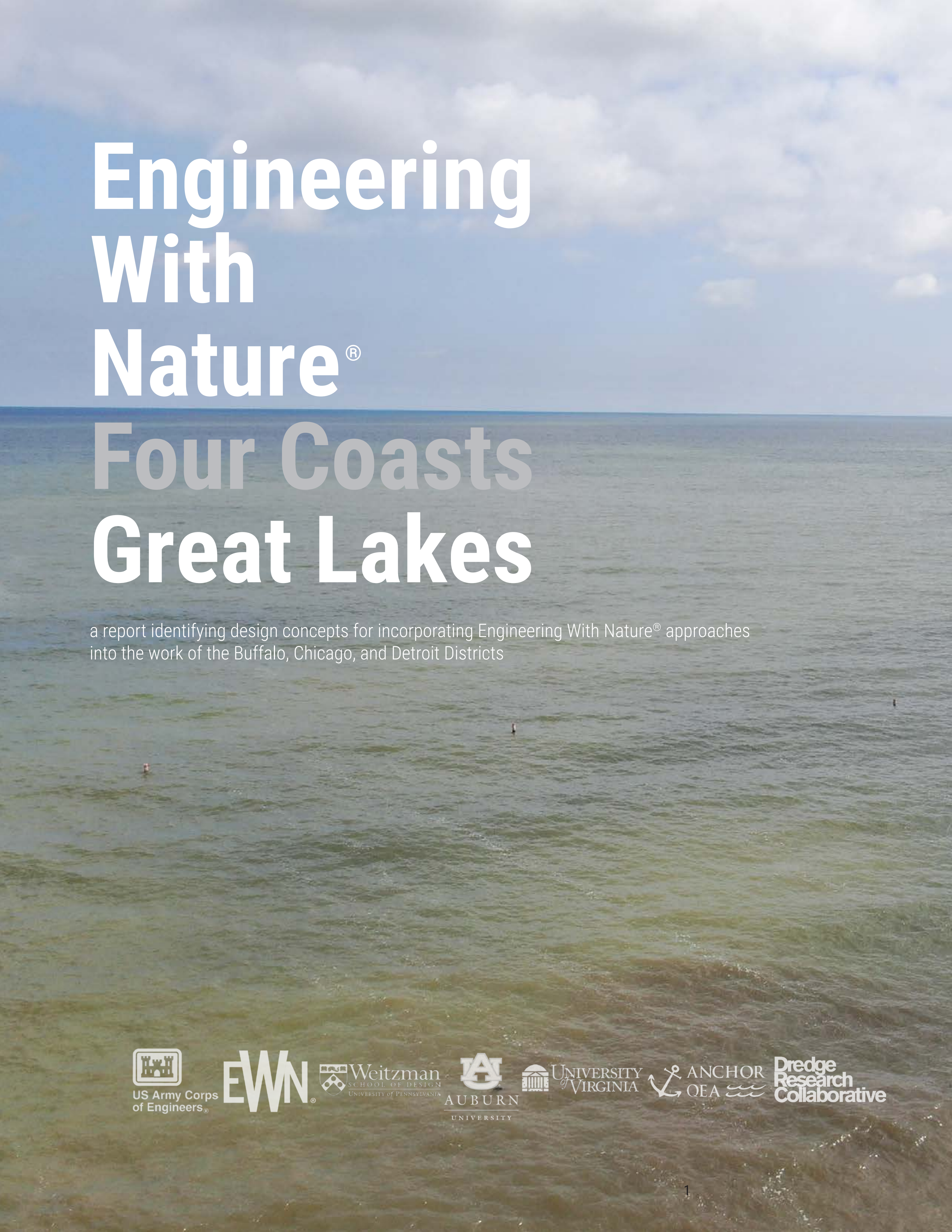
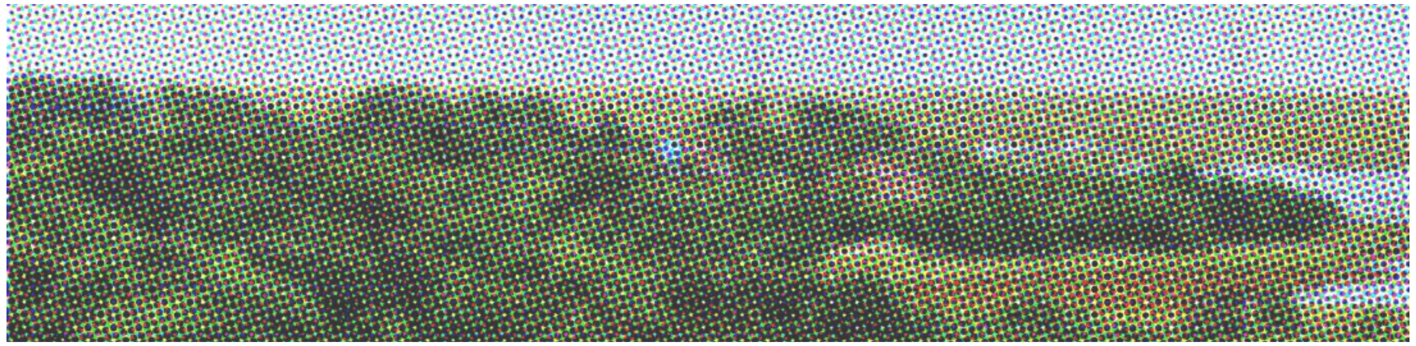


Engineering With Nature®
Four Coasts
Great Lakes

a report identifying design concepts for incorporating Engineering With Nature® approaches into the work of the Buffalo, Chicago, and Detroit Districts



Engineering With Nature®
Jeff King
David Bucaro
Patrick Kennedy
James Selegean
Josh Unghire
Frank Veraldi
Sam Belcik

University of Virginia
Brian Davis (co-PI)
Sean Kois
Houchen Lyu
Michael Schaefer Friedman
Sophie Maffie

University of Pennsylvania
Sean Burkholder (co-PI)
Theresa Ruswick

Auburn University
Rob Holmes (co-PI)
Marilyn Reish

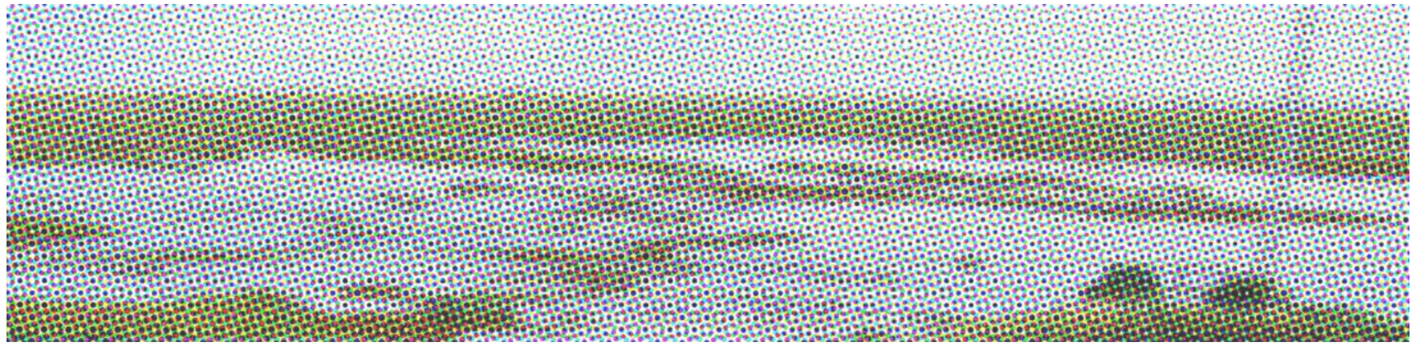
AnchorQEA
Ram Mohan
Mindy Strevig
Matt Henderson
Nathan Holliday
Jacob Sturz
Jillian Zwierz

Dredge Research Collaborative
Justine Holzman
Gena Wirth
Brett Milligan

Participating Division
Great Lakes

Cover Image:
Lake Michigan (Sean Burkholder)

Contact:
Jeff King, Deputy National Lead, Engineering With Nature Initiative®, USACE
Jeff.K.King@usace.army.mil
Brian Davis, Associate Professor, School of Architecture, University of Virginia
brd6eq@virginia.edu



This report covers findings from research cooperative agreement W912HZ-20-2-0049 **Incorporating Engineering With Nature® (EWN®) and Landscape Architecture (LA) Designs into Existing Infrastructure Projects**, an agreement between the **U.S. Army Engineering Research Development Center** (ERDC) and **Auburn University** (AU).

This report has been prepared by the investigators at **Auburn University**, the **University of Virginia**, and the **University of Pennsylvania** in collaboration with **AnchorQEA** and consultants from the **Dredge Research Collaborative**; it also incorporates research and insights from ERDC's **Engineering With Nature®** project team.

Engineering with Nature® is the intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaborative processes.

Sustainable development of water resources infrastructure is supported by solutions that beneficially integrate engineering and natural systems. With recent advances in the fields of engineering and ecology, there is an opportunity to combine these fields of practice into a single collaborative and cost-effective approach for infrastructure development and environmental management.

The Dredge Research Collaborative is an independent 501c3 nonprofit organization that investigates human sediment handling practices through publications, an event series, and various other projects. Its mission is to advance public knowledge about sediment management; to provide platforms for transdisciplinary conversation about sediment management; and to participate in envisioning and realizing preferred sedimentary futures.

http://engineeringwithnature.org
http://dredgeresearchcollaborative.org/

table of contents

Executive Summary

The Great Lakes Division spans three regional districts- Buffalo, Chicago, and Detroit, and covers eight states (Minnesota, Wisconsin, Michigan, Illinois, Indiana, Ohio, Pennsylvania, and New York). Their responsibilities encompass navigation, flood and coastal risk management, ecosystem restoration, and more, contributing significantly to the basin's economic prosperity, ecosystem health, and coastal communities. The Great Lakes Division can advocate for stewardship that balances this unique and extensive freshwater system's diverse economic, ecological, and cultural resources. This report documents three projects that seek to highlight and develop innovative Engineering with Nature designs that incorporate economic, ecological, and social resilience. In particular, the selected projects all center around alternative sediment management methods and seek to design with natural forces.

The work summarized in the EWN-LA Four Coasts Great Lakes report occurred between January 2023 and September 2023. After initial research and meetings with the EWN representatives in the three Great Lakes Division districts, one project per district was chosen based on its ability to represent the region's particular challenges and opportunities. The initial assessment of the relevant conditions of the Great Lakes Division is summarized in Part 1: Great Lakes Division. Part 2: Case Studies delves into each of the three selected projects, including:

+ Sediment Capture Wetlands, Green Bay, WI, in Chicago District

+ Dynamic Habitat Shoal, Conneaut, OH, in Buffalo District

+ Bluff Management, St Joseph, MI, in Detroit District

Introduction

Engineering With Nature® (EWN) is a program based out of the USACE Engineer Research and Development Center (ERDC). This report has been produced as part of a larger collaborative research project, referred to as the Four Coasts project. In this project, the engineering firm Anchor QEA and a team of landscape architects affiliated with the Dredge Research Collaborative (DRC) were tasked by the USACE ERDC as part of the EWN program to work with Proving Ground districts along the Atlantic Ocean, Pacific Ocean, Gulf of Mexico, and Great Lakes, collectively known as the four coastal regions, to identify key nature-based infrastructure opportunities. These collaborative partners selected three to five representative projects on each coast, with the projects ranging from the integration of natural and nature-based features (NNBF) to existing work to the advancement of new EWN opportunities that the project team has developed. This report documents five projects within the USACE Great Lakes Districts, including Chicago District, Detroit District and Buffalo Districts.

EWN is the philosophy behind the "intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaborative processes" (Engineering with Nature).

In the EWN approach, sustainable development of water resources infrastructure is supported by solutions that beneficially integrate engineering and natural systems. With recent advances in the fields of engineering and ecology, there is an opportunity to combine these fields of practice into a single collaborative and cost-effective approach for infrastructure development and environmental management.

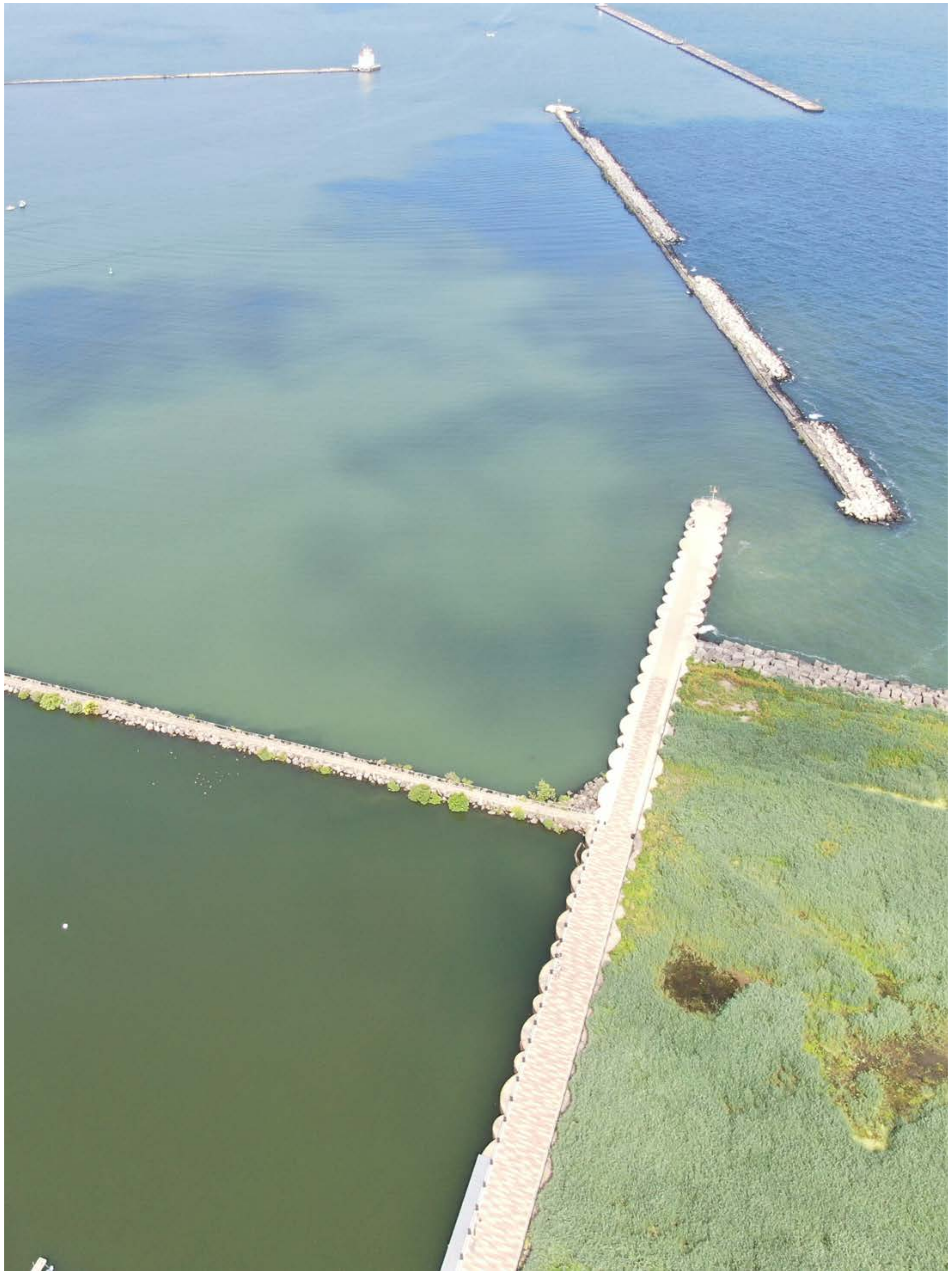
EWN outcomes are "triple-win," which means that they systematically integrate social, environmental, and economic considerations into decision-making and actions at every phase of a project to achieve "innovative and resilient solutions" that are more socially acceptable, viable, equitable, and ultimately, more sustainable.

Four Coasts builds on and expands four years of earlier work in the EWN-LA initiative, which has engaged new and existing water resources infrastructure projects in districts ranging from Alaska to Florida, with the aim of supporting the deployment of EWN approaches through the application of the methods and knowledge of landscape architecture. As a field, landscape architecture is presently concerned with many of the same issues of infrastructural performance and potential that EWN is currently pursuing, including the re-imagination of traditional infrastructure to meet more diverse criteria encompassing engineering functions, ecological value, cultural significance, and aesthetic benefits (Spirn, 1984; Mossop, 2006; Orff, 2016; Belanger 2017). The landscape architecture work of this initiative has been led by members of the DRC, including Sean Burkholder, Brian Davis, Rob Holmes, Justine Holzman, Brett Milligan, and Gena Wirth, together with ORISE Fellow Tess Ruswick, supported by colleagues and students at our respective universities, which, over the lifespan of the initiative so far, have been Auburn University, the University of Pennsylvania, the University of Toronto, and the University of Virginia.

For the current Four Coasts project, the DRC landscape architects have worked collaboratively with engineers at Anchor QEA to ensure concepts are based on sound engineering principles. This collaboration allows for the development of unique infrastructure concepts through an iterative process of concept development, technical assessment, and refinement. Broadly, the engineers on the research team bring a precise and analytical approach based on values that can be quantified, while the landscape architects offer a synthetic approach that considers cultural values alongside environmental characteristics. This collaborative integration of engineering and landscape architecture promotes a holistic alignment in the development and visualization of EWN design concepts.

PART 1

GREAT LAKES DISTRICTS



GREAT LAKES DISTRICTS

OVERVIEW

The Great Lakes region boasts an extensive coastline, which spans over 10,000 miles, a length longer than the combined United States' Pacific and Atlantic coastlines. As the largest freshwater reserve in the world, the Great Lakes provide a vital source of drinking water for millions of people in the United States. These waters and the surrounding wetlands are ecologically diverse and rich, supporting a wide range of flora and fauna, including many unique and endemic species. These habitats serve as critical spawning and nursing grounds for native fish species and essential stopover spots for shorebirds and waterfowl. Unfortunately, the Great Lakes have experienced significant coastal wetland loss. Since the 1800s, almost 50% of these wetlands have been lost to development pressures, land use change, and industrialization. This wetland loss has affected the coastal region's habitat, water quality, and flood control. This wetland loss has exacerbated other environmental stressors, such as harmful algae blooms and deteriorating water conditions. The Great Lakes have historically experienced fluctuating lake levels, and the coastal habitats are acclimated to an extensive range of conditions. However, climate change has intensified some of these natural conditions, resulting in more significant and frequent storm events and decreased ice coverage in the winter, contributing to increased coastal erosion along the lakes. The following EWN projects seek to mitigate these basin-wide stressors.

Economically, the region is home to a considerable number of both recreational harbors and commercial ports. These harbors support boating, fishing, and commercial shipping, contributing to recreational opportunities and the regional economy. The economy of the Great Lakes region, with its $3.1 trillion in Gross Domestic Product (GDP) and employment of over 25 million people, is primarily supported by the five major ports in the region: Chicago, Cleveland, Detroit, Duluth, and Milwaukee. In addition to these large federal ports, the USACE supports navigation in 56 other federal ports along the Great Lakes coastline primarily through channel maintenance and jetty and breakwater construction. Dredging, handling, and sediment placement comprise most of the division's annual work. Historically, this sediment has been viewed as a waste product and placed either offshore in deeper water or upland in confined disposal facilities, removing it from the natural system. Recently, there has been a growing desire to retain the sediment in the nearshore environment, regaining its value through the beneficial use of dredged material (BUDM) in wetland creation and nearshore nourishment projects.

◀ Lorain Harbor, Sean Burkholder

1 GREAT LAKES OVERVIEW
FOCUS PROJECTS

Through sediment management, the Great Lakes Division can foster and maintain the economic and ecological resilience of the region, bridging navigational needs with habitat creation. Current efforts are underway to address these opportunities, including regional sediment management efforts and BUDM projects, as seen in Unity Island in Buffalo. As regulatory pressures mount, trying alternative sediment management methods will become increasingly important, as seen in Ohio EPA's curtailment of open water placement (Sentinel-Tribune, 2022).

While BUDM projects can offer alternative uses of sediment, these projects can often be cost-prohibitive, requiring doublehanding and sometimes only providing a limited-time solution to a more significant, ongoing maintenance dredging issue. In response to these pragmatic concerns, passive sediment management utilizes natural coastal and fluvial forces, like winds, waves, and currents, to mobilize/transport/place sediment for desired outcomes, such as shoreline protection, navigation maintenance, habitat creation, and restoration. All three selected projects are case studies; each focused on a different passive sediment management strategy, including restoring a wetland from a fluvial system and utilizing BUDM, nourishing the near shore, and managing the bluffs. These projects are located within all three districts, Chicago, Buffalo, and Detroit, under different geomorphological and hydrological conditions, demonstrating how these techniques, and others, can be integrated throughout the division.

The three projects selected are:

+ Sediment Capture Wetlands, Green Bay, WI in Chicago District

+ Dynamic Habitat Shoal, Conneaut, OH in Buffalo District

+ Bluff Management, St Joseph, MI, in Detroit District

PART 2

EWN DESIGN CASE STUDIES

SEDIMENT CAPTURE WETLANDS

OVERVIEW

The Duck Creek Delta is a historically significant wetland complex just north of Green Bay, Wisconsin, and the mouth of Fox River. First named for its abundance of waterfowl, Duck Creek has long served as vital habitat and breeding grounds for countless plant and animal species. The creek winds northeast through the Oneida Reservation, Outagamie, and Brown Counties before emptying into the bay.

Over the years, the wetlands' overall quality and size have been depleted by both anthropogenic and natural processes. Heavy agriculture and development weep nutrients and other contaminants into the creek. High lake levels alongside intense storms erode the shoreline. Invasive species such as *Phragmites australis* overwhelm native plants and limit biodiversity, food, and habitat. Despite these challenges, the Duck Creek wetlands present an exciting opportunity to meld infrastructure with natural processes to benefit all inhabitants of the Green Bay area.

Through collaboration and partnerships with the USACE Chicago District, U.S. Environmental Protection Agency, and the Wisconsin Department of Natural Resources, our team has developed a proposal for a triad of constructed barrier islands that will protect the existing wetlands while guiding and accumulating sediment in strategic areas to expand them and potentially improve their quality.

These barrier islands, or sediment catchment islands, balance ecological, hydrological, and recreational benefits for the region. The barrier islands will protect the surrounding areas during storms and seiche conditions while providing habitat for rare and endangered waterfowl, native plant species, native fishes, and more. The wetlands will offer an expansive, resilient landscape in which all who visit may explore and enjoy.

◀ Duck Creek Delta, Sean Burkholder

1

PROJECT CONTEXT

HISTORIC SHORELINES

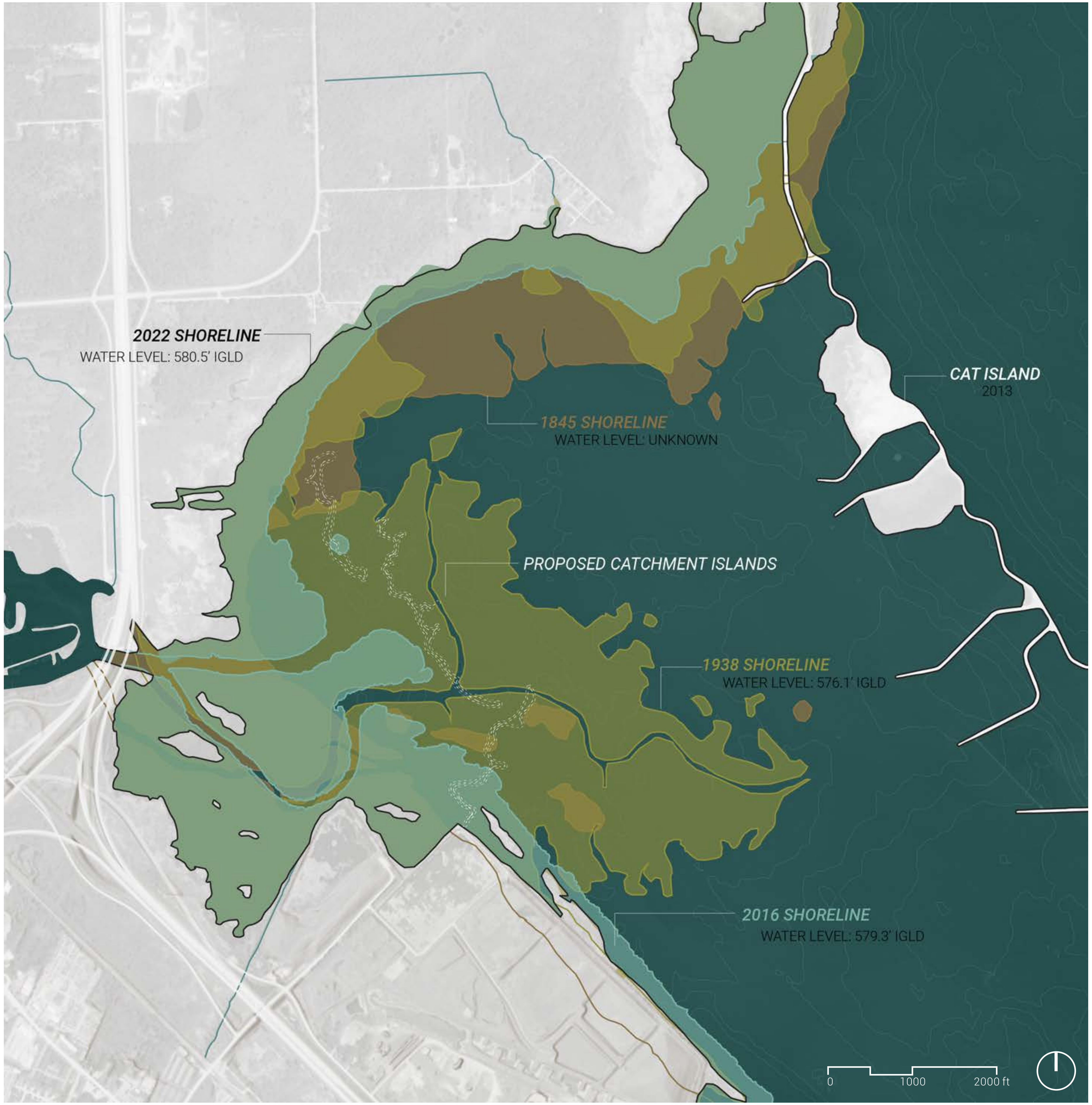
In 1845, a wide ribbon of marsh surrounded the mouth of Duck Creek, including a smattering of islands and a complex submergent marsh, as indicated by detailed depth measurements. Early accounts of the delta note the abundance of wild rice, *Zizania palustris*, which played an outsized role in attracting copious flocks of ducks and other migrating birds (Rentmeester, 1989). The Duck Creek wetlands were merely a portion of this massive marsh, documented in the 1845 survey by the Bureau of Topographical Engineers War Department (Wisconsin State Cartographer's Office, 2023), which extended from both sides of Fox River and, in some areas, spanned more than a mile between the bay and the land.

The creek has been heavily modified over the past two centuries to accommodate the needs of early industries such as lumber, stone quarrying, bricks, and shingles and serve as a trading route. As such, the overall quality and resilience of the creek and delta have fluctuated significantly. Lake levels rise and fall, invasive non-native species spread and overwhelm, heavy winter storms and ice shear erode the shoreline, and surrounding land use practices increase sedimentation and nutrient load. All these factors make this landscape highly dynamic and prime for restoration.

The oldest available aerial imagery of the delta dates to 1938 (Wisconsin State Cartographer's Office). This view shows a vast bird's foot delta of emergent marsh protected from strong wind and wave action by the Cat Island Chain less than a mile to the northeast. Research into historical records and photographs suggests that this version of the delta appears so vast due to increased sediment load from the prior decades in which much of the surrounding land was logged, farmed, and quarried with little regard for sediment control (Rentmeester, 1989, Thwaites, 1928). Further, in 1938, the recorded water level was just over 576' IGLD 85, about three feet below the historic mean level.

Multiple dams were also constructed near Pamperin Park in the early 1930s and likely began impounding much of the excess sediment shortly after that (American Rivers, 2023). All of this suggests that the 1938 extents were an artifact of conditions that no longer exist, a factor that we strongly considered in the restoration proposal.

Although the size of the 1938 delta was perhaps an unintended consequence of outdated land management practices, it nonetheless provided a larger wetland area for wildlife to inhabit while buffering native plant communities. After above-average water levels and strong storms in the early to mid-1970s, the Cat Island Chain was heavily eroded, resulting in land losses in the Duck Creek Delta (Wisconsin DNR, 2023). It never again rivaled the vastness apparent in 1938, and in the following years, the amount of emergent and submergent marsh varied significantly between years and even seasons.



2 CONCEPTUAL DESIGN

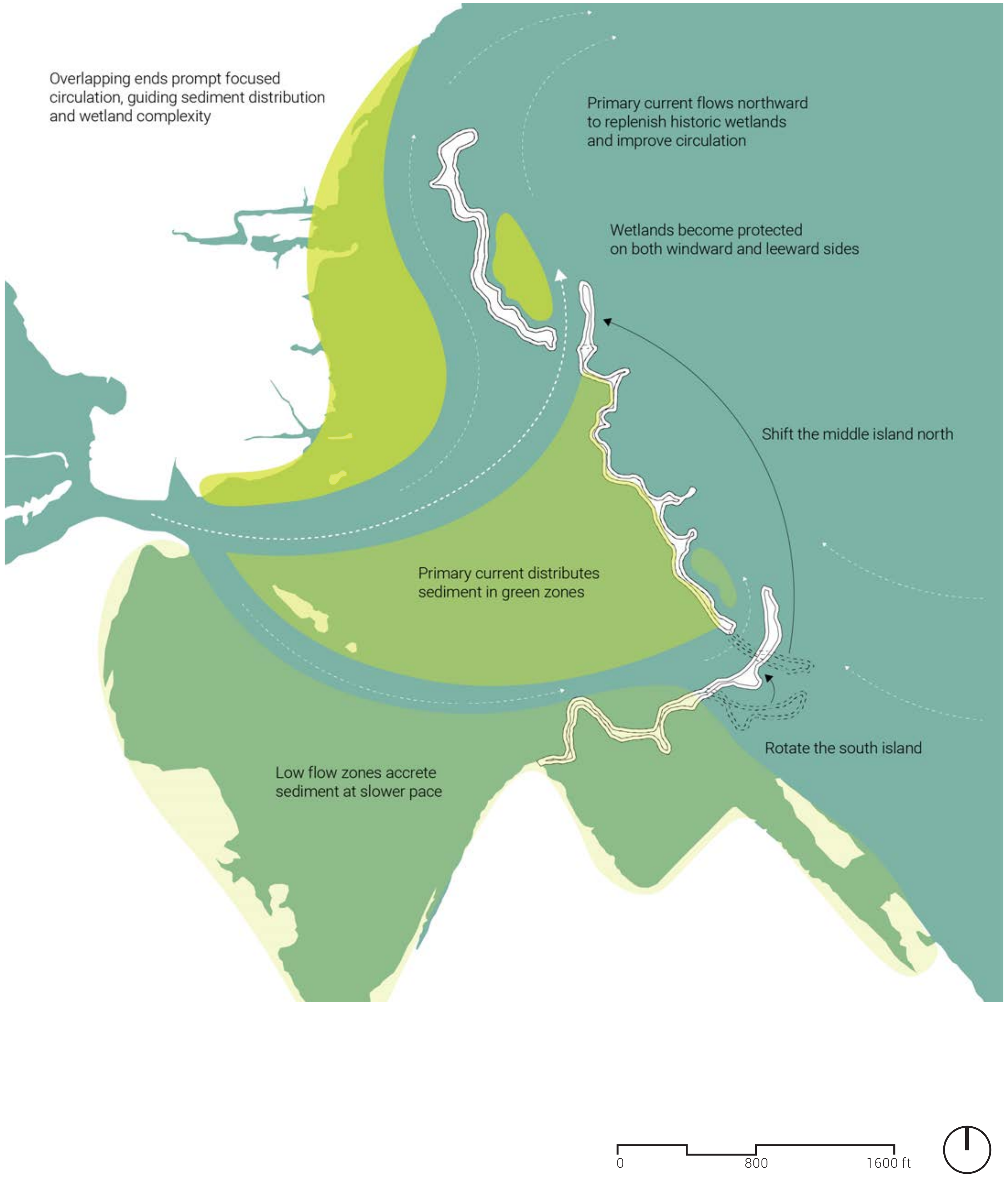
OVERLAPPING ISLANDS

With springtime snow melt comes Duck Creek's highest flow rates. Sparse vegetation allows for the increased flow to carry away more sediment from the creek's banks and deposit it downstream. Much of this sediment will enter Green Bay, where waves and currents disperse it. Alongside sediment, nutrients and pollutants from runoff also make it into the creek and the bay. Rather than letting this process be dictated by chance, it is possible to guide this sediment load into areas where it may accumulate and expand the delta's wetlands. This more extensive network of wetlands can then serve as a natural filter for contaminants, a carbon sink, and a coastal buffer.

This result can be achieved by slowing down the flow of Duck Creek as it enters Green Bay and directing its currents toward areas that have historically shown a wider band of marshland than present today, particularly the northern shore of Peats Lake. This slowing and redirection will be managed by constructing three sediment catchment islands. By studying the historic shorelines alongside complex wave and flow simulations, the islands will be placed to best catch sediment and guide the waters of Duck Creek as it reaches its terminus.

Informed by the craggy lines of the delta, as seen in the 1938 aerials, the catchment islands are designed to be naturalistic and irregular. This allows microhabitats to form in well-protected nooks and crannies, fostering greater biodiversity and varying growing conditions for different native plant communities. The arrangement of the islands is crucial. The overlapping islands encourage a directional flow towards the north, allowing for wetland flushing and increased water quality. This current can then carry and deposit sediment along the islands' shore and bay-facing sides. As a result, areas between two overlapping ends are doubly protected by an island on each side, forming a highly resilient landscape engineered to endure fierce winter storms.

The islands will be built through local excavation of nearby borrow pits or using BUDM. Using nearby sediment is cost-effective and ensures that the soil composition maintains regularity and is suitable for planting. Once in place, the islands will be seeded or planted with native grasses to limit erosion . Over time, these plantings will be monitored and maintained to ensure the health and success of these new plant communities, including submergent and emergent marsh, wet/mesic shrub prairie, and even areas of fringe sedge meadow. Wild rice, which has long enticed Duck Creek's namesake waterfowl, will be planted alongside native cattails, bulrushes, and sedges. Eelgrass, *Vallisneria americana*, a submerged aquatic vegetation that provides foraging, shelter, food, and spawning grounds for many fish and waterfowl species, will also thrive in the protected zones created by the islands.



3 COMPUTATIONAL MODELING
RESULTS

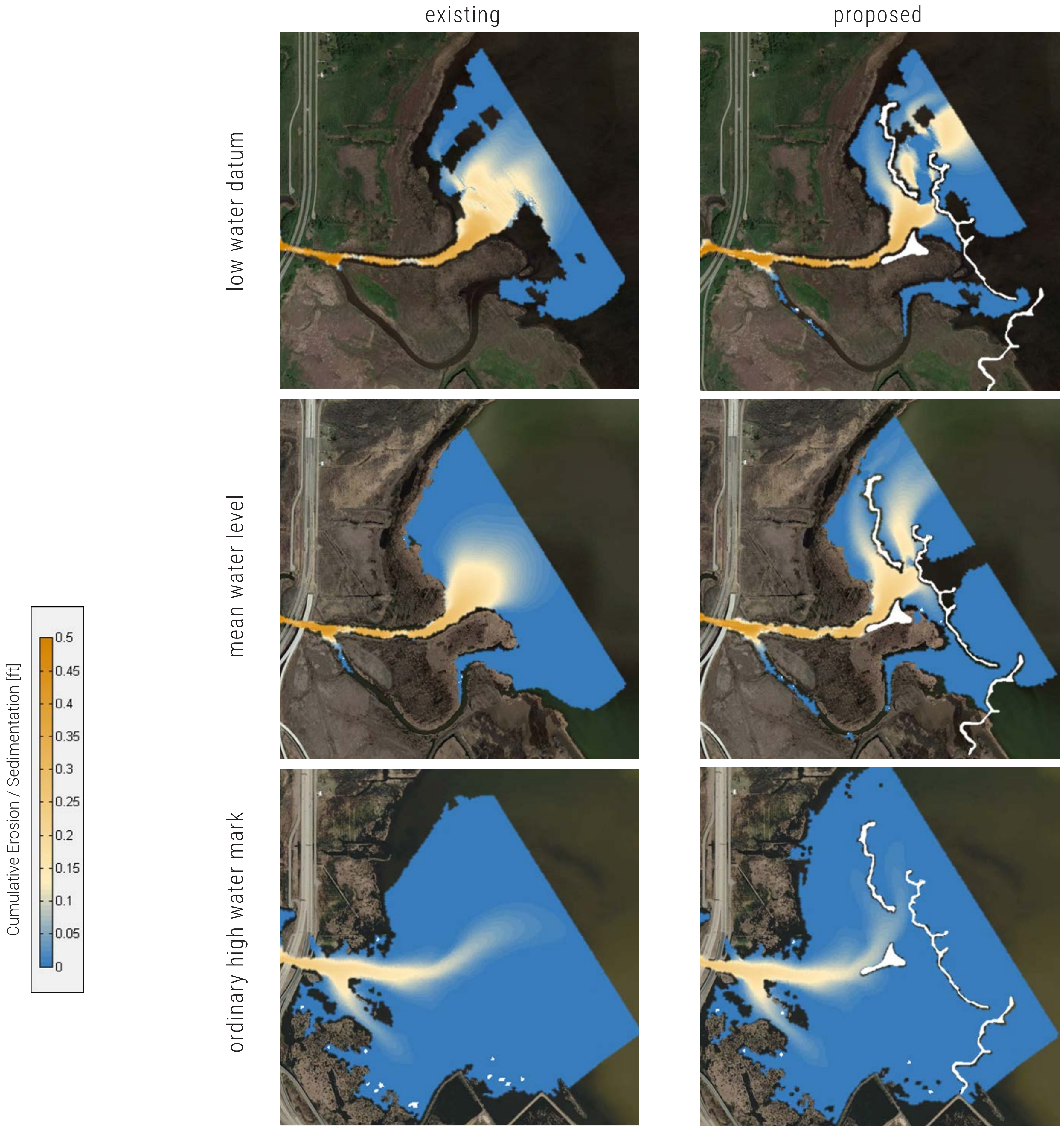
See the appendix for more details. The islands ‘ placement, elevation, and geometry were established through collaboration with USACE. Simulations were run to demonstrate the effectiveness of the design at low water datum (LWD) of 577.5,’ mean water level (MWL) of 579’, and ordinary high water mark (OHWM) of 581.5’ (IGLD 85). Results of these flow simulations found that lake water levels highly influence how sediment is distributed in the delta.

During LWD simulation, the results show flow paths restricted by the shallow water, resulting in some high-velocity areas where the Duck Creek discharge passes over shallow areas. Under existing conditions, the sediment deposition occurs in the river channel and fans out from the mouth, traveling farther than the mean water level simulations. With the barrier islands in place, some sediment deposits at the mouth, and sediment also travels north along the barrier islands and through the island gap. Most of the sediment that passes through the center gap is transported more than 1,000 feet into the bay or farther, out of the modeled domain. The flow constriction combined with extreme low water creates high velocities through the gap, which does not allow sediment to settle out. Flow areas to the north and south of the main channel are mostly cut off by the shallow water. The flow deflector has little effect because the footprint is almost entirely dry at LWD.

At MWL, Duck Creek is channelized most of the distance between Highway 141 and the proposed barrier islands. Under existing conditions, sediment deposits in the river channel and fans out in a uniform manner from the mouth. With the barrier islands in place, sediment deposits at the mouth but also travels and deposits north along the barrier islands and through the gap in the barrier islands directly in front of the channel. The model also suggests less deposition at the gaps in the barrier islands directly in front of the main channel and to the north, where the flow is constricted, and velocities are higher than in the surrounding area. The flow deflector has little effect because the footprint is mostly dry during MWL.

At Ordinary High Water Mark (OHWM) water level, Duck Creek discharges into open water after passing under Highway 141. Under existing conditions, the sediment deposition occurs primarily in the flooded river channel, farther upstream than in the LWD and mean water simulations. The high lake levels increase water levels in Duck Creek, reducing velocity and allowing sediment to settle out sooner. With the barrier islands in place, a small portion of sediment is deflected north along the barrier island and through the central gap, although most sediment has settled out before reaching that point. The flow deflector appears to redirect flow and sediment to the north. It does not appear to split flow and direct a significant portion of the sediment to the south.

While the islands worked as anticipated, the flow deflector seemed to have little to no effect on splitting the flow during LWD, MWL, and OHWM. Based on the modeling, we would recommend removing the flow deflector from future designs.



