Monhegan Breakwater Resiliency Study Technical Report

Monhegan Island, Maine

Submitted to:
Carley Feibusch – Municipal Administrator
Monhegan Plantation
P.O. Box 322
Monhegan, ME 04852

Submitted by:
GEI Consultants, Inc.
5 Milk Street
Portland, ME 04101
207.797.8901

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Project No. 2505689

Lisa Vickers
Project Manager / Senior Coastal Professional

Rooni Mathew, PhD, P.E.
Senior Professional

Table of Contents

List of Tables

List of Figures

Appendices

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B:\Working\MONHEGAN PLANTATION\2505689 Monhegan Breakwater\35 REPORTS\2505689_GEI_Monhegan Breakwater Study Report_FINAL_2026-05-11.docxAcronyms and Abbreviations

Acronyms and Abbreviations

BFE	Base Flood Elevation
DEM	Digital Elevation Model
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
GEI	GEI Consultants, Inc.
HAsT	Highest Astronomical Tide
LUPC	Land Use Planning Commission
MEMA	Maine Emergency Management Agency
MGS	Maine Geological Survey
MHHW	Mean Higher High Water
MHW	Mean High Water
MLLW	Mean Lower Low Water
MLW	Mean Low Water
NAVD88	North American Vertical Datum of 1988
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
SWEL	Stillwater elevation
USACE	United States Army Corps of Engineers

Executive Summary

Monhegan Plantation retained GEI Consultants, Inc. (GEI) to complete a resiliency study evaluating the performance of the existing Monhegan Harbor breakwater and to investigate conceptual alternatives to improve wave protection and long-term harbor resilience. The study was initiated in response to increasing coastal storm impacts, including damage sustained during the January 2024 storms, and to support future planning, funding, permitting, and design efforts for the harbor's critical infrastructure.

Monhegan Island is a remote year-round island community located approximately 10 miles offshore of Port Clyde, Maine. The harbor serves as a critical transportation, fishing, tourism, and public safety asset for the island. The existing breakwater, originally constructed in the 1930s and repaired multiple times over its service life, has experienced progressive degradation from repeated storm exposure. Most recently, the January 2024 coastal storms caused substantial damage to the structure, resulting in Federal Emergency Management Agency (FEMA) disaster assistance funding for repairs and potential mitigation improvements.

The primary objectives of this study were to:

- Evaluate the wave attenuation performance of the existing breakwater.
- Assess storm-driven wave conditions within the harbor.
- Develop and compare conceptual breakwater alternatives.
- Provide preliminary regulatory and implementation guidance to support future project phases.

The study incorporated coastal data review, topographic and bathymetric analysis, storm characterization, numerical wave modeling, conceptual engineering design, cost estimating, and regulatory review. Existing conditions were evaluated using National Oceanic and Atmospheric Administration (NOAA), FEMA, Maine Geological Survey (MGS), and recent site survey datasets. Wave modeling was completed using the US Army Corps of Engineers (USACE)-developed BOUSS-2D numerical wave model to simulate storm wave propagation and breakwater performance under extreme coastal storm conditions.

Model simulations evaluated existing conditions as well as multiple conceptual alternatives intended to improve wave protection within three priority harbor areas:

- Beach access.
- Wharf access.
- The inner and outer harbor basin.

The modeling analysis confirmed that the existing breakwater currently provides meaningful wave attenuation within the harbor but that its degraded condition and limited crest elevation reduce its effectiveness during major storm events. Simulations also demonstrated that alternative breakwater configurations could substantially improve wave protection within the harbor, particularly during extreme storm conditions comparable to Hurricane Irene and the January 2024 storms.

Two primary categories of conceptual alternatives were evaluated:

- Alternative 1: Reconstruction and enhancement of the existing breakwater within its current footprint; and
- Alternative 2: Construction of a new or relocated breakwater system at alternative harbor locations.

Alternative 1 would improve the structural integrity and performance of the existing breakwater while minimizing expansion into surrounding waters and likely reducing regulatory complexity. Alternative 2 concepts generally provided greater wave attenuation benefits and broader harbor protection but would involve substantially greater construction complexity, cost, and permitting considerations.

Concept-level rubble mound breakwater sections and preliminary cost estimates were developed to support future planning and funding discussions. Regulatory review identified that future implementation would likely require coordination and permitting through the USACE, Maine Land Use Planning Commission (LUPC), and Maine Bureau of Parks and Lands, Submerged Lands Program.

This study represents a feasibility- and planning-level evaluation intended to guide future decision-making. Additional efforts will be necessary prior to construction includes, in part, the advancement of a preferred alternative through preliminary and final engineering design, environmental permitting and agency coordination; and identification and securing of construction funding sources.

Overall, the study concludes that resiliency improvements to Monhegan Harbor's breakwater system are both feasible and necessary to improve harbor protection, reduce future storm damage risk, and support the long-term sustainability of Monhegan Island's working waterfront and transportation infrastructure.

1. Introduction

1.1. Project Background

GEI Consultants, Inc. was retained by Monhegan Plantation (Monhegan) to support the advancement of resiliency improvements for the existing breakwater at Monhegan Island. GEI has previously developed several resiliency studies and preliminary engineering design plans for Monhegan, including a resiliency study of the Plantation's wharf and its ongoing preliminary design, and a resiliency study of the island's Main Street corridor and breakwater.

Monhegan Plantation is a year-round island community in the Gulf of Maine located approximately ten miles from the mainland village of Port Clyde. The Plantation was established in 1839 and consists of Monhegan Island and Manana Island. Monhegan Island is approximately 513 acres, 350 of which are under conservation and management by Monhegan Associates, Inc.

The island has a year-round population of 64 according to the 2020 census, and a seasonal residential population of approximately 250. Tourism is prominent between spring and fall, with the Plantation's bird migrations, artistic culture, and natural beauty attracting visitors. The local economy is primarily supported by tourism, lobster fishing, and artist activities.

1.2. Breakwater History

Monhegan Island's inner/northern harbor is formed by Manana Island to the west, Smutty Nose Rock to the north, and a breakwater that extends westward from Monhegan Island to the south (Figure 1-1). The community has estimated that the breakwater has existed since the 1930s and has been repaired several times to restore its original configuration. It was comprehensively repaired in 1993 by resetting dislodged stone material and placing new granite block armoring stones on top of the entire breakwater. This effort was supported by federal Community Development Block Grant (CDBG) funds.

The breakwater was repaired in 2015 after being damaged by tropical storm Irene in August 2011, with funding support administered by the Maine Emergency Management Agency (MEMA). Washed out stone material was reset at the shoreward terminus of the structure, and granite block armoring was placed over the entire structure.

The breakwater sustained further damage from the 2024 January coastal storms which included record storm surge levels and devastating wave action. Monhegan declared disaster damage to the breakwater following these storms and was awarded $741,188.00 from FEMA to repair the breakwater to pre-disaster conditions. It is our understanding that Monhegan may also receive an additional $741,188.00 for mitigation measures at the breakwater such as extending or raising the breakwater or alternatively, relocating the breakwater within the harbor to provide greater protection.

This current study was supported by the Community Resilience Partnership Community Action Grant program funded through the State of Maine Governor's Office of Policy Innovation and the Future (GOPIF).

Figure 1-1. Aerial image of Monhegan Harbor Looking North.

Source: GEI Drone Imagery (8/13/2025)

1.3. Project Goals and Scope Overview

The primary goals of this study were to develop an understanding of the wave protection functionality of the existing breakwater and investigate potential alternative breakwater concepts that would further improve wave protection within the harbor region. For the purpose of this study, three target study areas were identified for improved wave protection – these areas are shown in Figure 1-2 and are listed below in order of priority for wave protection improvement:

1. Area 1: Beach access
2. Area 2: Wharf access
3. Area 3: Inner (northern) and outer (southern) harbor

Figure 1-2. Aerial Image of Monhegan Harbor Looking North, with the Three Areas Targeted for Study of Improved Wave Protection.

Source: GEI Drone Imagery (8/13/2025)

Findings from this study are intended to support further planning and design efforts for either enhancement or replacement of the existing breakwater. GEI has performed this study following the Scope of Work defined in the September 19^{th}, 2025 proposal (GEI, 2025), which included tasks for Coastal Wave Modeling, Conceptual Design Development, and Regulatory Review. This report summarizes the work performed and associated findings.

2. Site Conditions

To support the understanding of site conditions, wave modeling effort, and development of alternative breakwater concepts, various coastal data were reviewed and compiled for the study. Data compilation and synthesis included water levels, topographic and bathymetric elevation data, and storm simulation parameters, which are further described in the following sections.

2.1. Tidal and Flood Elevations

Tidal and flood elevations for Monhegan Harbor are summarized in Table 2-1 referenced to North American Vertical Datum of 1988 (NAVD88) and Mean Lower Low Water (MLLW) or Chart datum. Tidal elevations were determined using the NOAA Vertical Datum Translator Tool (NOAA, 2025b). The highest astronomical tide (HAsT) for the harbor was obtained from the, Maine Geological Survey (MGS) published values for Monhegan Island (MGS, 2025.

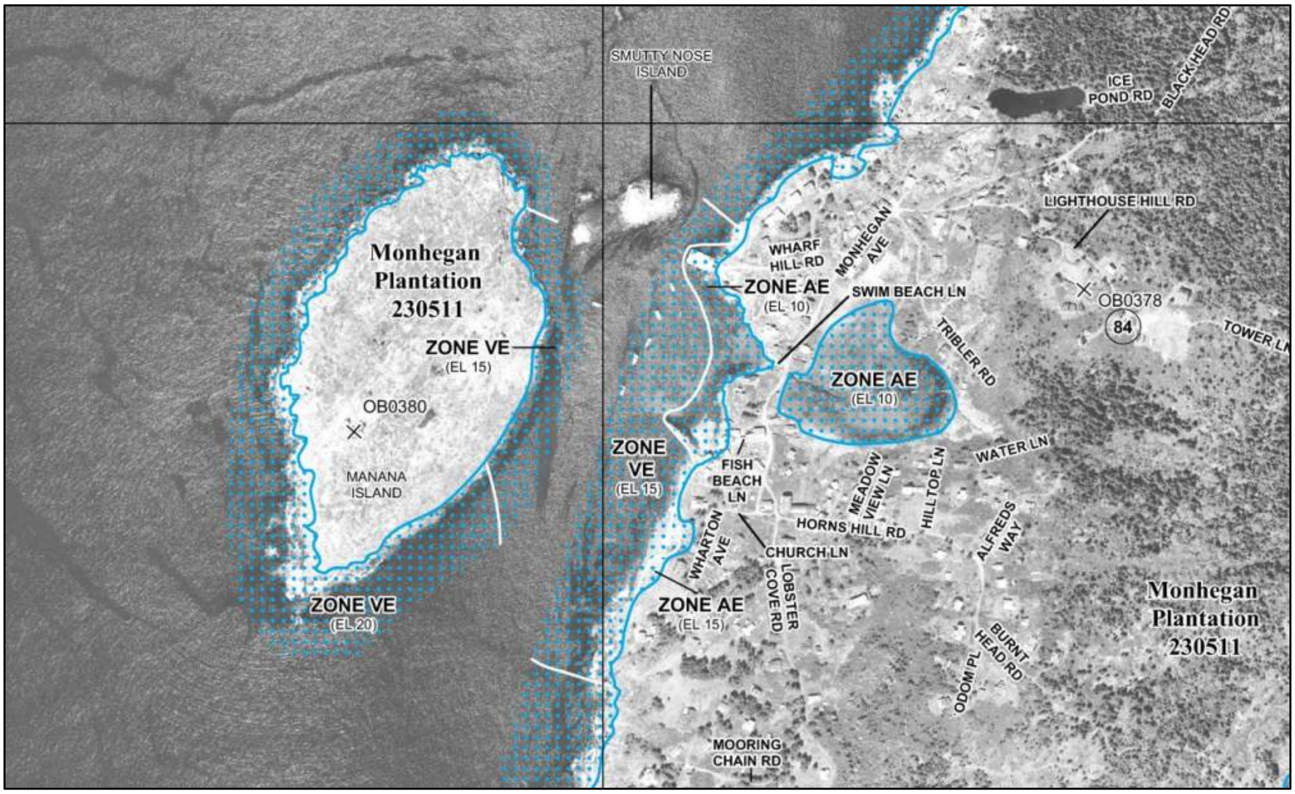
Predicted flood elevations were identified from FEMA's Flood Insurance Rate Map (FIRM) and Flood Insurance Study (FIS) for Lincoln County, effective July 16, 2015 (FEMA, 2015a; FEMA 2015b). A section of the relevant FIRM at Monhegan Island is shown in Figure 2-1. The FEMA Base Flood Elevation (BFE) is the water elevation predicted to have a 1% chance of being equaled or exceeded in any given year (i.e., 100-year event), including storm surge and wave action. The designation as an AE zone indicates a high-risk flood zone with a 1% annual chance of flooding in a given year. The designation as a VE Zone indicates a high-risk zone for coastal areas with a 1% annual chance of flooding in a given year and subject to wave action and high velocities. In VE zones, wave heights are predicted to be greater than 3 feet. The elevations published by FEMA are based on modeling that considers historic data but do not account for future changes due to sea level rise.