4 FLOURISHING WETLANDS
YEAR ZERO

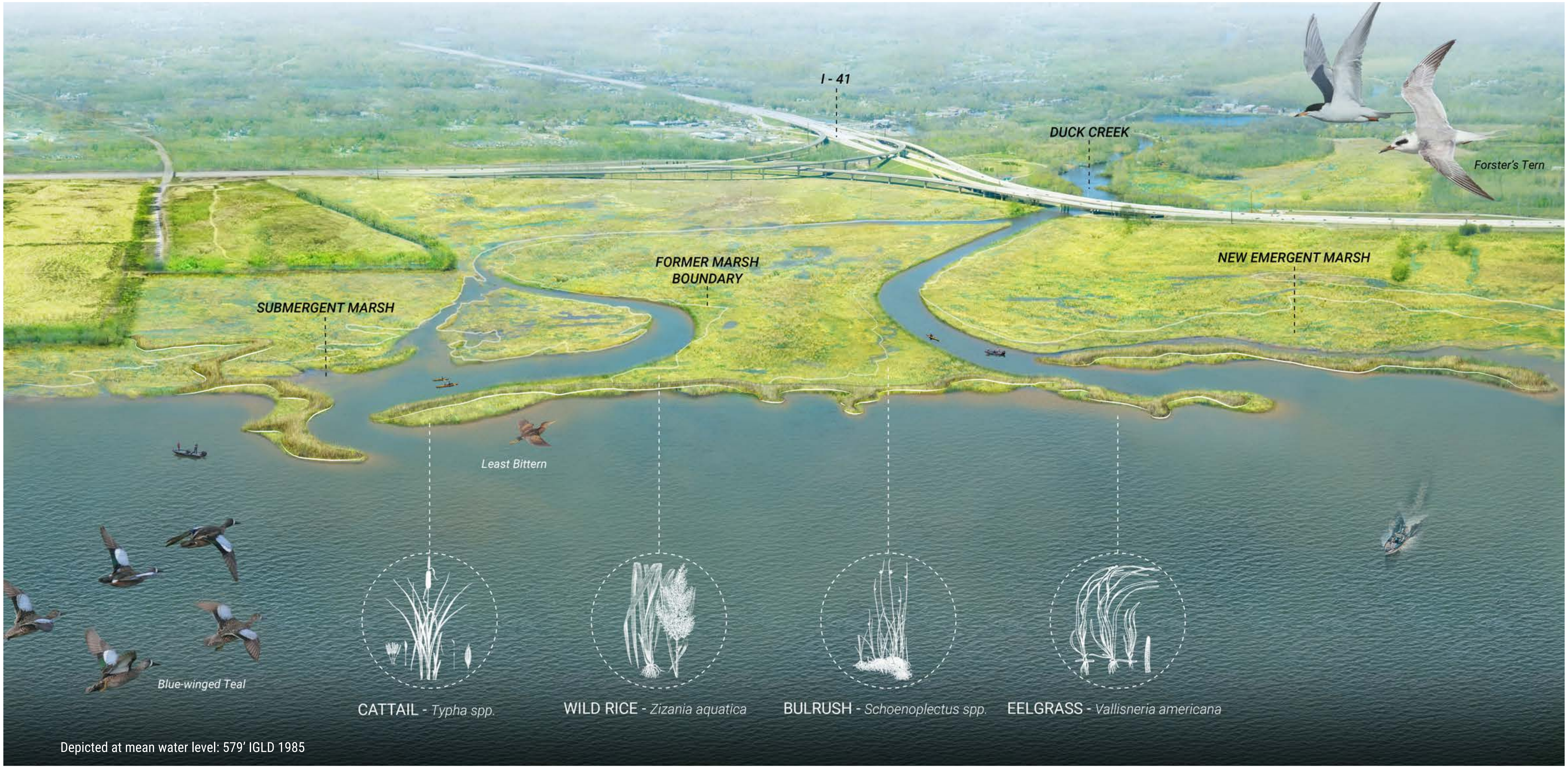
Strategically placed to guard the existing wetland network of Duck Creek Delta, the catchment islands will be built by sediment dredged from borrow pits in the immediate vicinity or by BUDM. The islands will then be seeded or planted with native wetland grasses to prevent erosion. Even before the wetlands expand, the islands will attract wildlife by offering protection from strong wind and wave action.

Depicted at mean water level: 579' IGLD 1985.

4 FLOURISHING WETLANDS
YEAR TEN-TWENTY

Ten to twenty years after installation, a robust network of emergent marsh, submergent marsh, and wet prairie will have developed inside the delta and around the catchment islands. The wetlands behind the north island will have filled in, and pockets of marsh will even have formed along the bay side of the islands as sediment accumulates in the nooks of the curving shoreline. Diverse plant communities centered around wild rice, cattails, bulrushes, and eelgrass will thrive and, in turn, create habitat for countless bird and fish species.

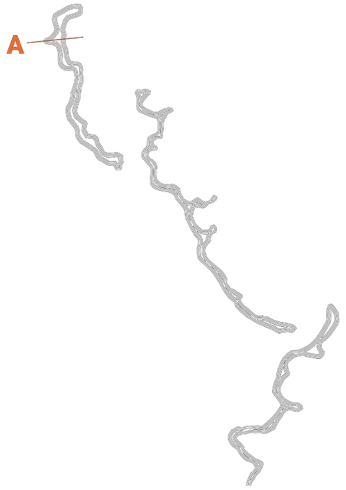
As a dense, healthy wetland, the delta will filter the water flowing into Green Bay, improving circulation and water quality behind the Cat Island Chain. Not just for wildlife, the delta will likewise serve residents and visitors of Wisconsin. The northern channel will remain wide, navigable, and deep enough for recreational watercrafts.



Depicted at mean water level: 579' IGLD 1985

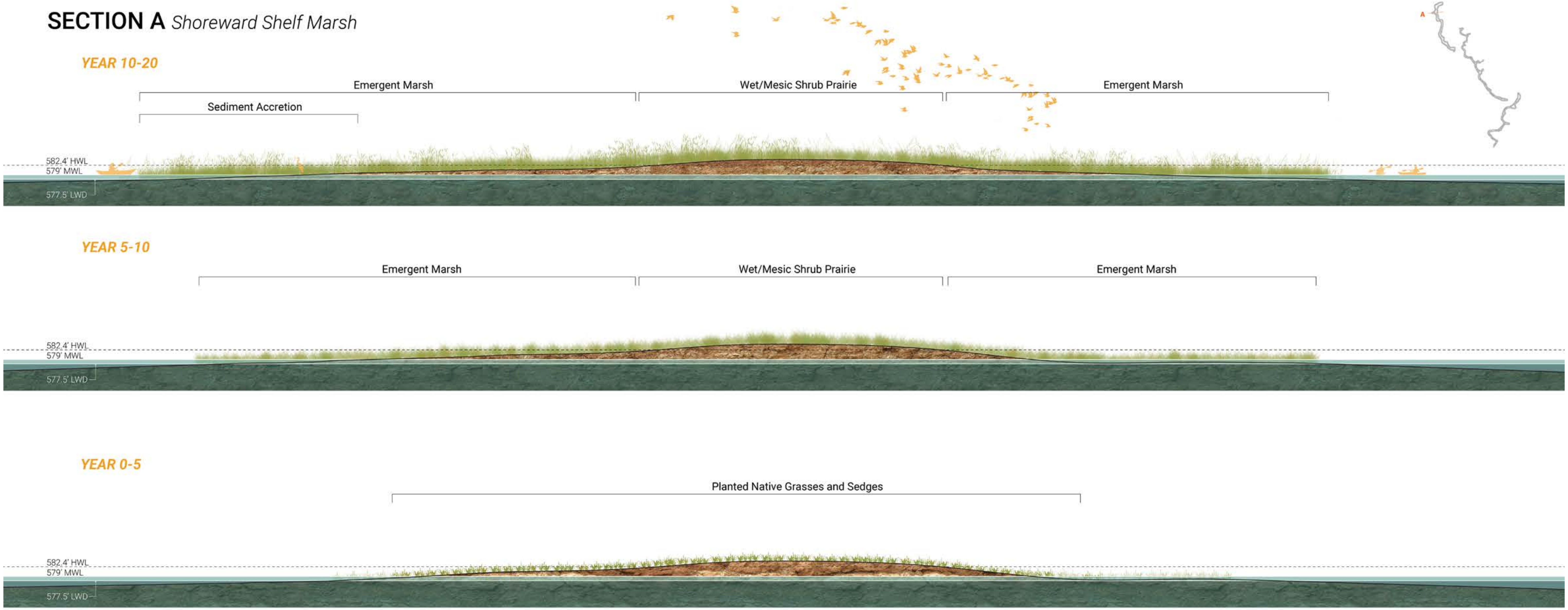
4 FLOURISHING WETLANDS

SECTION STUDY- NORTH ISLAND



The islands' design is deeply informed by the fluctuation of water levels within Lake Michigan and how this corresponds to existing plant communities and habitat zones. Cross sections of the islands highlight wide buffers of emergent marsh at mean water level. The islands stay emergent even at a historic high of 582.4' (IGLD85). Wet shrub prairie can be established at these higher elevations, offering diverse habitats for nesting shorebirds. This north island will play a significant role in accumulating sediment behind it, though some of the outflow of Duck Creek will maintain a small channel around the shoreward side.

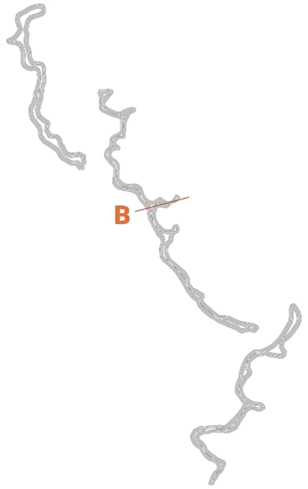
SECTION A *Shoreward Shelf Marsh*


YEAR 10-20

YEAR 5-10

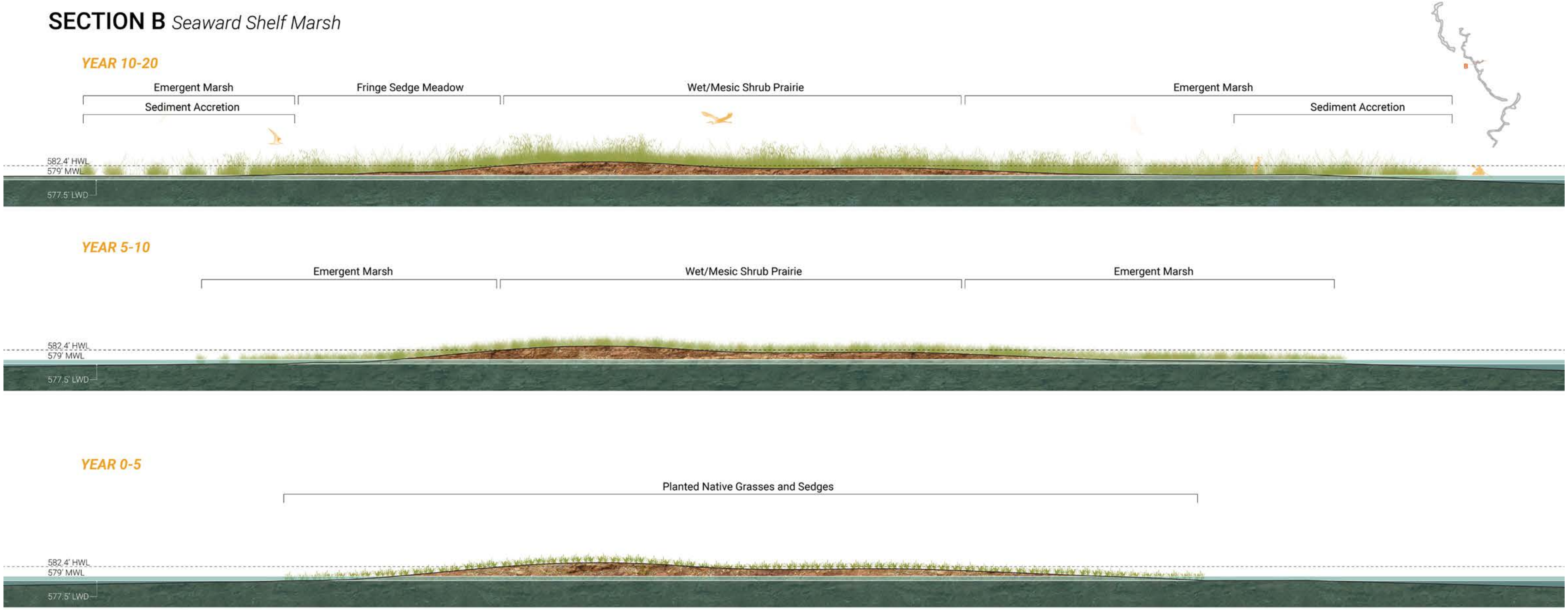
YEAR 0-5

4 FLOURISHING WETLANDS
SECTION STUDY- MIDDLE ISLAND

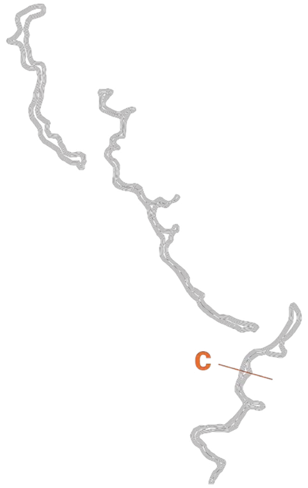


The middle island has a unique peninsula that forms one side of a small lagoon on the seaward side. This wide stretch of the island exemplifies an opportunity for multiple plant communities to establish side-by-side relative to elevation. Much of the area behind this island consists of existing emergent marsh and is expected to continue to fill in. On the bay-facing side, the long peninsula will act to trap sediment flowing northward, extending the marsh even further. Based on monitoring data and adaptive management, the bay-edge marsh may need soft-edged protection in future years.

SECTION B *Seaward Shelf Marsh*

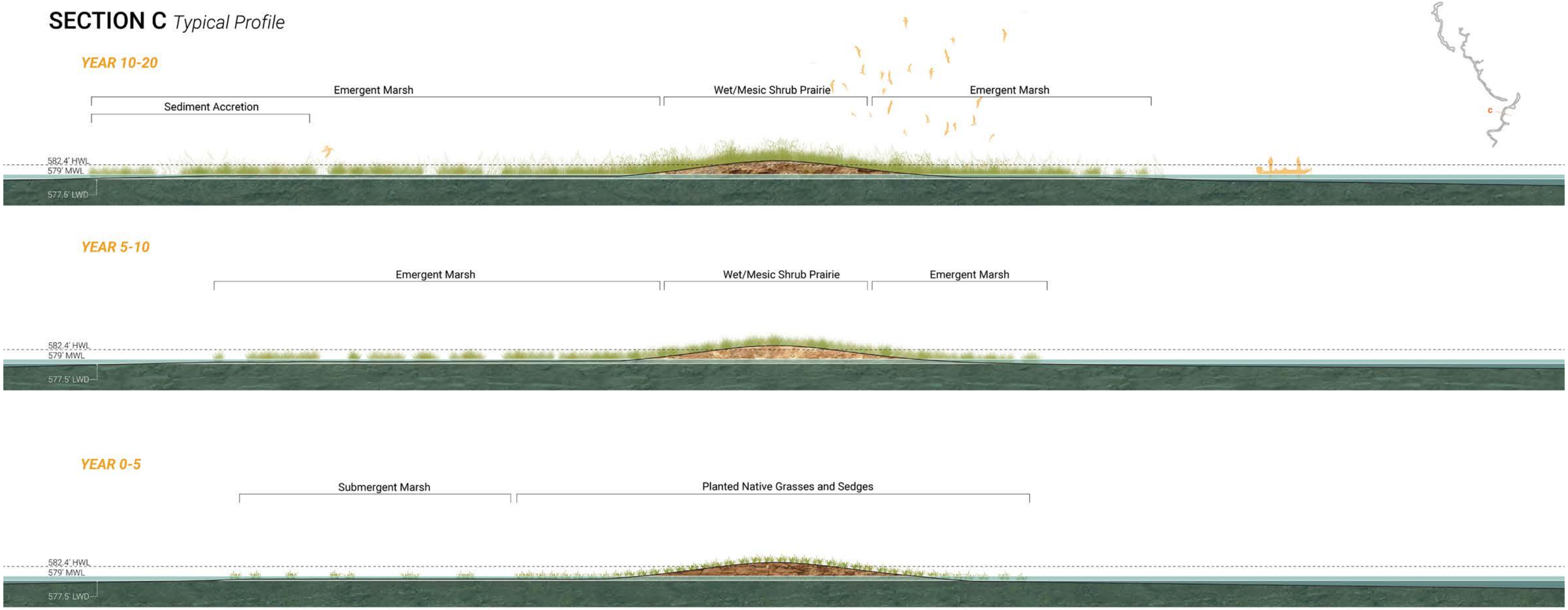


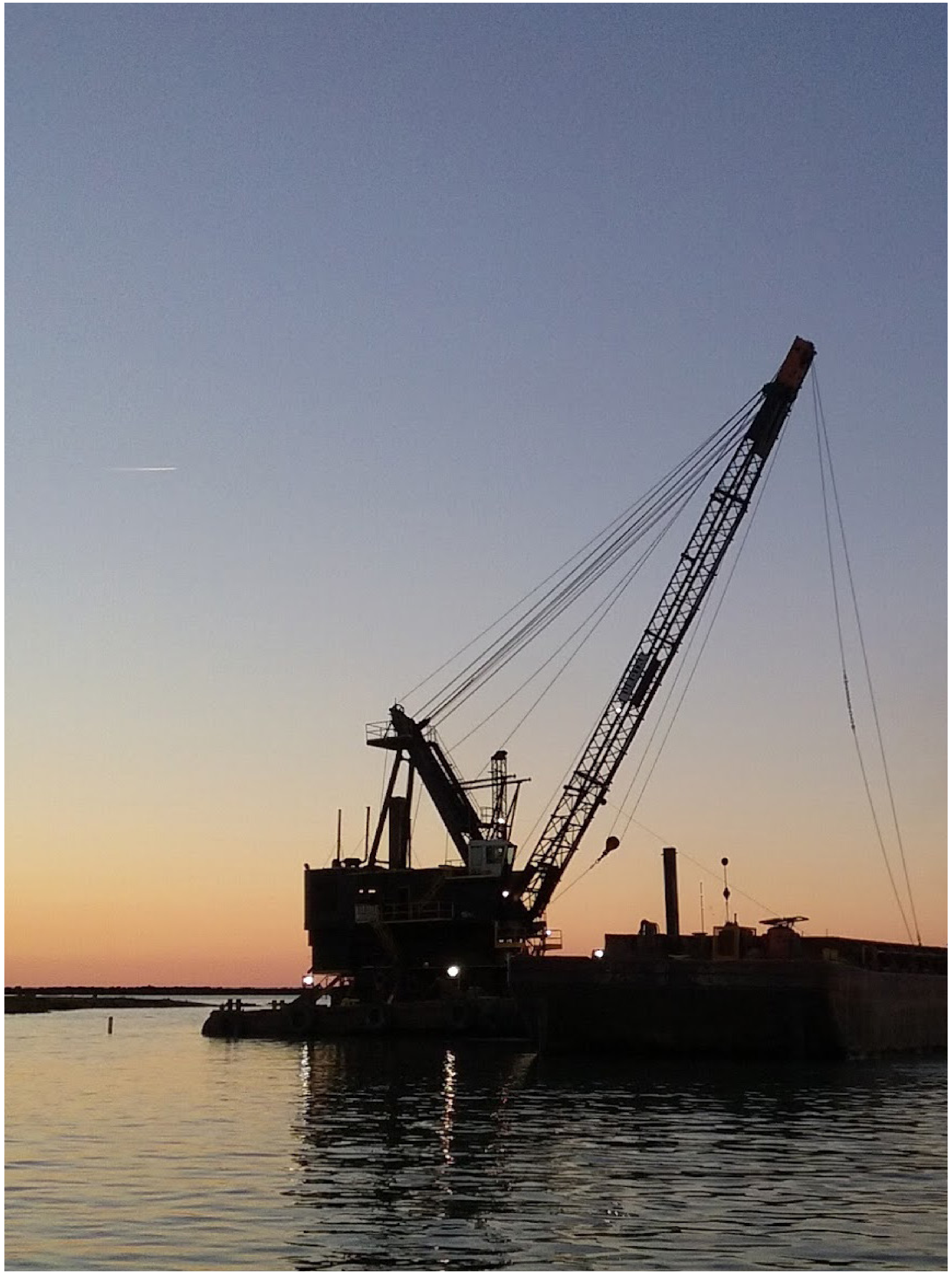
4 FLOURISHING WETLANDS
SECTION STUDY- MIDDLE ISLAND



The south island serves to fortify the wetlands against wave action refracting around the Cat Island Chain from the northeast. Much of the existing marsh behind this island is submergent, so with added protection and gradual sediment accretion, the marsh will transition to an emergent condition. The bay-facing waters should remain relatively deep and navigable, as modeling indicates limited sediment accretion. If need be, a future project could utilize the adaptive monitoring of Cat Island Chain to carefully open some flushing channels and inlets within the island to enhance water quality.

SECTION C *Typical Profile*





◀ Conneaut Harbor, Google Earth Image

DYNAMIC HABITAT SHOAL
OVERVIEW

The presence of the Conneaut Harbor breakwaters and other navigation infrastructure within the study area has adversely affected the natural movement of sediments along the southern shoreline of Lake Erie. This infrastructure has resulted in detrimental sediment erosion downstream from the harbor and has escalated erosion rates in the westernmost townships of the Commonwealth of Pennsylvania. Furthermore, this sediment erosion has contributed to the degradation of both terrestrial and aquatic habitats critical to the well-being of significant Great Lakes species.

The project aims to design and construct nearshore structures that can effectively hold and gradually disperse dredged sediment to nourish the nearshore. These dynamic habitat shoal structures are designed to hold one cycle of dredged material. The structures' open back also allows sediment dispersal to the nearshore during disturbance events. At the same time, the protective front promotes partial wave mitigation for sediment retention during daily events. In addition to nourishing the nearshore and increasing long-term dredge sediment capacity, the structures will offer fish habitat and erosion control.

The nearshore structures are specifically designed to function as fish habitat. These structures offer shelter, breeding grounds, and feeding areas for various fish species. This goal aligns with the broader objective of enhancing the Great Lakes ecosystem and supporting the sustainability of fish populations. In addition, the project aims to reduce erosion rates and protect the shoreline by strategically placing nearshore structures. These structures should act as barriers to wave action and help stabilize the shoreline, contributing to the overall resilience of coastal areas.

The specific location of the structure in the water column should be studied further to consider a range of priorities, including vessel safety, sediment retention capacity, and shoreline protection. These concepts will work in a variety of depths with varying degrees of sediment winnowing capabilities. They are presented here as a demonstrations of only two variations, which will require further design development before implementation.

1 PROJECT CONTEXT
CONNEAUT SEDIMENT

Severe erosion was observed along the bluffs stretching from Conneaut to Presque Isle, with the area near Conneaut Harbor experiencing particularly significant impacts from wave action. The presence of Conneaut Harbor breakwaters has disrupted the natural movement of sediments, reducing sediment transport from west to east along the shoreline. The harbor also captures riverine sediment that would otherwise disperse in the nearshore. This sediment amounts to approximately 75,000 cubic yards per year of maintenance dredging (Ohio EPA, 2021). The harbor's dredge materials primarily consist of fine-grain sediment, comprising 45-49% silt, 24-33% clay, and 18-27% fine sand (USACE, 2022). The river channel exhibits a higher proportion of silt and clay components and a minimal presence of fine sand.


Conneaut Harbor requires maintenance dredging of approximately 75,000 cubic yards per year.

---Ohio Environmental Protection Agency Harbour Sediment Authorization for Lake Erie Dredge From Conneaut Harbor

Silt component with the percentages of silts and clays ranging from 5.9%-86.6% with an average value of 35.2%.

A predominance of coarser grain size (sand) which lacks a significant silt component. The silt component in these sediments ranged from 0.5%-3.2% with an average value of 1.6%.

1 PROJECT CONTEXT

POTENTIAL PROJECT LOCATIONS

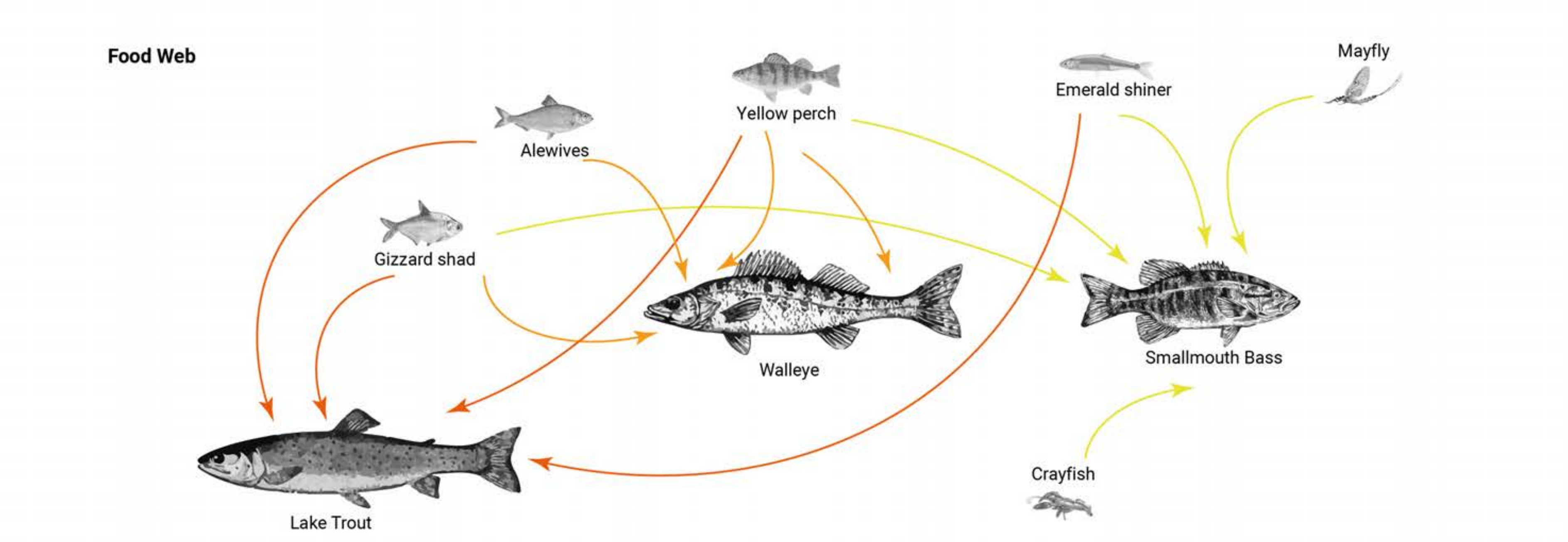
The EWN design team focused on creek mouths, spanning from Conneaut Harbor to Presque Isle along the southern shores of Lake Erie, as potential sites for this project. Creek mouths are recognized as biologically rich and dynamic ecosystems, particularly for fish spawning. These areas serve as crucial breeding and nursery habitats for many fish species. By placing dredge sediment near the creek mouth, the project aims to enhance and optimize these habitats, fostering fish populations and contributing to the conservation of aquatic biodiversity. Moreover, creek mouths are naturally less susceptible to erosion. Sediment erosion can destabilize bluffs and erode valuable shoreline habitats. Introducing sediment in a well-planned manner helps reduce erosion rates and preserve these critical habitats for both terrestrial and aquatic species.

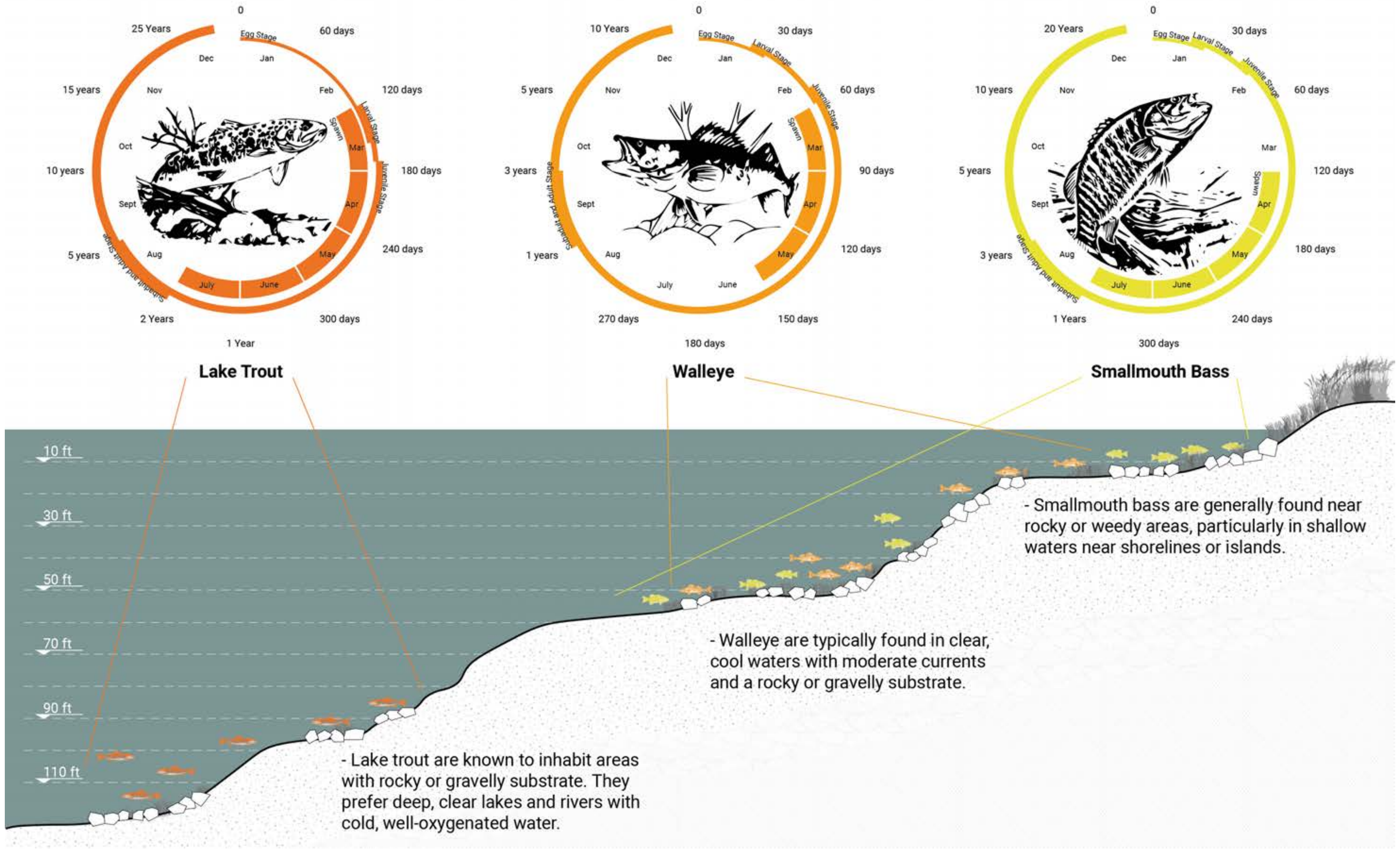
Situated within a 5-mile radius of Conneaut Harbor, we selected Raccoon Creek (see Creekmouth B on map) for our design proposal. Raccoon Creek possesses a naturally occurring point bar at its creek mouth. This point bar offers several advantages, including the potential to stabilize shoreline sediment, serve as a protective barrier against erosive water forces, and create essential habitats for a diverse range of aquatic and terrestrial species.

2

NEARSHORE RESEARCH
FISH HABITAT

The three main species of fish habitat of interest in the project were Smallmouth bass (*Micropterus dolomieu*), walleye (*Sander vitreus*), and lake trout (*Salvelinus namaycush*). Smallmouth bass inhabit regions near rocky or weedy areas, often favoring shallow waters near shorelines or islands. Walleye typically thrive in clear, cool waters characterized by moderate currents and a substrate of rocks or gravel, while lake trout are known to reside in areas featuring rocky or gravelly substrates, showing a preference for deep, clear lakes and rivers with stable, well-oxygenated water conditions. Despite these habitat distinctions, all three species share a common food web and engage in spring and early summer spawning.





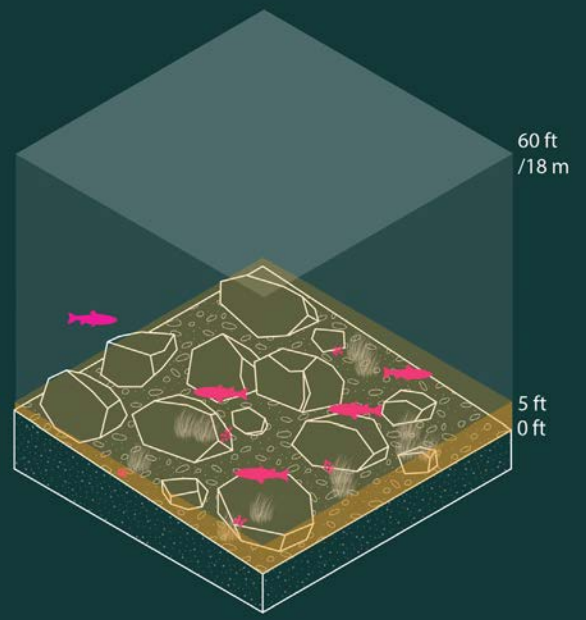
- Smallmouth bass are generally found near rocky or weedy areas, particularly in shallow waters near shorelines or islands.

- Walleye are typically found in clear, cool waters with moderate currents and a rocky or gravelly substrate.

- Lake trout are known to inhabit areas with rocky or gravelly substrate. They prefer deep, clear lakes and rivers with cold, well-oxygenated water.

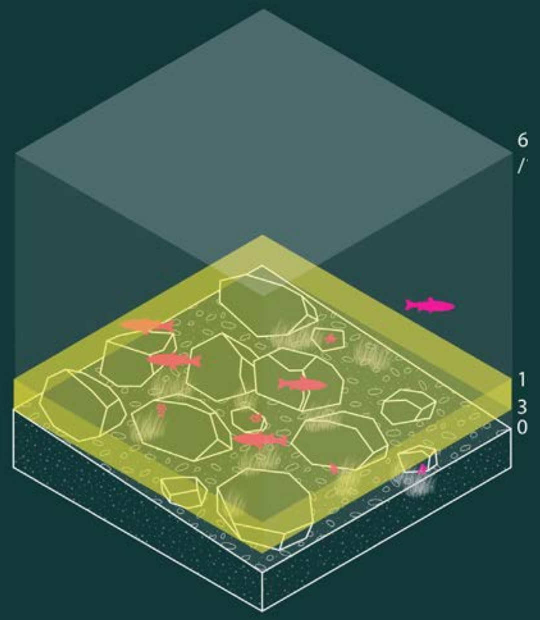
2 NEARSHORE RESEARCH
FISH HABITAT

Walleye typically dwell in depths of 30-60 feet during the day, moving to shallower waters (around 10-30 feet) at night and even shallower (1-2 feet) during spring spawning (Matley et al., 2020). Smallmouth bass occupy depths from a few feet to over 50 feet, spawning in waters 3-10 feet deep (Lane et al., 2002). Lake trout are found in depths exceeding 100 feet and favor specific spawning sites on the eastern sides of shallow offshore humps, typically in waters of 15-18 feet (Markham et al., 2022).



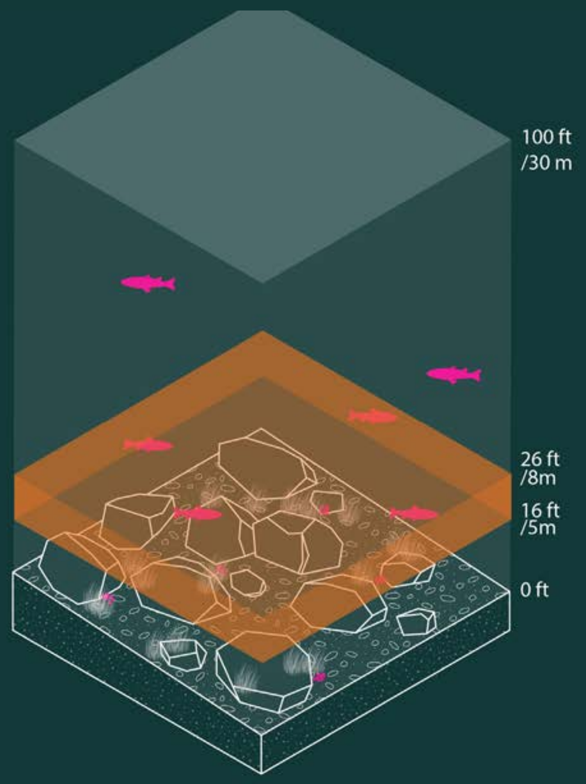
Walleye are often associated with areas that have good cover and food sources, such as submerged vegetation, rocky shorelines, and areas with high concentrations of prey fish.

During the **day**, walleye may be found around **30-60 feet** deep or more, while they may move to **shallower waters at night to feed**, often in the range of 10-30 feet deep. During the spring **spawning season**, they may move into even shallower waters, **1 to 2 feet.**



In Lake Erie, **smallmouth bass** are generally found nea rocky or weedy areas, particularly in shallow waters nea shorelines or islands. They may also inhabit deeper wat structures such as drop-offs, reefs, and shoals.

In general, smallmouth bass in Lake Erie can be found at depths ranging from a few feet to over 50 feet. They may **spawn in water depths ranging from 3 to 10 fee** (approximately 1 to 3 meters)

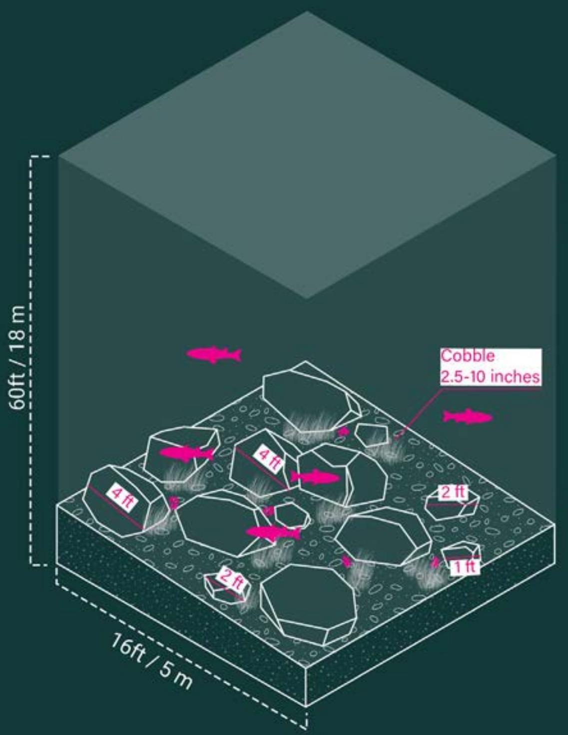


Lake trout are typically found in water depths greater than 100 feet (30 meters), although they may also be found in shallower water near shore during the spring and fall.

Lake trout utilized a very specific **spawning habitat type—the eastern side of shallow offshore humps in 5–8 m of water.** These sites were comprised of habitat typically associated with lake trout spawning with slopes of 5–14° and clean rubble-cobble sized rock with visible interstitial spaces.

2 NEARSHORE RESEARCH CASE STUDIES

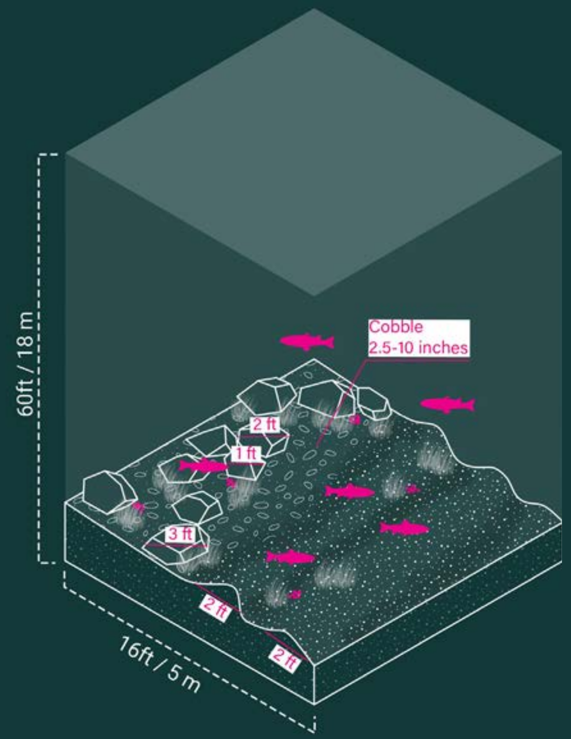
Precedent habitat enhancement projects were identified in the region and studied to understand the type, size, and depth of substrate preferred by the targeted fish species.



Boulder-Cobble
Location: Brocton Shoal, NY

Lakebed consists of multiple long sinuous boulder-cobble ridges.

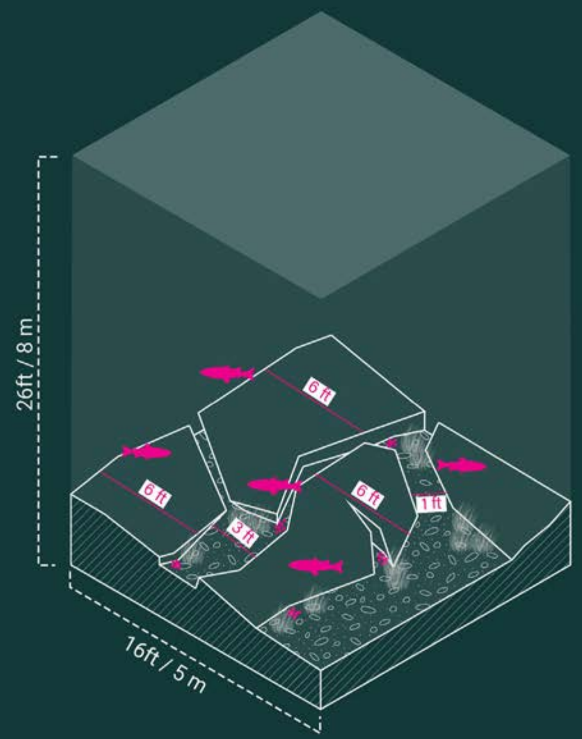
Great Lakes Fish and Wildlife Restoration Act Final Report: Identifying Potential Lake Trout Spawning Habitat in Lake Erie



Boulder-Cobble & Coarse Sand/Dunes
Location: Brocton Shoal, NY

Lakebed consists of boulder-cobble rock piles, and sand deposits with large-scale dune forms

ldlife Restoration Act Final Report: Identifying Potential Lake Trout Spawning Habitat in Lake I



Fractured Bedrock
Location: Presque Isle, PA

Lakebed consists of exposed fractured bedrock overlain by thin coarse sand deposits, and boulder-cobble rock piles.

Great Lakes Fish and Wildlife Restoration Act Final Report: Identifying Potential Lake Trout Spawning Habitat in Lake Erie

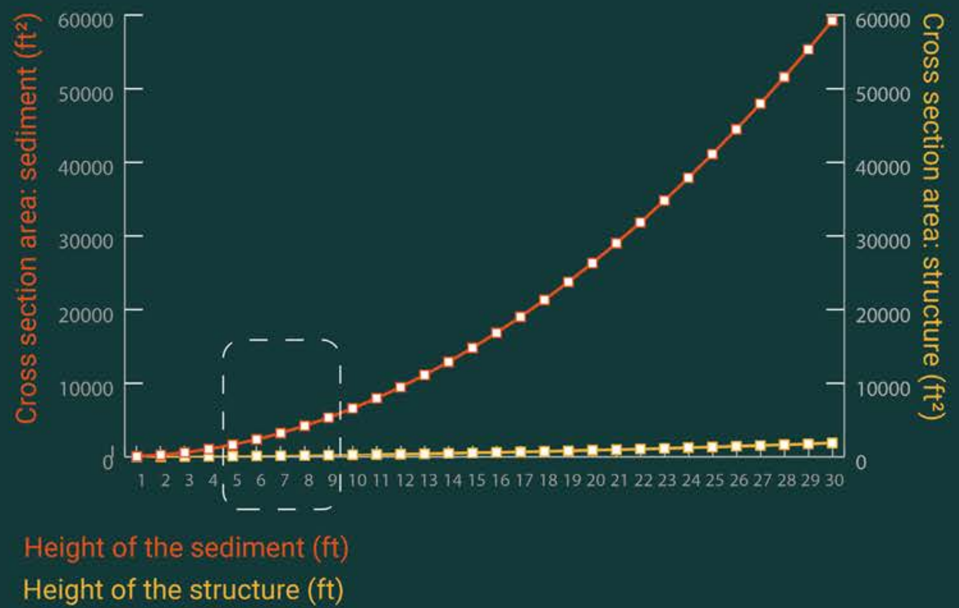
2

NEARSHORE RESEARCH

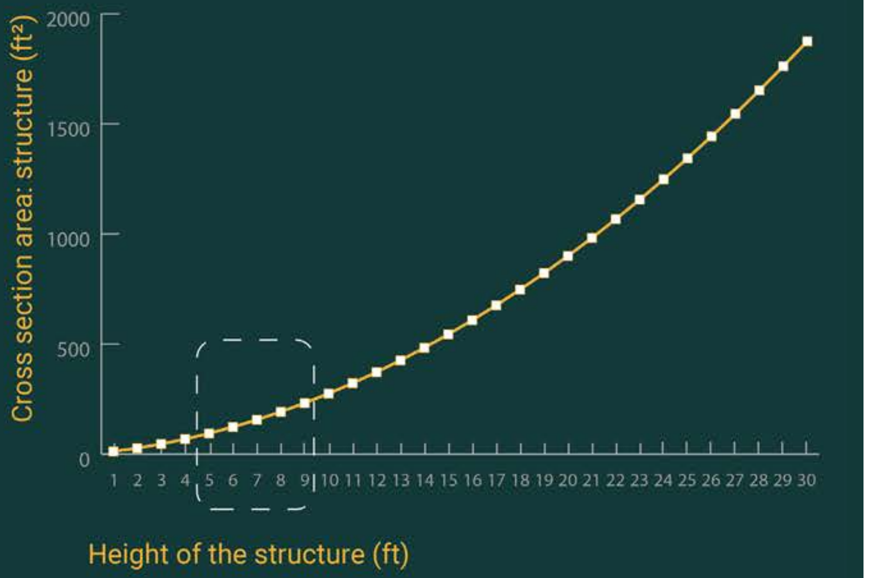
FORM OPTIMIZATION STUDIES

We calculated the correlation between the structure and the placed sediment cross-sectional areas on a <1% slope , the known slope of the nearshore (NOAA, 1999). The structure's height corresponds to its sediment-holding capacity. Based on our findings, an efficient structure for sediment containment falls within the range of 5-8 feet in height , resulting in a compact overall design. We have stayed below this upper range to have a submerged structure that could minimize stone size and cost while providing habitat and sediment placement benefits. It is important to note that taller structures would necessitate larger dimensions, leading to increased costs. Stone size depends on the feature's location within the nearshore, and additional analysis would be necessary to determine a more exact size range. However, based on the current location in the nearshore and the desire for the feature to be submerged under LWD, we anticipate that a 3–8-ton stone would be used.

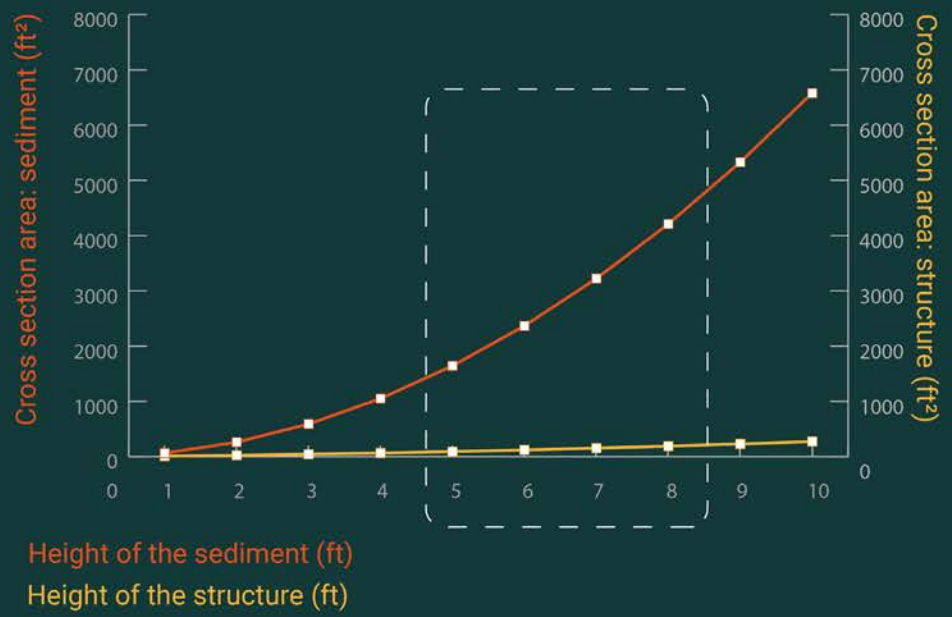
Relation between Structure and Sediment



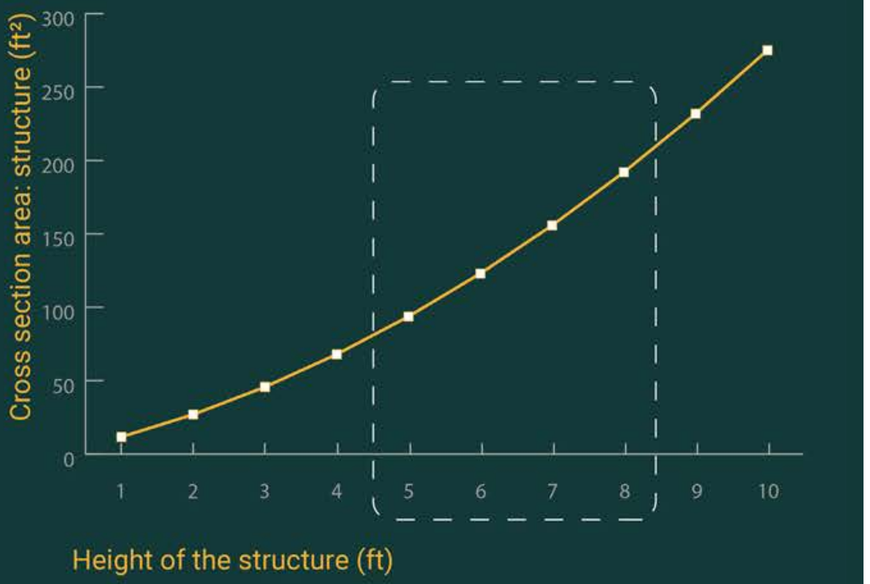
Relation between Cross-section area and Height of the structure



Zoom-in Relation between Structure and Sediment



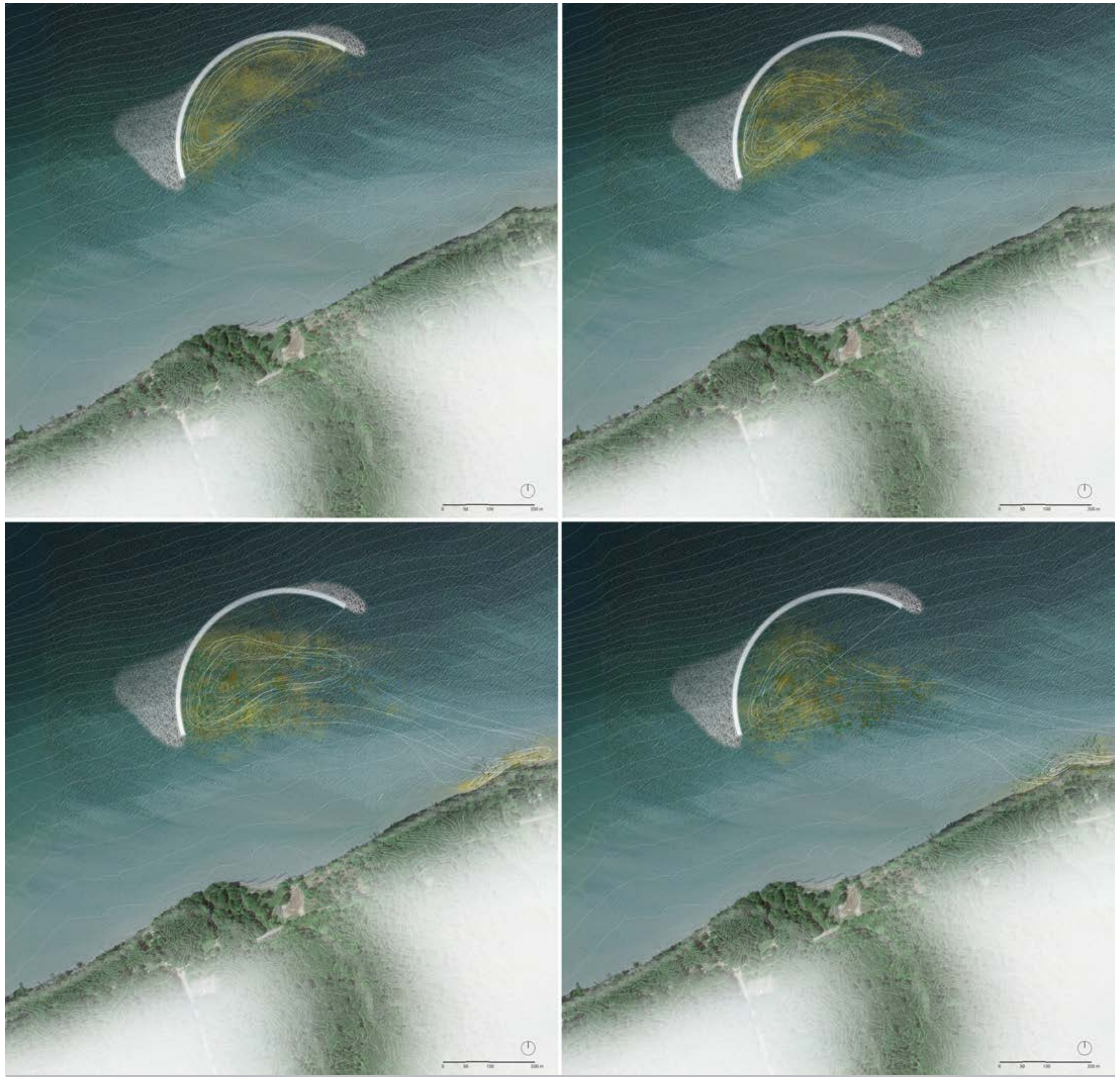
Zoom-in Relation between Cross-section area and Height of the structure



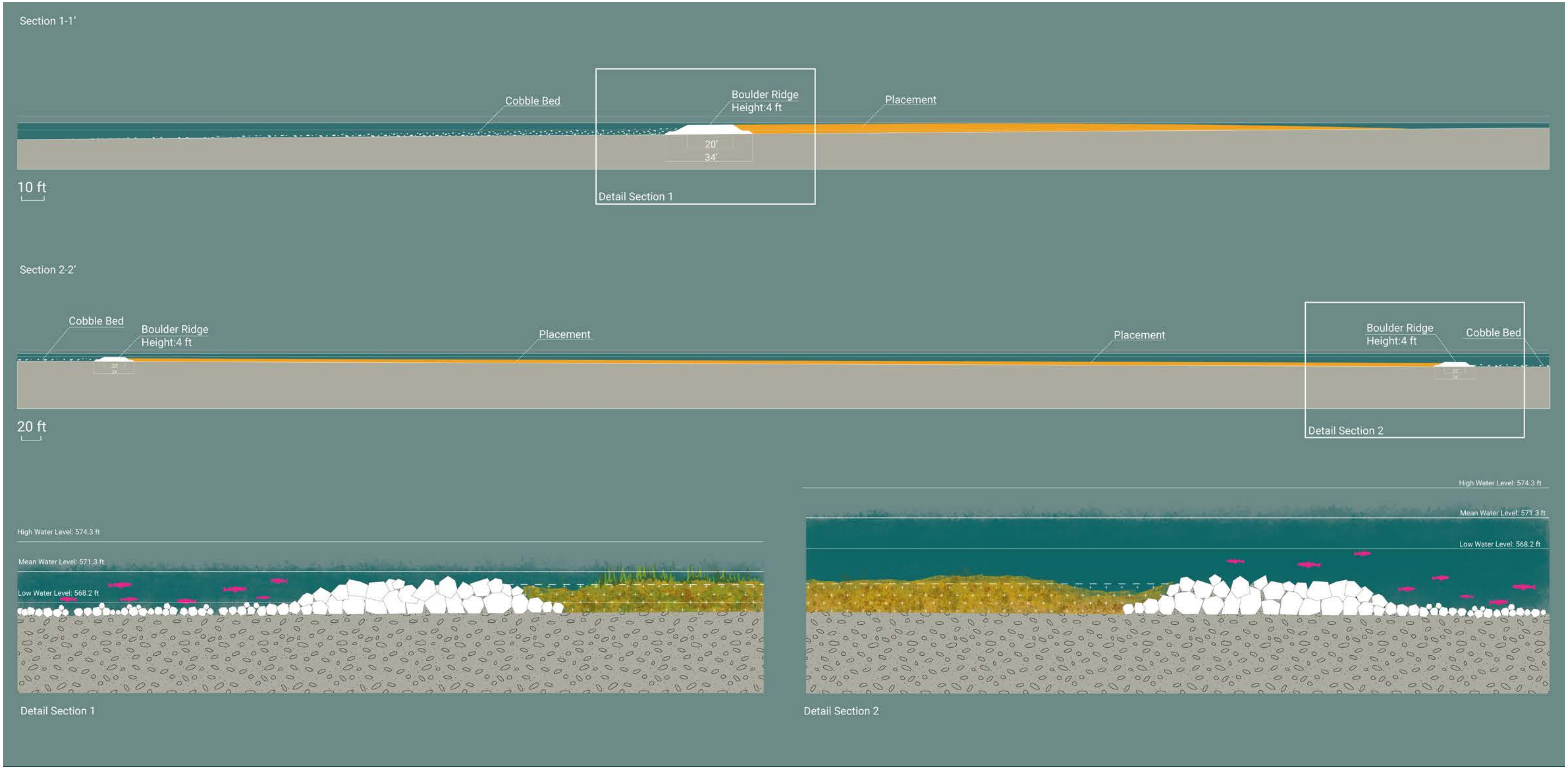
3 DESIGN CONCEPT
OPTION 1 PLAN

Design option 1 features a crescent-shaped submerged ridge. The portion of the structure behind the expansive tongue-shaped cobble bed and adjacent boulder ridge is a low wave action zone ideal for wetland creation. Over time, this area may support subaquatic vegetation and other wetland species, especially during periods of low water. Conversely, wave action will play a critical role in sediment transport with finer grained sediments being mobilized off shore and coarser grained sediments would contribute to the littoral drift system.

This design also incorporates a substantial cobble bed in a tongue shape positioned to diminish wave action from the prevailing direction. Additionally, another cobble bed is situated on the structure's eastern side. These cobble beds can serve dual purposes by supporting wetland creation and fish habitat, suitable for spawning and feeding activities.



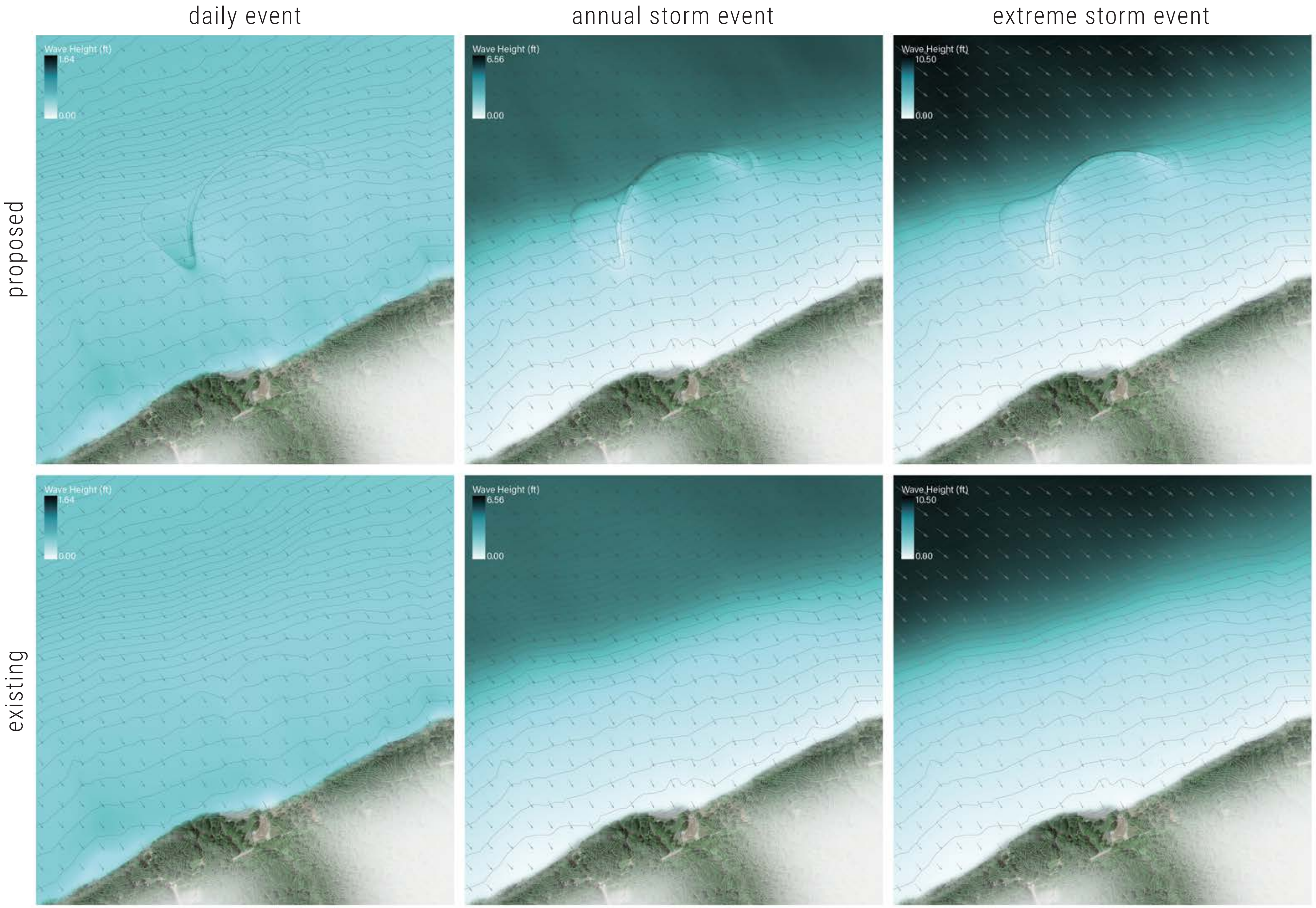
3 DESIGN CONCEPT
OPTION 1 SECTIONS



3 DESIGN CONCEPT
OPTION 1 WAVE PATTERN STUDIES

The design team utilized CMS Wave for an initial sense of patterns under median water level of 572.5 IGLD 85, under daily and large waves in the existing and proposed conditions. The existing conditions were modeled from NOAA Great Lake Bathemetry, 1999 (3-arc sec resolution), and USGS (1-arc sec) 2021. These studies were not meant to be a precise quantitative analysis but to provide a preliminary assessment of the proposed designs. Further analysis would be needed if the project went into engineering and design.

Based on the analysis, it is observed that the area situated behind the extensive tongue-shaped cobble field and adjacent boulder ridge experiences reduced wave heights. The wave energy would likely maintain the cobble bed clean of excess sediment, creating stable spawning grounds adjacent to a low-energy environment on the lee side.

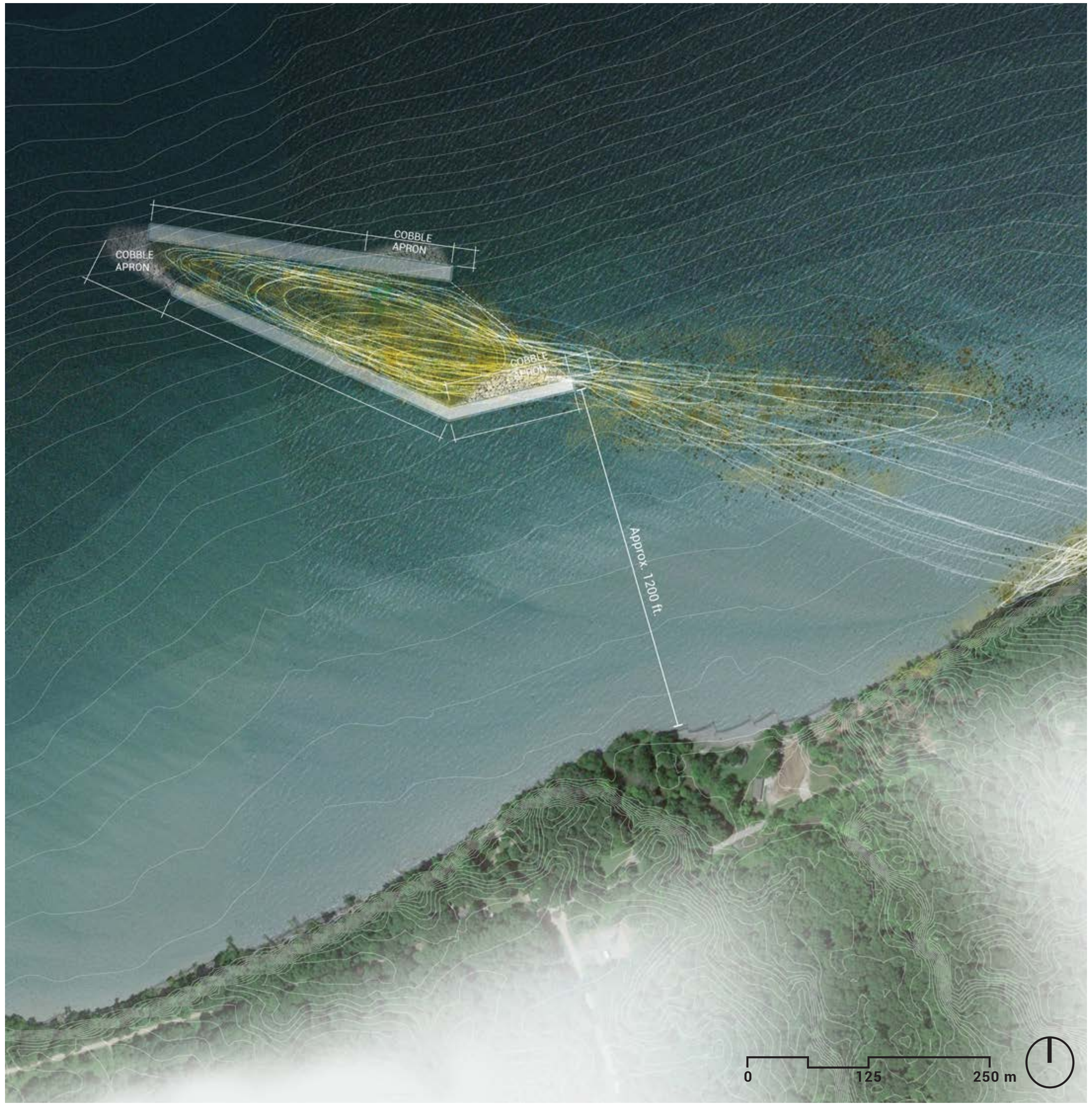


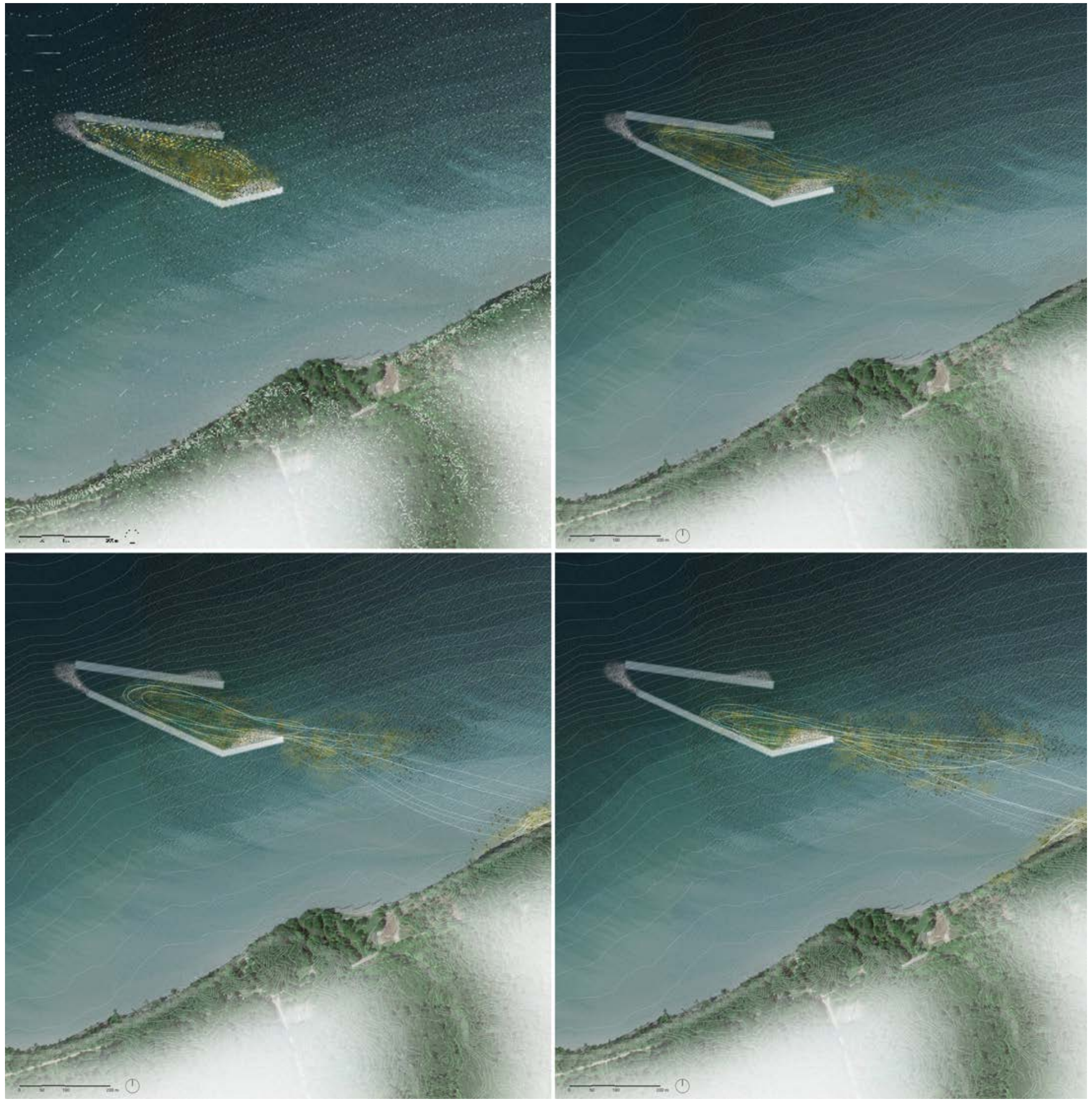
3 DESIGN CONCEPT
OPTION 2 PLAN

Design option 2 consists of two separate ridges and terminal cobble beds. The interstitial space between the ridges can be filled with dredged sediment. Their orientation creates a wedge that allows for a protected placement zone and creates terminal cobble beds at different elevations in the water column to offer multiple spawning opportunities. A cobble bed is placed at the northwest end, while two additional cobble beds are situated on the shallow end at varying depths. This arrangement of cobble beds will minimize toe erosion and enhance the stability of the structure.

Located at different depths, they should offer habitat diversity, providing crucial support for various fish species and the organisms they rely on for food.

Placed sediment, located between the boulder ridge structures, is gradually transported along the shoreline by wave action. This process plays a crucial role in decelerating shoreline erosion and bluff recession. As the sediment nears depletion, there is the opportunity for periodic replenishment through the placement of dredge sediment.

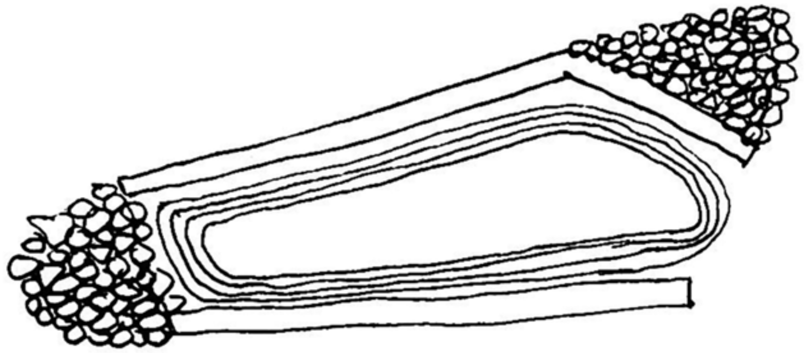


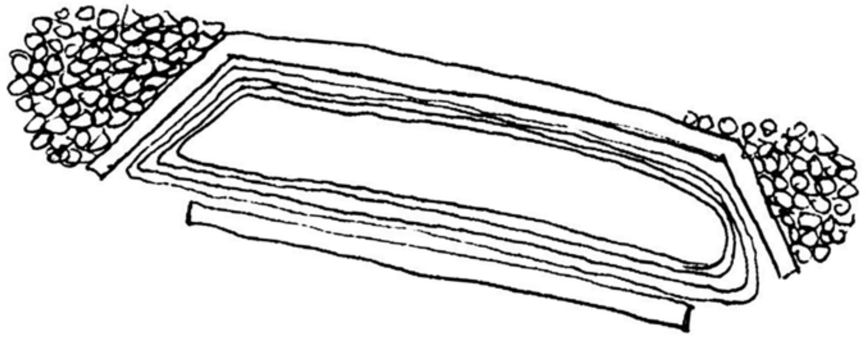


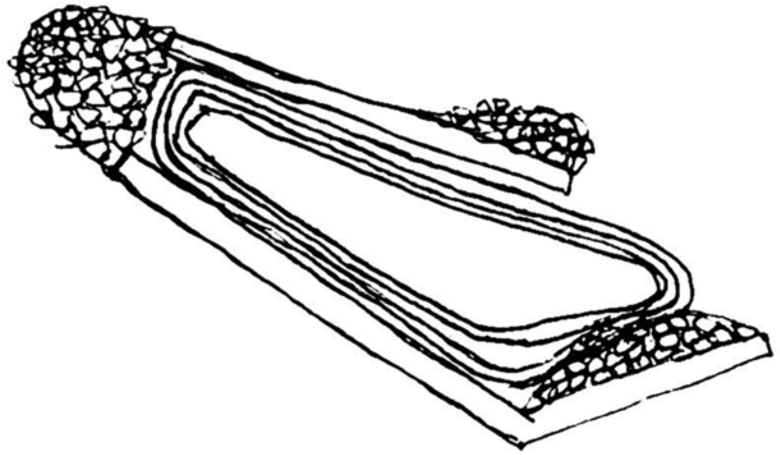
3 DESIGN CONCEPT

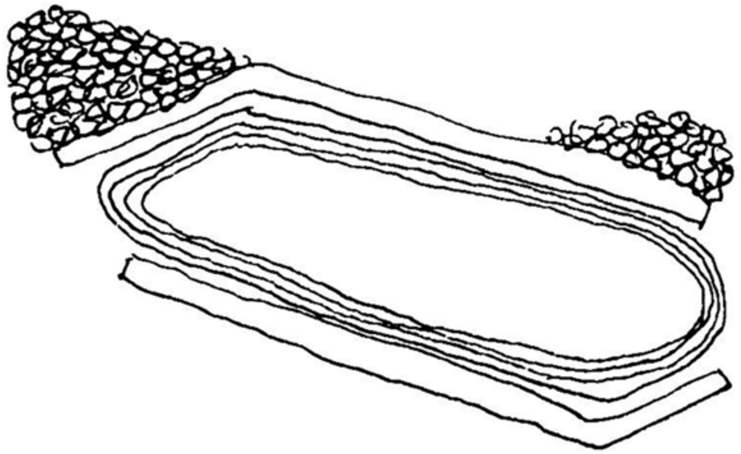
OPTION 2 PLAN (OPTIONS)

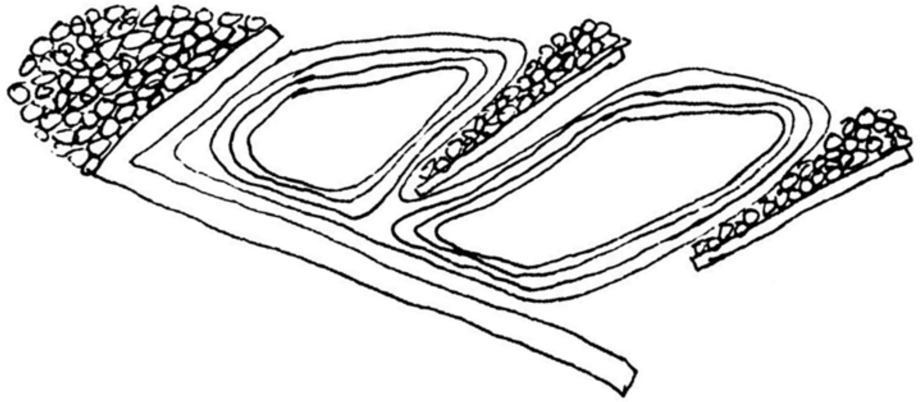
It should be noted that the exact arrangement of the concept can be altered to reflect a more detailed survey and the desired outcomes of the design (wetland establishment vs. nearshore nourishment, area of cobble beds vs. boulder ridges, enclosure and projection, and volume of sediment). The following sketches show some of these alternatives of Design 2. We have shown what we believe may be the optimum arrangement based on limited data but suggest additional data collection and alternative studies.