Table 2-1. Tidal and Flood Elevations

Water Elevation	Feet NAVD88[1]	Feet MLLW (Chart)	Data Source
BFE VE Zone (Harbor Entrance)	20.0	25.1	FEMA FIRM 23015C0514D, effective July 16, 2015
BFE VE Zone (Inner Harbor)	15.0	20.1	
BFE AE Zone (Wharf and Beaches)	10.0	15.1	
Highest Astronomical Tide	6.5	11.6	MGS HAsT line 2026, Monhegan Island
MHHW	4.6	9.7	NOAA VDatum
MHW	4.2	9.3	
NAVD88	0.0	5.1	
MSL	-0.3	4.9	
MLW	-4.8	0.3	
MLLW	-5.1	0.0	

Notes:
1. All elevations in this report reference vertical datum NAVD88 unless otherwise noted.
2. Water elevations are rounded to the nearest 1/10.

Figure 2-1. Section of FIRM at Monhegan Island.



Notes:

1. Ref: FIRM 23015C0514D for Lincoln County, Maine.

2.2. Topographic and Bathymetric Data

Topographic and bathymetric survey data were compiled for the breakwater location as well as the overall harbor and surrounding island region. Data were obtained from both public sources and previous site-specific survey collection efforts, including:

1. National Oceanic and Atmospheric Administration (NOAA) Continuously Updated Digital Elevation Model (CUDEM) - 1/9 Arc-Second Resolution Topo-Bathymetric-Topographic Tiles (CIRES, 2014)
2. 2022-2023 NOAA National Geodetic Survey (NGS) Topobathy Lidar DEM: Coastal Maine (NGS, 2026)
3. January 2025 Little River Land Surveying, Inc. at the existing breakwater (Little River Land Surveying, Inc. 2025)

The elevation data were used to develop the topo-bathy surface for the numerical modeling grid and conceptual drawings. The surface was developed by combining the three surveys, prioritizing the most recent and highest resolution coverages. As a result, the combined surface utilizes the Little River Land Surveying, Inc. (2025) survey for coverage at the location of the existing breakwater, the NGS (2026) 2022-2023 survey for coverage within the remaining harbor and shoreline/land areas, and the CIRES (2014) survey for bathymetric coverage outside the harbor and offshore of the island. Refer to Appendix A and B for modeling figures and drawings utilizing the combined elevation surface.

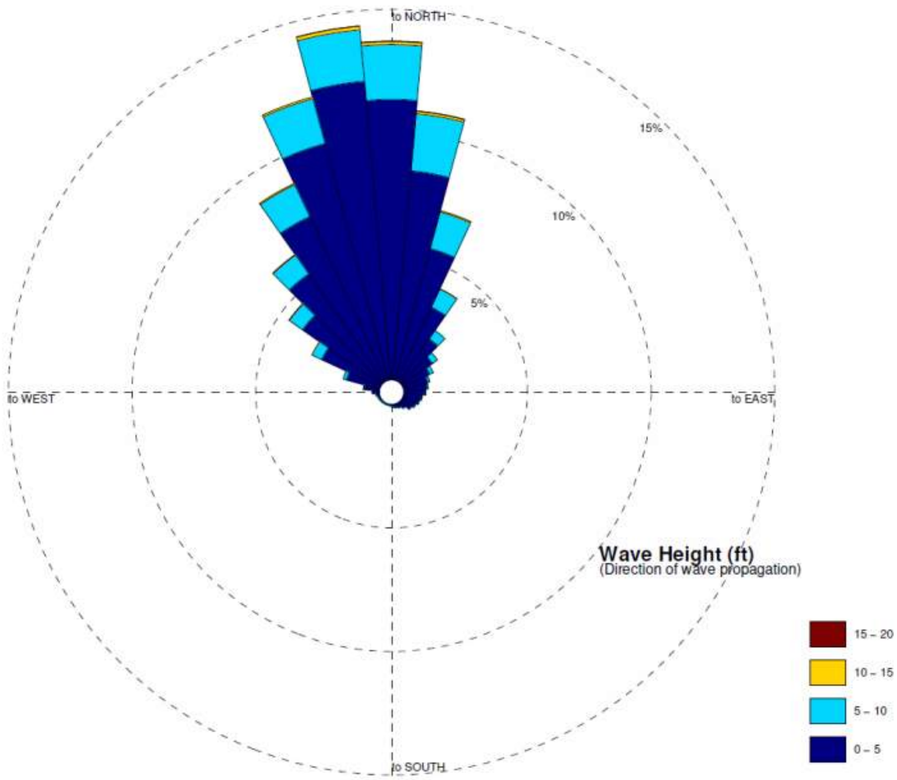
2.3. Storm Scenario Parameters

The numerical modeling task (described later in this report) simulates a specific storm scenario in order to evaluate the resulting wave conditions within the harbor. Various extremal conditions (i.e., storm water level and wave heights) were investigated, including the theoretical 100- and 500-yr events, as well as the historical 2011 tropical storm Irene event.

Figure 2-2. Location used to query wave and water level data from NOAA (2025).

Extremal water level and wave heights were investigated approximately 0.5 mile offshore of the southern entrance to the harbor (Figure 2-2) using information from the National Oceanic and Atmospheric Administration (NOAA). The information from NOAA consists of a long-term (1979-2022) hourly dataset of water levels and waves in the vicinity of the project site (NOAA, 2025a). Figure 2-3 shows the resulting wave rose of wave heights and periods at this location. As expected given the long wave fetch south of Monhegan Island, the wave climate is dominated by waves generally coming from the south and headed in the northern direction, with occasional wave heights up to nearly 20 ft.

Figure 2-3. Wave rose at a location 0.5 mile south of the existing harbor. Data from NOAA (2025).



The wave data were also processed to assess extreme event conditions. Figure 2-3 shows the results of an extreme value analysis for wave heights using a peak-over-threshold method (using a threshold of 3 m or 9.84 ft). The estimated 100-year and 500-year return period wave heights are 17.46 ft and 19.06 ft, respectively. As seen in Figure 2-4, maximum wave height during Hurricane Irene in 2011 exceeded the estimated 500-year wave height. Since the 2011 Irene storm is a historical event and was observed to cause significant damage to the existing breakwater, this was selected as the input storm scenario for all modeling simulations.

Figure 2-4. Extreme value analysis for wave height.

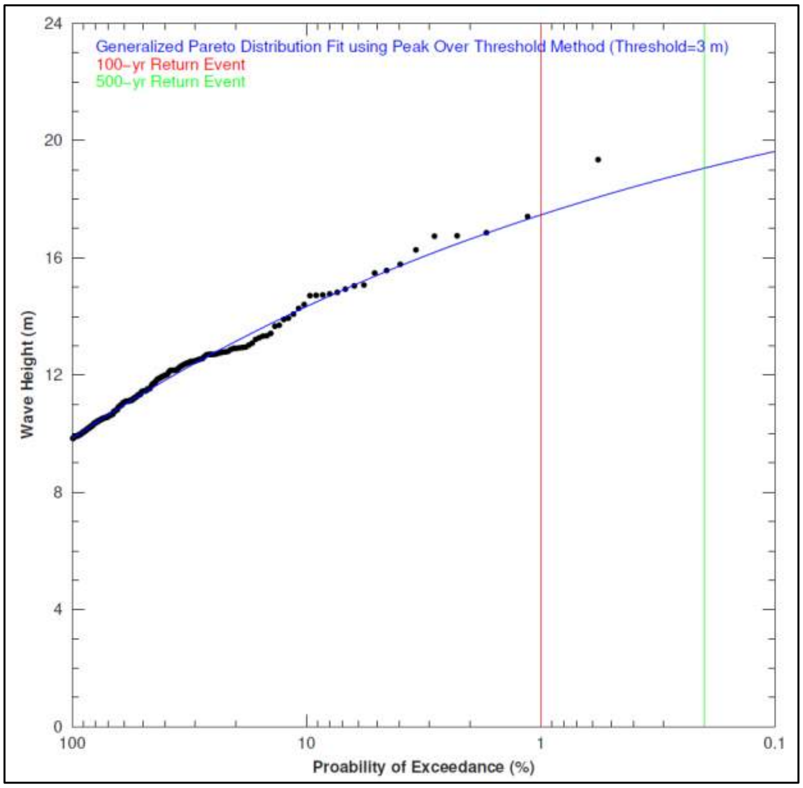
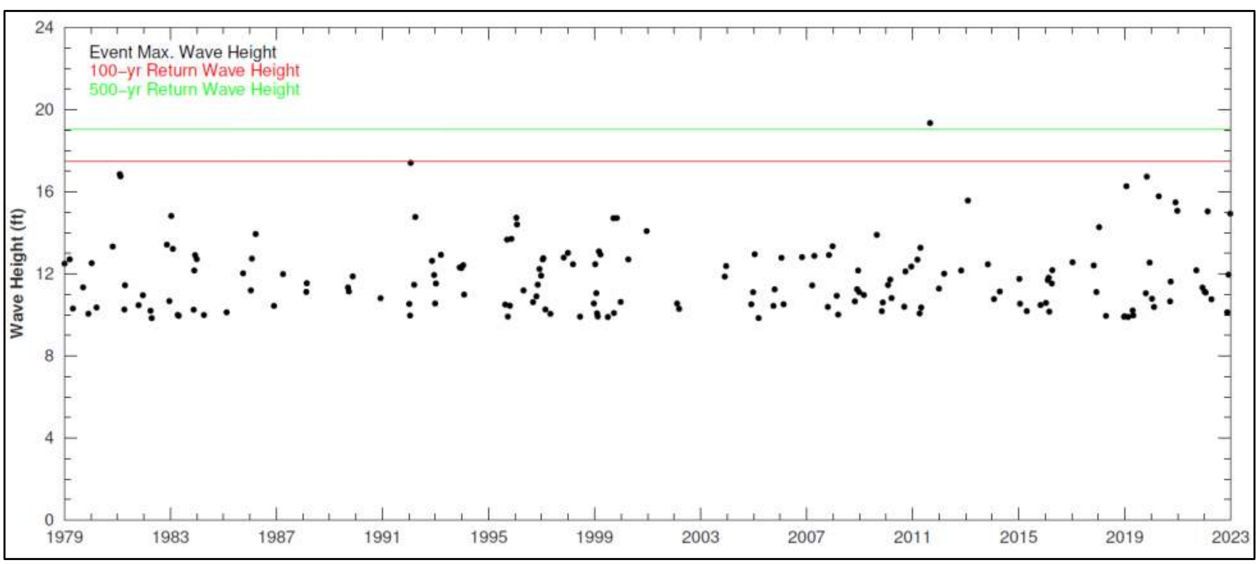


Figure 2-5. Time-series of individual wave events used in extreme value analysis.



Thus, the associated offshore input parameters used in the model simulations included the following:

- Significant wave height (H_s): 19.4 feet
- Wave period (T): 11.4 seconds
- Still water elevation (SWEL): 6.3 feet NAVD88

3. Wave Modeling

This study utilized the BOUSS-2D Boussinesq numerical wave model to simulate the propagation and transformation of coastal waves within the project area for the existing and alternative breakwater simulations. The following sections further describe the model development, alternative breakwater simulations, and results. GEI also provided a progress meeting presentation to Monhegan on March 6th, 2026, to review the model development, alternative breakwater simulations, and the preliminary results. These presentation slides have been updated with the final modeling results and are included in Appendix A.

3.1. Model Overview & Approach

The BOUSS-2D model was developed by the United States Army Corps of Engineers and is a standard tool used for alternatives analysis and detailed design of wave protection measures such as breakwaters. BOUSS-2D is a nonlinear, dispersive, Boussinesq-type numerical wave model that simulates time-domain wave propagation and transformation from offshore into the nearshore environment, including the project site. The model resolves the evolution of individual wave phases and explicitly accounts for key physical processes such as wave shoaling, refraction, diffraction, reflection, nonlinear wave–wave interactions, and depth-induced breaking (Nwogu and Demirbilek, 2001).