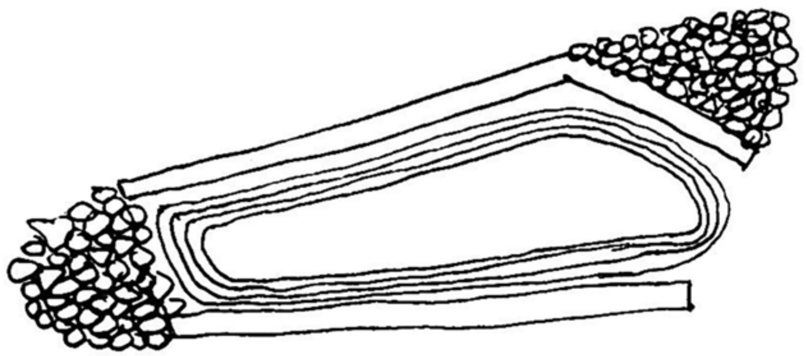






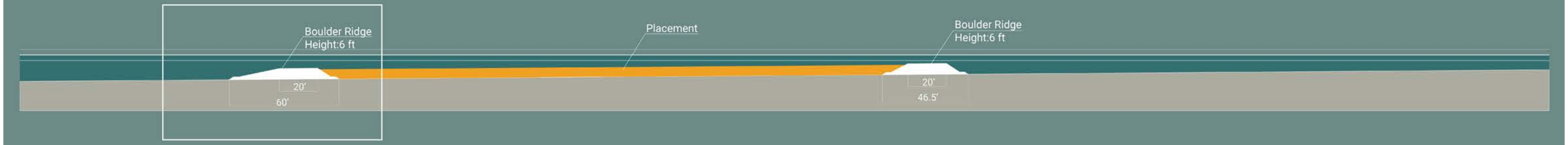




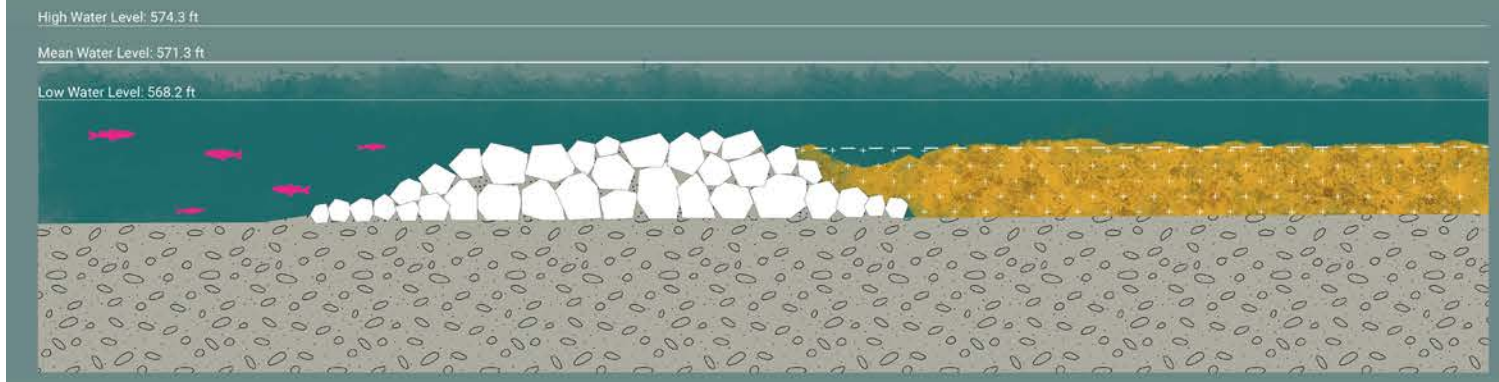


3 DESIGN CONCEPT
OPTION 2 SECTION

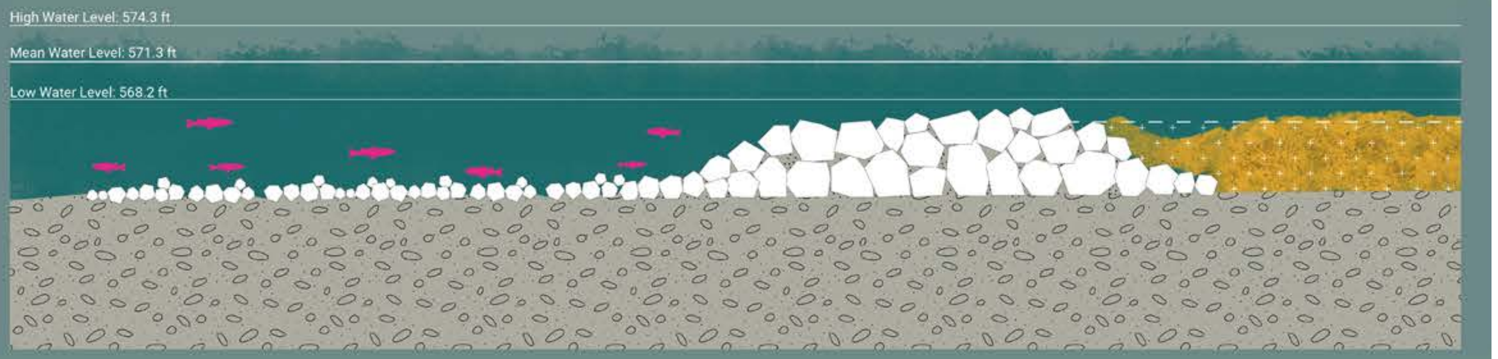
Section 1-1’



Section 2-2’



Detail Section 1



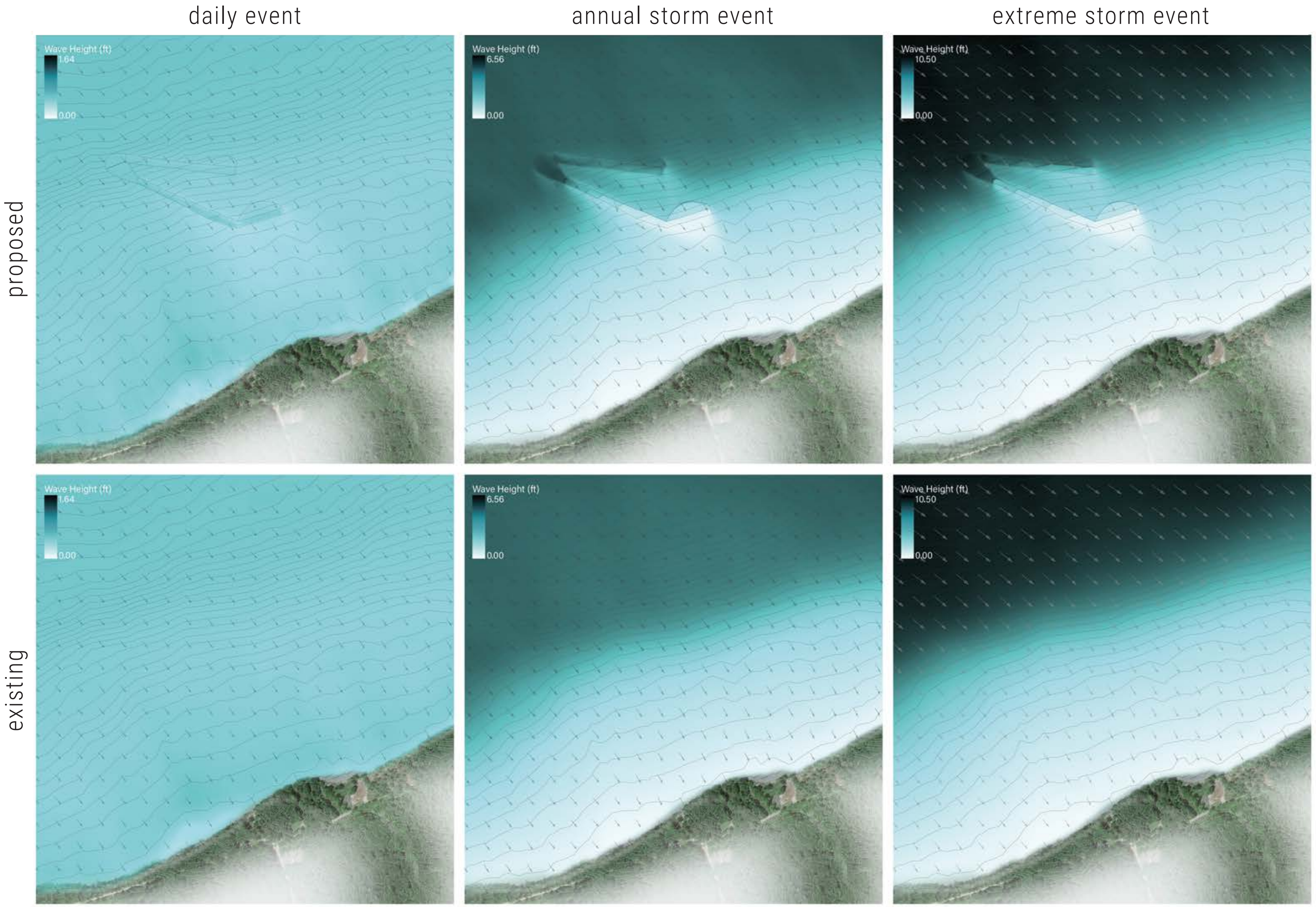
Detail Section 2

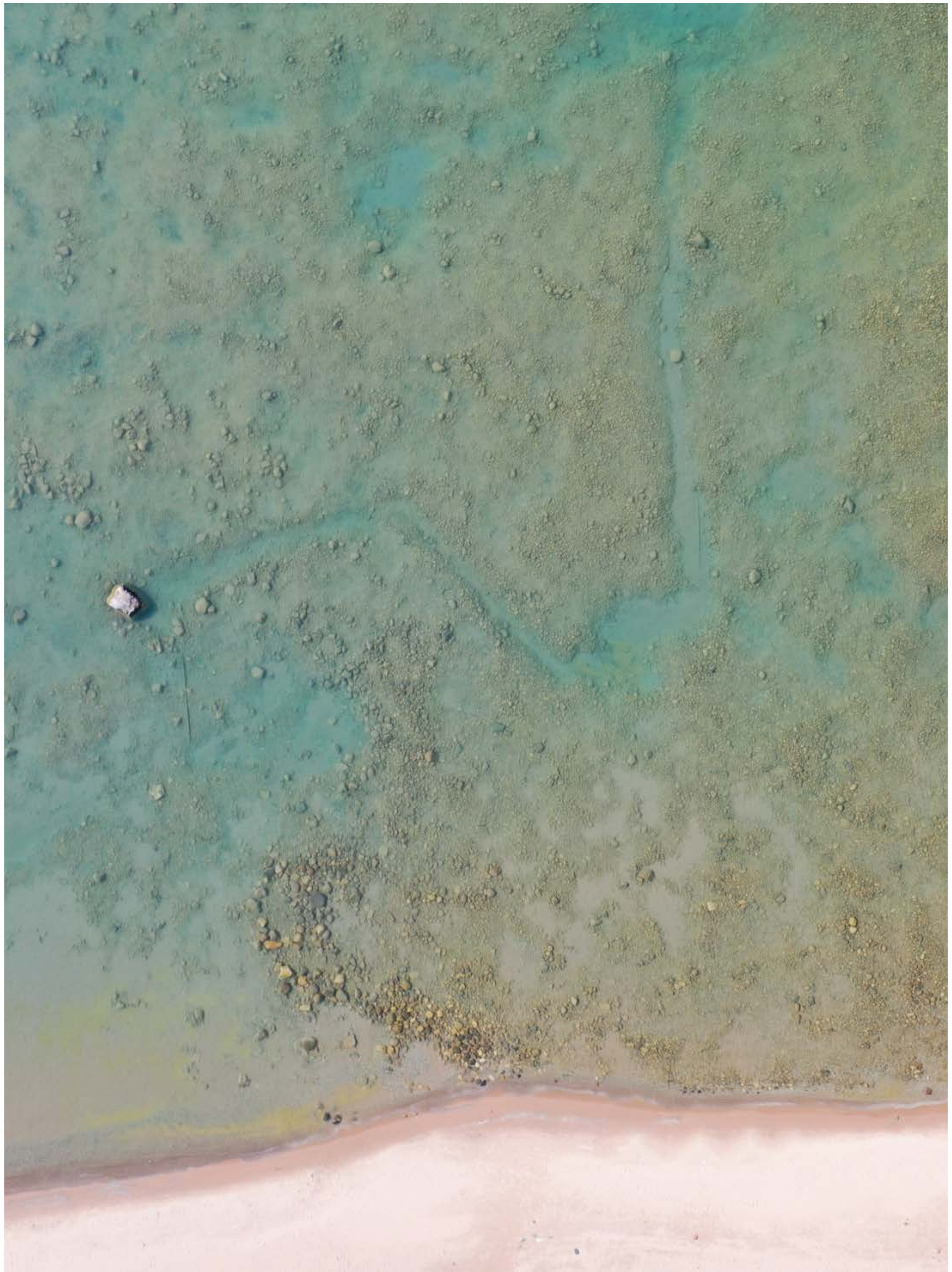
3 DESIGN CONCEPT

OPTION 2 WAVE PATTERN STUDIES

The design team utilized CMS Wave for an initial sense of patterns under median water level of 572.5' IGLD 85, under daily and large waves in the existing and proposed conditions. The existing conditions were modeled from NOAA Great Lake Bathemetry, 1999 (3-arc sec resolution), and USGS (1-arc sec) 2021. These studies were not meant to be a precise quantitative analysis but rather to provide an initial base assessment of the proposed designs. It is a good tool, but further analysis would be needed if the project went further into design.

The wave patterns suggest that the boulder field's middle area experiences less influence from wave action and thus may allow for decreased sediment settling time. Additionally, the two separate structures appear to be effective at attenuating wave energy between the structures and the shoreline, suggesting an overall reduction in shoreline erosion.





BLUFF MANAGEMENT

OVERVIEW

The bluffs and beaches of western Michigan form a continuous regional landscape for 250 miles between the national seashores at Indiana Dunes and Sleeping Bear Dunes. This landscape is marked by vast dune fields historically timbered or mined for sand and gravel. The towns and harbors, including Muskegon and St. Joseph, rely in part on these industries and attendant processes of dredging. Tourism and real estate development are essential sectors of the economy and culture in this area due to the attractiveness of the beaches and bluffs throughout this stretch. During the early 20th century, partly as a response to the associated shoreline stabilization of coastal privatization and the landscape changes from industrial logging operations, some of these prominent features in the landscape were granted protection through national seashore and state park designation. In this landscape, the material that erodes from bluffs nourishes the adjacent beaches and shores. While beneficial for the habitat and recreational uses of the region, these same erosional processes are undesirable from the point of view of property owners who live there and municipalities that rely on that tax base. This paradox– erosion is necessary but undesirable– is common throughout many coastal communities, and some of the lessons learned from the following project could be applied elsewhere. However, it should be noted that the area's local geomorphology and historical land uses are unique, and consequently, the proposals described below are tuned to those particular conditions.

◀ Nearshore boulder field present just offshore at Woollam Family Nature Preserve near Harbor Springs, Michigan. Used as a precedent for Boulder Field Concept on pg. 64

1

PROJECT CONTEXT
EASTERN LAKE MICHIGAN

At the request of the USACE Detroit District, our team studied the bluff-and-beach system of eastern Lake Michigan. It was chosen because of a confluence of factors:

+ Dredging and BUDM practices have been ongoing in the region for decades.

+ Access to good quality beaches is a public health and environmental justice issue.

+ These beaches are essential to the local tourism economy.

+ The difficult paradox of the need for bluff erosion to nourish beaches and nearshore environments and its undesirability from the perspective of property owners and municipalities has proven to be costly and intractable by using conventional shoreline armoring and dredging approaches.

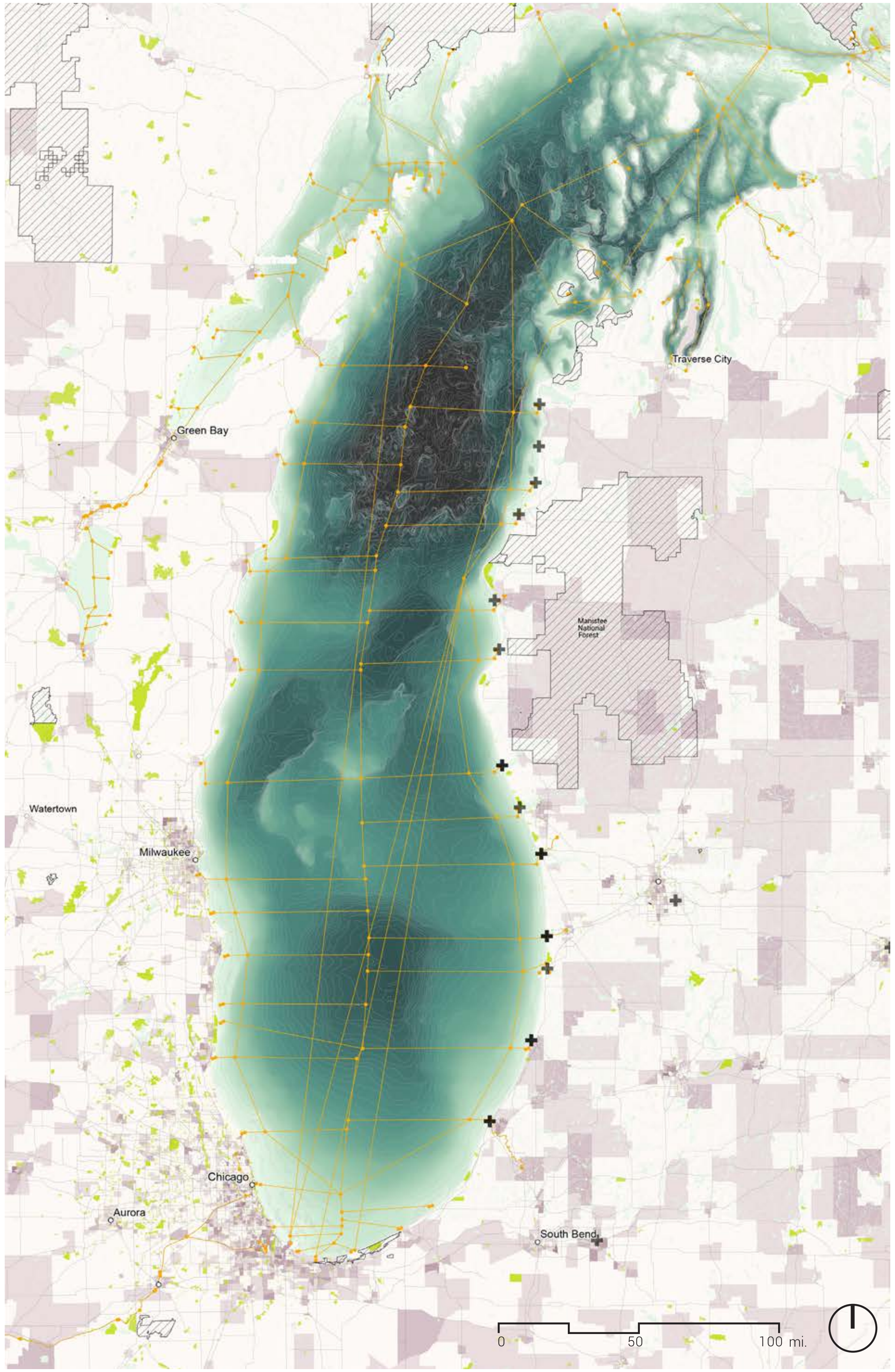
Together, these factors represented an opportunity to explore the potential of innovative nature-based solutions to address coastal resilience problems in ways that are broadly applicable throughout the 250-mile Michigan dune field region. This region is unique, but it is only an extreme example of a common condition found along many of the sandy coastlines of the United States, where the relationships between geomorphology, hydrology, ecology, and human uses interlock in ways that produce wicked problems without simple solutions. These problems demand innovative, sensitive approaches that work with, and not against, natural processes and cultural values.

U.S. Census Bureau's American Community Survey (ACS) 2017-2021 5-year estimates

Residents below Fed Poverty Level

▨	401 - 800
▨	801 - 1200
▨	1201 - 2000
■	2001 - 4721

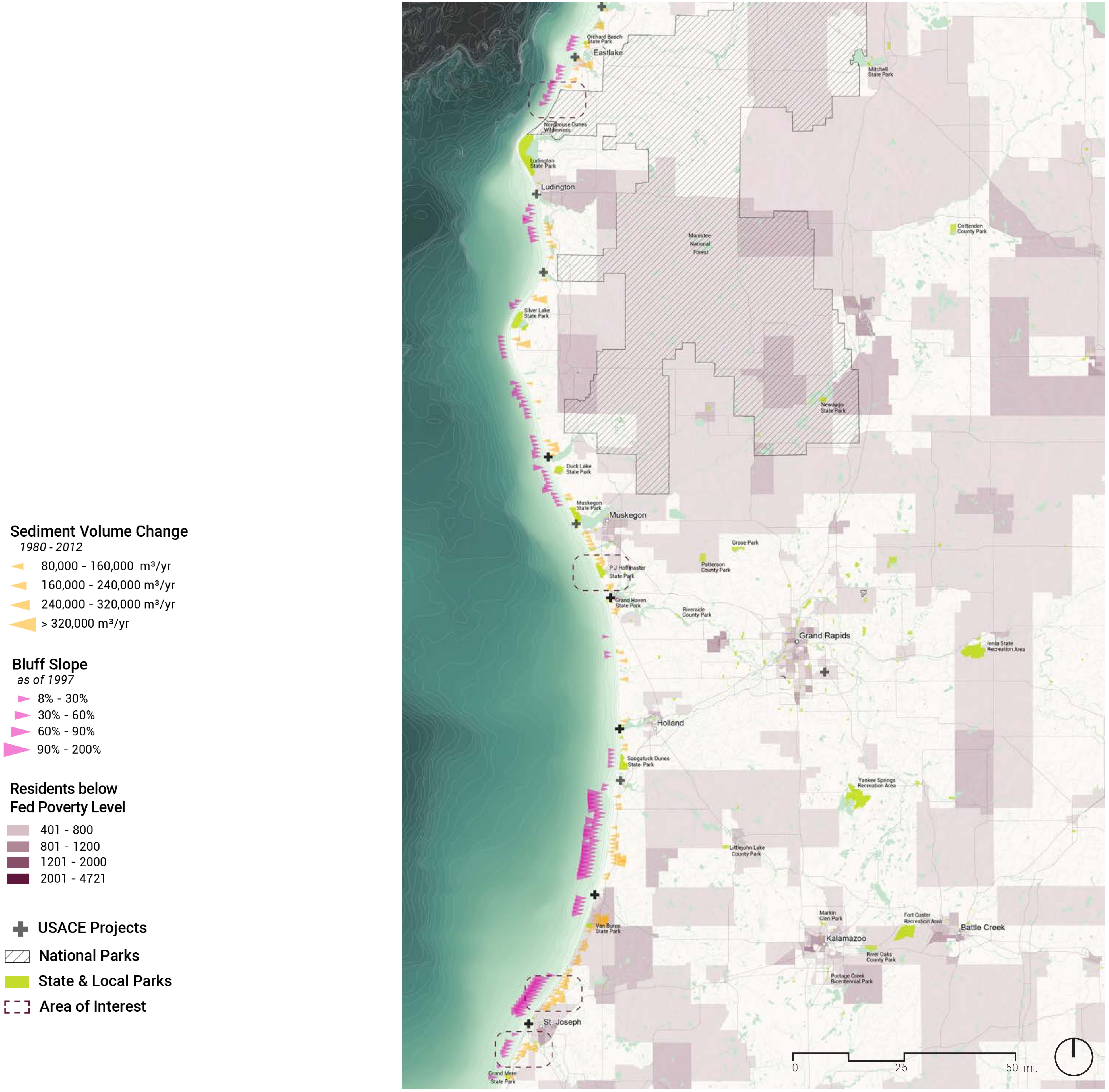
✚	**USACE Projects**
▨	**National Parks**
🟩	**State & Local Parks**
⬚	**Area of Interest**



1 PROJECT CONTEXT
EASTERN LAKE MICHIGAN

The study began with a desktop analysis of the available geomorphology data describing bluff recession, elevation, slope, bathymetry, longshore sediment transport, and wave and wind climate. Additionally, we researched current uses and practices of the bluff and beach landscape to understand how natural infrastructure could enhance these cultural values while addressing the problems of beach erosion and bluff recession.

After a discussion with the local USACE Districts to understand their goals and learn from their insights, our DRC and Anchor QEA team held a workshop in Philadelphia, PA, to generate ideas and explore some of the implications of different approaches. From that workshop, the team at the University of Virginia continued to develop the most promising concepts, which we quickly whittled down to two alternatives–the “boulder field and littoral sediment placement” and the “sediment rundown.” Each of these draws from natural processes and sediment sources outside the immediate area of concern to minimize bluff recession while nourishing nearby beaches. In each case, the initial capital costs are relatively small, and instead, the project relies on periodic sediment placement. Though the ongoing work necessitates ongoing costs, this practice-based approach is in keeping with natural processes, allowing for adaptations and modification with changing conditions and monitoring.

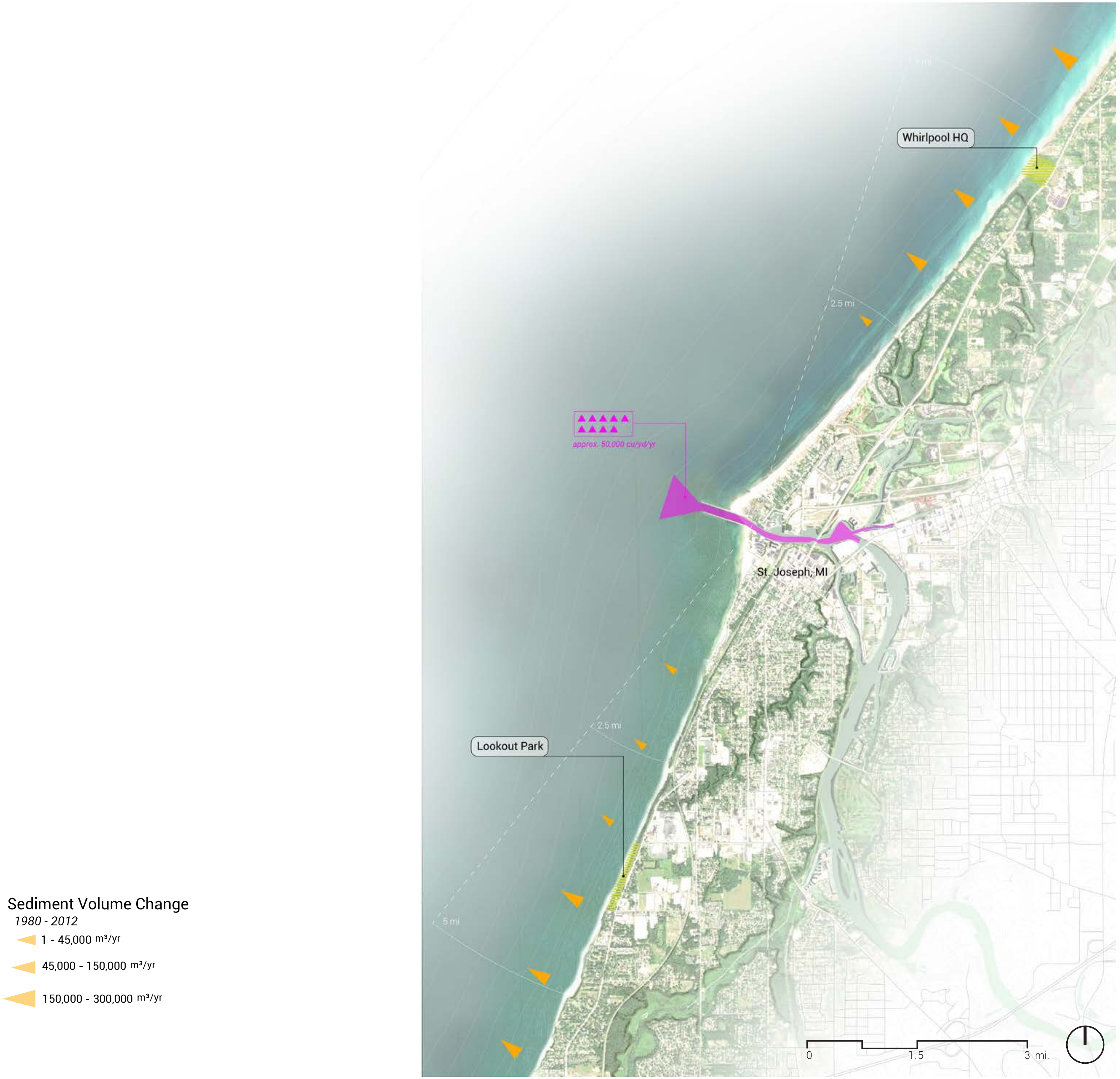


U.S. Census Bureau’s American Community Survey (ACS) 2017-2021 5-year estimates

USACE Mobile District Spatial Data Branch (Data Management)Sediment Budget Analysis System (SBAS) Eastern Lake Michigan 1980-2012. https://sbas-erdcchl.hub.arcgis.com/.

1 PROJECT CONTEXT
ST JOSEPH BLUFFS

Through this analysis, we identified St. Joseph as an area for more detailed study. St. Joseph has many characteristics that are representative of the Michigan dune field region, including bluff recession, frequently nourished beaches, public shoreline access, and a history of small-scale maintenance dredging and BUDM. Our demographic analysis also showed that St. Joseph has an underserved population that would benefit from more public amenities, like beaches, which can provide recreational and health benefits. Equitable outcomes are essential in our approach and the USACE's work, especially along the Great Lakes coast, where access and safety issues can impact people differently based on class and race.

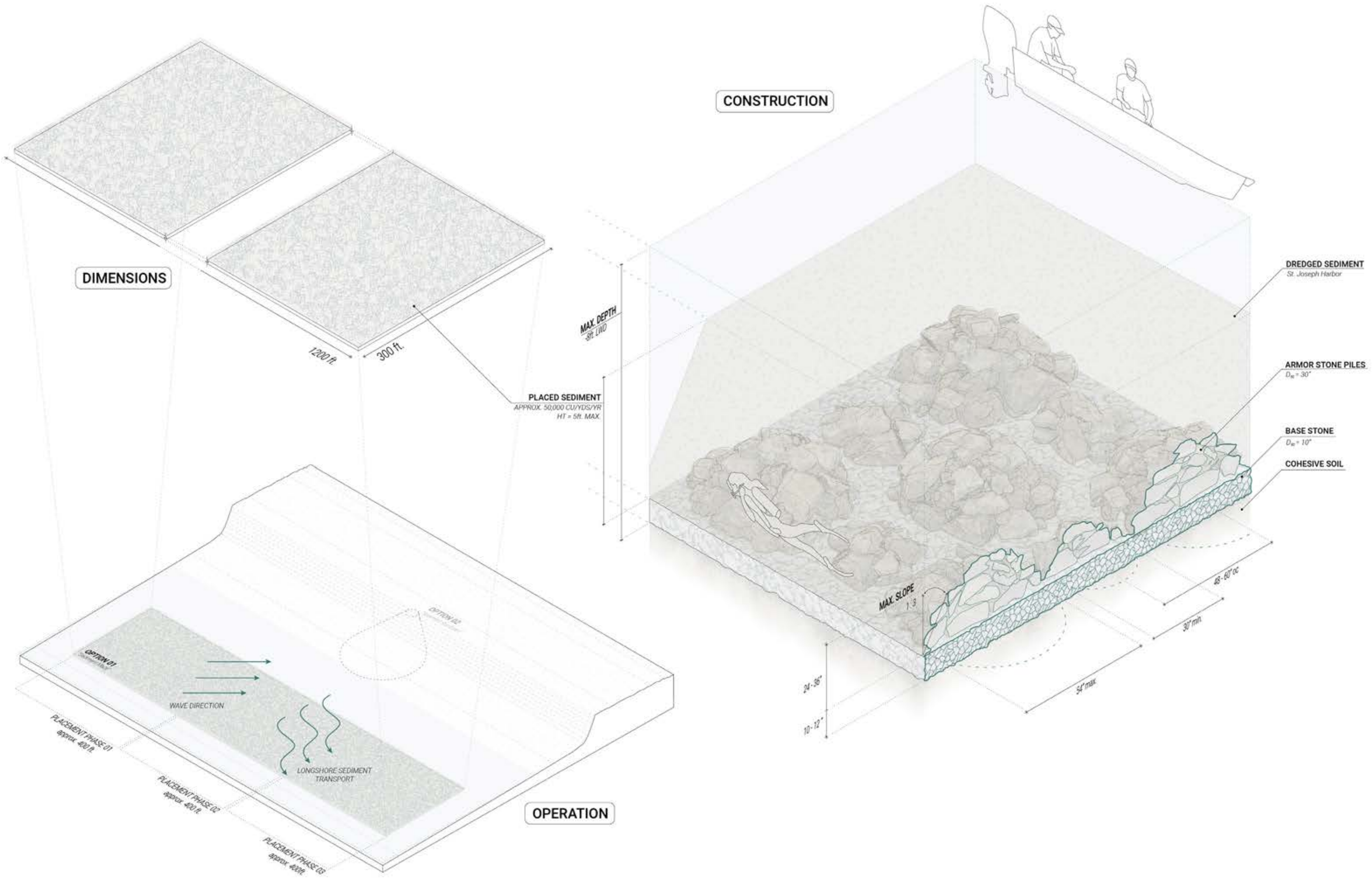


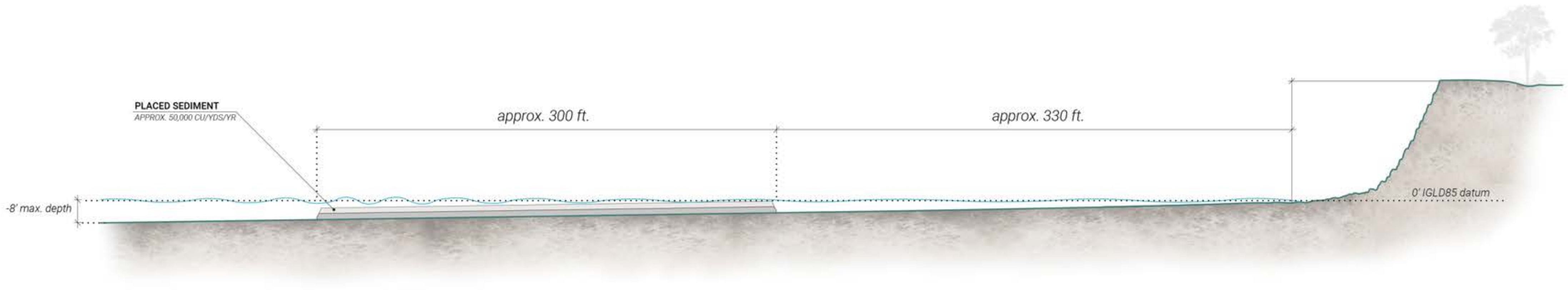
2

CONCEPT DEVELOPMENT
BOULDER FIELD

This concept takes inspiration from the boulder field present just offshore across northern Michigan, such as at the Woollam Family Nature Preserve near Harbor Springs, Michigan. The glacial deposit of boulders and cobbles in the nearshore environment decreases wave attack on the nearshore while enabling a usable beach and swimming area. Our boulder field concept is located further offshore, approximately 6-8' below LWD, and made from 24"-48" diameter boulders, placed either on a bed of cobbles or, when already present, on a cohesive nearshore. They are placed far enough offshore to prevent tombolo formation and long-term trapping of sand in the nearshore.

The boulders work collectively in a field to attenuate some wave energy and are placed sufficiently deep in the water column to avoid impact from ice formation. The boulder field will also provide a placement location for dredged sediment from nearby harbor maintenance. Placing sediment in the adjacent nearshore, rather than directly on the beach, will allow fines to winnow out, thus enhancing the quality and stability of the nearby beach. The boulder field will reduce wave energy, allowing the sand to disperse gradually, nourishing the downshore beaches over time.



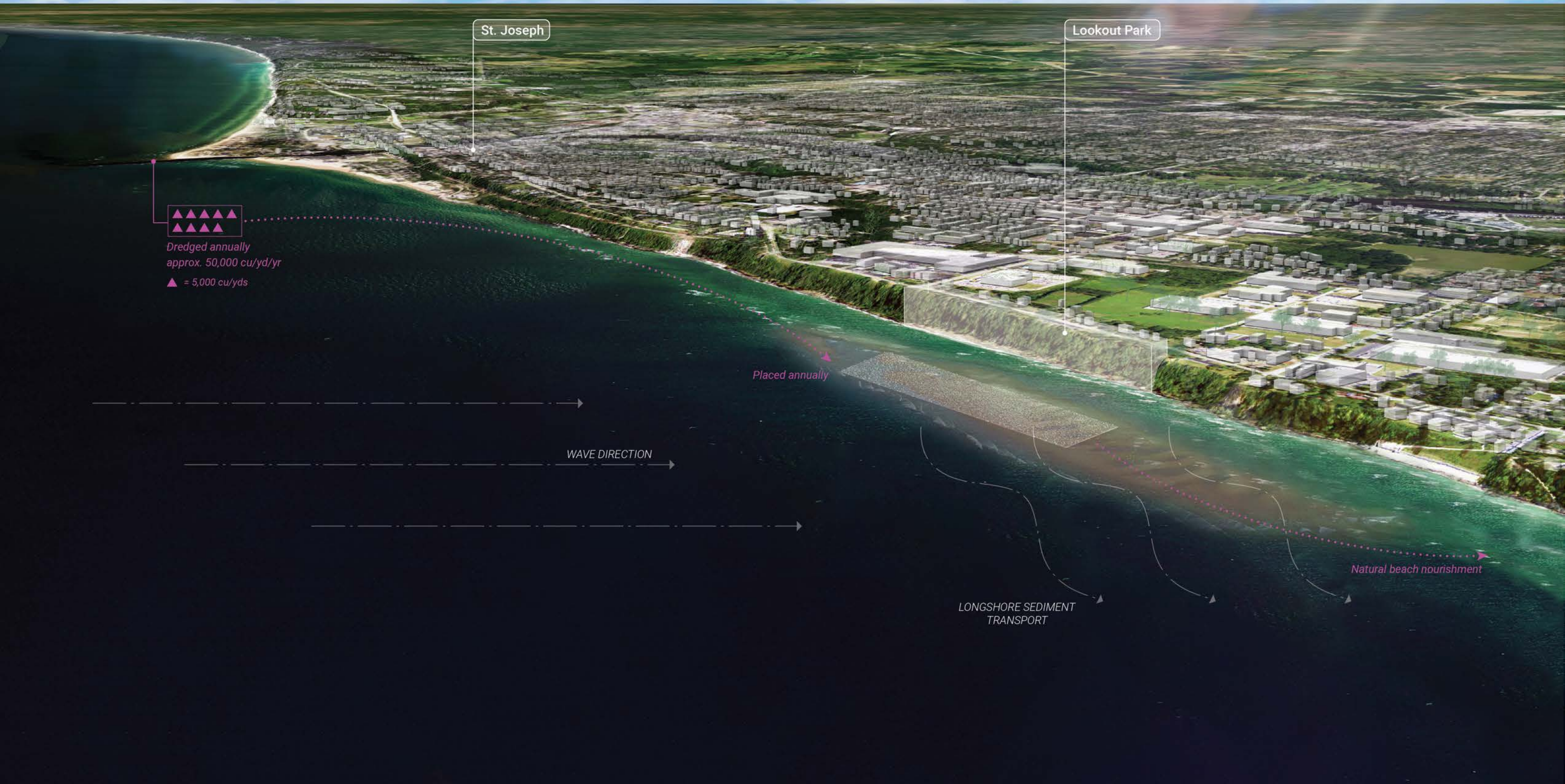


2

CONCEPT DEVELOPMENT

BOULDER FIELD

The boulder field and littoral sediment placement mediate and modulate human and natural processes in the coastal landscape. First, it provides some wave energy attenuation. Collectively, the width of the proposed feature (approximately 300') can lead to wave energy loss through dissipation. Second, the clustering of cobbles and boulders may provide fish spawning and nursery habitat around and between boulders. Finally, the feature provides a placement location for approximately 50,000 cubic yards of sediment per year, meeting the needs of the navigation work in St. Josephs and allowing the material to feed the nearshore processes downshore from the dredging.



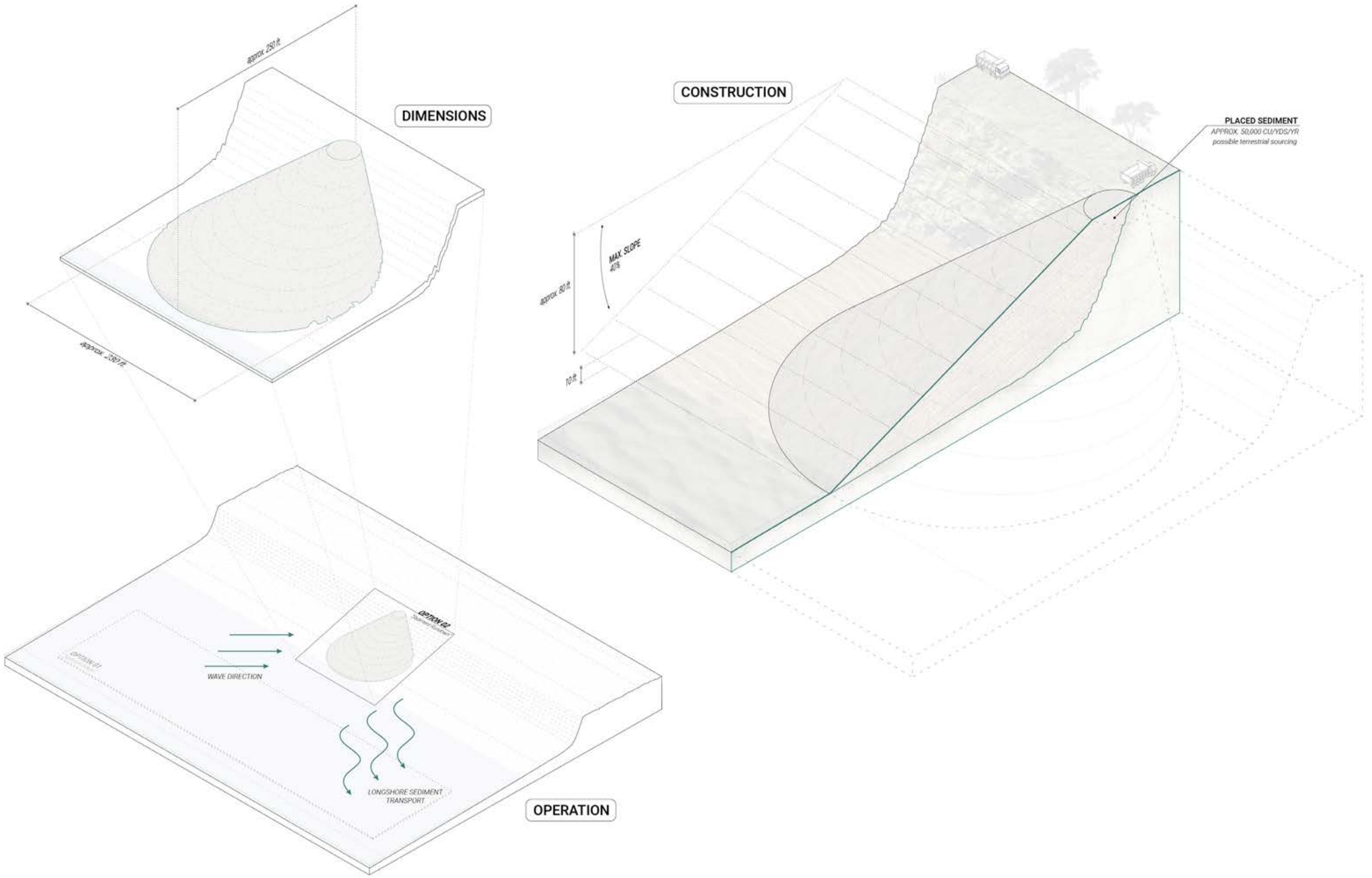
2 CONCEPT DEVELOPMENT
SEDIMENT RUNDOWN

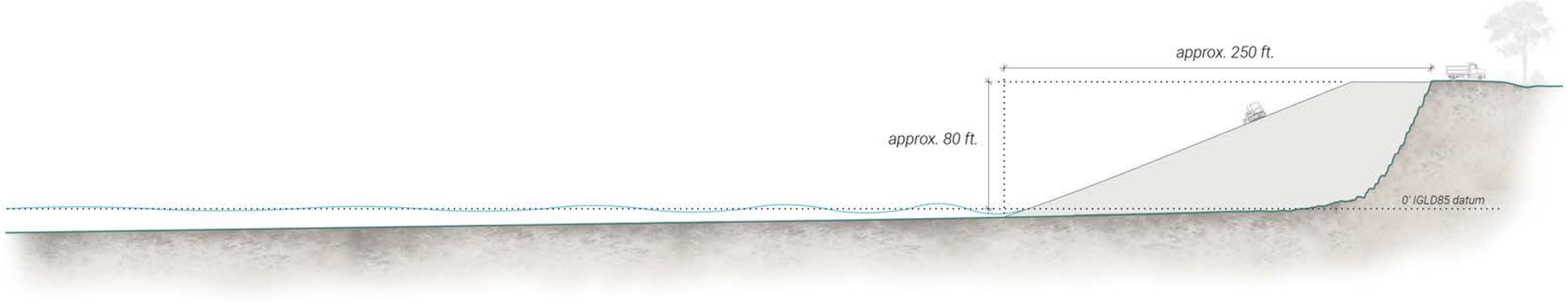
Art can become a physical resource that mediates between the ecologist and the industrialist. [We] must become aware of art and nature, or else [we] will leave pollution and ruin in [our] wake.

\- Robert Smithson

Sediment rundown proposes mimicking and scaling up the talus landforms found on bluff faces throughout the region. This project can be sited in an area that maximizes benefits downshore to beaches and eroding bluffs while minimizing any disruption to current uses. In this concept, sand is mined from a terrestrial location and trucked to a receding bluff with an existing road. The amount of sand is determined by analyzing bluff recession and geometry to approximate the volume lost each year under present conditions. To this end, we have approximated the volume at 50,000 cubic yards to visualize the practice under current water levels and bluff recession rates.

We identified a bluff based on its proximity to terrestrial mines, location along the shoreline, and current vacant land use. At this location, dump trucks bring in and unload sand down the face of the bluff. A large talus landform is created on the bluff face through the simple action of dumping. Wave action at the base of the hill removes the talus and moves it downshore. The well-graded mixture, delivered straight from the sand mine, maintains the cobbles and sand mixture, resulting in better stability and taking advantage of strand formation and winnowing processes in the nearshore. The result is a landform that is cheap to build and reliably erodes, resulting in downshore bluffs that are more protected at the toe and beaches that are nourishedbeaches that are nourished.

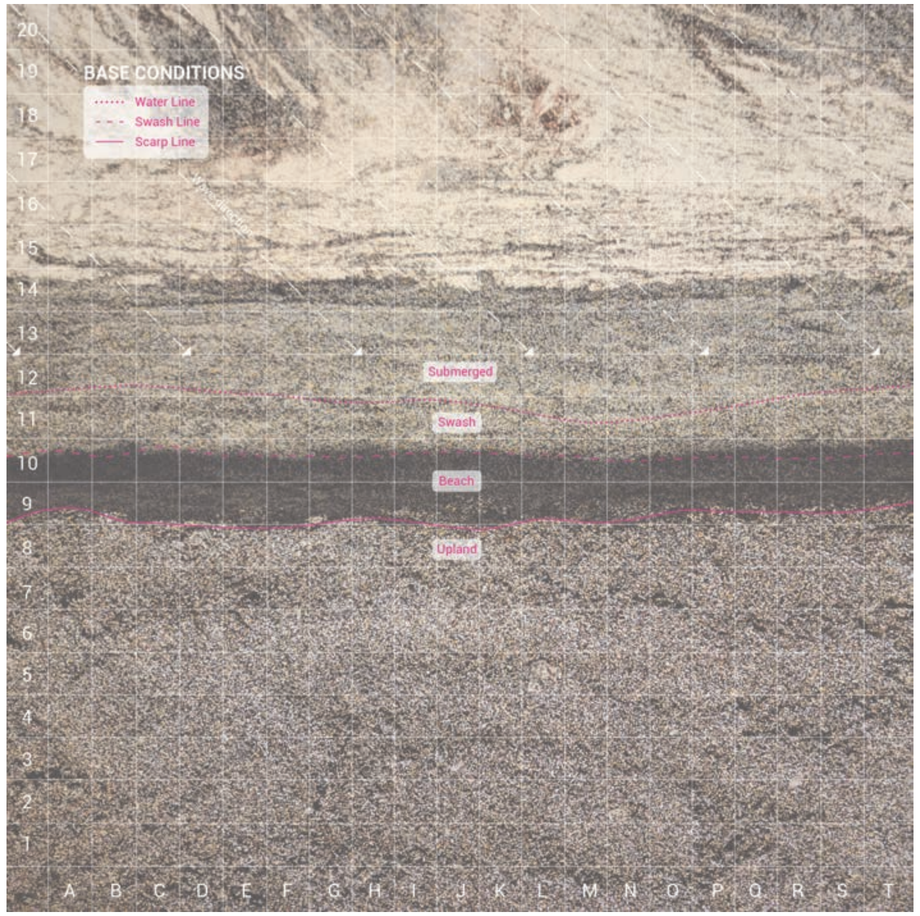


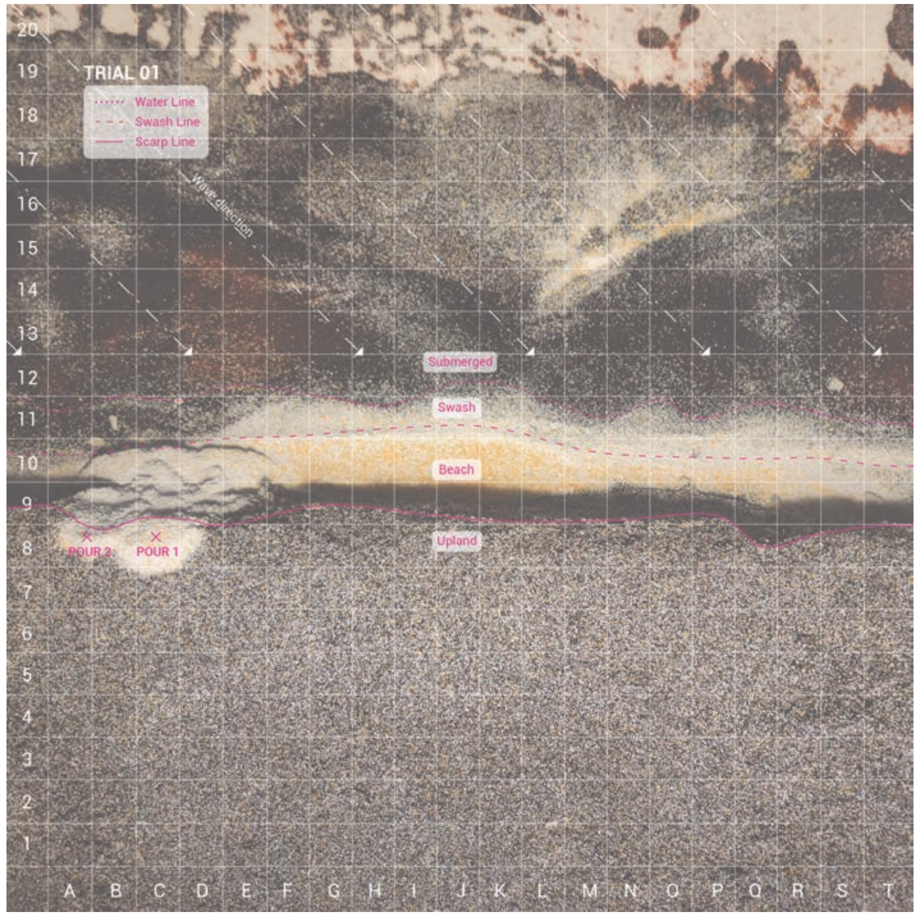


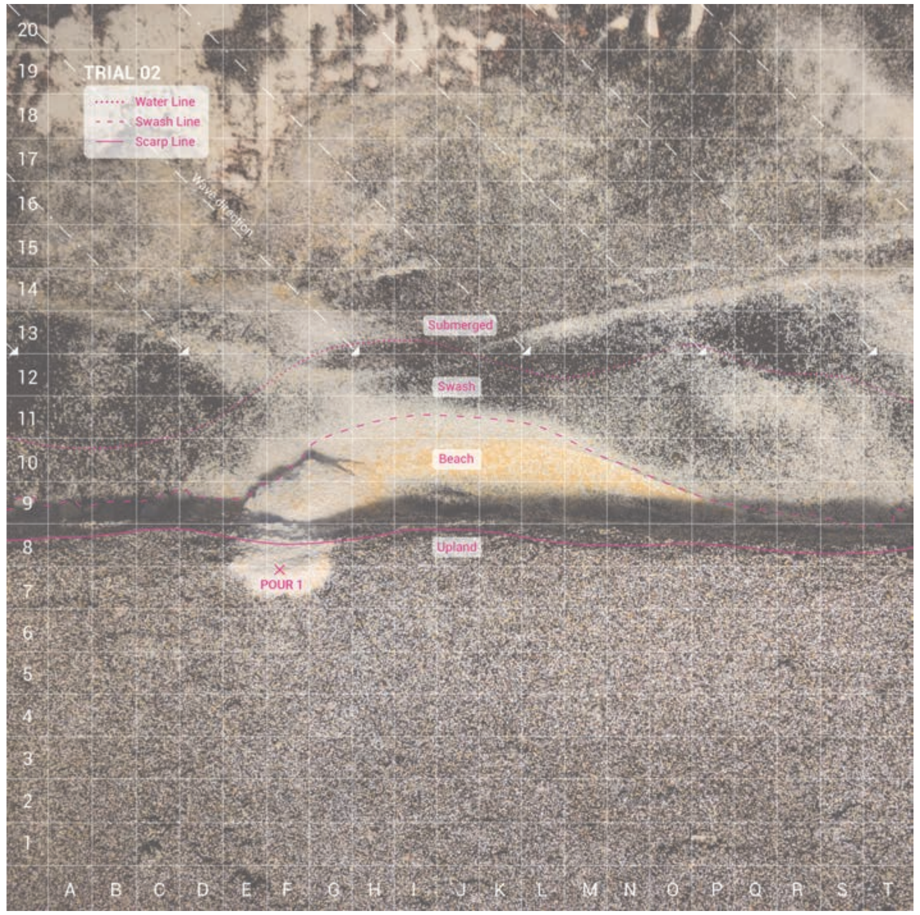
2 CONCEPT DEVELOPMENT

SEDIMENT RUNDOWN PHYSICAL MODELING

In addition to analyzing existing datasets, studying regional geomorphology, and researching relevant precedents, we undertook qualitative modeling on a small geomorphology table to explore the concept and to better understand its applicability with varying bluff-face geometry and wave conditions. We used a modeling media color-coded by size, with white representing large sand, black representing fine sand, and yellow representing gravel. We simulated the talus formation by pouring dry sediment through a cone at the edge of a small bluff being acted on by waves. The results showed reliable, localized effects, including no disruption upshore, salient formation along the beach downshore, and a wider nearshore environment near the talus landform.







2

CONCEPT DEVELOPMENT
SEDIMENT RUNDOWN

As the prior talus erodes and water levels rise in the spring, several thousand yards of sand are placed at the bluff site through this method. Each year, as the talus is created, people from the town can watch its formation and erosion, learning about the processes of the lake and how the bluff relates to their beach. This practice would accelerate or scale up under high water regimes and may cease or decrease during periods of low or median water levels. Because it is a practice and not based on a one-time, capital-intensive solution, it can fit within a sensitive, adaptive management paradigm.

References

Bélanger, P. (2013). *Landscape as infrastructure: a base primer*. Routledge.

Fish and Wildlife Service. 2010. *Identifying Potential Lake Trout Spawning Habitat in Lake Erie*. https://www.fws.gov/media/identifying-potential-lake-trout-spawning-habitat-lake-erie.

Foyle, A. M., & K. L. Schuckman. (2021). Reduced Sediment Export to the Pennsylvania Lake Erie Littoral Zone during an Era of Average Lake Levels. *Journal of Great Lakes Research*. *47* (6): 1644–55. https://doi.org/10.1016/j.jglr.2021.08.023.

Lake Erie Committee, Great Lakes Fishery Commission. (2021.) *A Plan to Support Lake Trout Rehabilitation in Lake Erie, 2021-2030*. https://www.dec.ny.gov/docs/fish_marine_pdf/glfcleltplan.pdf

Lane, J.A. Portt, C.B. & C.K. Minns. (2002). Spawning Habitat Characteristics of Great Lakes Fishes. *Government of Canada Publications*. https://publications.gc.ca/site/eng/9.562511/publication.html.

Markham, J. L., Robinson, J.M., Wilson, C.C., Vandergoot, C.S., Wilkins, D.P., Zimar, R.C., & M.N. Cochrane. Evidence of Lake Trout (*Salvelinus Namaycush)* Natural Reproduction in Lake Erie. *Journal of Great Lakes Research*. 48 (6): 1728–34. https://doi.org/10.1016/j.jglr.2022.09.013.

Matley, J. K., Faust, M. D.,. Raby, G. D., Zhao, Y., Robinson, J., MacDougall, T., Hayden, T. A., Fisk, A. T., Vandergoot,C.S. & C. C. Krueger. 2020. Seasonal Habitat-Use Differences among Lake Erie's Walleye Stocks. *Journal of Great Lakes Research*. 46 (3): 609–21. https://doi.org/10.1016/j.jglr.2020.03.014.

Mossop, E. (2016). "Landscapes of Infrastructure." In *The Landscape Urbanism Reader*, ed. C. Waldheim. Princeton Architectural Press.

Ohio Environmental Protection Agency. (2021). *Harbor Sediment Authorization for Lake Erie Dredge from Conneaut Harbor*. Accessed September 20, 2023. https://edocpub.epa.ohio.gov/publicportal/ViewDocument.aspx?docid=1646450#:~:text=Ohio%20EPA%20has%20determined%20that,%2C%20safety%2C%20or%20the%20environment

Ohio Environmental Protection Agency. *Beneficial Use*. Accessed September 20, 2023. https://epa.ohio.gov/divisions-and-offices/materials-and-waste-management/dmwm-programs/beneficial-use.

Orff, K. & SCAPE Landscape Architecture. (2016). *Toward an urban ecology*. The Monacelli Press.

Rentmeester, J. & L. Rentmeester. 1989. *Early Duck Creek History*. J. Rentmeester. https://books.google.com/books?id=e1ggnQEACAAJ.

Roberts, M. A. (2018). "The Wisconsin History Spot: The Early History of Duck Creek." *The Press*. https://gopresstimes.com/2018/09/27/early-history-of-duck-creek/.

Sentinel-Tribune. (2022). Ohio EPA says no sediment dumping in Lake Erie. Accessed September 14, 2023. https://www.sent-trib.com/2022/03/11/ohio-epa-says-no-sediment-dumping-in-lake-erie/

Schmid, K. (2013). Mapping and Portraying Inundation Uncertainty of Bathtub-Type Models. *Journal of Coastal Research*. *30* (3): 548. https://doi.org/10.2112/JCOASTRES-D-13-00118.1.

Spirn, A.W. (1984). *The granite garden: urban nature and human design.* Basic Books.

United States Environmental Protection Agency. (2019). *Lower Green Bay/Fox River AOC.* Collections and Lists. New York, Great Lakes. https://www.epa.gov/great-lakes-aocs/lower-green-bayfox-river-aoc.

USACE, Buffalo District. (2022). *Federal Interest Determination Report, Conneaut Harbor*. https://www.lrb.usace.army.mil/Portals/45/docs/regulatory/publicnotices/2022-06/PN-LRB-2018-00803.pdf

Wisconsin Department of Natural Resources. *Green Bay West Shores Wildlife Area*. Accessed September 1, 2023. https://dnr.wisconsin.gov/topic/Lands/GBWS/index.html.

Wisconsin Department of Natural Resources. *Lower Green Bay and Fox River Area of Concern*. Accessed September 12, 2023. https://dnr.wisconsin.gov/topic/GreatLakes/GreenBay.html.

Data Sources

American Rivers. “Map of U.S. Dams Removed Since 1912 —.” Accessed September 22, 2023.https://www.americanrivers.org/threats-solutions/restoring-damaged-rivers/dam-removal-map/.

ESRI. USA_Parks (FeatureServer). Accessed September 25, 2023. https://services.arcgis.com/P3ePLMYs2RVChkJx/arcgis/rest/services/USA_Parks/FeatureServer.

Giese, Erin, and Dr. James Horn. “Priority Areas - Fish & Wildlife Habitats - Green Bay Area of Concern.” Accessed September 1, 2023. https://www.uwgb.edu/green-bay-area-of-concern/fish-wildlife-habitats/priority-areas/.

Great Lakes Aquatic Habitat Framework.” Accessed September 20, 2023. https://www.glahf.org/data/.

Hotchkiss, W. Otis. (1914). “↑ Duck Creek Quarry - UWDC - UW-Madison Libraries.” Accessed September 12, 2023. https://search.library.wisc.edu/digital/AP6GXMZSXWTZOV9B.

Messager, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O. (2016). Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nature Communications: 13603. doi: 10.1038/ncomms13603. Accessed September 25, 2023. https://www.hydrosheds.org/products/hydrolakes.

National Geophysical Data Center, 1999. Bathymetry of Lake Erie and Lake St. Clair. National Geophysical Data Center, NOAA. doi:10.7289/V5KS6PHK. Accessed September 25, 2023 https://www.ncei.noaa.gov/products/great-lakes-bathymetry

National Oceanic and Atmospheric Administration (NOAA). Great Lakes Environmental Research Laboratory (GLERL) Great Lakes Dashboard.” Accessed September 20, 2023. https://www.glerl.noaa.gov/data/dashboard/GLD_HTML5.html.

National Oceanic and Atmospheric Administration (NOAA) “Lake Level Viewer, United States Great Lakes.” Accessed September 20, 2023. https://coast.noaa.gov/llv/#/lake/erie

Ohio Environmental Protection Agency. Dredge Materials Application Restricted Areas. Accessed September 20, 2023. https://epa.ohio.gov/monitor-pollution/maps-and-advisories/dredge-materials-application-restricted-areas.

Thwaites, F. T. (1928). *Drainage Ditch along Duck Creek*. UWDC - UW-Madison Libraries. Accessed September 12, 2023. https://search.library.wisc.edu/digital/AAOTX2VMARUOAB8B.

Thwaites, F. T. (1928). *Logged Moraine*. UWDC - UW-Madison Libraries. Accessed September 12, 2023. https://search.library.wisc.edu/digital/A7AREM4KHKUUOU8V

United States Census Bureau. “American Community Survey 1-Year Data (2005-2022).” Census.gov. Accessed September 25, 2023. https://www.census.gov/data/developers/data-sets/acs-1year.html.

United States Geological Survey (USGS). Stream Gage Duck Creek Near Howard, WI, 04072150. Accessed September 12, 2023. https://waterdata.usgs.gov/monitoring-location/04072150/.

USGS. (2021). 1 Arc Second n42w081 20210630. Accessed September 20, 2023. https://www.usgs.gov/the-national-map-data-delivery/gis-data-download.

USACE Detroit District. “Water Level Data.” Accessed September 22, 2023. https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Water-Level-Data/.

USACE Geospatial Data. Accessed September 25, 2023. https://geospatial-usace.opendata.arcgis.com/.

USACE Mobile District Spatial Data Branch (Data Management) Sediment Budget Analysis System (SBAS) Eastern Lake Michigan 1980-2012. Accessed September 25, 2023.https://sbas-erdcchl.hub.arcgis.com/.

USACE ERDC. WIS - Catalog. Station ST92039. Accessed September 20, 2023. https://wisportal.erdc.dren.mil/.

United States Lake Survey. (1853). “Head of Green Bay and Entrance to Fox River, Wisconsin - UWDC - UW-Madison Libraries.” Accessed September 12, 2023. https://search.library.wisc.edu/digital/A3BC6Q7MWXYREM8C.

Wisconsin State Cartographer’s Office. “Wisconsin Historic Aerial Image Finder (WHAIFinder).” Accessed September 12, 2023. https://maps.sco.wisc.edu/WHAIFinder/#7/44.750/-89.750.

APPENDIX 1

DUCK CREEK SEDIMENT CAPTURE ISLANDS– COASTAL MODELING ANALYSIS

Prepared for:

US Army Corps of Engineers
ERDC
EWN

Prepared by:

ANCHOR QEA
Dredge Research Collaborative

1 INTRODUCTION

This report describes coastal modeling performed by Anchor QEA, LLC, to support the restoration of the Duck Creek Delta in Green Bay, Wisconsin (Figure 1). Lower Green Bay once contained one of the largest and most diverse wetland habitat complexes in the Great Lakes (Figure 2). Historically, these wetlands were protected from high-energy wave and storm actions by the Cat Island Chain. High water levels and intense storms destroyed most of the chain in the late 1970s, exposing the Duck Creek Delta to erosion. Duck Creek was re-aligned during the construction of Highway 141 (Brown County 2023). Additionally, changes in land use within the Duck Creek watershed likely contributed to higher maximum discharge and erosion. As part of the ongoing Cat Island Restoration Project, the U.S. Army Corps of Engineers (USACE) constructed a 2.5-mile wave barrier protecting the western side of lower Green Bay in 2014, creating an opportunity for the Duck Creek Delta to be restored (Port of Green Bay 2018).

The Duck Creek Delta restoration is part of the larger Duck Creek Delta Complex project within the Lower Green Bay and Fox River Area of Concern. The objective of this Engineering with Nature (EWN) project is to research and conceptualize potential natural and nature-based features (NNBF) to restore the Duck Creek deltaic marsh to its historical extent (based on 1938 aerial imagery), including 720 acres of wetland. The Dredge Research Collaborative (DRC) and Anchor QEA modified a conceptual design for Duck Creek Delta restoration using NNBF principles as part of the EWN initiative funded by the USACE Chicago District.

The proposed conceptual design includes creation of a barrier island system through sediment placement to capture discharged sediment from Duck Creek to naturally form a deltaic marsh of about 400 acres when including induced and existing wetlands and habitats. The structures are intended to encourage deposition in the historical wetland footprint without adversely affecting water quality or obstructing navigation. To support the design, Anchor QEA performed wave, hydrodynamic, and sediment transport modeling. The purpose of this modeling was to evaluate the effect the barrier island system may have on sediment deposition patterns and local hydrodynamics.

2 COASTAL SETTING

The Duck Creek Delta is located in lower Green Bay on Lake Michigan, approximately 3 miles northwest of the City of Green Bay and the Fox River mouth (Figure 1). Duck Creek discharges into extensive shallow mudflats, with stands of emergent aquatic plants near the mouth and along the shoreline. The delta is protected from wave action from the northeast by the wave barrier constructed in 2014 as part of the Cat Island Restoration Project.

2.1 Lake Michigan Water Levels

Water levels in the Great Lakes are driven by natural processes, such as precipitation, evaporation, and ice cover, as well as manufactured controls. USACE has established jurisdictional benchmarks for regulatory and navigational purposes. The ordinary high water mark (OHWM) corresponds to the elevation contour representing the line on the shore established by high water levels indicated by physical characteristics such as soil types, shelving, and vegetation. The low water datum (LWD) was established as a minimum practical water level for use as a navigational benchmark. Other water levels that were considered as part of this study include the long-term monthly mean and the all-time high monthly water level.

Water levels in Lake Michigan have regressed toward long-term monthly mean after unusually high water in the past few years, reaching record highs in 2019 and 2020. Figure 3 displays Lake Michigan water levels from 1900 to 2023 as recorded by the National Oceanic and Atmospheric Administration (NOAA) Lake Michigan-Huron master gauge at Harbor Beach, Michigan. The following list provides important Lake Michigan water levels:

- LWD is 577.5 feet above the International Great Lakes Datum of 1985 (IGLD85; USACE 2023a)
- Long-term monthly mean is 578.9 feet IGLD85 (USACE 2023b)
- OHWM is 581.5 feet IGLD85 (USACE 2023a)
- All-time high is 582.35 feet IGLD85 (USACE 2023b)

Figure 4 shows a cumulative frequency distribution of hourly water level measurements from the Harbor Beach, Michigan, NOAA station, with observations from 1900 to 2023 (NOAA 2023a). More than 90% of observations fall between the LWD and OHWM.

The geometry of Green Bay creates ideal conditions for storm surges. Wind and waves from the northeast force water into the southern end of Green Bay, creating a local short-term water-level rise. A storm surge of 5.41 feet above mean lake level occurred in 1990 (Melby et al. 2012). Because the model used for this study simulates storm surge, static Lake Michigan water level data were used as initial conditions for the model. Monthly mean Lake Michigan water level data were analyzed to determine initial model water levels. Storm surge was then generated by the model.

2.2 Winds and Wave Climate

Wind-generated waves are formed when wind imparts energy to the water surface over a period of time. The wave heights generated by wind depend on several factors, including wind speed, wind duration, fetch distance (the distance over water that the wind can transmit energy), and water depth. Figure 5 shows a wind rose plot of hourly wind speeds and directions measured from 1970 through 2023 at Green Bay Austin Straubel International Airport (ISU 2023). This station was selected because of its long record relative to offshore data sources. The primary wind directions are northeast and southeast.

Northeast winds act along the entire length of Green Bay and create the largest waves, currents, and storm surges in the bay. The site is also exposed to locally generated waves from the southeast. A statistical analysis was performed on the wind data to determine the return-internal wind speeds by direction. Figure 5 also displays the computed return-period wind speeds for northeast and southeast winds. The annual (1-year return interval) wind events from the northeast and southeast were simulated to evaluate waves and hydrodynamics from relatively common high-wind events.

2.3 Duck Creek Discharge

Duck Creek flows from headwaters near Seymour, Wisconsin, to the mouth of lower Green Bay, draining a watershed of approximately 150 square miles consisting primarily of agricultural land. Duck Creek carries sediment from the watershed to the Duck Creek Delta and mudflats of lower Green Bay.

Water depths near the Duck Creek mouth are shallow with a gentle slope, so small changes in water levels expose or inundate large areas of land (see the images of the Duck Creek Delta at high and low water in Figure 6). At lower water levels, Duck Creek is channelized for approximately half a mile east of Highway 141, with emergent wetlands on either side. At higher water levels, Duck Creek discharges directly into the open bay after passing under Highway 141.

The channel splits after passing under Highway 141. The southern branch is the historical channel associated with the 1938 wetland extent. The northern branch was formed after the creek was realigned during construction of the highway.

2.4 Proposed Structures

The proposed structure footprint and elevation are shown in Figure 7. The structure consists of three outer barrier islands created from various sediment types. Gaps in the barrier islands allow for exchange of water to reduce water-quality issues caused by stagnation. The wishbone-shaped flow splitter is intended to route flow and sediment to either side.

3 HYDRAULIC ANALYSIS

To evaluate the effect the barrier island system may have on sediment deposition patterns and changes in local hydrodynamics, 2D coupled hydrodynamic flow, wave, and morphology models were used to simulate nearshore waves, water levels, currents, and sediment transport under a variety of meteorological conditions. This section includes details on the model grid development, selected simulations, and the associated logic for their selection and use.

3.1 Study Questions and Model Simulations

The modeling was performed to answer the following two study questions:

1. How will the proposed barrier islands affect sediment deposition patterns during a sediment loading event?

2. How would the presence of the barrier islands change wave and circulation patterns in lower Green Bay?

To answer the first study question, the model was used to simulate a sediment loading event from Duck Creek to lower Green Bay in the vicinity of the Duck Creek Delta. Given the range of Lake Michigan water levels, the model was used to understand the potential effect water level has on the sediment transport patterns.

To answer the second study question, the model was used to simulate a range of wind, wave, and Lake Michigan water levels to evaluate wave and circulation patterns in the vicinity of the Duck Creek Delta.

It should be noted that only single-event simulations were performed as part of this work. Long term simulations were not performed. The purpose of these model simulations was to investigate the impact of the proposed barrier islands during typical morphology driving events.

3.2 Model Selection

The numerical model selected for use in this evaluation was Delft3D. This model, supported by Deltares, was developed and validated for use in riverine, estuarine, and open-coast hydrodynamic systems. Wave growth and transformation modeling were performed with the 2D Delft3D-WAVE (WAVE) model. The WAVE model is based on the Simulating Waves Nearshore (SWAN) model. The SWAN model was developed by the University of Delft and includes all relevant wave processes, such as refraction, shoaling, diffraction, and wave breaking. The hydrodynamic modeling was performed with the 2D version of the Delft3D-FLOW (FLOW) model. The FLOW model was used to compute hydrodynamic information resulting from water level fluctuations and wind forcing to the WAVE model (via online coupling) and to evaluate changes in current velocity and bed shear stress patterns due to the proposed islands. Delft3D-Morphology was used to model sediment transport and deposition, based on forces and hydrodynamics determined from the other models.

The modeling included two domains:

1. Duck Creek Delta: High-resolution hydrodynamic and morphologic model intended to analyze sediment deposition patterns within the proposed barrier islands. This domain did not include wave modeling.

2. Green Bay: Varied resolution wave and hydrodynamic model intended to analyze waves and currents near the project site. This domain did not include morphological modeling.

3.3 Model Grids

3.3.1 Duck Creek Delta Domain

The Duck Creek Delta domain was used to evaluate sediment deposition patterns from Duck Creek. The extent of the Duck Creek Delta domain comprises Duck Creek from Velp Avenue to the mouth, as well as the proposed barrier island footprint and all areas within the barrier islands that would be inundated at OHWM (Figure 8). The Duck Creek channel grid is curvilinear to direct flow with minimum friction, and the overbanks and deposition areas are fully unstructured. The grid types and cell sizes are summarized in Table 1. After initial simulations, cell size for the barrier islands was reduced to better resolve the geometry.

Table 1
Duck Creek Delta Grid Summary

Region	Cell Type	Cell Shape	Edge Length (m)
Duck Creek Channel	Curvilinear	Rectangular	5x8
Duck Creek Overbank	Unstructured	Triangular	7x7x7
Duck Creek Delta	Unstructured	Triangular	10x10x10
Barrier Islands	Unstructured	Triangular	4x4x4

Notes:
Edge lengths are approximate. m: meter

3.3.2 Green Bay Domain

The Green Bay domain model combines the Duck Creek Delta grid with a Green Bay-wide grid to simulate waves and hydrodynamics across the entirety of Green Bay while maintaining high resolution near the project site. The extent of the model is shown in Figures 8 and 9. These simulations were intended to analyze waves and hydrodynamics near the project site.

The Green Bay domain simulations included both FLOW and WAVE grids. A system of three nested WAVE grids was developed to transfer wave information from a coarse Green Bay wide grid to a fine project grid. The square grid cell sizes are 500 meters (m), 125 m, and 31.25 m. The low resolution 500-m grid is coarse to save computational time and allows for wave and current generation in Green Bay. The grids are stepped down as they approach the project site for a smooth transfer of wave data to the higher resolution grids.

The FLOW grid used for the Green Bay domain includes the Duck Creek Delta grid, with an expansion to cover all of Green Bay (Figure 9). The far-field cell size is stepped down at a rate similar to the WAVE grids. This method allows the model to generate waves and currents, rather than the user prescribing them at boundary conditions.

3.4 Model Elevation Data

Bathymetry and topography data were compiled from multiple data sources and converted to meters below LWD, UTM 16N for use in the Delft3D model. The sources follow, in order of priority:

1. Proposed digital elevation model: Sampled to a 5x5-foot grid for use in Delft3D model. Provided by the DRC on July 21, 2023.

2. 2022 lower Green Bay survey: Primary bathymetric data source for lower Green Bay. Provided by USACE on July 13, 2023.

3. 2010 Brown County LiDAR: Primary source of upland data near the mouth of Duck Creek and lower Green Bay. The LiDAR data were collected during near-record low-water levels, exposing much of the Duck Creek Delta (USIEI 2010).

4. NOAA Electronic Navigational Charts (ENC) harbor points: Secondary bathymetric data source for lower Green Bay, used to fill data gaps from USACE lower Green Bay survey (NOAA 2023b)

5. NCEI lake-wide bathymetry: Source for far-field upland and bathymetric data (NOAA 1996)

Figure 10 shows the compiled data interpolated to the model grids. In-channel data for Duck Creek was limited to six soundings from NOAA ENC. Best professional judgment was used to interpolate and extrapolate from these soundings to create the channel.

3.5 Model Boundary Conditions

Locations of all boundary conditions for the local and Green Bay domains are shown in Figure 8.

3.5.1 Duck Creek Delta Domain

<u>3.5.1.1 Duck Creek Discharge</u>

The bankfull event was used in this evaluation to simulate a sediment loading event from Duck Creek to lower Green Bay. It is often referred to as the channel-forming event and occurs approximately every 1.5 years. Because it occurs so frequently, flows at or below bankfull discharge tend to be responsible for the majority of a stream's sediment transport. Larger discharges may move more sediment in a given time period, but because they are so rare, they contribute relatively little to annual sediment transport. The bankfull discharge is therefore a reasonable estimate for typical sediment loading and transport for this type of study.

Discharge data were developed from the period of record at United States Geological Survey (USGS) Gaging Station 04072150—Duck Creek Near Howard, Wisconsin. Data were processed using Hydrologic Engineering Center Statistical Software Package version 2.3 for this assessment. The 1.5 year recurrence flow at this gage was found to be 1,065 cubic feet per second (cfs).

3.5.1.2 Synthetic Hydrograph

A synthetic hydrograph was developed based on recorded events reaching the bankfull discharge determined from analyses at USGS Gage 04072150. Six events that reached approximately 1,065 cfs were identified (Table 2).

Table 2
Recorded Events Peaking near Bankfull Discharge for USGS Gage 04072150—Duck Creek near Howard, Wisconsin

Event Date	Maximum Discharge (cfs)
April 1, 2022	1,110
October 11, 2018	1,070
June 16, 2015	1,010
April 11, 2011	1,040
March 30, 2004	991
April 12, 2001	1,080

The 15-minute discharge data were plotted, and timing was adjusted so that peak discharge occurred at the same time for each flow event (Figure 11). A visual comparison of the hydrographs was performed, and a synthetic hydrograph was developed to provide a typical discharge profile. The rising limb was developed from the April 2022 event, and the falling limb used the April 2001 event (Figure 12).

The Duck Creek discharge boundary was applied approximately 1.2 miles upstream of Highway 141. The

Equation 1

$$Q_s = aQ^b$$

where:

Q_s = sediment discharge

a = calibration parameter

Q = stream discharge

b = calibration parameter

Because it is an exponential relationship, Equation 1 introduces bias to the estimate and artificially reduces sediment load estimates at a given stream discharge. The rating curve analysis tool has two built-in methods of removing bias: the Duan and Ferguson methods. Both provide simple multiplication factors used to correct the relationship but are calculated with different methodologies. Results are shown in Table 3.

Table 3
Parameters Determined by HEC-RAS Rating Curve Analysis Tool for Equation 1

A	B	Duan	Ferguson
0.0199	1.3204	1.6400	1.7461

A comparison of the biased relationship to the Duan and Ferguson corrections is provided in Table 4 and Figure 13. Sediment loading for the model used the Duan bias correction (Figure 13).

Table 4
Relationships Between Stream Discharge and Sediment Loading

Stream Discharge (cfs)	Sediment Load (biased; tons/day)	Sediment Load (Duan = 1.6400; tons/day)	Sediment Load (Ferguson = 1.7461; tons/day)
0.01	4.54E-05	7.45E-05	7.93E-05
0.10	9.50E-04	1.56E-03	1.66E-03
1	1.99E-02	3.26E-02	3.47E-02
10	4.15E-01	6.81E-01	7.25E-01
100	8.68E+00	1.42E+01	1.52E+01
1,000	1.82E+02	2.98E+02	3.17E+02
2,500	6.09E+02	9.99E+02	1.06E+03
5,000	1.52E+03	2.49E+03	2.66E+03

Note: Duan and Ferguson correction factors from HEC-RAS version 6.3.1 rating curve analysis tool using data from June 23, 2023.

Because there were limited field data available to determine grain-size distribution, density, and critical shear stress parameters, sediment characteristics were based on site evaluations and default parameters in Delft3D. Given the low gradient of Duck Creek and mudflats seen in aerial images offshore of the delta, sediment at the site was characterized as primarily fines. In the absence of full gradations or more specific field data, it was assumed the site is dominated by fine materials in the silt and clay size range rather than sands or gravels.

Morphological modeling in Delft3D requires information about sediment properties such as density, settling velocities, and critical shear stresses (the hydraulic bed shear at which sediment begins moving). Because these data were not available, a default "mud" setting was used for this study.

This places potentially large uncertainty bounds on the model, as there are few measured data to inform sediment properties. Particularly with fine sediment like silts and clays, there is potential for significant variation in cohesion. These sediments are often classified as cohesive. As they sit on a streambed, they consolidate and become more resistant to erosion. As material deposits on top of the sediment column, the underlying layers are compressed, further increasing erosion resistance. Because this varies both spatially and vertically in the sediment bed, there is inherent uncertainty when modeling cohesive material. Lacking any of the critical shear stress measurements, there is greater uncertainty in the model results.

3.5.1.4 Water Levels

The Duck Creek Delta domain simulations have a water level boundary applied outside of the barrier islands (Figure 8), which allows for a smooth continuation of flow into and out of the domain. These simulations do not include wind or waves, so the water level can be assumed constant and waves and currents do not need to be specified at the boundary.

3.5.2 Green Bay Domain

3.5.2.1 Water Levels

The Green Bay domain model includes water level boundaries at the northeast corner of Green Bay, where the bay connects with greater Lake Michigan, and at Sturgeon Bay (Figure 8). The boundaries are set far from the project site to allow waves, currents, and storm surges to be generated by the model with little to no boundary effects.

3.5.2.2 Duck Creek and Fox River Discharge

Duck Creek and Fox River discharge boundaries were set to the long-term median discharge values, as summarized in Table 5.

Table 5
Green Bay Domain Discharge Boundary Values

Boundary	USGS Station	Discharge (cfs)
Duck Creek	04072150	11
Fox River	040851385	4,210

4 MODEL RESULTS

This section describes the results of the modeling of sediment transport patterns as well as hydrodynamic conditions in lower Green Bay.

4.1 Barrier Islands Effect on Sediment Deposition

To evaluate the barrier islands effect on sediment deposition patterns, the bankfull flow and sediment discharge event was simulated for existing conditions and the proposed conditions. The simulations were conducted with the following three Lake Michigan water levels:

- LWD elevation (577.5 feet IGLD85), as a bounding case to evaluate deposition patterns at lower lake levels
- Long-term monthly mean water level (578.9 feet IGLD85), representing typical conditions
- OHWM water level (581.5 feet IGLD85), representing a bounding case for when the lake levels are high

Duck Creek Delta domain models were simulated for the entire 5-day hydrograph plus a 24-hour spin-up. Velocity and bed shear figures (Figures 18, 22, and 26) show a snapshot at the peak of the hydrograph.

Reference lines used in the Delft3D model to measure sediment loading into and out of the area of interest are shown in Figure 14. The results at each water level condition are described in the following subsections.

4.1.1 Mean Water Level Simulations

Figures 15 to 18 display results from the Duck Creek Delta domain mean Lake Michigan water level simulation. At mean water level, Duck Creek is channelized most of the distance between Highway 141 and the proposed barrier islands. Under existing conditions, sediment deposits in the river channel and fans out in a uniform manner from the mouth (Figure 15). With the barrier islands in place, sediment deposits at the mouth but also travels and deposits north along the barrier islands and through the gap in the barrier islands directly in front of the channel. The model also suggests less deposition at the gaps in the barrier islands directly in front of the main channel and to the north, where the flow is constricted and velocities are higher than in the surrounding area. The flow deflector has little effect because the footprint is mostly dry during mean water level.

Figure 16 shows the depositional changes caused by the barrier islands by comparing the proposed conditions to existing conditions. Red areas indicate more deposition under proposed conditions, and blue areas have more deposition under existing conditions. In general, proposed conditions show more sediment to the north on either side of the barrier islands and slight increases in deposition along the channel.

Figure 17 shows the differences in sediment loading volume from existing to proposed conditions. The dashed lines represent proposed conditions, and the solid lines represent existing conditions. The blue line shows the volume of sediment that reaches Highway 141. The red line shows sediment deposited between Highway

141 and the barrier islands, and the gray line shows sediment that passes through the barrier islands. This chart shows that, although the location of deposition changes, there is little difference in the total volume of sediment captured in the delta area between existing and proposed conditions. There is a slight decrease in sediment that makes it to Highway 141, indicating that sediment is dropping out farther upstream under proposed conditions, possibly because of flow restriction from the barrier islands. This is also seen in Figure 16.

Figure 18 shows bed shear and velocity results from the proposed condition simulations. Velocity and bed shear peak in the channel at the gaps in the barrier island where flow is constricted. The inundated portions of the site surrounding the channel are shallow at mean water level, so despite the wide inundation boundary, there is limited additional flow area for Duck Creek discharge. As a result, the flow is still largely confined to the channel, leading to the model results shown in Figure 18.

It should be noted that the sediment deposition predicted by the model as a result of the sediment loading event during existing conditions is likely resuspended and redistributed by waves and currents, which should be considered during future design and modeling.

4.1.2 Low Water Datum Simulations

Figures 19 to 22 display results from the Duck Creek Delta domain LWD simulation (in which water levels are 1.4 feet lower than the mean water levels). Duck Creek is very shallow and channelized most of the distance between Highway 141 and the proposed barrier islands. The results show flow paths restricted by the shallow water, resulting in some high-velocity areas where the Duck Creek discharge passes over shallow areas. Under existing conditions, the sediment deposition occurs in the river channel and fans out from the mouth, traveling farther than the mean water level simulations (Figure 19). With the barrier islands in place, a portion of sediment deposits at the mouth, and sediment also travels north along the barrier islands and through the island gap. Most of the sediment that passes through the center gap is transported more than 1,000 feet into the bay or farther, out of the modeled domain. The flow constriction combined with extreme low water creates high velocities through the gap, which does not allow sediment to settle out. Flow areas to the north and south of the main channel are mostly cut off by the shallow water. The flow deflector has little effect because the footprint is almost entirely dry at LWD.

Figure 20 shows the depositional changes caused by the barrier islands, with red areas showing more deposition under proposed conditions and blue areas having more deposition under existing conditions. In general, proposed conditions increase deposition in the channel, north of the central barrier island gap and far into the bay.

Figure 21 shows the differences in sediment loading volume from existing to proposed conditions. The blue line shows the volume of sediment that reaches Highway 141. The red line shows sediment deposited within the barrier islands, and the gray line shows sediment that makes it past the barrier islands. Similar to the mean water level simulation, there is little change to the total sediment captured, except that the proposed condition simulation has increased deposition in the channel upstream of Highway 141. This is potentially due to flow constriction caused by the combination of extreme low water levels and the relatively tight barrier island gap, reducing velocity in Duck Creek.