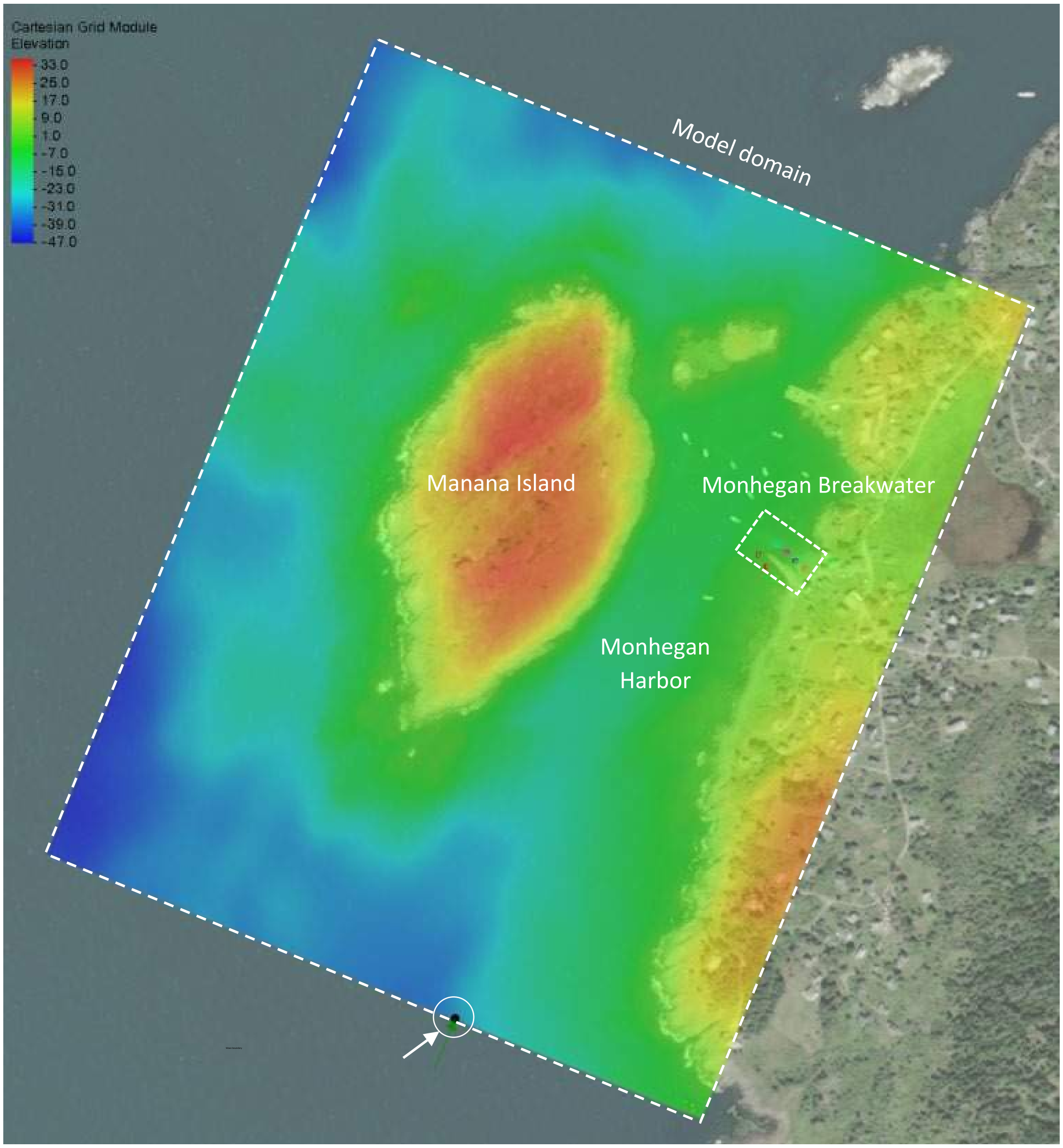
As a phase-resolved wave model, BOUSS-2D is particularly well suited for evaluating wave conditions in the vicinity of the Monhegan Breakwater, where complex wave–structure interactions dominate the local wave field. In this setting, wave reflection and diffraction significantly occur over spatial scales comparable to, or smaller than, the representative wavelength. BOUSS-2D's solution of the fully nonlinear Boussinesq equations enables accurate resolution of these rapid, sub-wavelength spatial variations in free-surface elevation and velocity that cannot be represented by phase-averaged spectral wave models.

3.1.1. Computational Domain and Grid

3.1.1.1. <u>Model Domain</u>

The model domain was defined with the southwestern edge at the location used for the wave-extremes analysis described in Section 2.3, which serves as the offshore wave-forcing boundary for the simulations. The remaining domain extents were selected to encompass sufficient offshore and nearshore areas to allow waves to fully develop and propagate through Monhegan Harbor and around Manana Island. The selected domain configuration ensures that wave transformation processes affecting the breakwater— including refraction, diffraction, and reflection—are resolved appropriately. In addition, the computational domain fully captures the harbor basin and breakwater features necessary for accurate numerical wave model simulations.

Figure 3-1. Model Domain.



3.1.1.2. Computational Grid Generation

The BOUSS-2D model employs a structured Cartesian computational grid and solves the governing nonlinear Boussinesq equations using an explicit finite-difference scheme. This structured finite-difference grid framework provides numerical efficiency and stability while enabling accurate, phase-resolved simulation of wave propagation, reflection, and diffraction processes in the nearshore and around coastal structures. In the present model, uniform 5-m by 5-m grid cells were used for the computational mesh.

The orientation of the BOUSS2D computational gird was selected based on the general direction of the incident waves of the offshore sea state.

The combined topography and bathymetry surface was used to define cell elevations for the BOUSS-2D computational grid, after which Cartesian grid smoothing was applied to enhance numerical stability and reduce spurious wave reflections associated with abrupt cell-to-cell depth changes. Global smoothing was performed using a 3 × 3 filter window, a maximum allowable elevation change of 0.5 m per smoothing pass, and a filter ratio of 0.25. This configuration provides moderate, localized smoothing by limiting elevation adjustments and preserving the majority of the original bathymetric signal, while effectively removing small-scale roughness that could adversely affect the finite-difference solution of the Boussinesq equations.

3.1.2. Wave Generation and Boundary Conditions

3.1.2.1. <u>Wave Generation</u>

Boundary conditions were used to define waves propagating from the open ocean into the project area via the southern end of the model domain. The boundary conditions provide the forcing necessary to model wave propagation, transformation, and interaction with coastal features within the model domain. The boundary conditions were developed using NOAA tabulations at a location approximately 0.5 mile south of the existing breakwater as described in Section 2.3.

In the present analysis, irregular unidirectional waves were selected for wave generation in the BOUSS-2D model as they provide a realistic representation of offshore sea-state variability while maintaining a single dominant wave approach direction toward the harbor. This configuration allows wave energy to propagate efficiently into Monhegan Harbor and toward the breakwater without dilution due to directional spreading. Compared to regular waves, irregular unidirectional conditions better capture temporal variability in wave heights and periods, and produce more conservative, near-structure wave conditions by concentrating wave energy in the primary direction of interest. This approach maximizes wave exposure at the breakwater and is therefore appropriate for evaluating worst-case wave transformation and wave–structure interaction.

In BOUSS-2D, the wave generator creates a time-varying water surface based on a chosen wave spectrum. When Synthesize is selected, the model generates this signal internally using random phases (controlled by a seed) over a specified duration to produce stable and repeatable wave conditions.

For the present analysis, incident waves were generated using a synthesized irregular unidirectional JONSWAP (<u>Jo</u>int <u>N</u>orth <u>S</u>ea <u>Wa</u>ve <u>P</u>roject) spectrum, with the significant wave height and peak wave period listed in Table 3-1. The JONSWAP spectrum was selected to represent fetch-limited, wind-generated storm seas with enhanced peak spectral energy characteristic of energetic offshore conditions influencing the Monhegan Breakwater; the peak enhancement factor (γ) concentrates energy at the dominant period, minimum and maximum wave periods constrain the spectrum to physically and numerically relevant frequencies, and the spectrum was rescaled to ensure the synthesized time series reproduces the specified significant wave height and peak period. These parameters are defined based on the JONSWAP spectrum definitions in BOUSS-2D.

Table 3-1. Wave Spectral Parameters

Parameter	Value
Significant wave height (ft [m])	19.3 [5.9]
Peak wave period (s)	11.3
Peak enhancement factor (γ)	3.3
Minimum wave period (T_{min})	7.22
Maximum wave period (T_{max})	25.0

3.1.2.2. Water Levels

Based on the wave extremes analysis, the 2011 coastal storm Hurricane Irene, which caused significant damage to Monhegan Island, was selected to represent a historic design event for the Monhegan Breakwater. According to NOAA (2025), the estimated still water level near Monhegan Island (Figure 2-2) during Hurricane Irene was 6.3 ft NAVD88. In contrast, the U.S. Army Corps of Engineers' Coastal Hazard System – North Atlantic Comprehensive Coastal Study (CHS-NACCS) estimates still water level associated with a 500year return period coastal storm in this vicinity of 8.0 ft NAVD88, approximately 1.7 ft higher than that observed during Hurricane Irene (USACE, 2015).

Still water level reflects the combined effects of astronomical tide, storm surge, and wave setup. The CHSNACCS still water elevations are derived from a statistical analysis of extreme water levels generated using coupled ADCIRC/STWAVE simulations of 1,050 synthetic hurricanes, spanning a wide range of storm intensities and tracks. For the present study, two modeling scenarios were therefore implemented in BOUSS2D: (1) a historic event corresponding to the observed Hurricane Irene water level, and (2) a hypothetical design event corresponding to the CHS-NACCS 500year storm still water level at ADCIRC Save Point 6807. The inclusion of the 500year still water level provides an appropriate basis for a design level evaluation of the Monhegan Breakwater and establishes a conservative modeling condition, as the increased water depth allows larger waves to reach the breakwater with reduced depth induced breaking, resulting in higher potential wave loading.

Figure 3-2. CHS-NACCS ADCIRC Save point near Monhegan Island.

Water levels for the modeled storm scenarios were applied in BOUSS-2D using the tidal offset option, which adjusts the still water level relative to the bathymetry. A value of 1.92 m (6.3 ft) was used for the Hurricane Irene scenario (extracted from NOAA CORA analysis), and 2.44 m (8.0 ft) was used for the 500-year design scenario (extracted from CHS-NACSS). These offsets were applied uniformly across the model domain to set the initial still water level for wave generation and propagation.

3.1.3. Representation of Existing Breakwater

Topographic and bathymetric elevations from the 2025 site survey were used to define the geometry and extent of the existing Monhegan Island breakwater. The survey indicates significant structural degradation, including undermining of the breakwater crest and substantial loss of the stem cross-section, with damage more severe along the stem (i.e., the section of breakwater extending beyond the shoreline) than at the breakwater root (i.e., the shoreward portion of the breakwater). To represent these spatial variations in structural condition within the BOUSS-2D model, the breakwater geometry was idealized using piecewise linear segments along its longitudinal profile, with segment-specific widths and porosity values assigned to characterize the distinct stem and root sections of the structure.

Based on established engineering practice and published guidance on rubble-mound breakwater behavior, an effective porosity of 0.5 was assigned to represent the existing breakwater condition, reflecting long-term stone displacement, settlement, and loss of fines that increase internal void space.

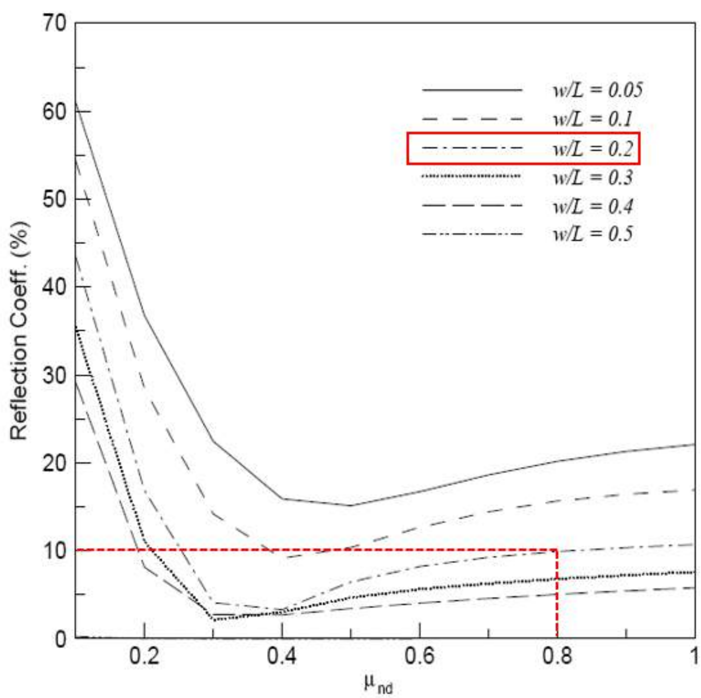
Table 3-2. Characteristics of Existing Breakwater

Parameter	Breakwater root	Breakwater stem
Width (ft [m])	39.4 [12]	19.7 [6]
Porosity	0.5	0.5

3.1.4. Damping Regions and Sponge Layer Treatment

Damping layers were applied along the open and land boundaries of the BOUSS-2D model domain to minimize artificial wave reflection and ensure numerical stability. Based on guidance provided in the XMS Wiki for BOUSS-2D damping layers, a damping coefficient of 0.8 was selected, corresponding to an anticipated wave reflection of approximately 10%. A damping layer width of 40 m was used, and the deepwater wavelength associated with the design wave conditions (H_s = 5.9 m, T = 11.4 s) was calculated as 202.9 m, resulting in a normalized width ratio (w/L) of 0.2. For this ratio, the BOUSS-2D reflection curves indicate that a damping coefficient of 0.8 produces reflection levels within a reasonable and acceptable range. The selected damping parameters therefore provide effective absorption of outgoing wave energy without excessive computational cost or adverse influence on near-breakwater wave conditions.