Figure 22 shows bed shear and velocity results from the proposed condition simulations. Velocities reach more than 5 feet per second in the gaps in the barrier islands directly in front of the Duck Creek channel and at the northern edge of the barrier islands. Bed shear values reach more than 5 pascals, which would likely erode existing sediment and carve out deeper channels at the gaps.

4.1.3 Ordinary High Water Mark Simulations

Figures 23 to 26 display results from the Duck Creek Delta domain OHWM simulation (in which water levels are 4 feet higher than the LWD water levels and 2.6 feet higher than mean water levels). At OHWM water level, Duck Creek discharges into open water after passing under Highway 141. Under existing conditions, the sediment deposition occurs primarily in the flooded river channel, farther upstream than in the LWD and mean water simulations (Figure 23). The high lake levels increase water levels in Duck Creek, reducing velocity and allowing sediment to settle out sooner. With the barrier islands in place, a small portion of sediment is deflected north along the barrier island and through the central gap, although most sediment has settled out before reaching that point. The flow deflector appears to redirect flow and sediment to the north. It does not appear to split flow and direct a significant portion of the sediment to the south.

Figure 24 shows the depositional changes caused by the barrier islands, with red areas showing more deposition under proposed conditions and blue areas having more deposition under existing conditions. The barrier islands appear to have little effect at OHWM level because most of the sediment has settled out before reaching the islands. There is a shift in deposition toward the north, likely caused by a combination of the flow splitter and flow being directed out of the barrier island gap.

Figure 25 shows the differences in sediment loading volume from existing to proposed conditions. The blue line shows the volume of sediment that reaches Highway 141. The red line shows sediment deposited within the barrier islands, and the gray line shows sediment that makes it past the barrier islands. The chart shows little difference between existing and proposed conditions, with a 2.7% increase in captured sediment.

Figure 26 shows bed shear and velocity results from the proposed condition simulations. Velocity and bed shear are much lower than in the LWD and mean water level simulations because of the increased flow area caused by higher water levels.

4.2 Barrier Islands Effect on Waves and Circulation Patterns

To evaluate the barrier islands' effect on waves and circulation patterns, model simulations were conducted with the following two wind directions:

- Winds blowing from the northeast, which act along the entire length of Green Bay and create the largest waves, currents, and storm surges in the bay
- Winds blowing from the southeast, because the site is exposed to locally generated waves from the southeast in lower Green Bay

An annual event was selected for these simulations to represent a more frequent extreme event generating waves from these directions. The simulations were performed for a period of 48 hours, with median discharge set at Duck Creek and Fox River. All wave simulations were set to fully developed, meaning the waves are not limited by the duration of the wind.

4.2.1 Northeast Wind Simulation

Figures 27, 28, and 31 display results from the proposed conditions Green Bay domain 1-year northeast wind simulation. Figure 27 displays the modeled significant wave height at OHWM level. Significant wave height is a common metric used in coastal design and is calculated as the average of the largest one-third of waves in a given sea state. As seen in Figure 27, the model predicted wave heights of more than 4 feet in Green Bay. The higher resolution grids show incoming wave heights greatly diminished by Long Tail Point and Cat Island, largely protecting the site from wave action. The waves that do impact the site through diffraction or propagation are reduced to less than 0.2 foot by the proposed barrier islands.

To visualize circulation patterns in this part of lower Green Bay, Figure 28 shows a time series of a simulated dye tracer originating in Duck Creek, showing the movement of water from Duck Creek during the 1-year northeast wind event at mean water level. The results show the dye following the shoreline to the southeast after clearing the barrier islands. The dye continues along the shore to the Fox River, where it starts to be pushed into the bay by the Fox River discharge plume. This is consistent with Figure 31, which shows a counterclockwise movement of water in the bay between Duck Creek and Cat Island.

4.2.2 Southeast Wind Simulation

Figures 29 to 31 display results from the proposed conditions Green Bay domain 1-year southeast wind simulation. As seen in Figure 29, the model predicted wave heights reaching 2.2 feet in Green Bay. The higher resolution grids show the wave heights diminishing after passing over the navigation channel into the shallow mudflats. Waves approximately 1 foot in height reach the proposed barrier islands. The islands shelter the mouth of Duck Creek and reduce wave height to approximately 0.4 foot.

Figure 30 shows a time series of a dye tracer originating in Duck Creek, showing the movement of water from the creek during the 1-year southeast wind event at mean water level. The results show the dye moving with the wind to the northwest, following the shoreline and Cat Island back toward the east. This is consistent with Figure 31, which shows a clockwise movement of water in the bay between Duck Creek and Cat Island.

5 CONCLUSION

Anchor QEA performed wave, hydrodynamic, and sediment transport modeling to evaluate a barrier island system designed to induce sediment deposition to restore the Duck Creek Delta to its historical footprint. This modeling included analysis of sediment deposition at different Lake Michigan water levels as well as analysis of waves and hydrodynamics in Green Bay.

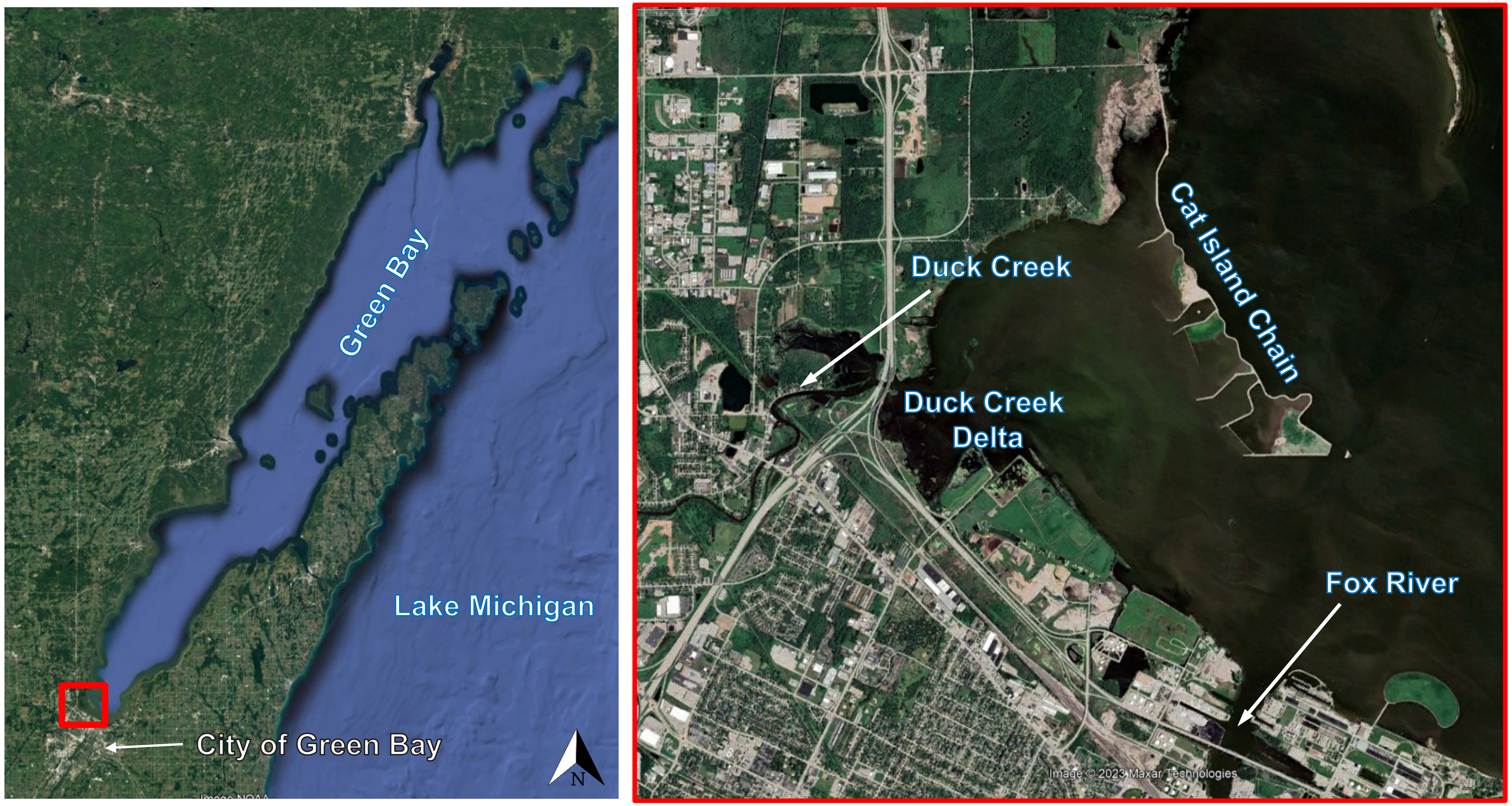
The results of the sediment transport modeling indicated that deposition patterns induced by the barrier islands vary based on Lake Michigan water levels. At mean water levels, the islands change the deposition pattern by redirecting flow toward the north. At low water levels, the barrier islands create a flow restriction in combination with the shallow water, causing some sediment to deposit farther offshore than under existing conditions. At high water levels, the barrier islands have little effect. The high lake levels create a backwater into Duck Creek, reducing velocities and causing sediment to deposit before reaching the barrier islands.

While the modeling showed little difference, at all water levels, in the total volume captured behind the proposed islands, the Green Bay domain wave and hydrodynamic models showed that the barrier islands can promote wetland growth by providing protection from waves and currents. The islands perform as barriers, shielding the newly deposited sediment from waves and currents which cause erosion, thus allowing sediment accumulation and the creation of emergent wetlands. Model results showed that currents and wave heights are significantly reduced behind the proposed barrier islands, and simulated dye-tracer studies showed that there is a healthy exchange of water through the barrier island gaps, making it unlikely that the proposed structure will cause water-quality issues by creating stagnant water. Note that the specific interactions between the proposed breakwater barriers and the existing Cat Island Chain were not modeled in this study, as they were beyond the current scope. Investigations on such effects and potential new flow channels through the chain could be considered for future phases of the EWN proving ground study.

Future Modeling Recommendations

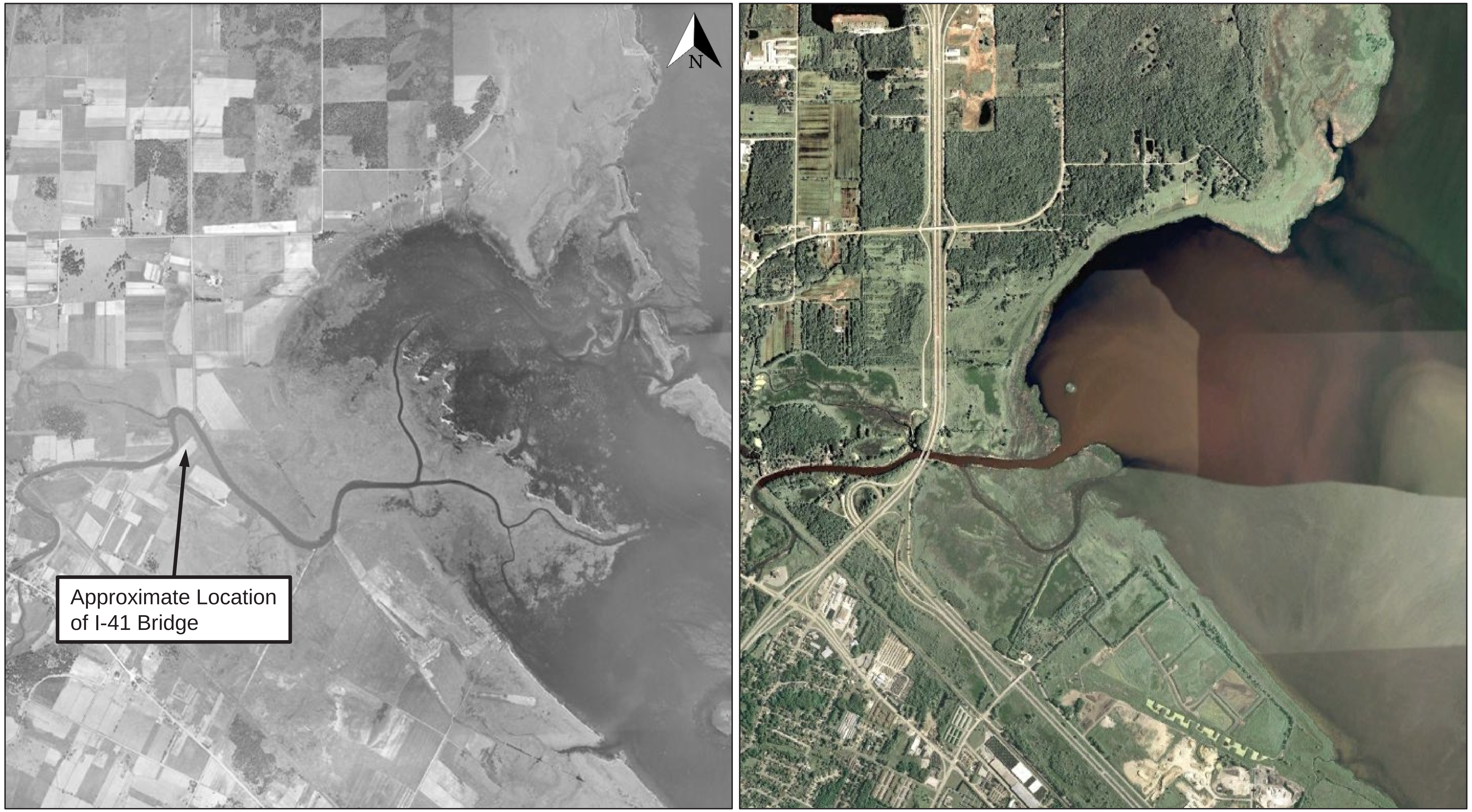
Future modeling simulations should consider:

- Incorporating wave data from the Green Bay domain under existing conditions, using a more detailed wave grid, in order to compare differences in wave heights and diffraction and their relationship to the possible resuspension of sediment and its movement. For precision, it is recommend that the future investigation include an in-field collection of sediment samples to determine critical shear stresses of the existing sediment and it's susceptibility to erosion under different conditions.
- Include an evaluation of the interactions between the proposed barrier islands and a more up-to-date model of the existing Cat Island chain, post-2019 as they are modeled in this report.
- Consider a range of flows from both Duck Creek and the Fox River, which should be more representative of a variety of conditions currently present in the bay, as well as under the changing climatic conditions. Significantly, higher flows should be evaluated.
- Seiche conditions should be evaluated by adjusting the model environments to reflect an appropriate wind set-up for the Green Bay domain.



Note: Aerial imagery from Google Earth

Figure 1
Site Location

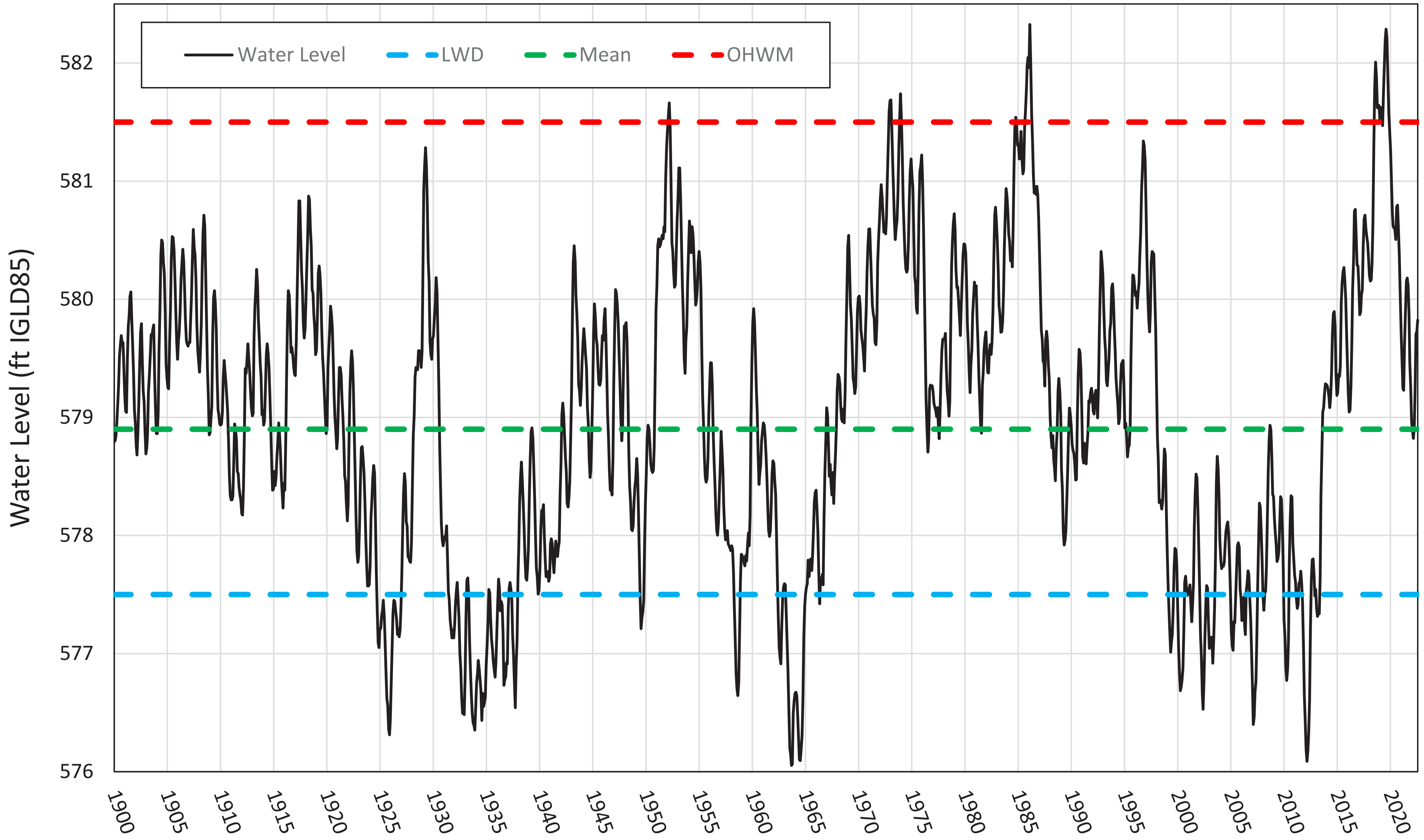


Note: Left photo from Brown County website, right photo from Google Earth

Summer 1938 – 578.45 ft IGLD85

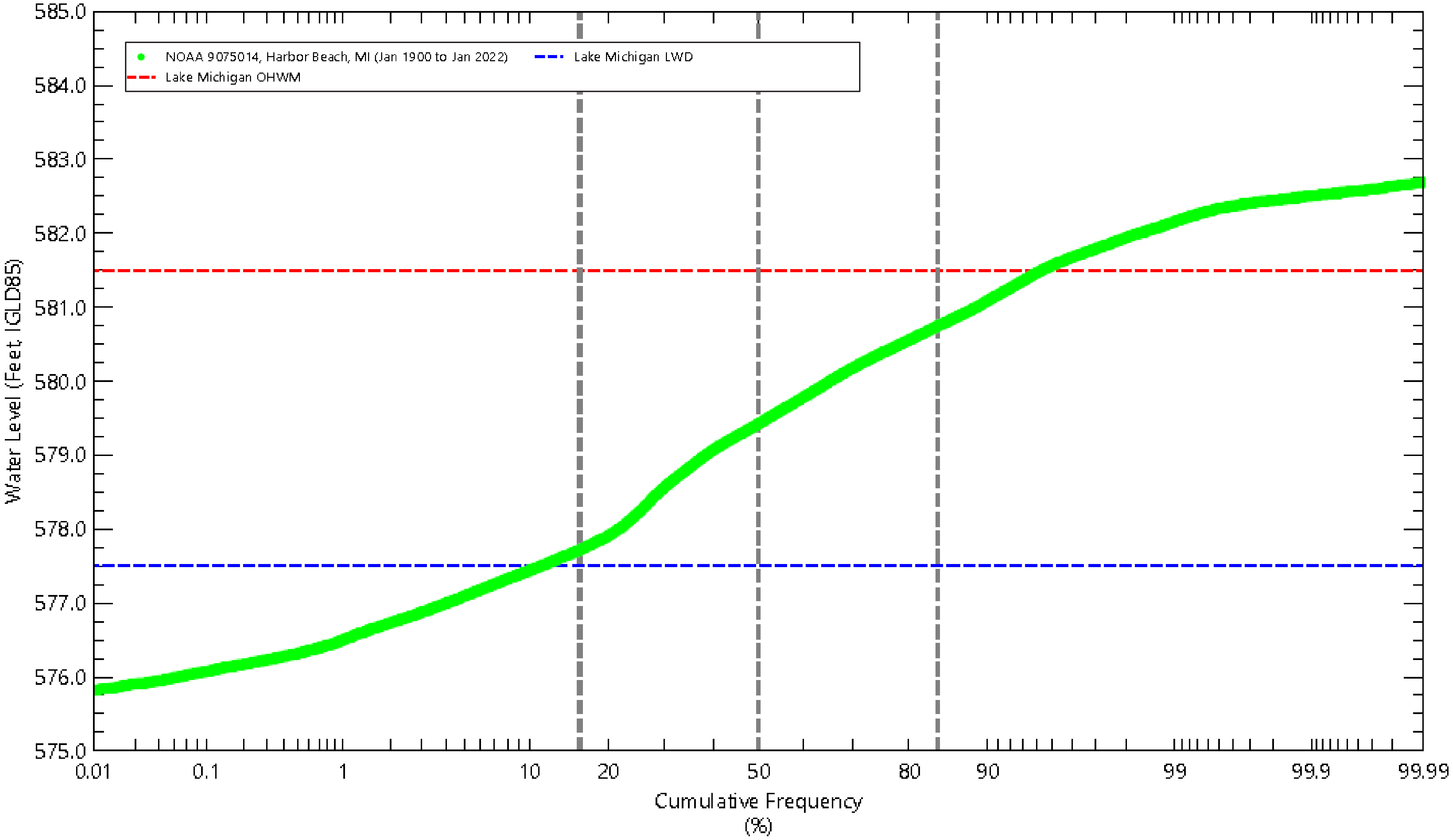
Summer 2010 – 578.22 ft IGLD85

Figure 2
Duck Creek Historical Wetland Extents Comparison



Notes: Data from NOAA Station 9075014
LWD: Low Water Datum; 577.5 ft IGLD85
Mean: 578.9 ft IGLD85
OHWM: Ordinary High Water Mark; 581.5 ft IGLD85

Figure 3
Lake Michigan Hydrograph



Notes: Data from NOAA Station 9075014
LWD: Low Water Datum; 577.5 ft IGLD85
Mean: 578.9 ft IGLD85
OHWM: Ordinary High Water Mark; 581.5 ft IGLD85

Figure 4
Lake Michigan Cumulative Frequency Distribution Chart

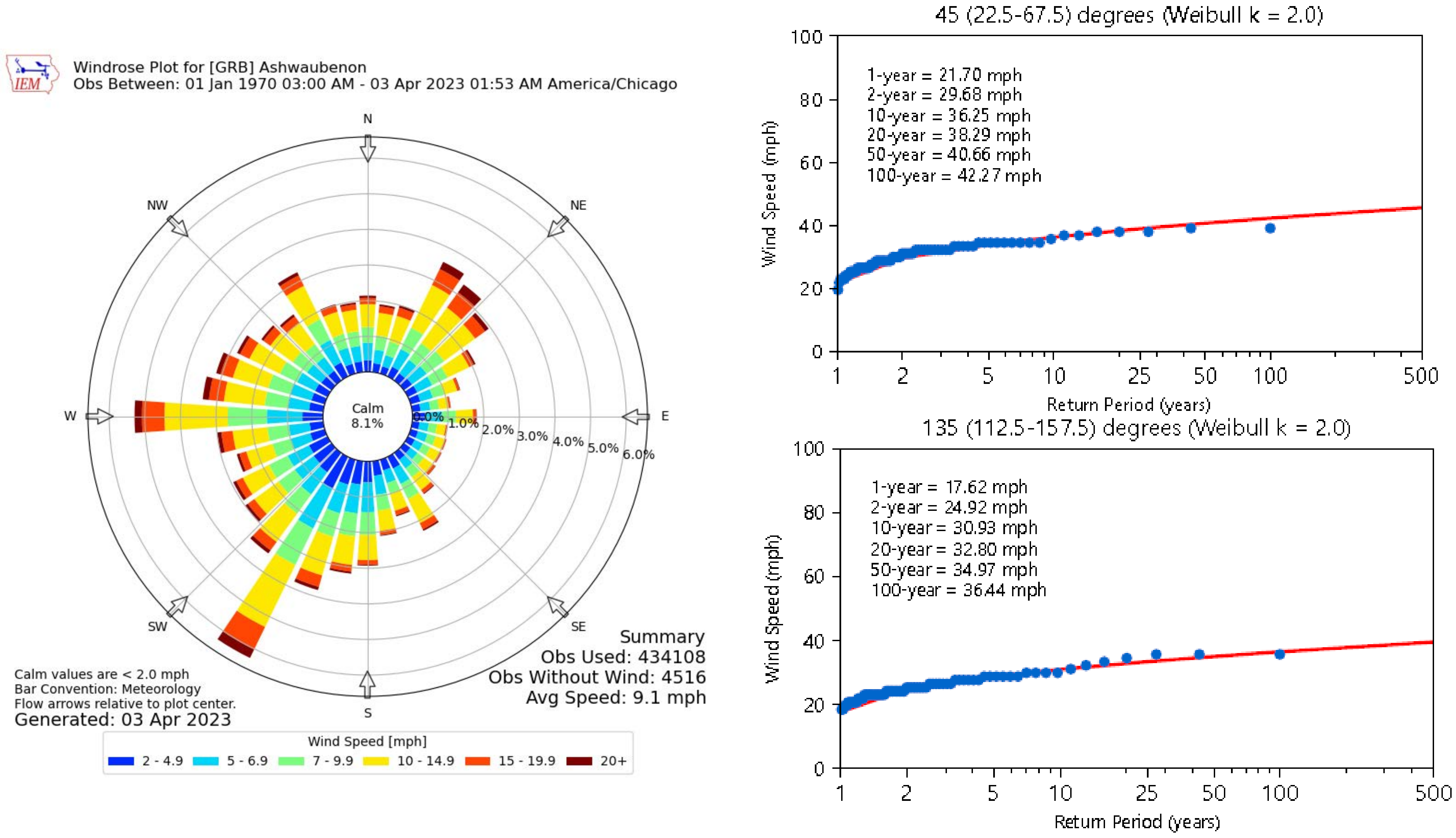


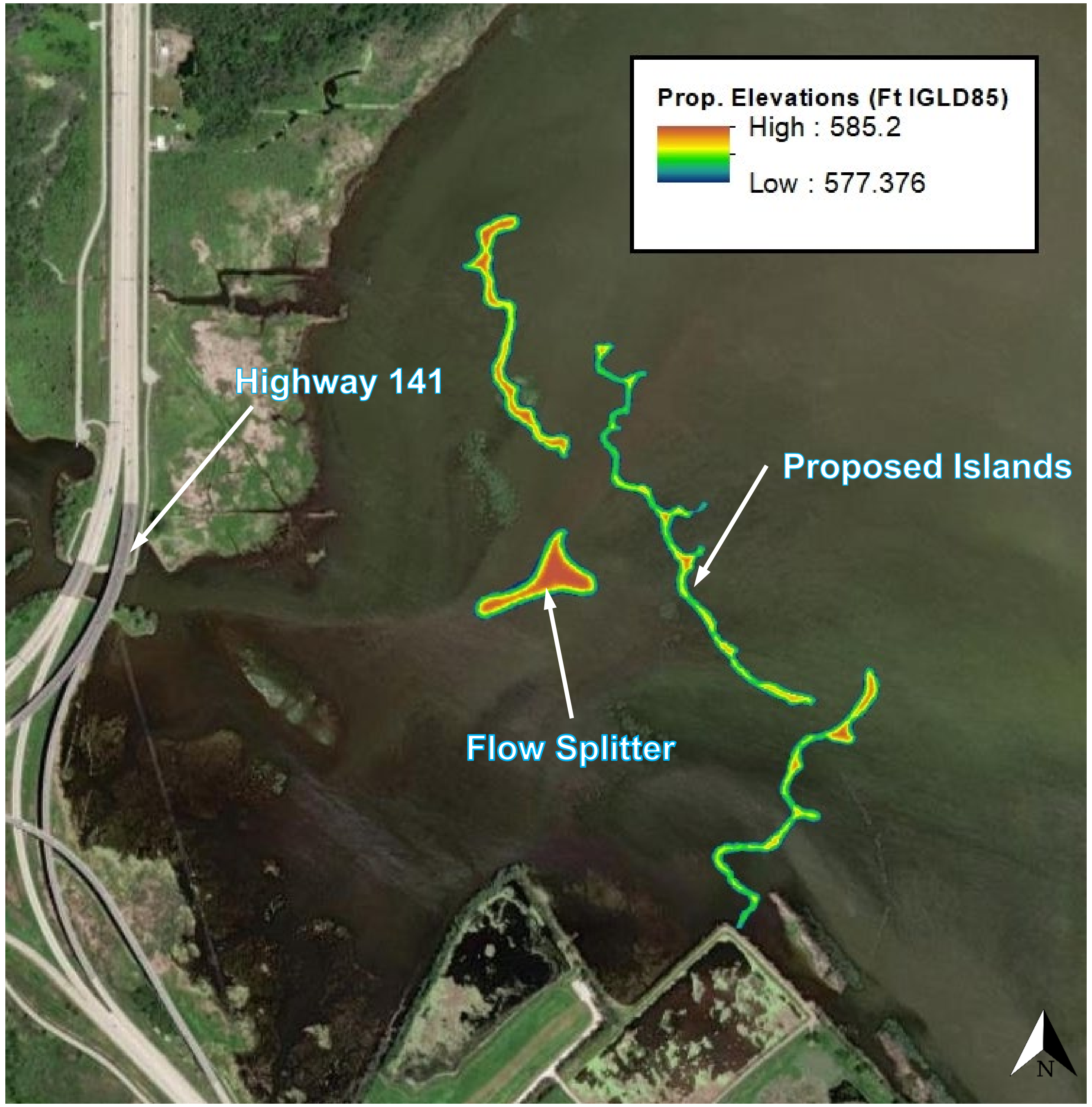
Figure 5
Austin Straubel Airport Wind Rose and Wind Speed Return Periods

Note: Aerial imagery from Google Earth

Summer 2010 – 578.22 ft IGLD85

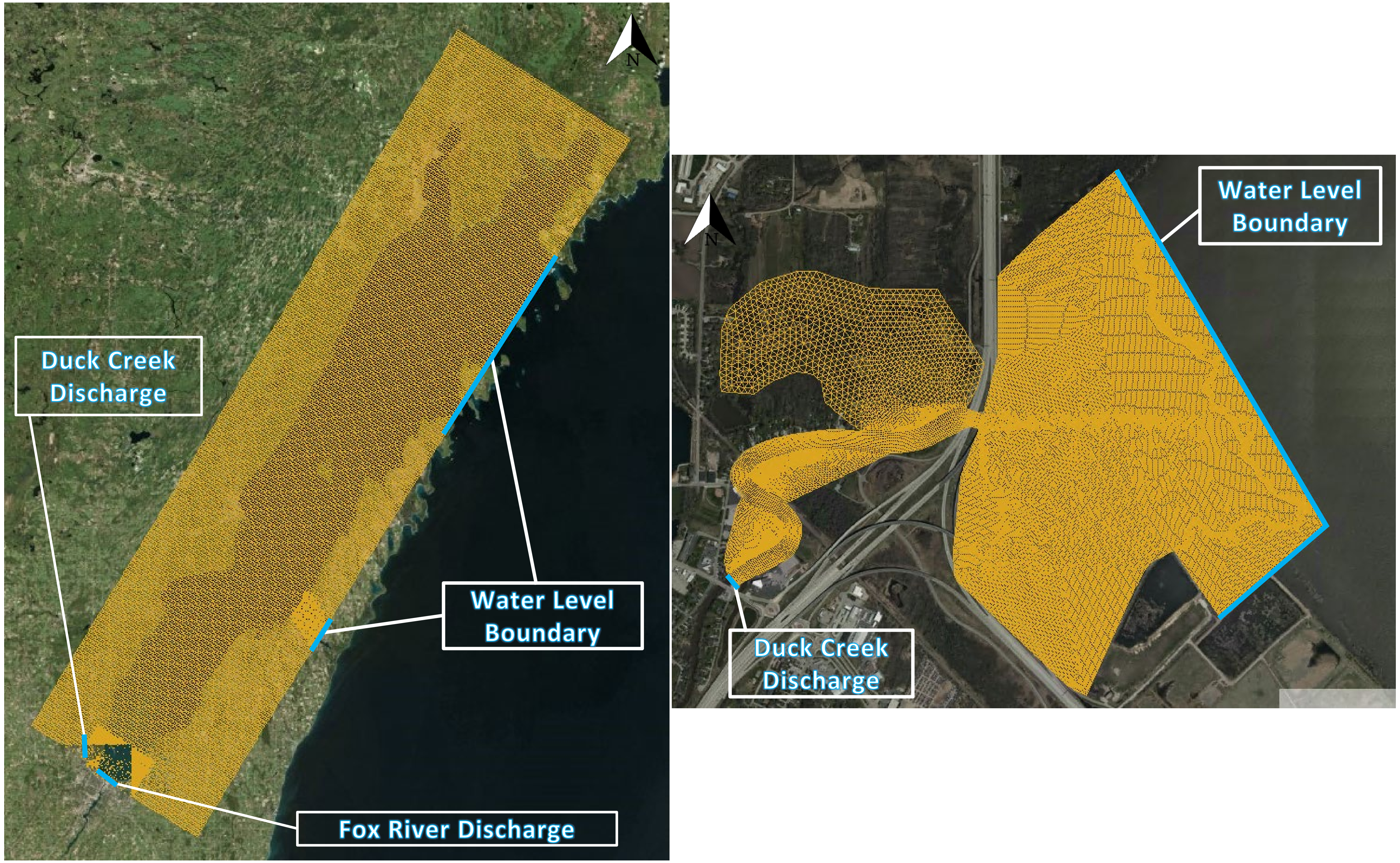
Summer 2022 – 580.5 ft IGLD85

Figure 6
Comparison of the Duck Creek Delta Between High and Low Water Levels



Note: Aerial imagery from Google Earth

Figure 7
Proposed Barrier Island Layout



Note: Aerial imagery from Bing

Figure 8
Delft 3D Model Domain and Boundary Conditions

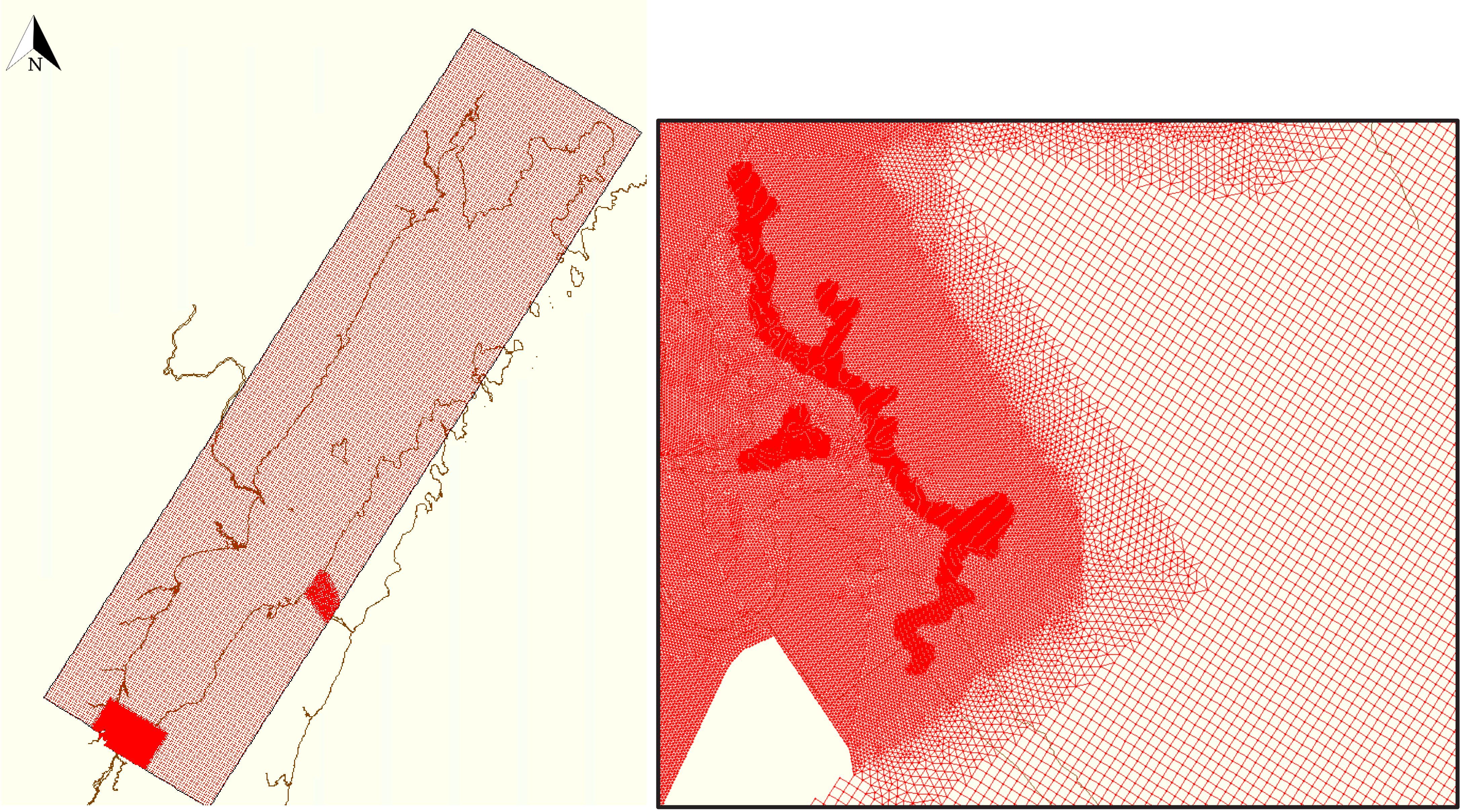
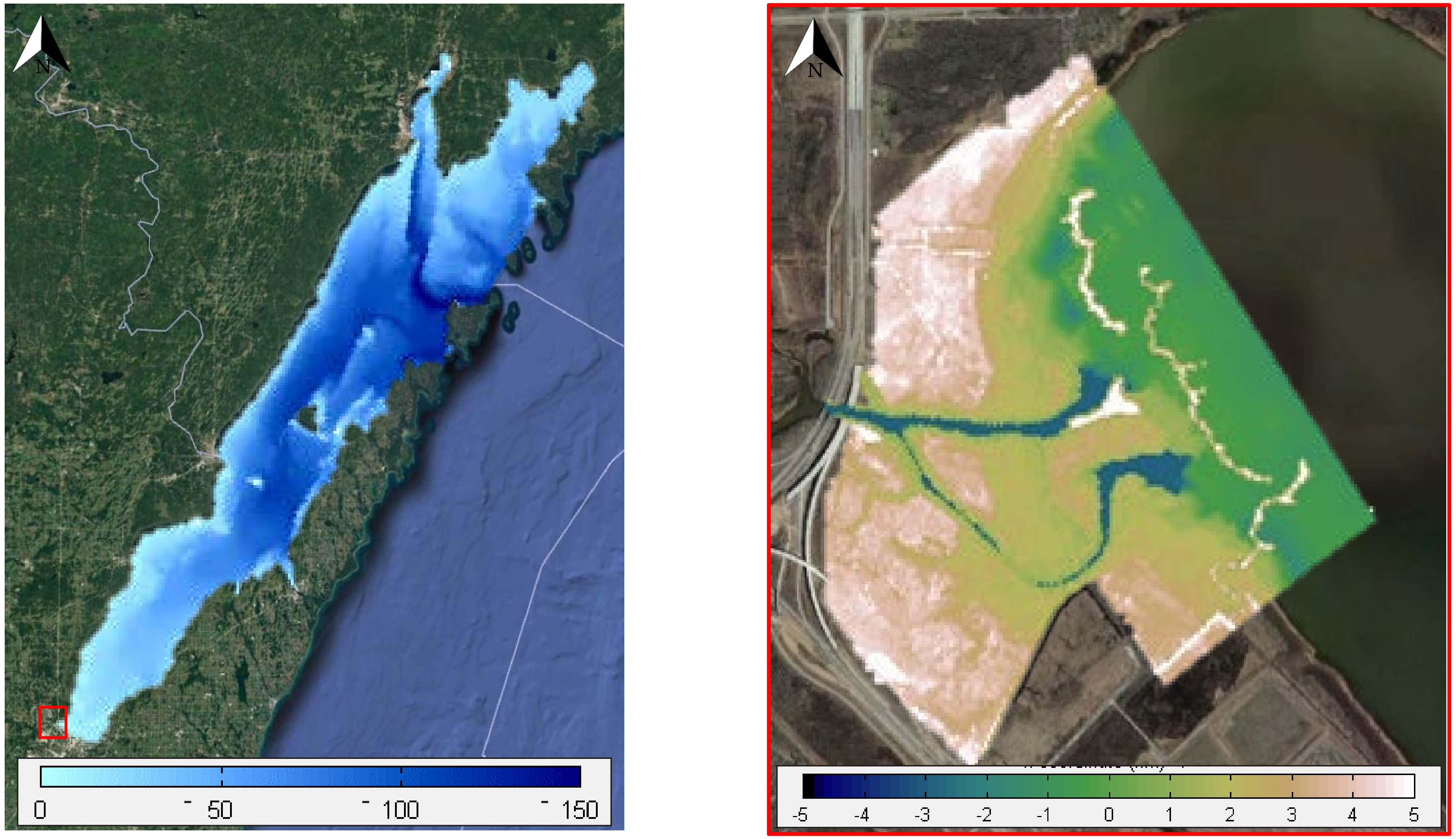