Figure 3-3. Percentage of Wave Reflection vs. Damping Coefficient.



3.1.5. Physical / Numerical Model Control Parameters

3.1.5.1. Bed Roughness

Review of historic and contemporary aerial photography, together with published geologic and seafloor mapping studies, indicates that the nearshore areas surrounding Monhegan Island and Manana Island are dominated by exposed igneous bedrock (primarily gabbro) with localized boulder and cobble lag deposits, and only minimal accumulations of mobile sand or gravel. Monhegan and Manana Islands consist almost entirely of resistant gabbroic bedrock, producing steep, rocky shorelines and submerged rock platforms that are clearly visible in both historic and recent imagery. Regional multibeam and sediment mapping conducted under the Maine Coastal Mapping Initiative further indicates that the inner continental shelf and nearshore areas in the vicinity of Monhegan Island are characterized by rock, boulder, and coarse gravel substrates, with fine-grained sediments largely absent due to persistent high-energy wave conditions that winnow out sand and mud. The absence of continuous beaches or sand bodies in aerial photographs, coupled with widespread wave breaking directly against rock outcrops, confirms that the Monhegan nearshore zone is a bedrock- and boulder-controlled coastal system, rather than a sediment-dominated environment (Marvinney, 2010).

Given these conditions, bottom friction in the BOUSS-2D model was represented using a constant Chézy coefficient (C) of 30 to characterize the high roughness associated with exposed bedrock and coarse rubble in the vicinity of the Monhegan Breakwater. The Chézy coefficient is related to Manning's roughness coefficient (n) through the hydraulic radius (R), commonly approximated by water depth in coastal applications, as $C=R^{1/6}/n$. For representative water depths in nearshore and harbor at Monhegan, a Chézy value of 30 corresponds approximately to a Manning's n in the range of 0.04–0.06, which is consistent with values typically used for rocky sea-beds, boulder fields, and rubble-mound. Accordingly, the selected Chézy coefficient of 30 provides a physically realistic and conservative representation of near-bed roughness for the Monhegan Breakwater BOUSS-2D simulations, ensuring appropriate dissipation of wave energy over the rough bed while remaining consistent with observed site conditions.

3.1.5.2. Turbulence

Subgrid-scale turbulence in BOUSS-2D is represented using a Smagorinsky-type eddy viscosity formulation, which provides supplemental dissipation of unresolved horizontal motions. In the Monhegan Breakwater simulations, a Smagorinsky coefficient of 0.2 was used. This value is appropriate given that wave energy dissipation is primarily governed by physically resolved processes, including depth-induced wave breaking, bottom friction over a rough bedrock seabed, and dissipation associated with porous breakwater transmission. The selected coefficient provides sufficient numerical stabilization without overstating turbulent dissipation, thereby preserving physically realistic and conservative wave transformation and wave-structure interaction results near the breakwater.

In addition, the turbulent length scale defines the characteristic size of unresolved horizontal eddies and is determined by the model based on the Cartesian grid resolution, typically as a function of the representative grid spacing. For this model, a turbulent length scale of 5.88 m was recommended, indicating that unresolved eddy motions are on the order of the grid size. Together, these parameter selections provide adequate stabilization of the numerical solution while maintaining physically realistic and conservative simulation of wave transformation processes in the vicinity of the Monhegan Breakwater.

3.1.5.3. Parameters of Wave Runup / Breaking and Nonlinear Processes

In the present analysis, wave runup was disabled, wave breaking was enabled, and the weak nonlinear option was selected. These model control settings are appropriate for the objectives and level of detail associated with the current phase of work, which is focused on feasibility-level evaluation of wave conditions and wave–structure interaction at the Monhegan Breakwater.

Wave runup was disabled because the study objective is to assess incident and transformed wave conditions in the vicinity of the breakwater, including reflection, diffraction, and near-structure wave heights, rather than detailed prediction of overland uprush or inundation on adjacent shorelines or structural crests. The runup module is typically employed for detailed assessments of coastal flooding, overtopping, or structural freeboard requirements, which are beyond the scope of the present feasibility analysis.

Wave breaking was enabled to explicitly represent depth-limited and structure-induced wave breaking, which constitutes a primary physical mechanism for wave energy dissipation in the Monhegan nearshore environment. Inclusion of breaking ensures that the dominant nonlinear dissipation processes associated with shoaling waves and interaction with rough bathymetry and the breakwater are realistically captured.

The weak nonlinear option was selected because wave energy dissipation in the present simulations is already adequately represented through a combination of wave breaking, bottom friction over a rough bedrock seabed, and interaction with a porous rubble-mound breakwater. For feasibility-level purposes, the weak nonlinear formulation provides a computationally efficient and numerically stable approach that is sufficient for estimating near-breakwater wave conditions, without introducing additional complexity associated with higher-order nonlinear wave–wave interactions.

It is noted that the present modeling represents a screening-level and feasibility assessment intended to characterize overall wave climate effects and relative performance of the existing and conceptual breakwater conditions. As the project advances toward a design-level or design-build study, more detailed physics may be required. In particular, future analyses may warrant activation of the wave runup module to evaluate crest freeboard, overtopping potential, and shoreline response, as well as use of the strong nonlinear option to fully resolve higher-order nonlinear wave processes under extreme storm conditions. Such enhancements would be appropriate once final geometry, crest elevations, and structural details are defined and design performance criteria are established.

Furthermore, the present BOUSS2D wave model is not calibrated with any observed data. GEI recommends performing a data collection to record water levels and wave characteristics at the project site for a time period that may likely include a coastal storm for model calibration as part of the model application to support design.

3.2. Breakwater Alternatives & Model Simulations

The BOUSS-2D model developed using the inputs described in the preceding section was then used to simulate the storm waves within the project area for both existing conditions and alternative breakwater concepts, with the purpose of understanding how the wave protection may be improved within the project site. Note that for the proposed breakwater alternatives, a porosity of 0.4 was adopted to represent tighter packing and controlled placement associated with new construction. These porosity values are consistent with typical ranges used in hydraulic modeling and were implemented in BOUSS-2D to represent wave transmission and energy dissipation characteristics of the existing and proposed breakwater configurations.

Alternative 1 concept includes limited mitigation improvements of the existing breakwater, whereas Alternative 2 is representative of a new or relocated breakwater concept. Considering how large the overall project area is, three sub-alternatives were developed as part of Alternative 2, each located in different positions within the harbor. Figure 3-4 shows the location of the breakwater alternatives modeled.

Figure 3-4. Breakwater Alternatives.

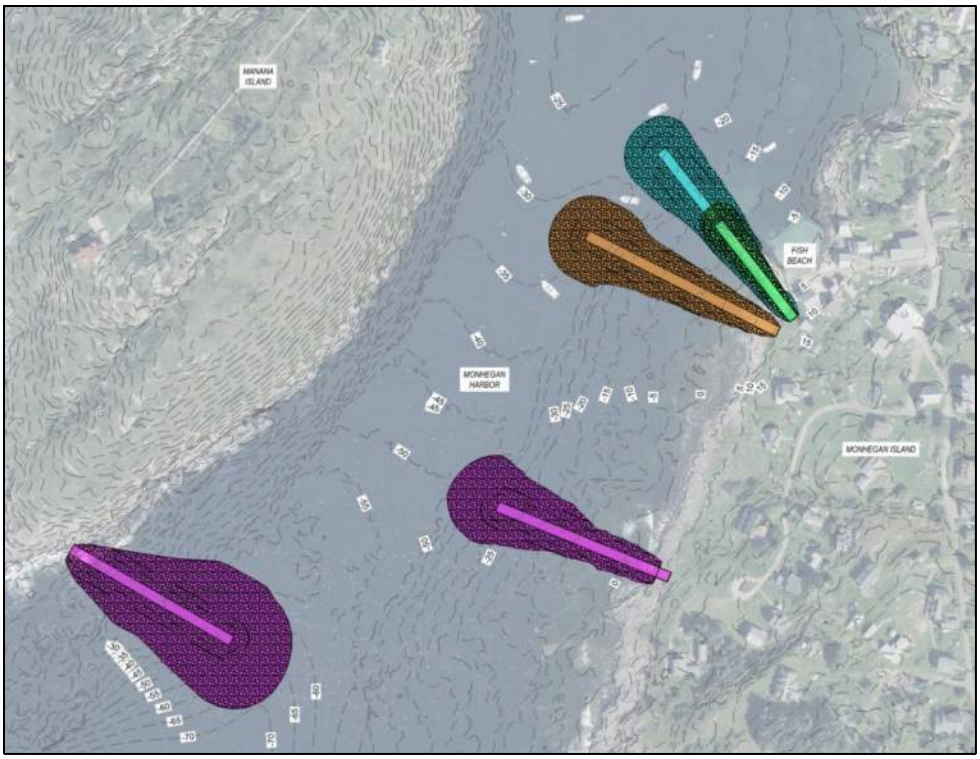


Table 3-3 provides a list of the resulting model simulations and associated alternative breakwater descriptions. For the alternative breakwater model simulations, the geometry was built into the elevation grid using concept-level assumptions for the breakwater cross sections. Figures of the modified grids for each alternative are available in the Appendix A slides as referenced in the table below.

Table 3-3. List of Model Simulations and Associated Alternative Breakwater Descriptions

Model Simulation	Alternative Name	Description of Concept	Breakwater Geometry Assumptions for Model Grid	Appendix A Reference Figure
1	Existing conditions	No changes to existing breakwater.	N/A (elevations based on survey)	Slide 5 (original elevation grid)

Model Simulation	Alternative Name	Description of Concept	Breakwater Geometry Assumptions for Model Grid	Appendix A Reference Figure
2	Alternative 1	Limited mitigation improvements (reconstruct existing breakwater following an engineered cross section design, while remaining within the existing footprint)	10 ft NAVD88 crest elevation 1:1.5 side slopes	Slide 10
3	Alternative 2A	New extended breakwater at existing location	15 ft NAVD88 crest elevation 1:1.5 side slopes	Slide 14
4	Alternative 2B	New relocated breakwater south of existing breakwater		Slide 17
5	Alternative 2C	New harbor entrance breakwater system, including two separate structures located at the southern entrance of the harbor		Slide 20

3.2.1. Additional Considerations for Shoreline Protection

While this study is intended to focus on improvements to the breakwater's functionality, it should be recognized that any type of breakwater enhancement will only afford wave protection in the lee side of the breakwater – any areas on the windward/wave-ward side will remain unprotected. Furthermore, it is understood that the section of shoreline just south of the existing breakwater has experienced erosion/scarping and is vulnerable to wave impacts. Thus, in addition to any type of breakwater enhancement that is selected for Monhegan Island, integration of additional protection at the shoreline adjacent to the breakwater is recommended for consideration (i.e., such as a rock revetment). A rough schematic of this concept, representing additional shoreline protection at the south side of Alternative 1 is available on Appendix A Slide 9. However, no additional shoreline protection is included in the model simulations for this study.

3.3. Model Results

Upon completion of each simulation, the BOUSS-2D model produces output datasets that contain spatially varying results across the model domain (grid). Model results are available for a range of parameters, such as mean wave (water) level, mean wave direction, significant wave height, mean velocity, as well as animations for wave (water) surface elevation and velocity magnitude. For simplicity of evaluating the relative comparison of results among the breakwater alternatives, discussion of the model results for this study focuses on the computed significant wave height (H_s) values. The significant wave height values are the average of the highest (largest) one-third of wave heights simulated over the duration of the model run. Statistically, approximately 15% of waves over the same duration could be equal or higher than this value. However, the significant wave height is often found to correlate well to visual estimates of wave height conditions in real world scenarios and is often used as design criteria in engineering projects, thus using this parameter is a reasonable approach to evaluating and comparing results among the alternatives.

Significant wave height results were evaluated and compared among the alternative simulations through visual inspection of the output H_s maps (i.e., H_s results across the whole model domain), as well as quantitative evaluation of resulting H_s values at representative "observation points" in the model domain. Refer to Appendix A for the graphical results of the wave model results. The observation points were located within each of the wave protection priority Areas – refer to Figure 3-5 for the location of each observation point. A summary of the qualitative and quantitative results is provided in Table 3-4 for wave results during the Hurricane Irene scenario.

Figure 3-5. Location of Area observation points within the model domain (displayed contours represent the existing conditions elevation surface).