Figure 9
Green Bay Domain Model Grid

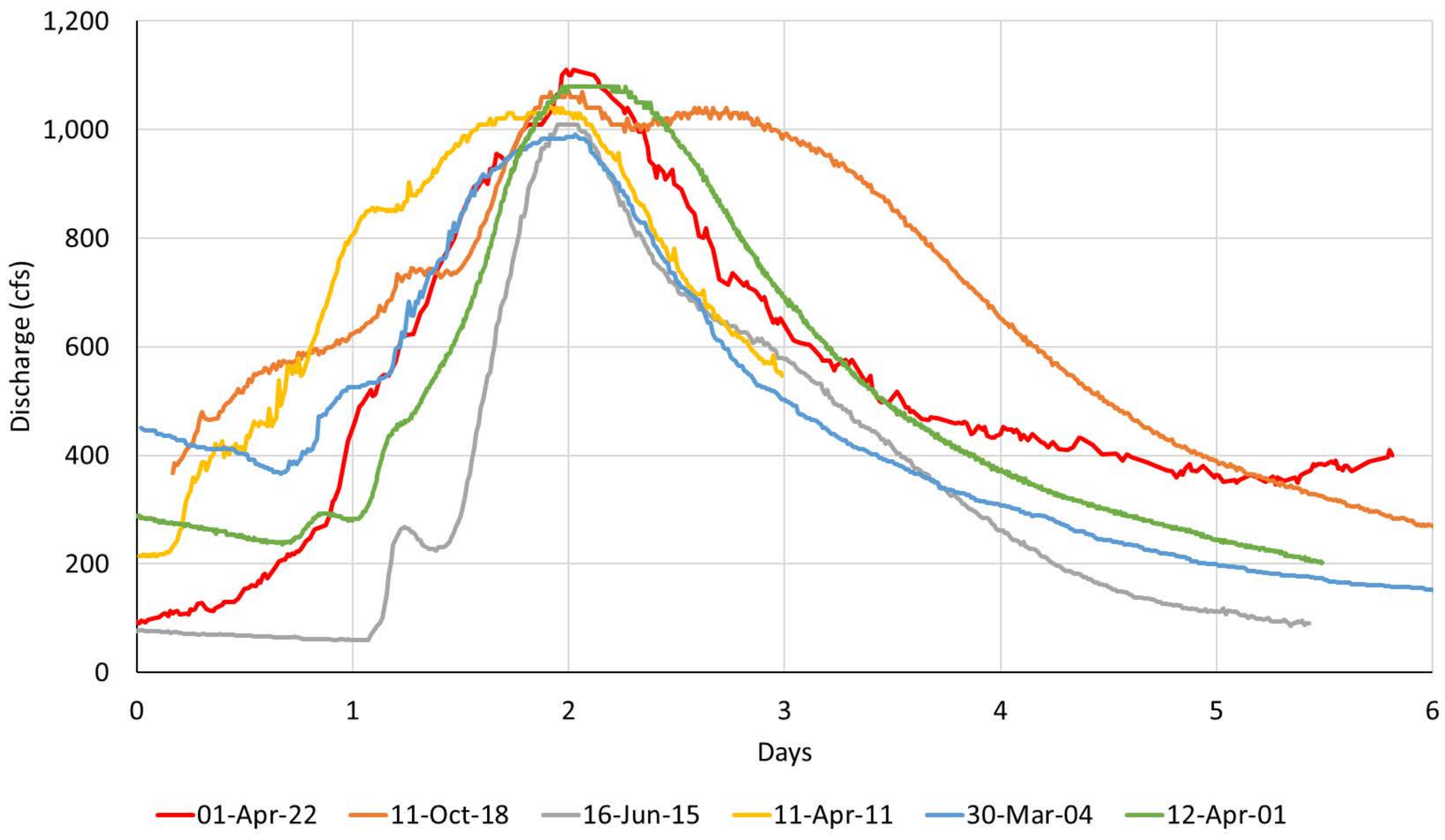


Elevation LWD [ft]

Elevation LWD [ft]

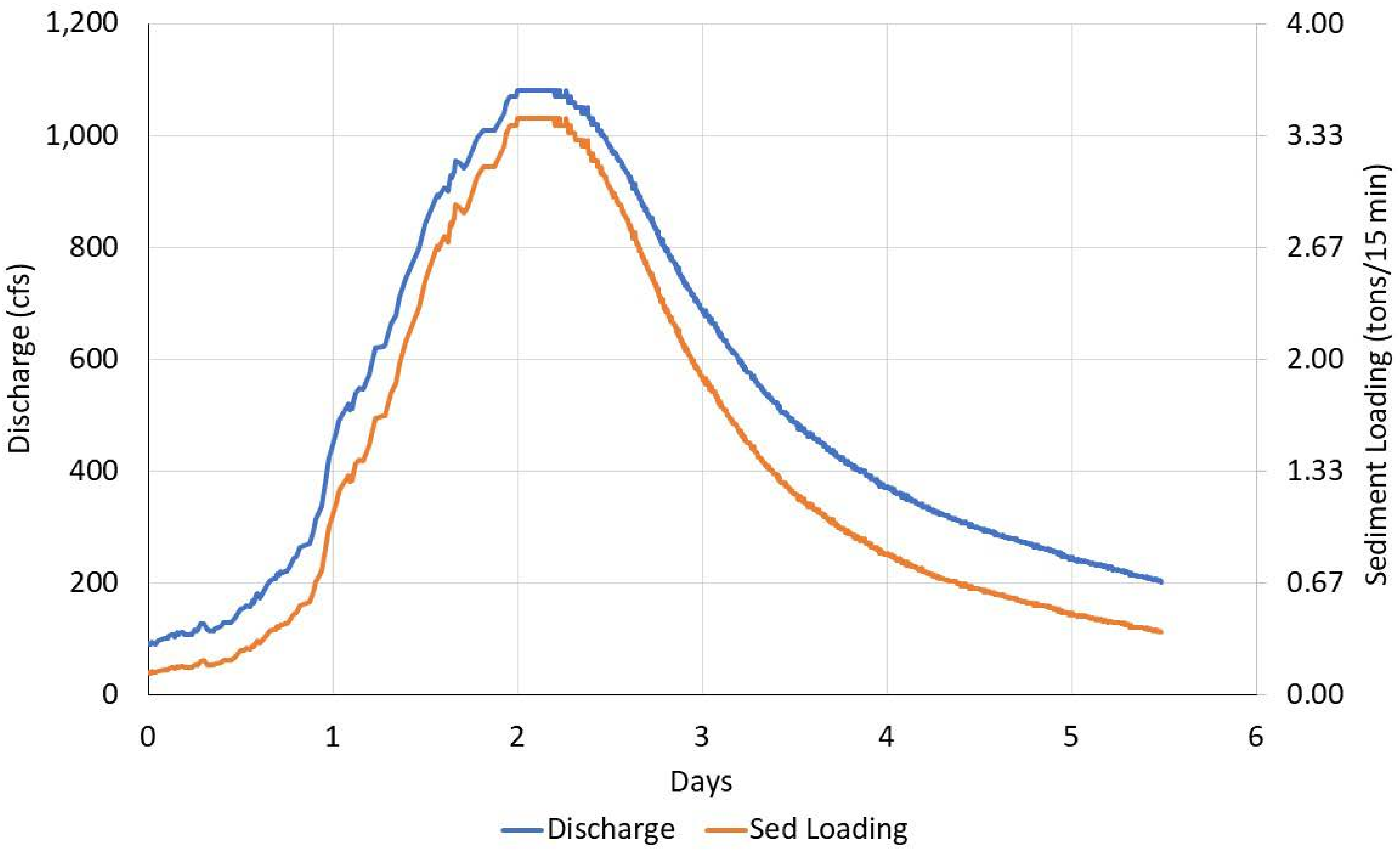
Notes: LWD = 577.5 ft IGLD85; Low Water Datum
Proposed elevations shown in right image
Aerial imagery from Google Earth

Figure 10
Model Elevations



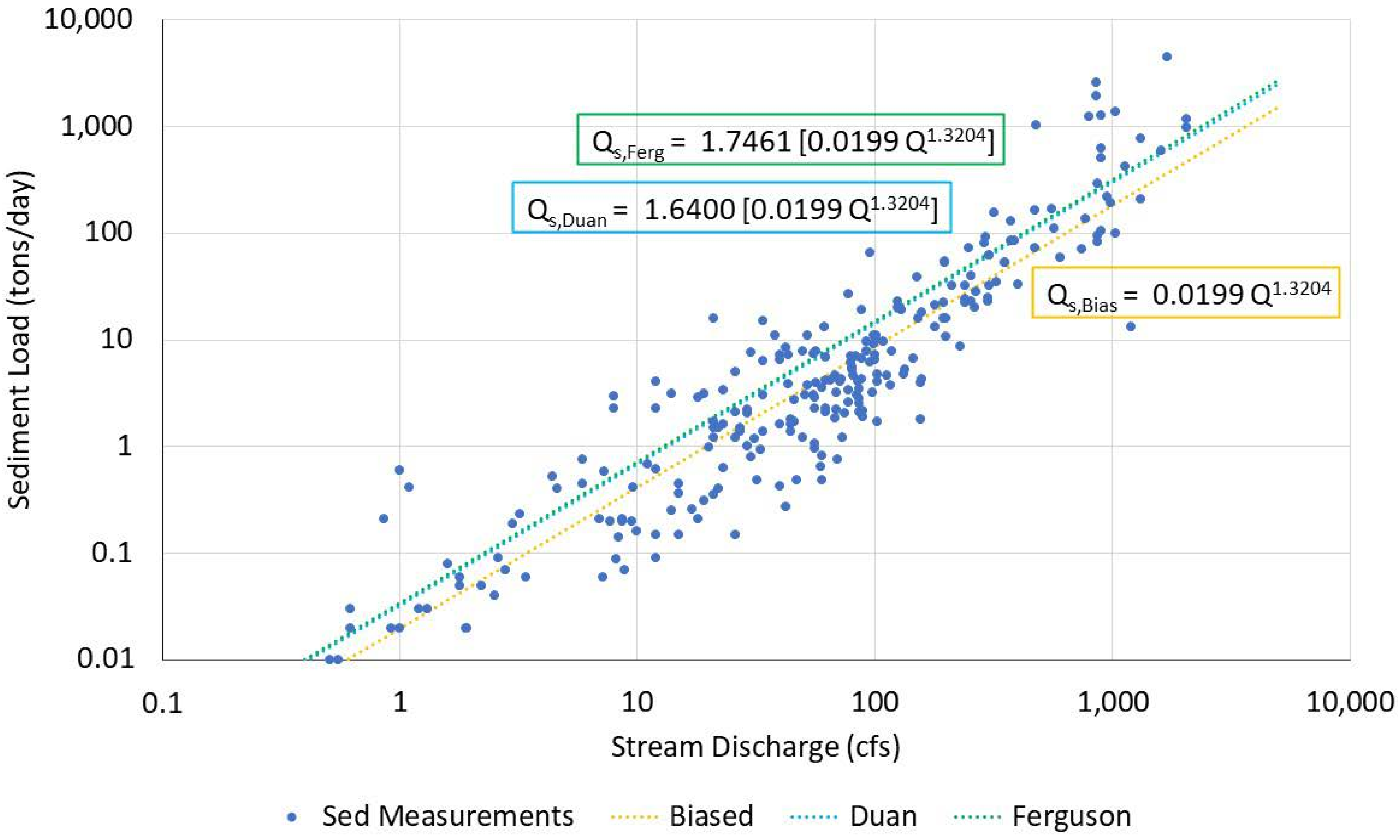
Discharge information from 15-minute data at USGS Gage 04072150 – Duck Creek near Howard, WI. Events selected for approximate peak discharge of 1,065 cfs (1.5-year recurrence flow) to evaluate bankfull discharge events.

Figure 11
Duck Creek Hydrographs – Measured Discharge Events



Discharge and sediment load data from USGS Gage 04072150 – Duck Creek near Howard, WI. Discharge hydrograph rising limb from April 2022 event; falling limb from April 2001 event. Stream discharge and sediment loading relationship based on outputs of HEC-RAS v 6.3.1 rating curve analysis tool corrected with Duan methodology.

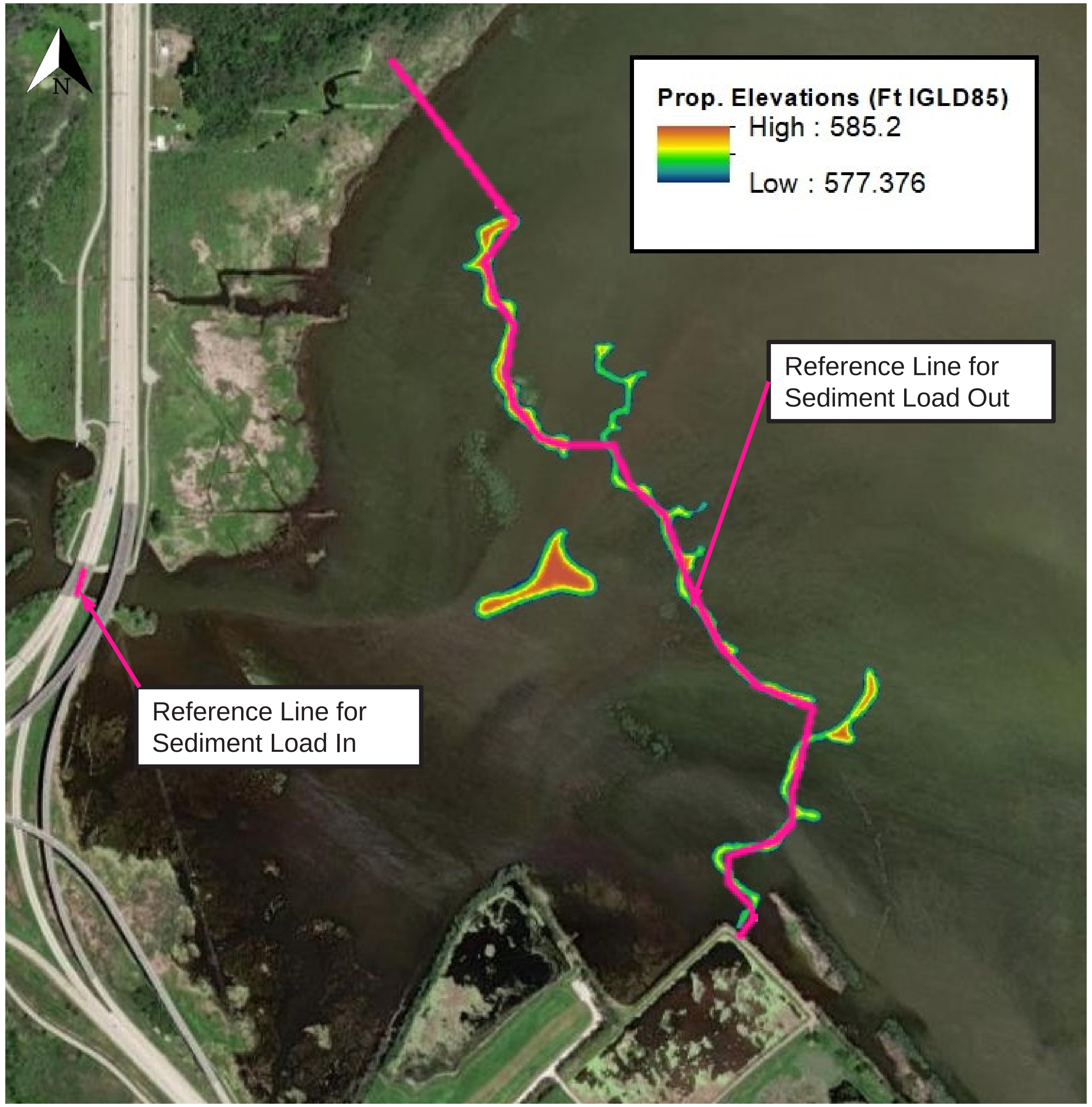
Figure 12
Duck Creek Hydrograph – Synthesized Inflow Hydrograph and Sediment Loading



Sediment load data from USGS Gage 04072150 – Duck Creek near Howard, WI. Biased, Duan correction, and Ferguson correction best-fit lines from HEC-RAS v 6.3.1 rating curve analysis tool.

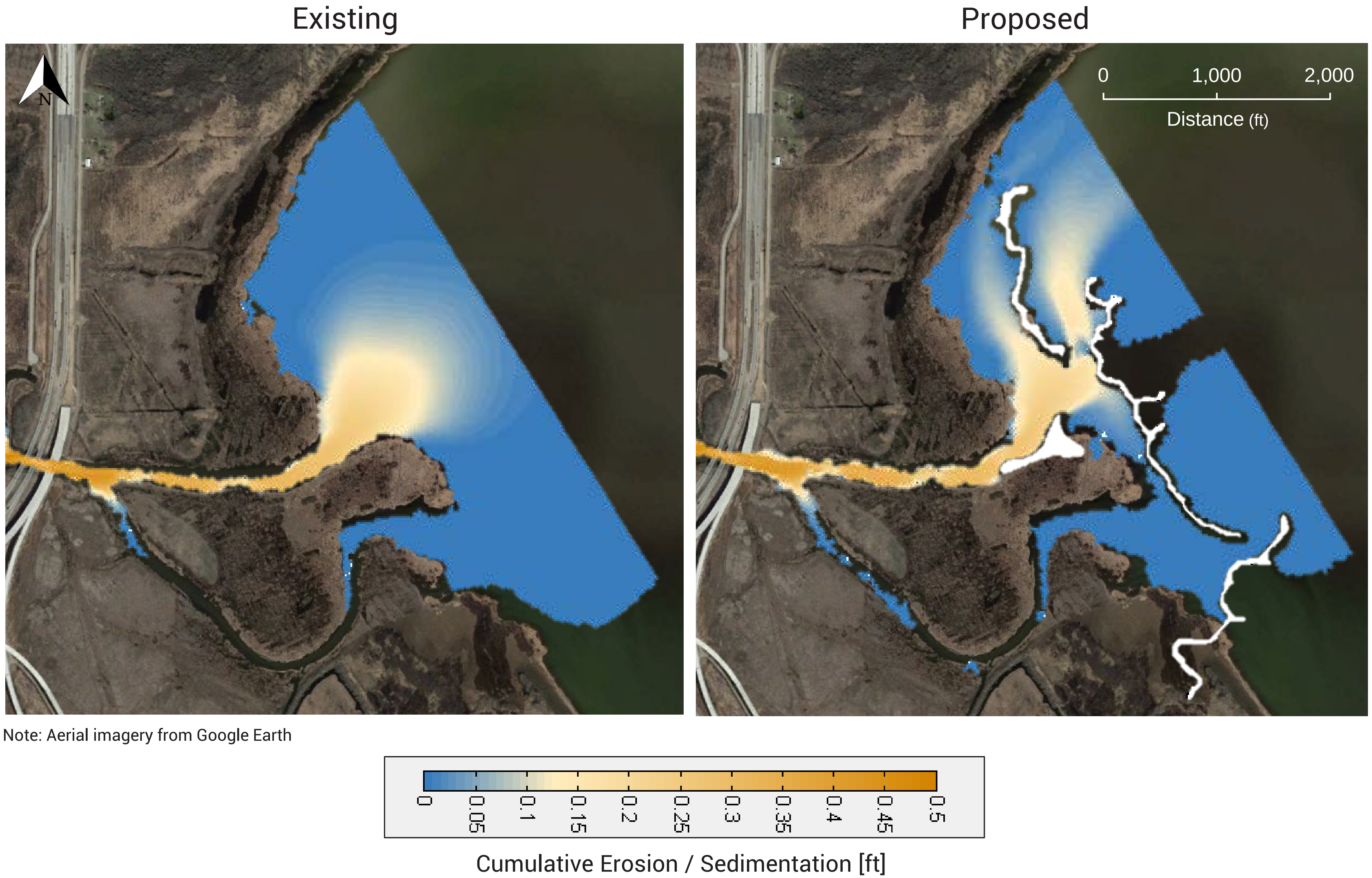
Figure 13

Modeled Sediment Loading Curve from HEC-RAS Sediment Rating Curve Analysis Tool



Note: Aerial imagery from Google Earth

Figure 14
Sediment Load Measurement Reference Lines

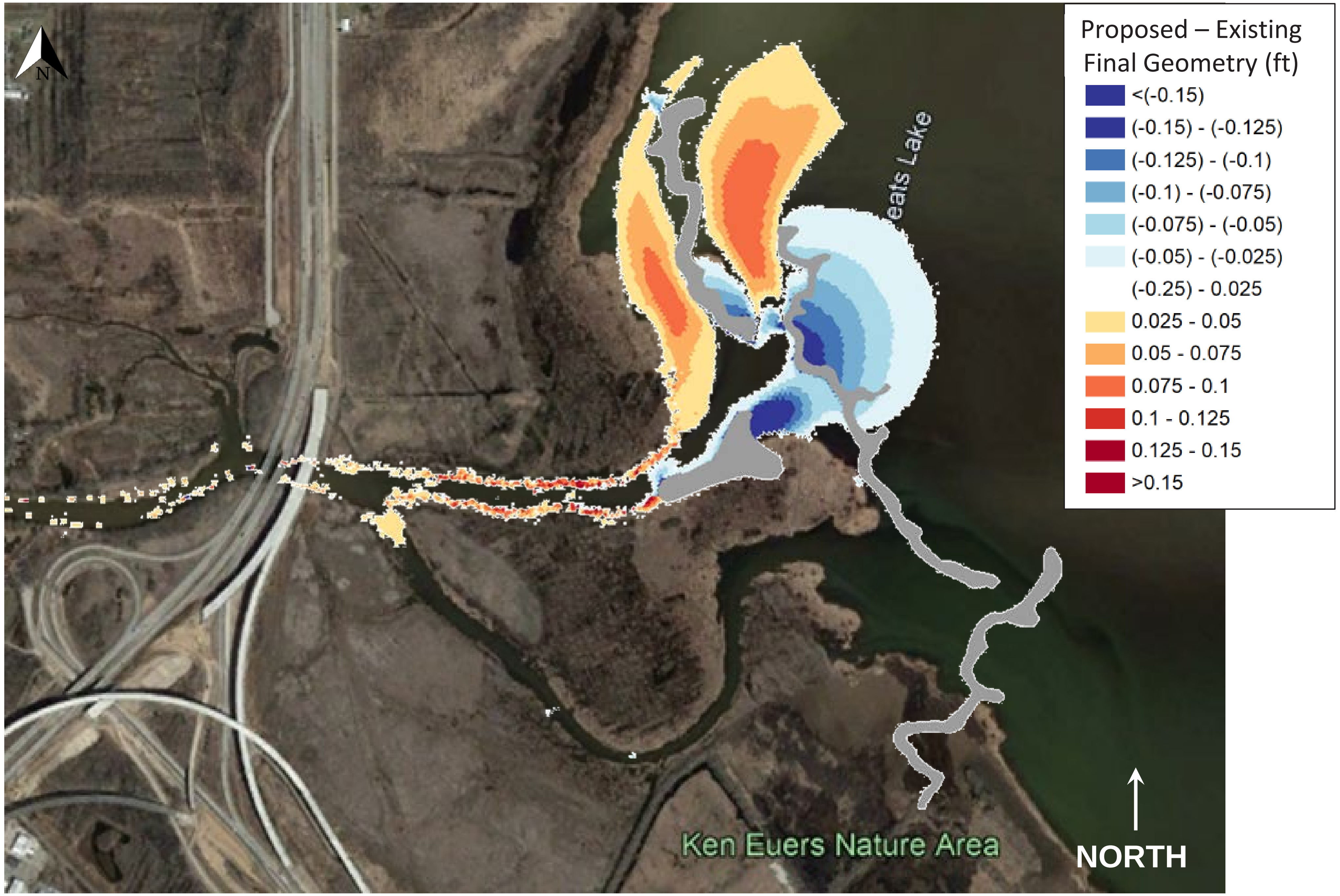


Existing

Proposed

Note: Aerial imagery from Google Earth

Figure 15
Deposition Comparison, Mean Water Level



Note: Aerial imagery from Google Earth

Figure 16
Deposition Difference, Mean Water Level

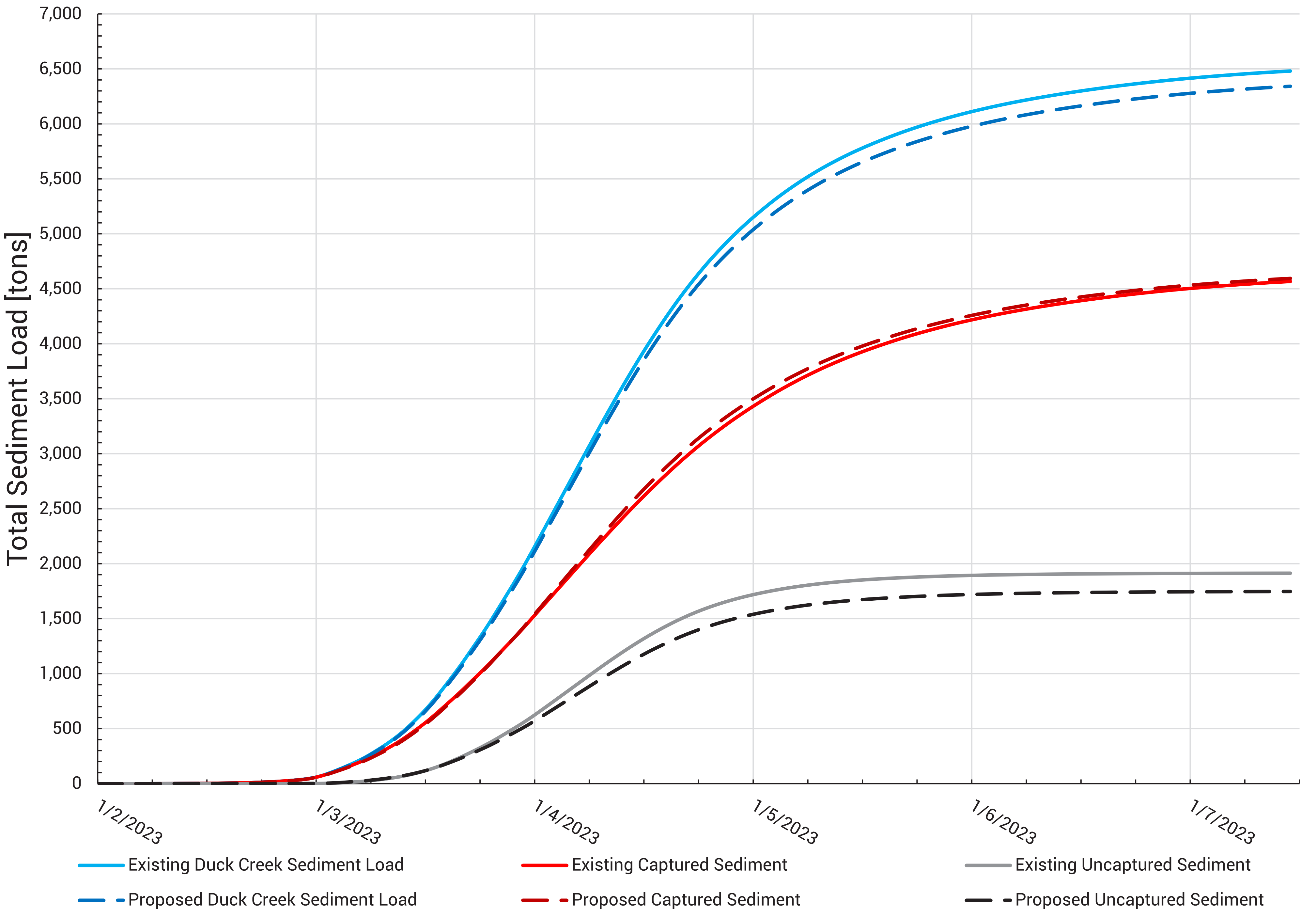
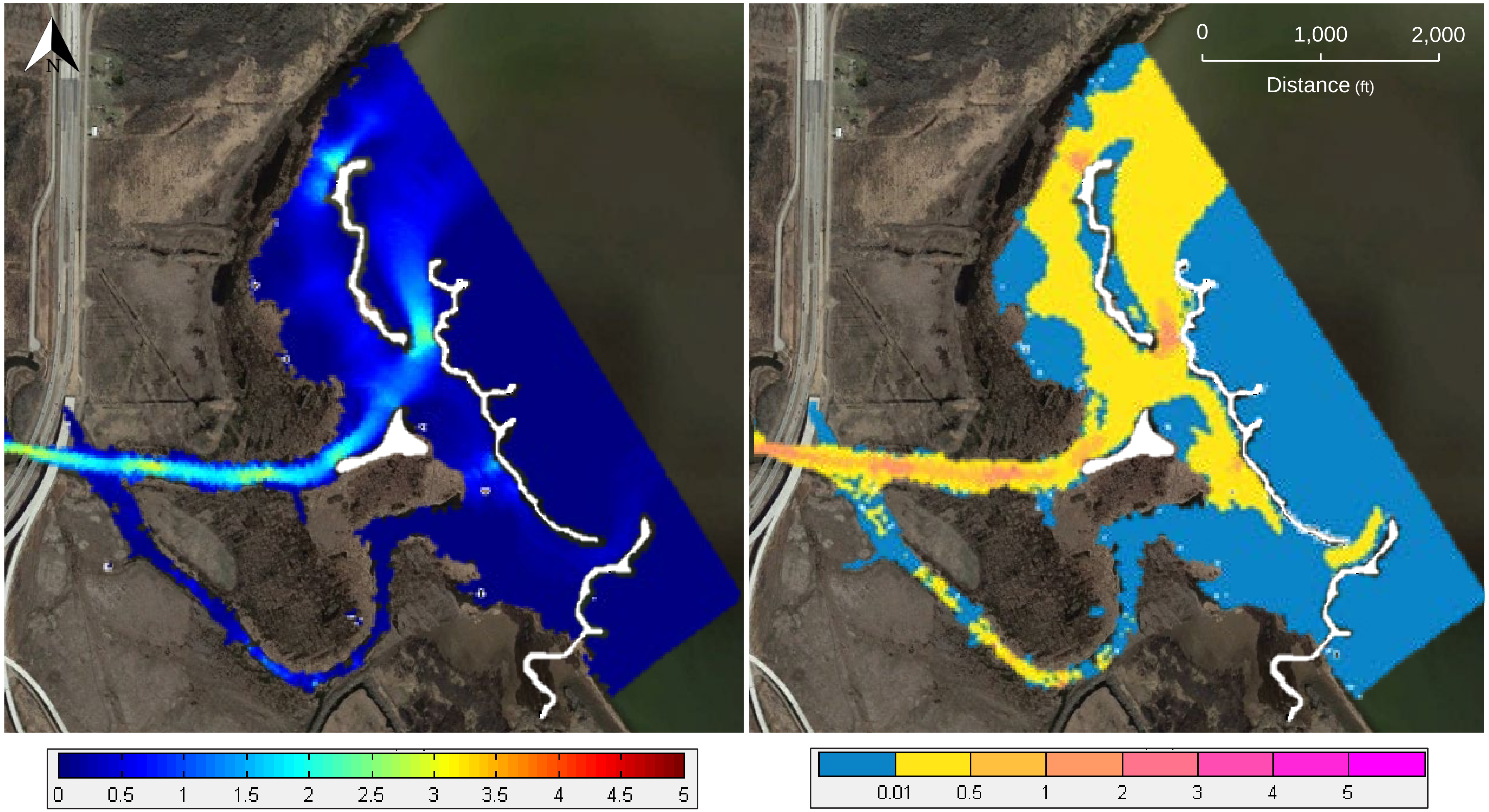


Figure 17
Cumulative Sediment Loading, Mean Water Level

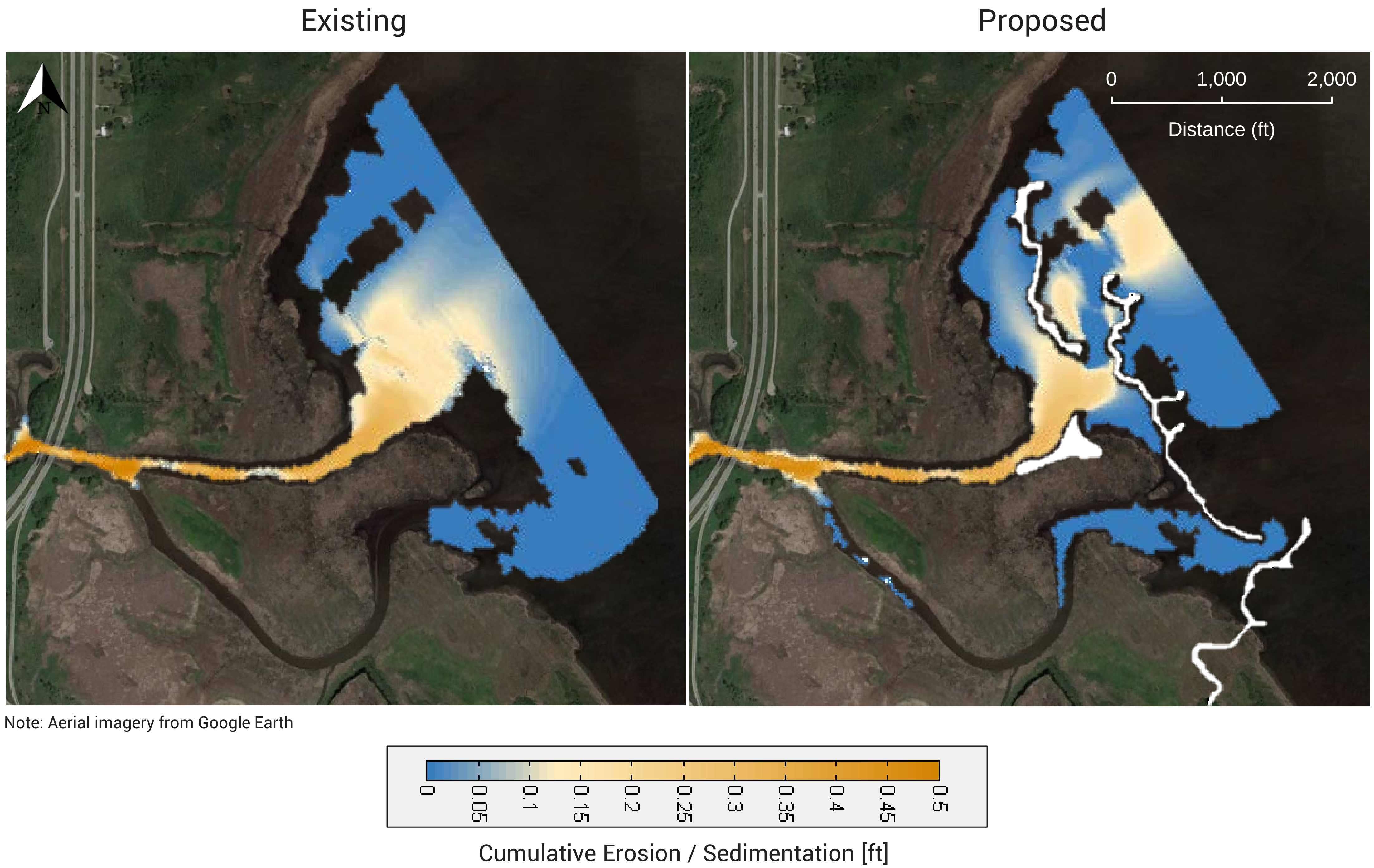


Velocity [ft/s]

Bed Shear [Pa]