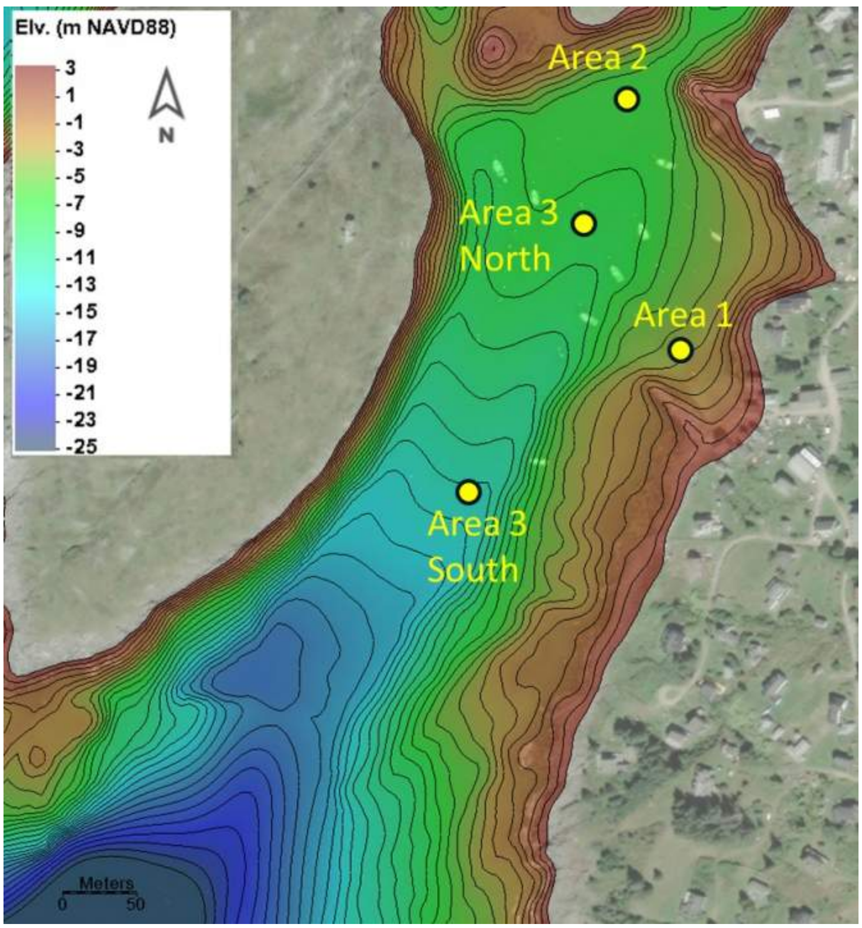


Table 3-4. Qualitative and Quantitative Summary of H_s Results by Priority Area and Breakwater Alternative

	Existing Conditions	Alternative 1 (Limited Mitigation Improvements)	Alternative 2A (New Extended Breakwater at Existing Location)	Alternative 2B (New Relocated Breakwater)	Alternative 2C (New Harbor Entrance Breakwater System)
Summary of Breakwater Functionality Based on Hs Results	Protection is mostly limited to Area 1	Improved protection is mostly limited to Area 1	Significant improved protection to Area 1 with additional improved protection to Areas 2 and 3 North	Significant improved protection for Areas 1, 2 and 3 North	Significant improved protection for all Areas
Appendix A Figure of Hs Grid Results	Slide 8	Slide 11	Slide 15	Slide 18	Slide 21
Appendix A Figure of Hs Grid Results Compared to Existing Conditions	N/A	Slide 12	Slide 16	Slide 19	Slide 22
H_s (ft) at Representative Observation Points					
Area 1	0.2	0.1	<0.1	<0.1	<0.1
Area 2	1.3	1.1	0.4	<0.1	0.1
Area 3 North	2.1	1.9	0.5	0.1	0.2
Area 3 South	5.2	5.0	5.0	5.0	0.8
Color Legend: % Reduction in Hs Compared to Existing Conditions					
	0-20%				
	20-50%				
	50-80%				
	80-100%				

3.3.1. Key Takeaways from Results

Based on the relative comparison of Hs results among the alternative breakwater simulations, key takeaways are summarized below:

- For priority Area 1 (Beach access)
  - Considering wave conditions at the beach access are relatively small[1] for existing conditions, all breakwater alternatives provide mostly similar levels of improved wave protection. Alternative 1 provides the least amount of wave protection improvement; however, there are additional benefits associated with limited mitigation improvements to the existing

[1] Based on the simulated storm conditions and assumed model parameters. Model results may not be a highly accurate representation of actual wave conditions during the 2011 Irene event.

breakwater that are not captured in this study, such as improved structure resiliency during future storm events and therefore less frequent maintenance/repairs.

- For priority Area 2 (Wharf access)
  - Considerable wave protection improvement is only provided by the Alternative 2 concepts (A, B, C). While Alternative 1, with a repaired/rehabilitated existing breakwater, shows a minor reduction in H_s values from the model results, it would likely not provide noticeable improvement to protect the project site from coastal storms that are likely to intensify with impacts of climate change. Thus, in order to ensure wave protection improvements are provided to the wharf access area, a new larger/longer breakwater would be needed, such as the Alternative 2 concepts. Among the Alternative 2 concepts, 2B and 2C provide the most significant improvement in wave protection at the wharf.
- For priority Area 3 (Inner/northern and outer/southern harbor)
  - Area 3 North: Similar to Area 2, considerable wave protection improvement is only provided by the Alternative 2 concepts, where Alternatives 2B and 2C provide the most significant improvements in wave protection at the inner/northern harbor.
  - Area 3 South: Wave protection improvement is only provided by Alternative 2C. Breakwaters only provide wave protection on the lee side. Therefore, any enhanced or new breakwaters constructed at/near the existing breakwater will not provide wave protection improvements to the southern portion of the harbor.

While this section focuses solely on wave protection functionality of the simulated breakwater concepts, these results represent only one metric of comparison among the alternatives. Each alternative will have additional benefits and challenges with other comparison metrics such as cost, constructability, stakeholder input, regulatory limitations, etc. For example, while Alternative 2C is the only modeled concept to provide wave protection for the whole harbor, implementing a new harbor entrance breakwater system such as this concept is likely to be impractical due to costs. The following sections of this report provide commentary on estimated costs and regulatory considerations for the modeled alternatives. Additional engineering analysis is recommended for any breakwater concept that is identified as preferred by Monhegan.

4. Breakwater Concept Design

Concept designs and their associated cost estimates for the rubble mound breakwater alternatives were developed based on the wave modeling as discussed in Section 3 of this report. This study considered the following four alternatives, as referenced in the modeling section and on the concept design plans:

- Alternative 1
- Alternative 2A
- Alternative 2B
- Alternative 2C

The concept design plans are attached in Appendix B. A brief summary of their rubble mound construction type and the associated cost estimates for each alternative is provided below.

4.1. Rubble Mound Breakwater

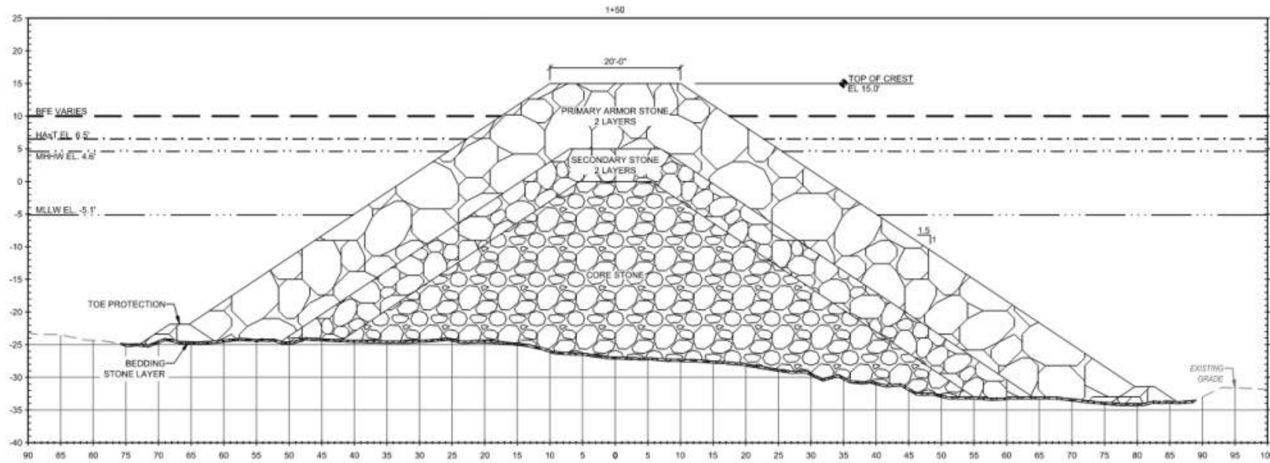
A rubble mound breakwater construction was pursued for the concept designs of this study. Other breakwater construction types, such as a pile supported wave screen or floating wave attenuators, were not considered practical for the wave climate and physical setting at Monhegan, as these structures would not effectively protect Fish Beach, the Public Wharf, and Monhegan Harbor.

The rubble mound breakwater concept designs consist of a trapezoidal shaped structure with sloping sides constructed using different size stone units and aggregate which together serve to break waves on the exposed side and limit wave transmission into the protected area. This design consists of the following stones/aggregates:

- <u>Primary Armor Stone Layer:</u> The outer or primary layer consists of large, stacked stone units which form the visible surface of the structure. While this layer is the most visible, its primary purpose is to stabilize the structure and prevent scour at its base.
- <u>Secondary Armor Stone Layer:</u> Provided beneath the primary armor and consists of smaller stone units. The size of these stones is based on their ability to provide stability to the primary armor layer while not being washed out through the voids in the outer layer. The stone units in the secondary layer are typically half the size of the primary layer.
- <u>Core Layer</u>: Provided beneath the secondary layer and consists of the smallest aggregate sizes in the breakwater to serve as the primary mechanism for limiting wave transmission due to its reduced void volume between each aggregate. A geotextile is provided around the core to prevent washout of the fine material through the voids in the larger stone layers above.

The design of the breakwater's side slopes and stone sizes depends on the wave condition at the location of the breakwater. The conservative conceptual design yielded primary armor stones 5-6 feet wide, with a side slope of 1.5H:1V at both sides. This resulted in a crest width of 20 feet for all alternatives, which would allow for a minimum of three primary armor stones to be placed at the crest of the breakwater. Further design development at a preferred breakwater location would likely allow this design to be refined, potentially reducing footprint and cost of the structure. The crest elevation for Alternative 1 is at 10 feet to match the existing breakwater, and the crest elevation for the Alternative 2 designs are all at 15 feet. A final crest elevation could also be refined during later phases of design. A typical breakwater section from the concept design plans' Alternative 2 is shown in Figure 4-1.

Figure 4-1. Typical Alternative 2 Breakwater Section.



The design life of a rubble mound breakwater is expected to exceed 100 years with periodic maintenance needs. The most likely maintenance would involve resetting the primary armor stones after storm events if significant movement of the stones occurs.

4.2. Cost Estimate

Table 4-1 provides the estimated costs associated with each conceptual breakwater alternative. Note, Alternative 2C contains separate estimates for the east (Monhegan Island) and west (Manana Island) structure. The estimates include both engineering design and construction for the respective alternative.

These estimated costs are based on concept-level design development which carries a high level of uncertainty, and there are many factors that could arise during design development that could impact cost. A 30% estimating contingency has been included to account for the level of unknown at this time.

Table 4-1. Concept Design Alternatives Cost Estimate

Alternative	Cost (in millions $)
1	$3.1 M
2A	$14.2 M
2B	$16.8 M
2C (East)	$15.2 M
2C (West)	$35.3 M

The costs for each alternative varies from approximately $3.1 M for Alternative 1 to over $50 M for Alternative 2C, with the cost for the 2C east and west breakwater coming in at approximately $15.2 M and $35.3 M, respectively. The significant increase in cost is attributed to the structure extending into deeper water, which requires a larger amount of core fill and armor stone to maintain the 1.5/1 slope down to the seabed. The cost estimates also assume all fill and stone material will be brought from the mainland by barge, which drives up costs as compared to mainland construction. The island could look to quarry material from Monhegan or Manana Island, which would reduce construction costs by eliminating the need to barge the large stones and core fill from the mainland.

5. Regulatory Review

The proposed conceptual designs for breakwater improvements at Monhegan Island, including Alternative 1 (limited mitigation improvements) and Alternatives 2A – 2C (construction of new breakwater configurations and locations) will require review and authorization by state and federal regulatory agencies. The following sections summarize the anticipated regulatory review requirements. A regulatory pre-application meeting was held with representatives from the United States Army Corps of Engineers (USACE) and the Land Use Planning Commission (LUPC) on April 15, 2026, to discuss the preliminary model results and proposed breakwater alternatives. This information is provided for planning and informational purposes only and is not intended to replace project-specific coordination with regulatory agencies. Once an alternative is advanced to preliminary design, additional early coordination with the appropriate agencies is recommended to confirm applicable regulatory requirements.

5.1. USACE

The USACE regulates waters of the United States under Section 404 of the Clean Water Act and navigable waters of the United States under Section 10 of the Rivers and Harbors Act. Under Section 404, the USACE's jurisdiction extends to the high tide line, which is the line of intersection of the land with the water's surface at the maximum height reached by a rising tide. Under Section 10, the USACE's jurisdiction in tidal waters extends to the mean high-water line. All proposed alternatives will require USACE authorization due to work occurring below these jurisdictional limits; however, the level of review differs between Alternative 1 and Alternatives 2A through 2C, as described below.

5.1.1. Alternative 1

Provided this alternative does not result in substantial changes to the footprint or alignment of the existing breakwater, the work may be authorized under the Maine Regional General Permit – Category C (RGP-C) for structures. Under this category, activities must be limited in scope (e.g., repair, replacement, or minor expansion of an existing structure). A Pre-Construction Notification (PCN) would be required, including plans, an alternative analysis, impact quantification, and a description of construction methods. The USACE will review the proposal for consistency with general permit conditions, including water quality certification, Coastal Zone Management Act, and compliance with other federal requirements including Essential Fish Habitat, Endangered Species Act (ESA) consultation, and National Historic Preservation Act (Section 106) review, as well as evaluation of existing and potential changes to flood elevations.

5.1.2. Alternatives 2A through 2C

Given the scale of each of these alternatives, an Individual Permit is anticipated. The USACE review will evaluate the project purpose and need, alternatives analysis, and potential impacts to navigation and aquatic resources. The review will also address Coastal Zone Management Act consistency, Essential Fish Habitat, ESA consultation, National Historic Preservation Act (Section 106) compliance, and potential changes to the flood elevations. Compliance with the National Environmental Policy Act (NEPA) may also be required, depending on the extent of impacts, and is typically conducted with the Individual Permit review. The USACE will publish a public notice to initiate a formal comment period, allowing for public input and identification of stakeholder concerns. Following this review process, the USACE will issue a decision, which may include permit conditions and, where impacts are unavoidable, requirements for compensatory mitigation.

5.2. LUPC

The project area is located within the unorganized territory of the State and therefore falls under the jurisdiction of the LUPC. Each alternative will require LUPC approval and the permit process requires a detailed alternative analysis outlining the avoidance and minimization of environmental impacts as well as compliance with and flood hazard standards. Flood hazard review will likely include evaluation of base flood elevations (BFE) and potential changes associated with the proposed alternatives to ensure no adverse impacts on adjacent properties. The applicant must also demonstrate financial capacity to complete the project and sufficient title, right, or interest (TRI) in the areas proposed for development.

5.3. Maine Bureau of Parks and Lands – Submerged Lands

The expansion or construction of a new breakwater below the mean low water (MLW) line requires authorization from the Maine Bureau of Parks and Lands through a Submerged Lands Lease or Easement, as the structure represents a permanent occupation of state-owned submerged lands. The applicant must demonstrate that the project is consistent with the State's Public Trust Doctrine by avoiding unreasonable interference with navigation, fishing, and recreation. If approved, the authorization is typically issued as a lease with annual rent and conditions requiring compliance with all permits and ongoing maintenance of the structure.

6. Recommendations and Next Steps

The information presented in this report is intended to guide Monhegan in pursuing enhancements to their breakwater protection in Monhegan Harbor, whether by rebuilding the existing breakwater or by pursuing a new breakwater location within the harbor. The following sections outline the high-level steps of continuing the design development process and working towards constructing a new breakwater in Monhegan Harbor.

6.1. FEMA Funding

It is recommended that, in the short term, Monhegan utilize the funding from FEMA to repair the breakwater to pre-disaster conditions. This includes restacking existing stones and adding new stones to the existing breakwater structure. If an additional $741,188.00 is available from FEMA for mitigation measures, Monhegan could consider this funding to lengthen, expand, or connect the existing breakwater to the adjacent shoreline as presented in Alterative 1 or 2A. However, if an alternative at a different location, such as Alternative 2B or 2C, is pursued, consideration should be given to how FEMA mitigation funding is allocated, including whether it is more appropriately applied to improvements to the existing breakwater or toward the design of a relocated structure.

Under Alternatives 2B or 2C, the Plantation may be able to retain the existing breakwater and construct an additional breakwater in a new location, pending regulatory review. This approach has the potential to provide enhanced wave attenuation and improved protection to Fish Beach and the harbor through the combined function of both structures.

It should be noted, however, that alternatives involving new or relocated breakwaters would likely introduce additional regulatory complexity, particularly related to permitting, environmental review, and potential compensatory mitigation, and would result in substantially higher project costs. These alternatives are anticipated to exceed the level of funding typically available through FEMA mitigation programs and would therefore require identification of supplemental funding sources.

6.2. Local Support

Community members and stakeholders should review the findings and conceptual alternatives presented in this report and provide feedback to the Plantation regarding the relative benefits, concerns, and priorities associated with each breakwater alternative. Community input will be an important component in identifying a preferred path forward, particularly given the breakwater's importance to harbor access, public safety, fishing operations, transportation, and overall community resiliency.

Based on feedback received and further consideration of technical and financial factors, the Plantation should identify a preferred breakwater alternative to advance into subsequent phases of study and design. Selection of a preferred alternative is not intended to commit the Plantation to a final design or construction approach; rather, it will establish a focused framework for advancing preliminary engineering, permitting evaluations, cost refinement, and stakeholder coordination.

In evaluating and selecting a preferred alternative, the Plantation should consider several factors discussed throughout this report, including anticipated construction cost, long-term maintenance considerations, wave protection effectiveness, constructability, location, property ownership and easement requirements, environmental permitting constraints, operational impacts to harbor users, and overall community goals. Additional considerations may include funding eligibility, resilience to future storm conditions and sea level rise, and the ability to phase improvements over time as funding and project priorities evolve.

6.3. Project Funding

The cost of undertaking the development of a breakwater is significant, particularly at a remote island site like Monhegan. Implementing the preferred concept plan is likely to require a funding strategy that utilizes multiple sources of funding for additional studies, design development, permitting, and construction.

The Plantation should be prepared to pursue all potential sources of funding to support further phases of the project, as the availability and timing of funding may drive the project schedule. Future grants for design and construction may include a combination of local, state, and federal funding resources and programs.

A phased implementation strategy, particularly for more complex alternatives such as Alternative 2C, should be considered to address funding and regulatory timelines. An initial phase could focus on targeted investigations, preliminary design, and permitting using available grant funding. Subsequent phases could advance final design and construction as additional funding is secured. This approach allows the Plantation to maintain project momentum, reduce upfront financial burden, and adapt to evolving funding opportunities while progressing toward long-term coastal resilience goals. Additionally, for Alternative 2C specifically, phasing could include construction of one breakwater (e.g., the primary structure providing the greatest immediate wave attenuation benefit) as an initial construction phase, followed by construction of the second breakwater under a later phase as additional funding becomes available. This approach allows the Plantation to achieve incremental improvements in coastal protection while managing costs, funding constraints, and permitting timelines.

6.4. Design Development and Permitting

The breakwater plans developed during this study were designed to a conceptual level and will require further detailed design to reach construction ready documents.

Completing final design documents would require additional field work and modeling to verify the existing conditions at the preferred breakwater location. This additional work could include, but is not limited to:

- Additional detailed site survey.
- Detailed wave modeling, building upon and refining the results of this study.
- A subsurface investigation including borings to confirm soil and rock conditions.

- Environmental studies to understand the resources and constraints relevant to permitting the proposed project.

Coordinating with the applicable regulatory agencies, as described in Section 5, will also be critical to undertaking a successful project. The relevant agencies should be kept informed of the project scope as it develops to allow for early identification of regulatory constraints and confirmation of required permits. Upon completion of design development to a sufficient level of detail (typically 30% complete), applications can be prepared and filed with local, state and federal agencies to begin the permit review process. The regulatory review of a significant waterfront improvement project such as this one may take 12 months or more to complete. The project timeline should include an appropriate permit review period as this can often be a major driving factor in the schedule.

6.5. Construction, Operation, and Maintenance

Upon receipt of regulatory approvals, preliminary plans would be advanced to final design and developed into a bid package that includes detailed drawings, technical specifications, and contract documents. In most cases, a public bid process would be held to invite qualified marine contractors to bid on the project and this process allows the project to be bid competitively and is likely to be a requirement of grant funding agencies. Construction scheduling will depend on several factors, including contractor availability, regulatory in-water work windows, and the Plantation's operational priorities, particularly the need to minimize disruptions during peak tourism periods and the active fishing season.

Following construction, the Plantation should implement a monitoring and maintenance program to maximize the breakwater's design life. Rubble mound breakwaters typically require limited maintenance; however, its condition should be regularly monitored to identify any displacement of armor stone, settlement, or localized damage, particularly after coastal storms events, to ensure no damage has occurred. Timely maintenance and repair of minor issues will help prevent more extensive degradation and extend the overall service life of the structure.

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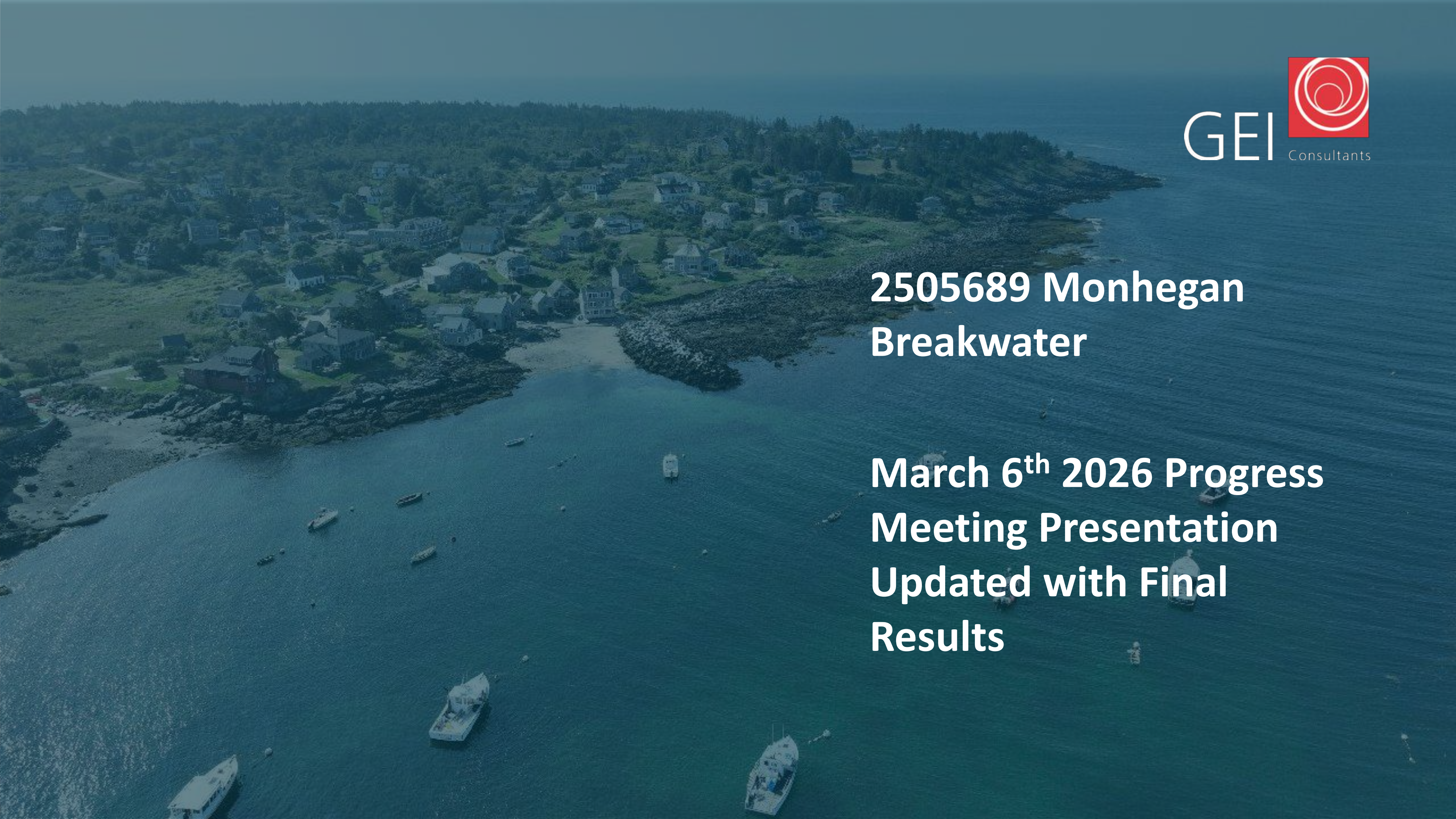
Appendix A Wave Modeling Assessment Results



GEI Consultants

2505689 Monhegan Breakwater

March 6th 2026 Progress Meeting Presentation Updated with Final Results

Agenda

- Purpose & scope overview
- Modeling approach
- Breakwater alternatives & modeling results