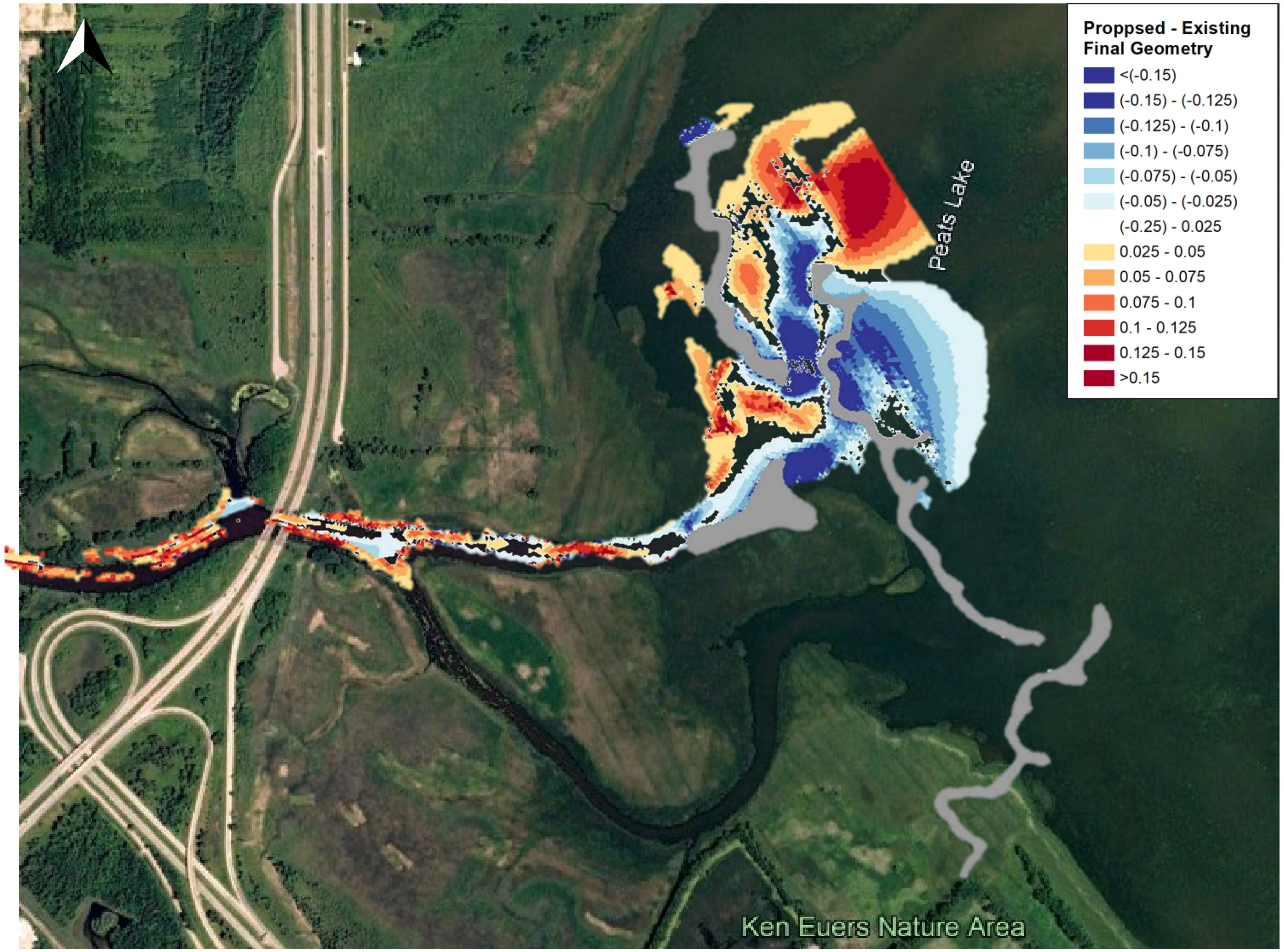
Note: Aerial imagery from Google Earth

Figure 18
Velocity and Bed Shear Stress, Mean Water Level



Note: Aerial imagery from Google Earth

Figure 19
Deposition Comparison, Low Water Datum



Note: Aerial imagery from Google Earth

Figure 20
Deposition Difference (ft) , Low Water Datum

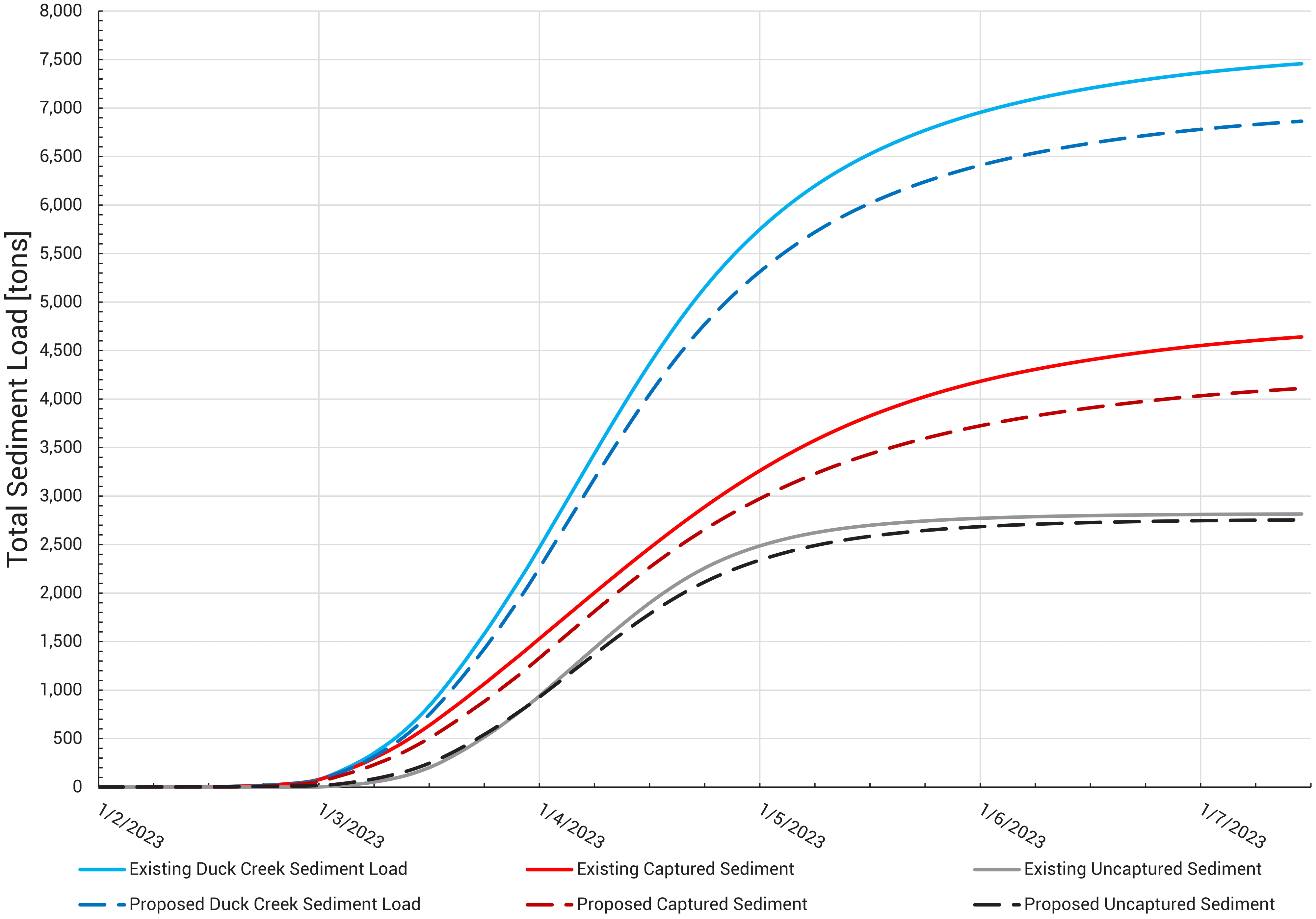
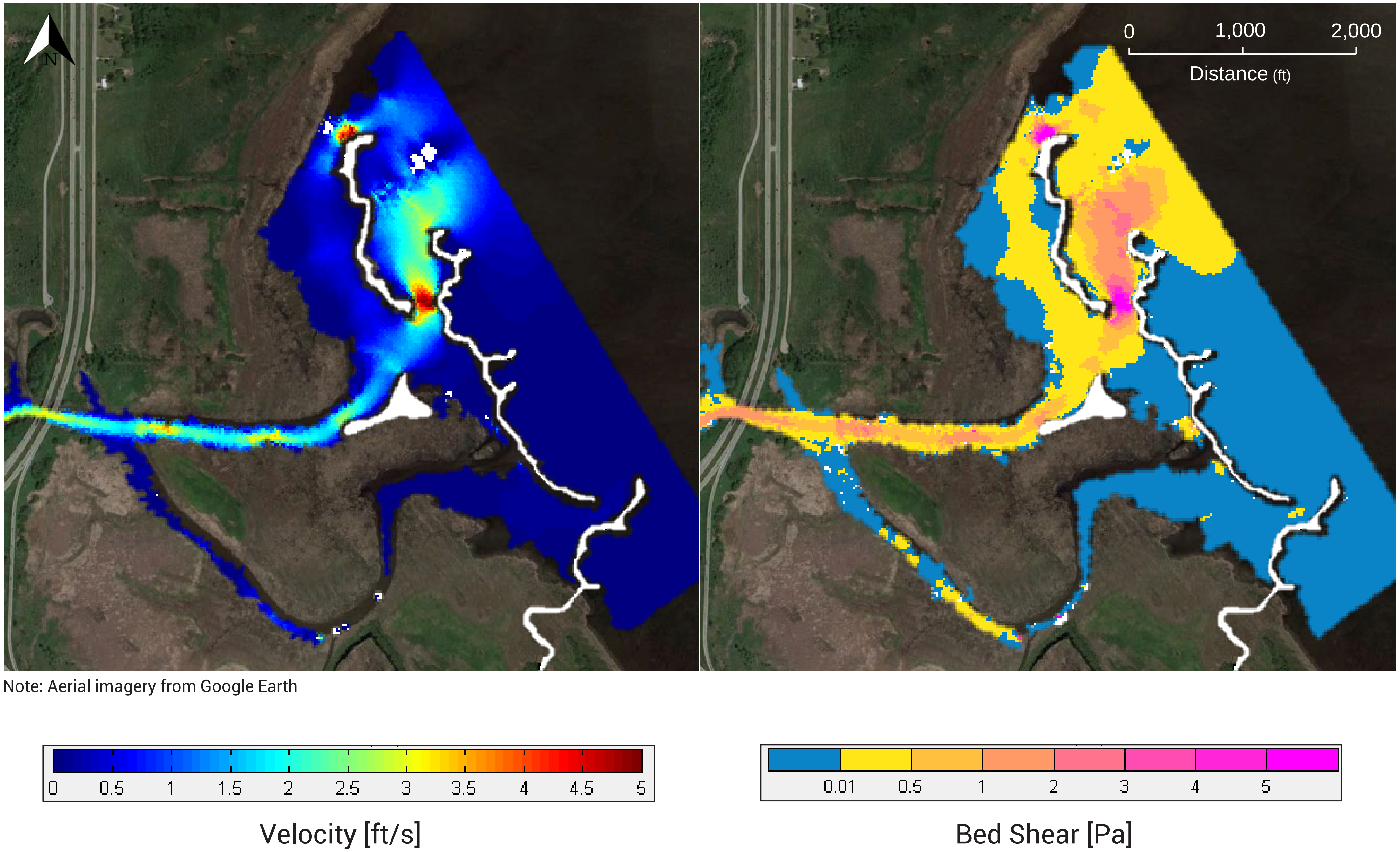
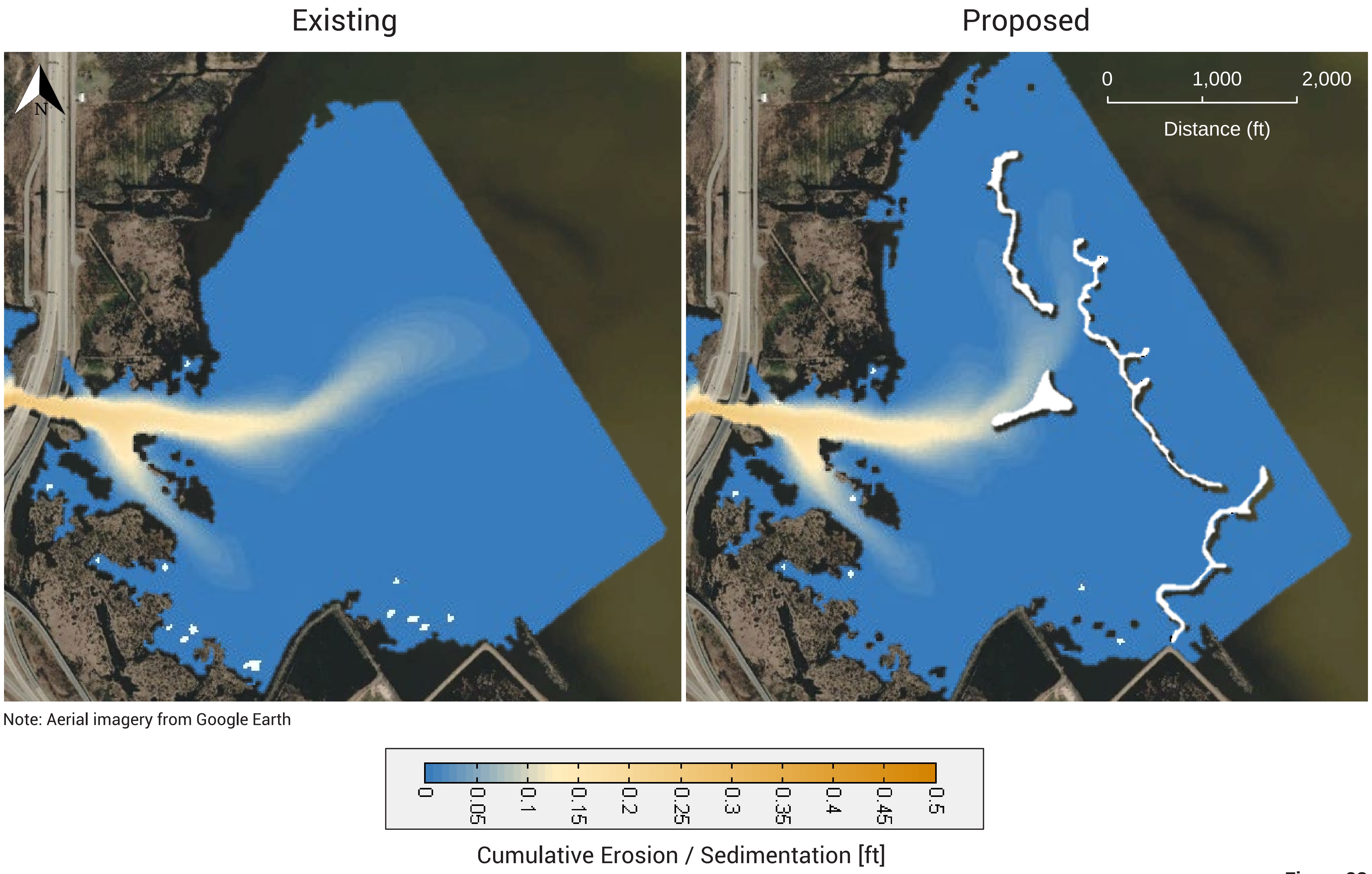


Figure 21
Cumulative Sediment Loading, Low Water Datum



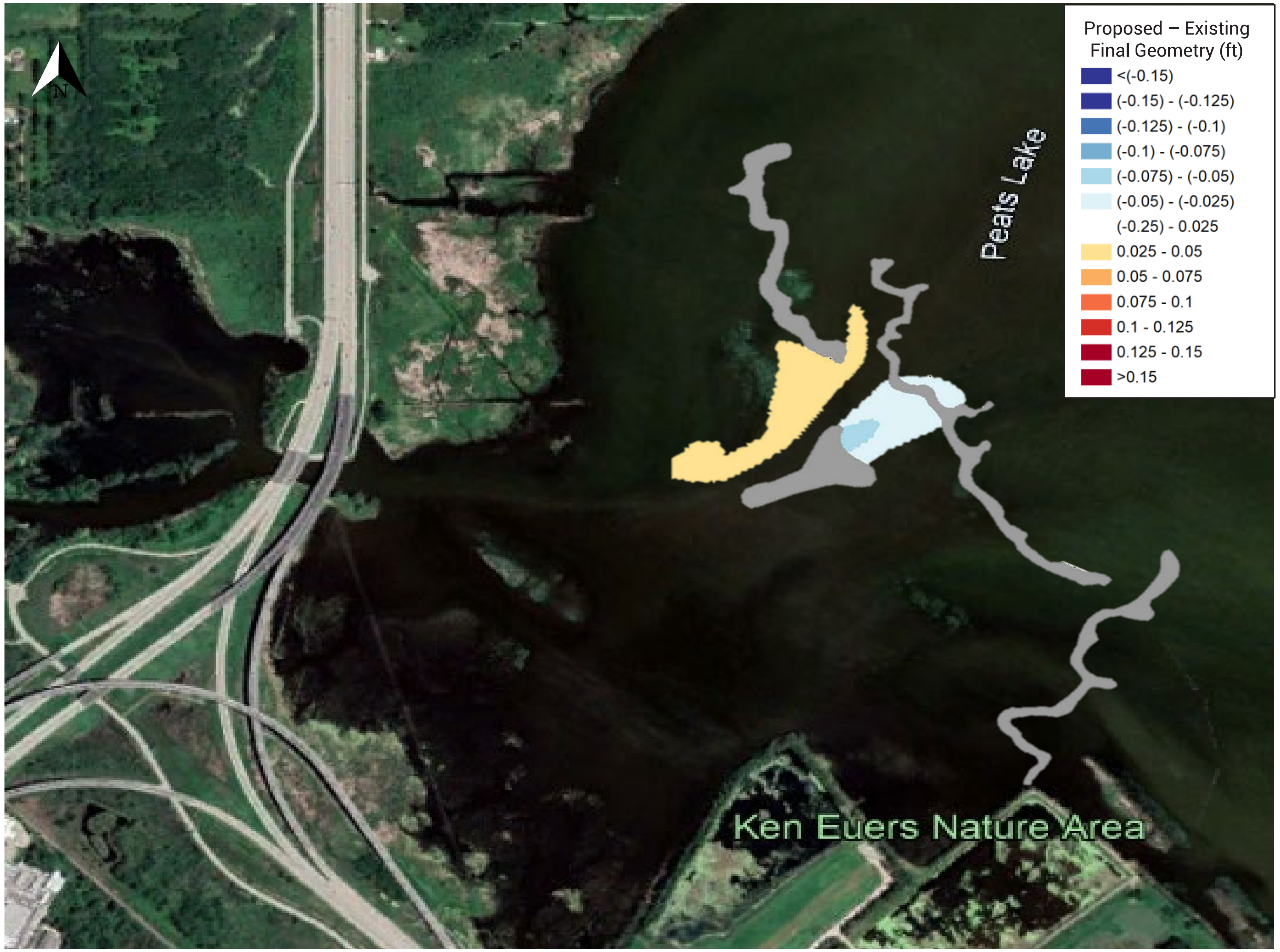
Note: Aerial imagery from Google Earth

Figure 22
Velocity and Bed Shear Stress, Low Water Datum



Note: Aerial imagery from Google Earth

Figure 23
Deposition Comparison, Ordinary High Water Mark



Note: Aerial imagery from Google Earth

Figure 24
Deposition Difference, Ordinary High Water Mark

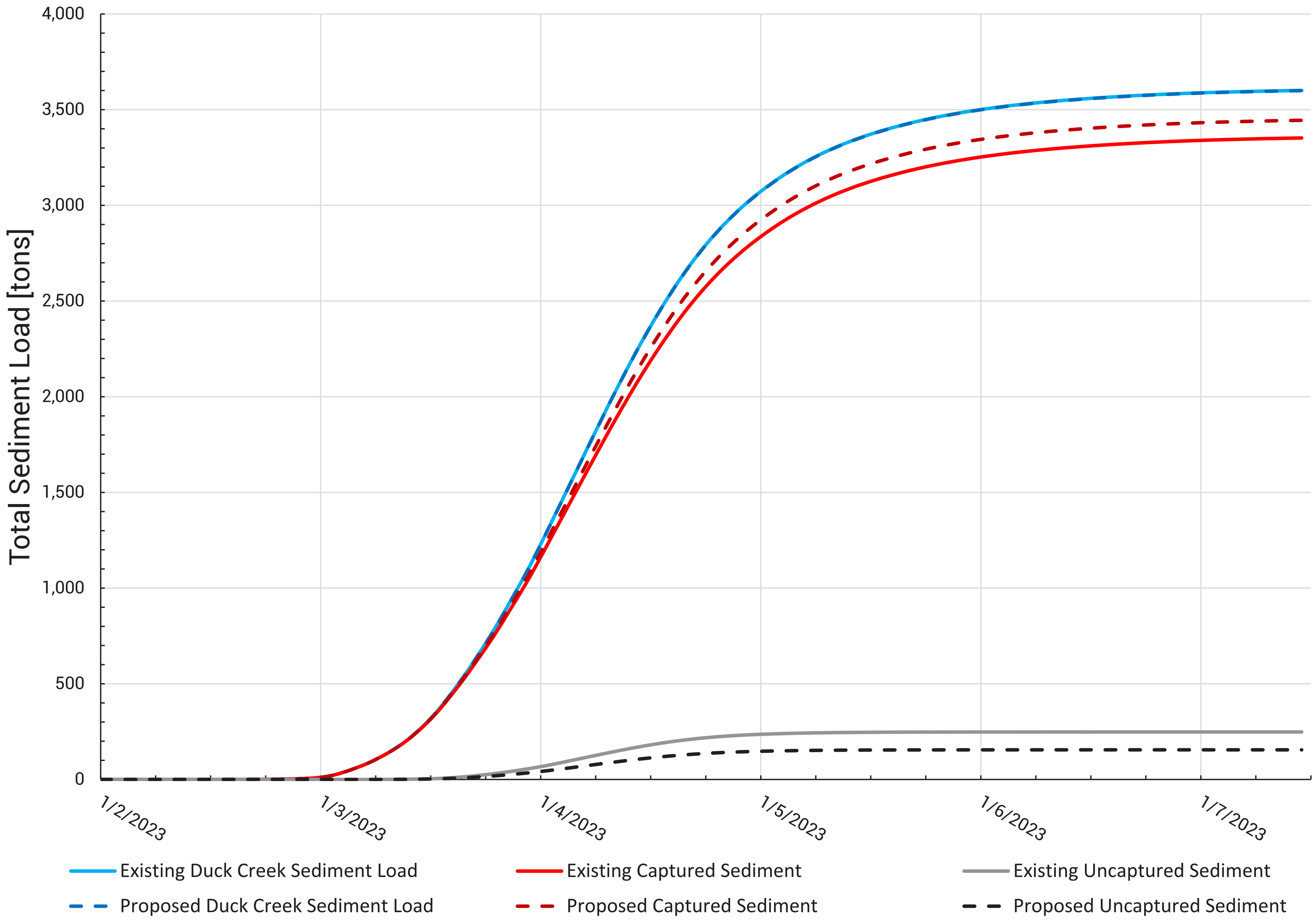
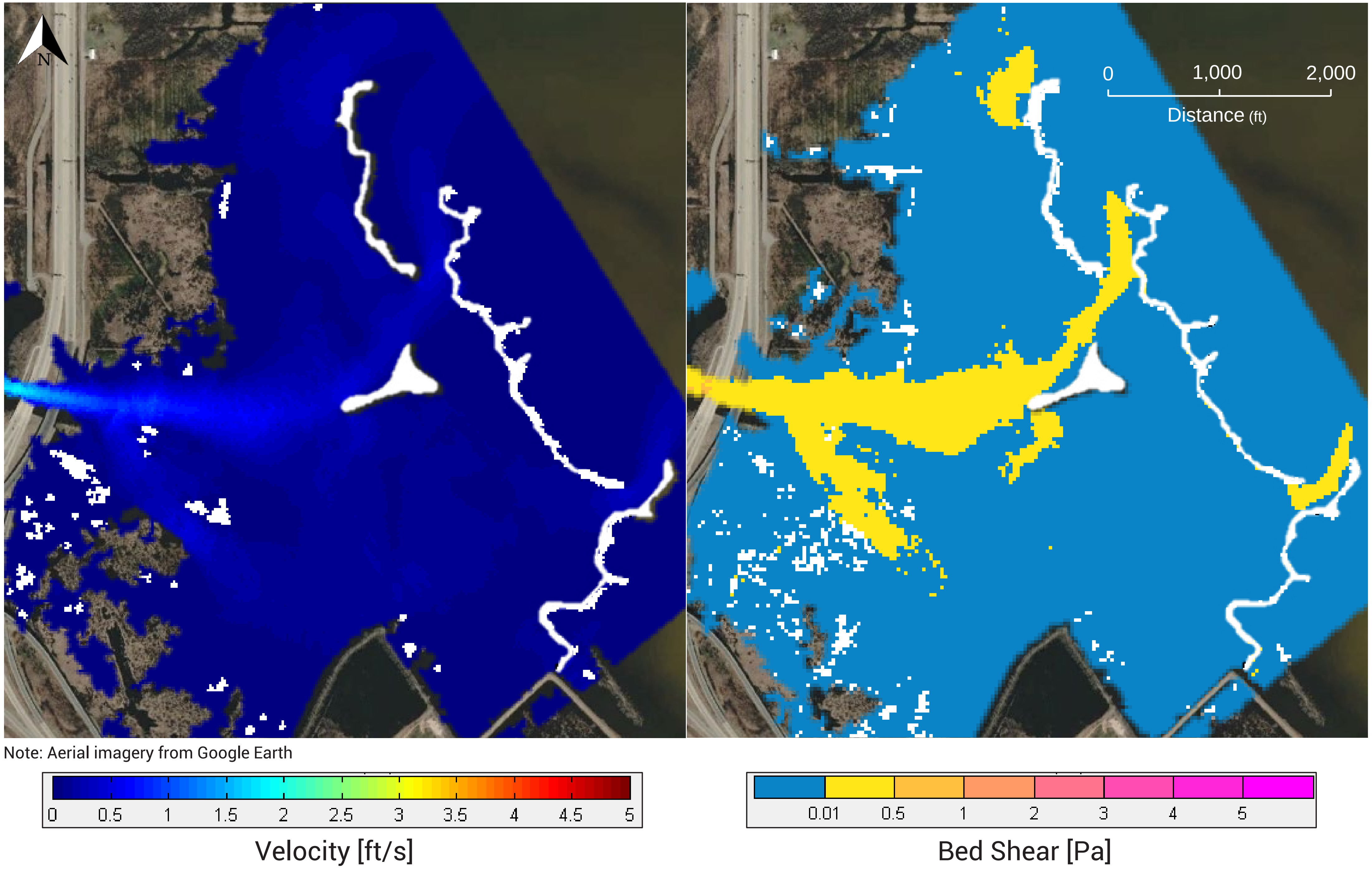
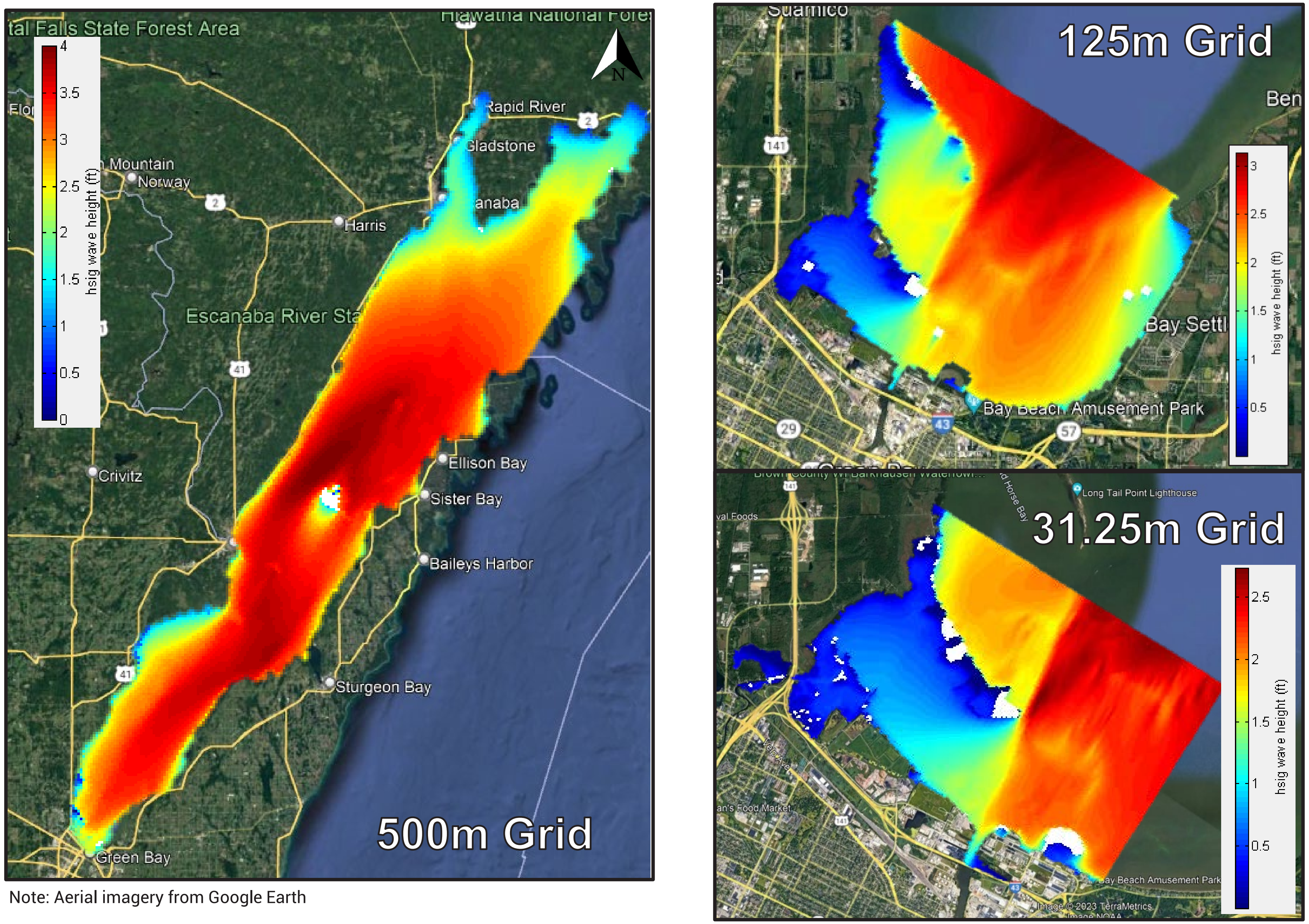


Figure 25
Cumulative Sediment Loading, Ordinary High Water Mark



Note: Aerial imagery from Google Earth

Figure 26
Velocity and Bed Shear Stress, Ordinary High Water Mark



Note: Aerial imagery from Google Earth

Figure 27
Wave Height, 1-Year Northeast Wind, Ordinary High Water Mark

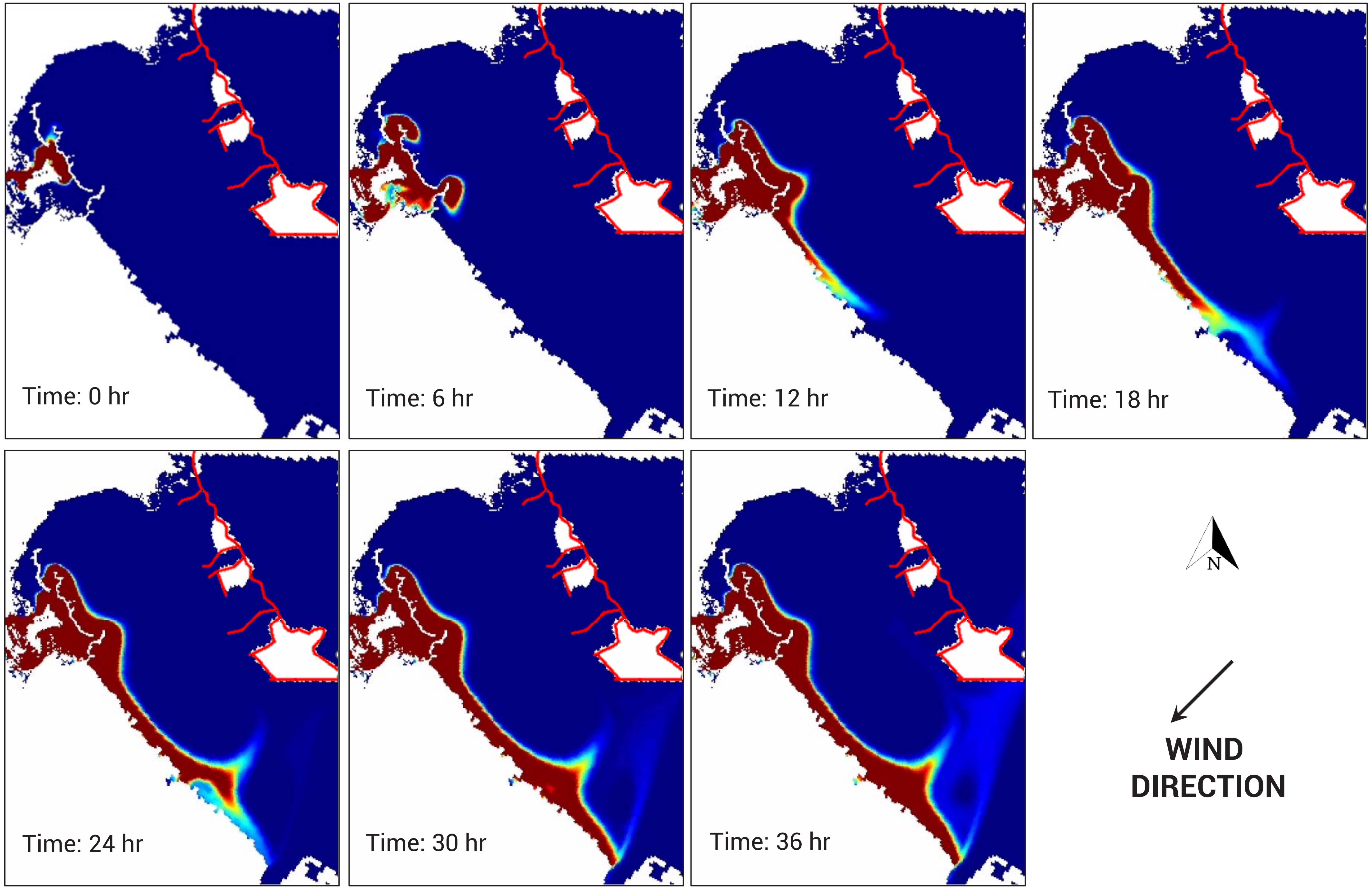
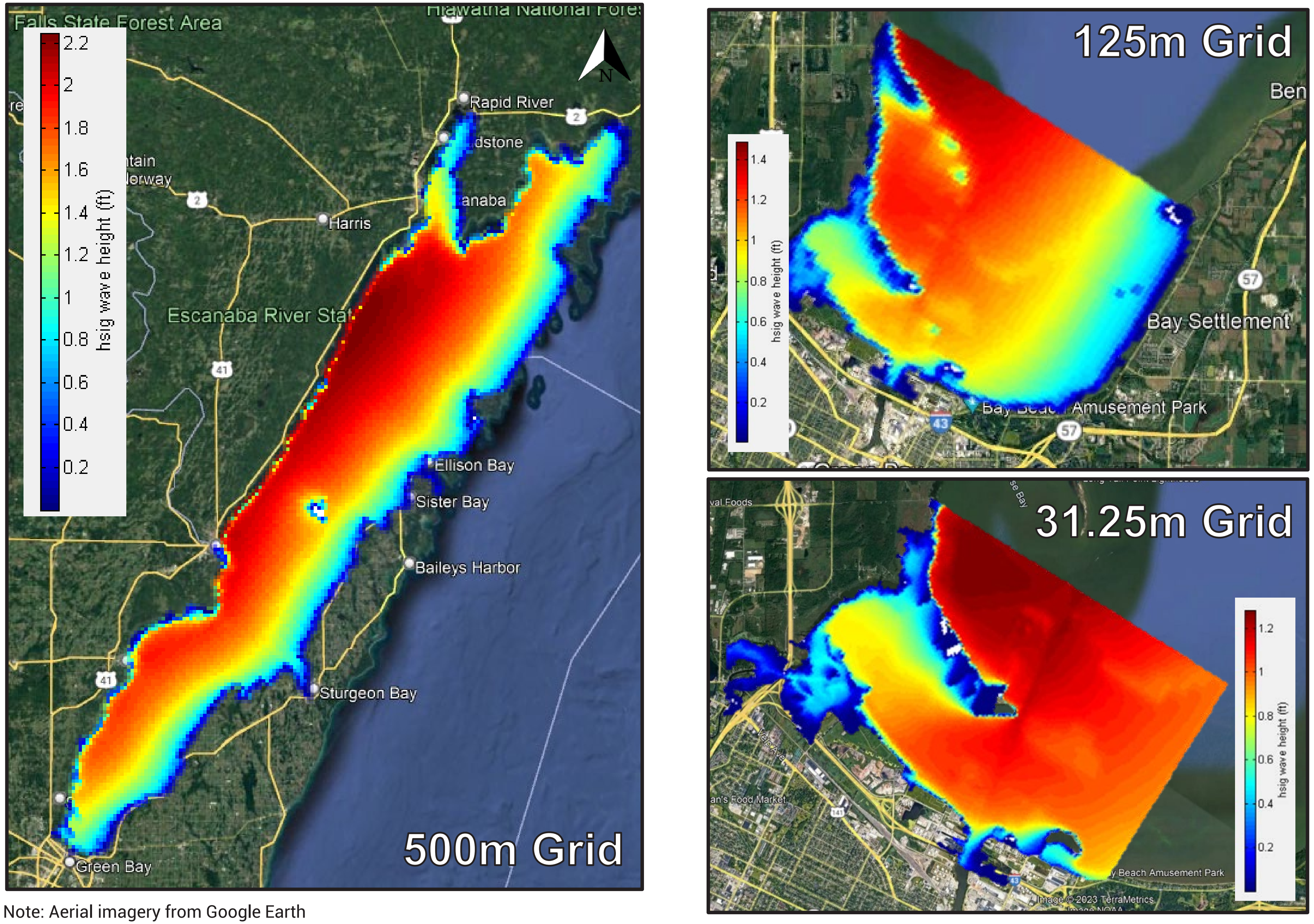


Figure 28
Duck Creek Tracer, 1-Year Northeast Wind, Mean Water Level



Note: Aerial imagery from Google Earth

Figure 29
Wave Height, 1-Year Southeast Wind, Ordinary High Water Mark

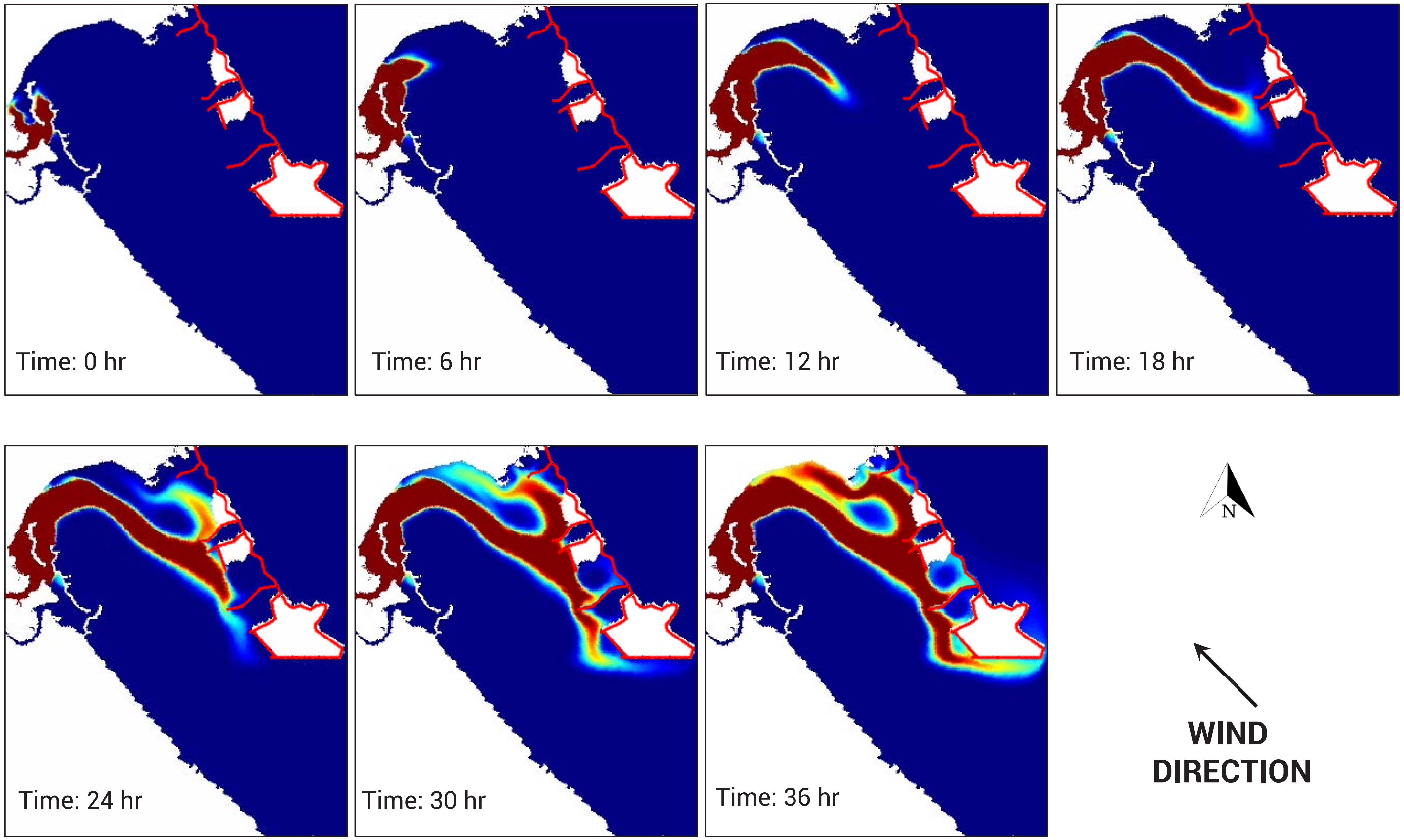


Figure 30
Duck Creek Tracer, 1-Year Southeast Wind, Mean Water Level

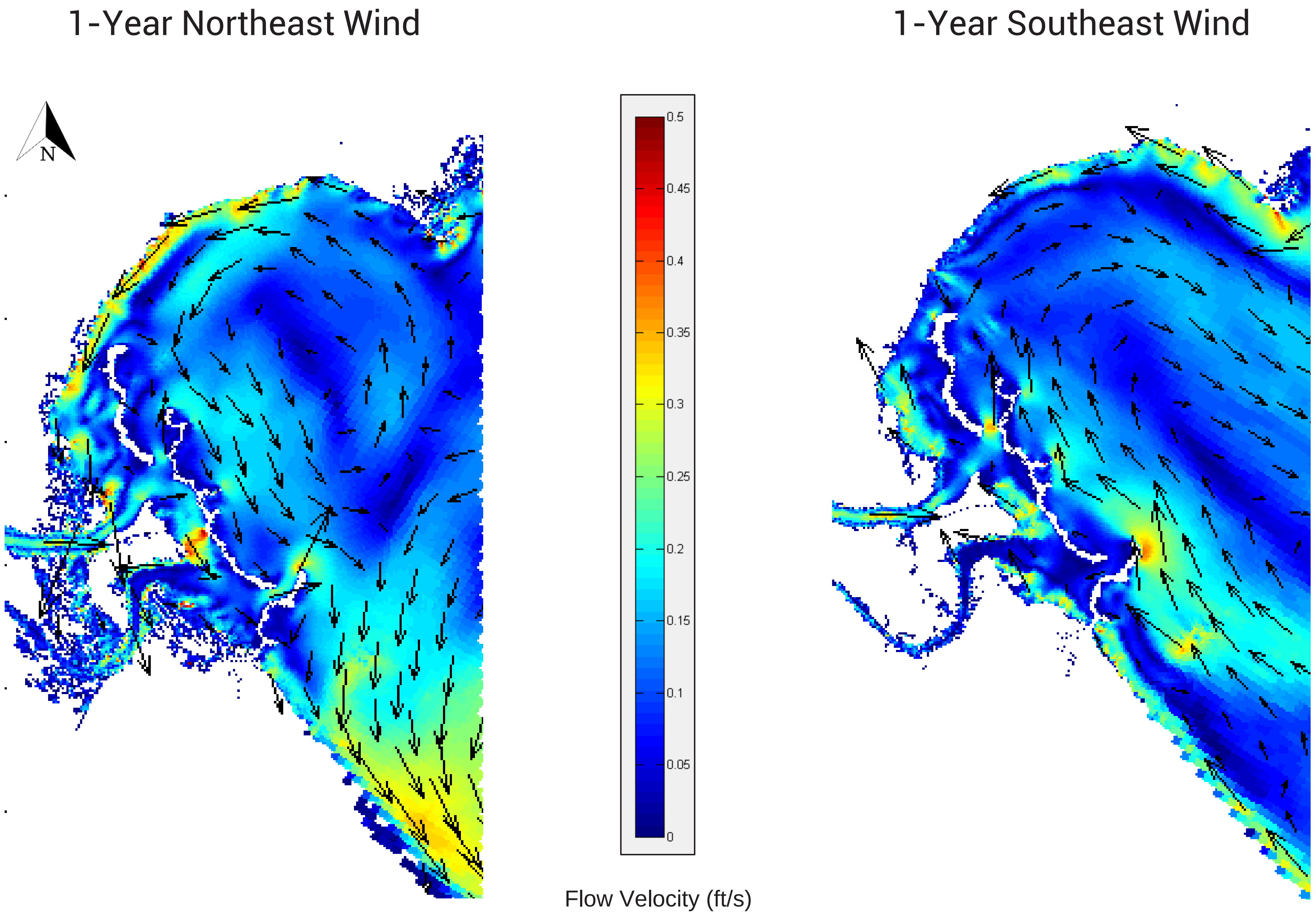


Figure 31
Lower Green Bay Velocity