Purpose & Scope Overview

- Purpose of Study:
  - Develop conceptual breakwater alternatives to improve protection from wave energy
  - Areas for improved protection in order of priority:
    1. Access beach cove
    2. Wharf
    3. Harbor

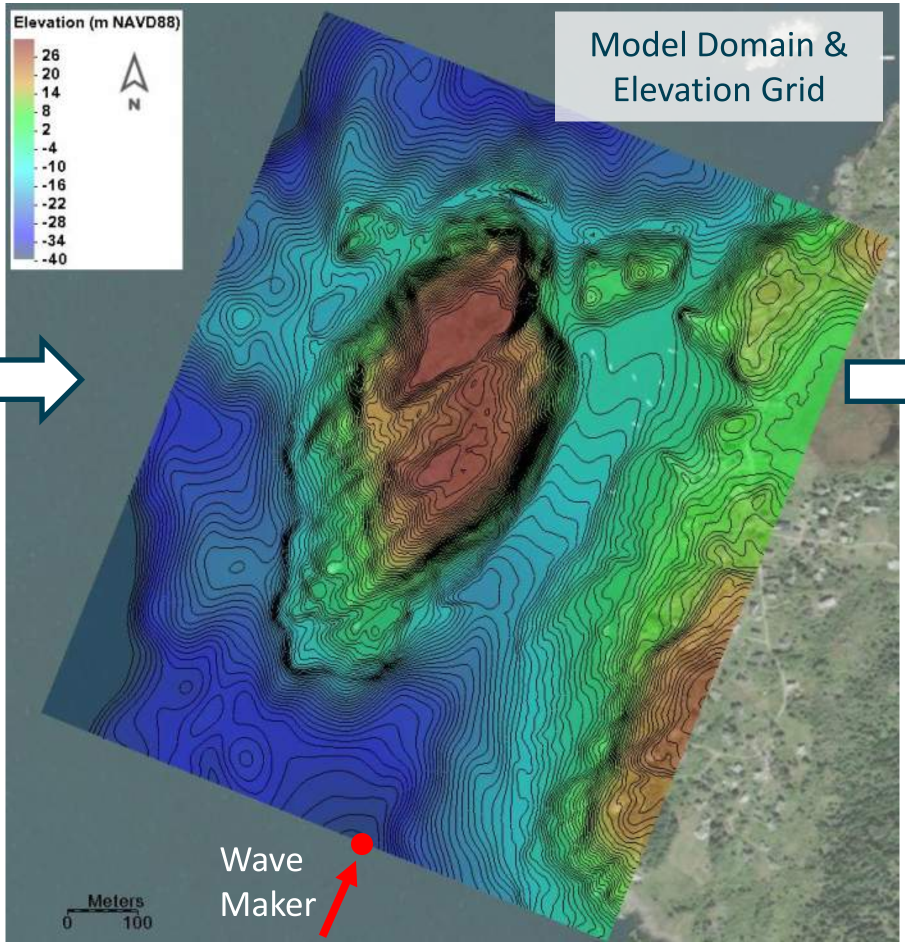
Purpose & Scope Overview

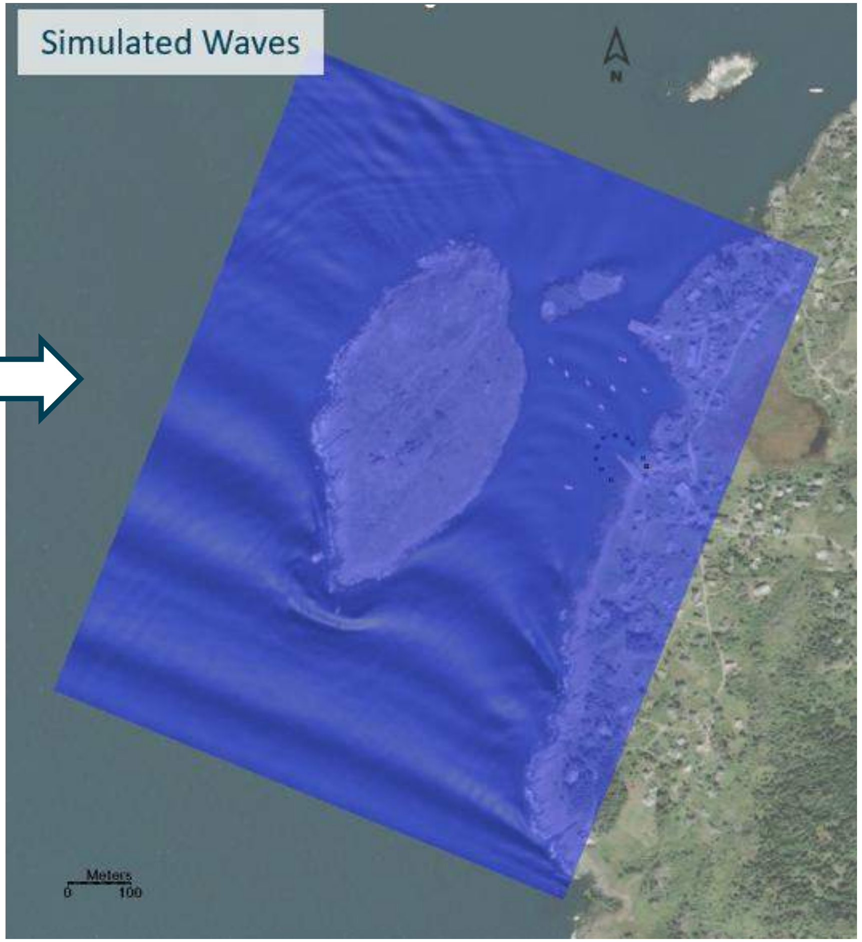
- Task 1: Coastal Wave Modeling
  - Develop BOUSS-2D numerical wave model
  - Simulate wave dynamics in storm conditions for three scenarios:
    - Existing breakwater conditions
    - Alternative 1: improvements at existing breakwater
    - Alternative 2: new breakwater design/location
- Task 2: Concept Design Advancement
  - Advance 3 concept designs based on modeling results (drawings and cost estimates)
- Task 3: Regulatory Review & Summary Memorandum
  - Agency coordination for alternatives and Pre-App meeting
  - Summary of assessment and findings in memo

Model Development

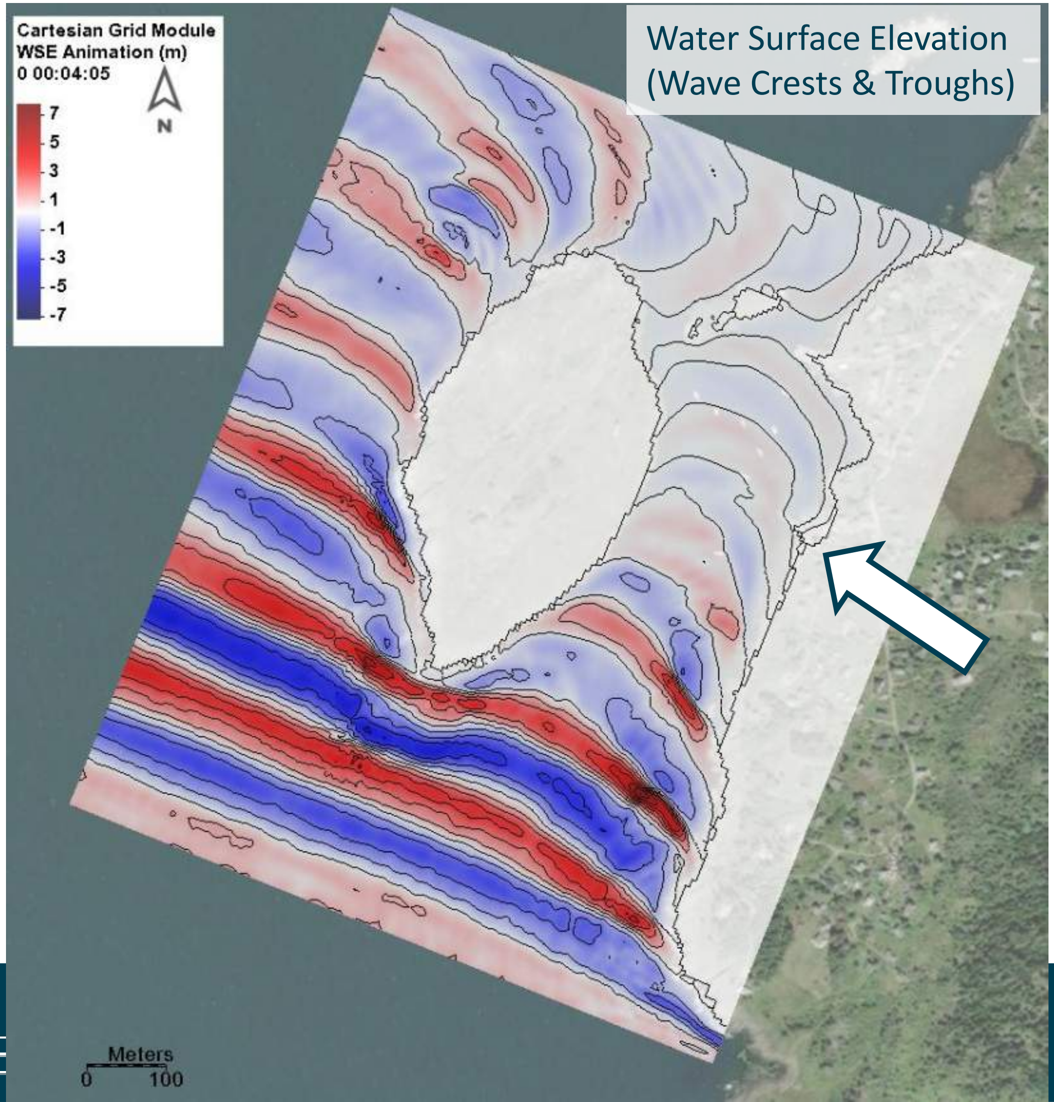
Key Inputs

- Bathymetry & topography
- Grid extents, boundary, resolution
- Model parameters
- Storm simulation conditions
  - 2011 Tropical Storm Irene: Hs = 19.3 ft, T = 11.4 s, WL = 6.3 ft NAVD88
  - Similar to 500-yr event

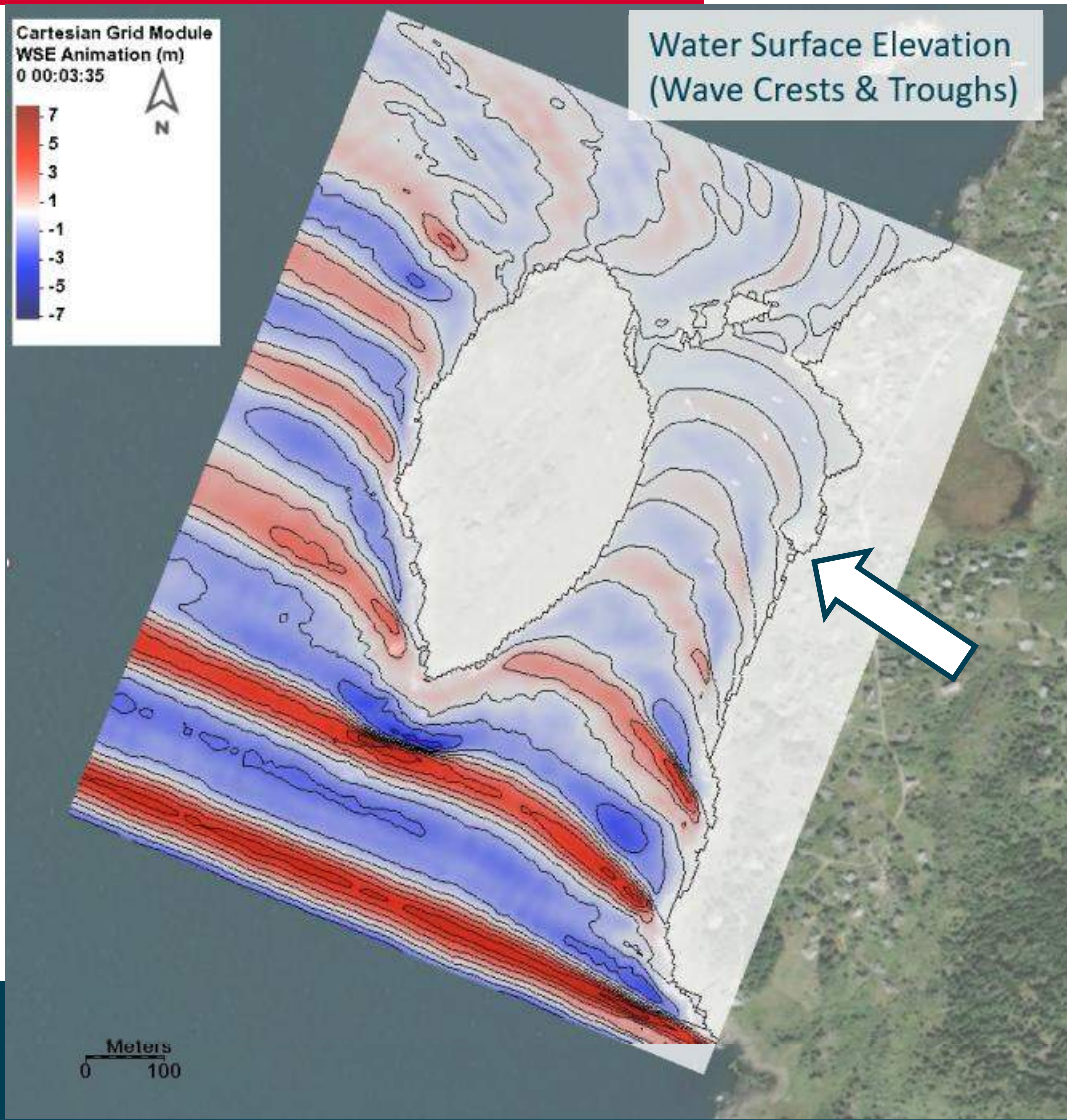


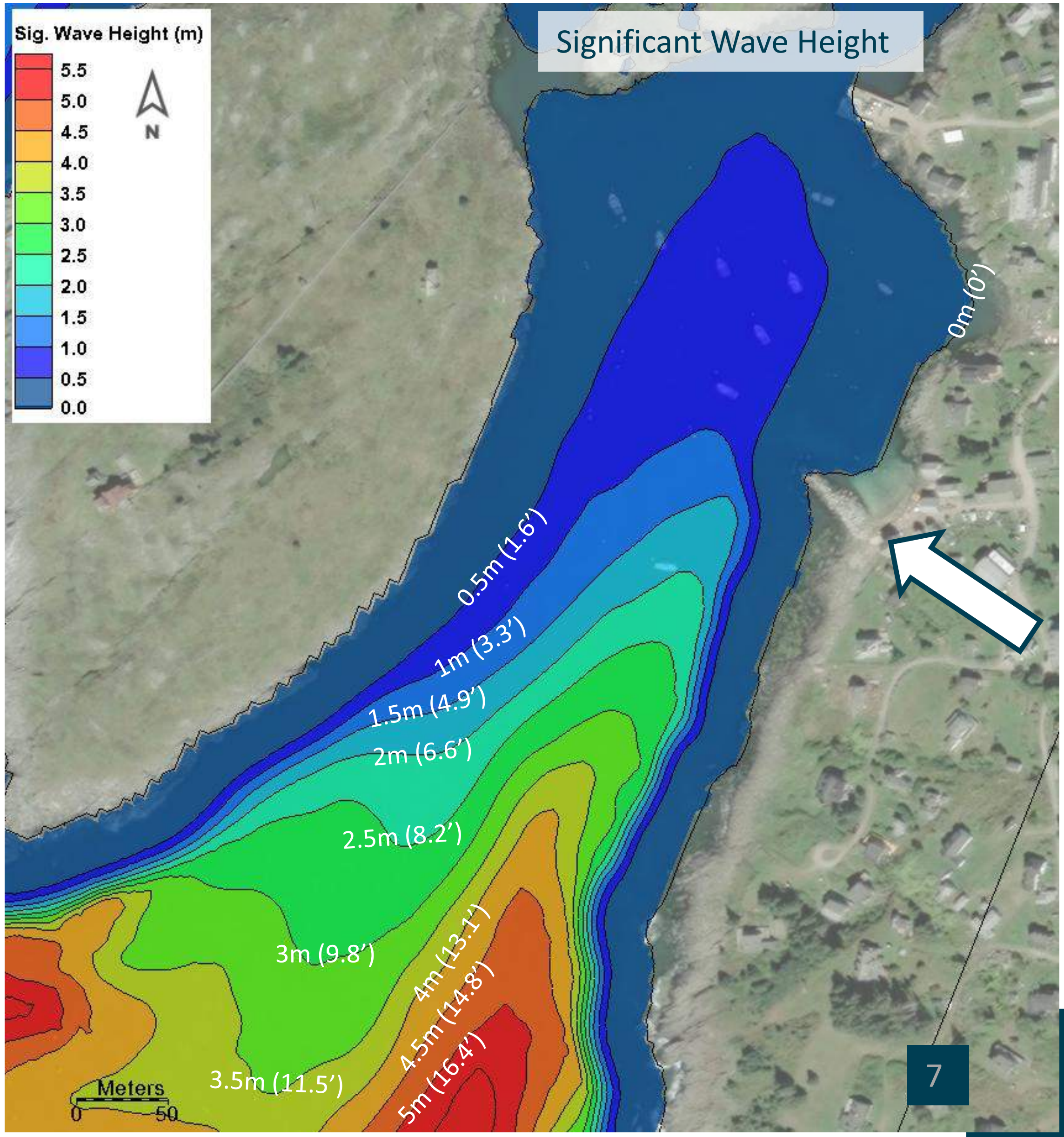


Model Outputs

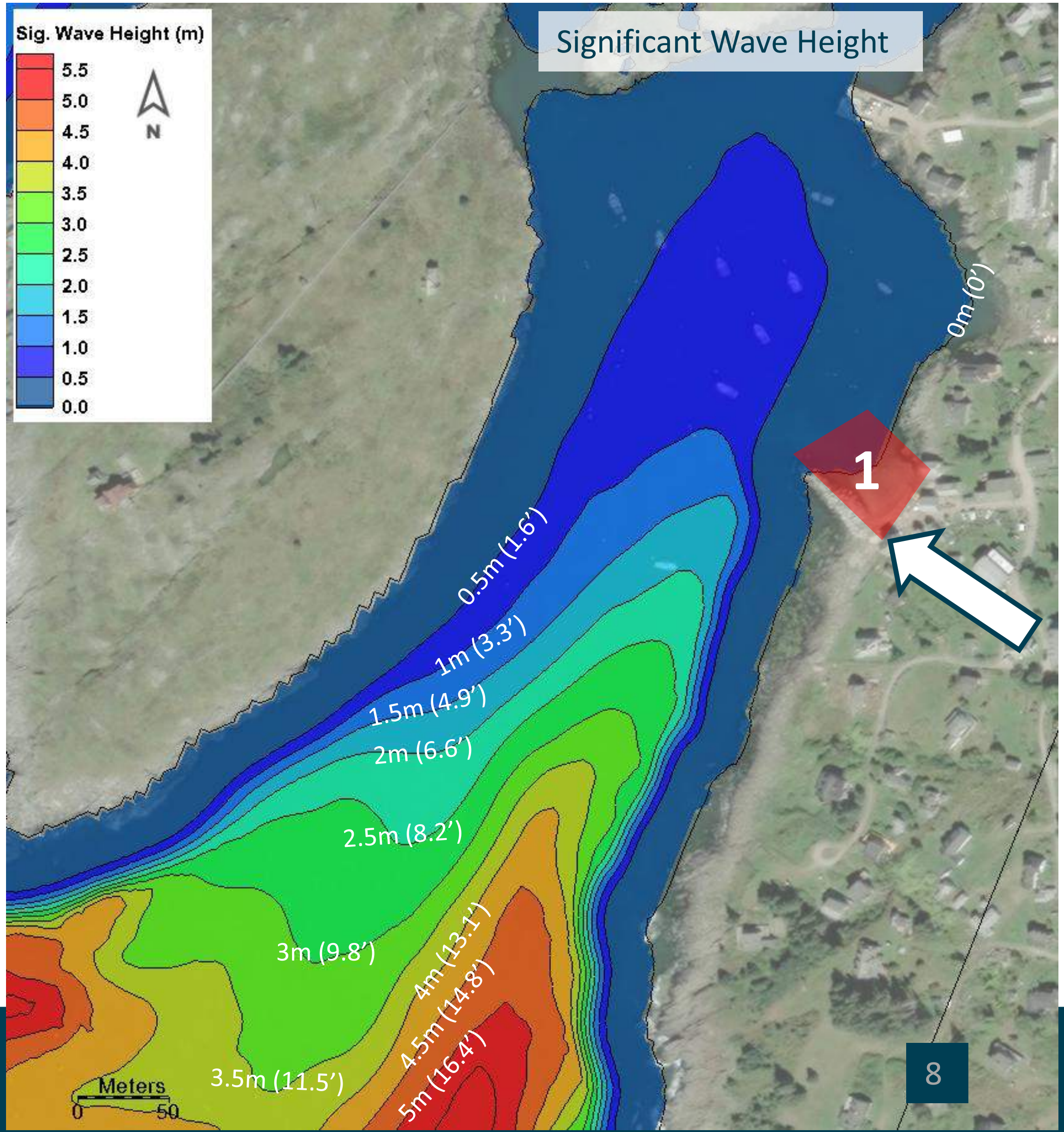


Model Results: Irene Storm Event with Existing Breakwater Conditions





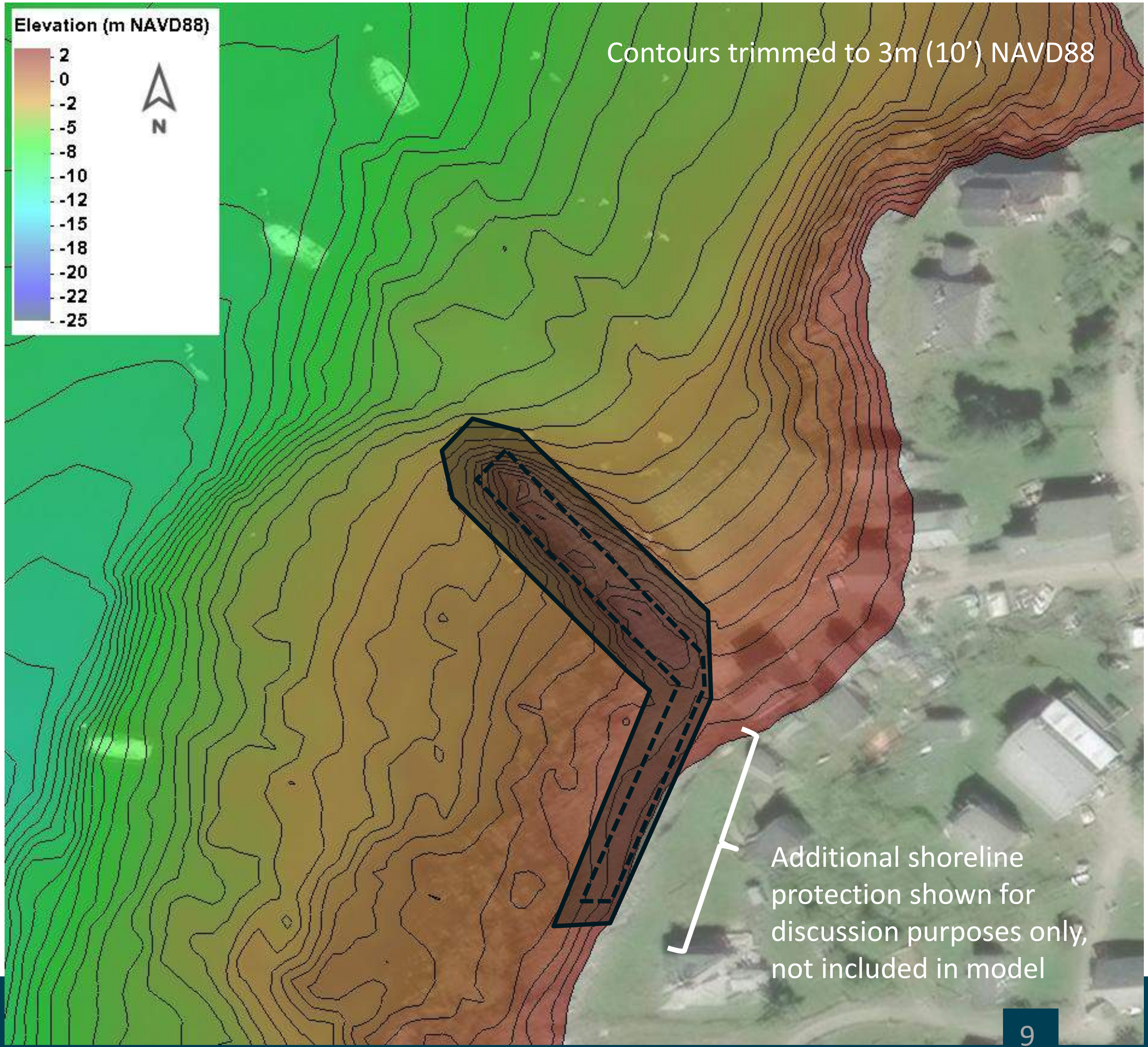
Model Results: Irene Storm Event with Existing Breakwater Conditions



Proposed Alternative 1

Alternative 1

- Objective:
  - Improve breakwater function through limited mitigation
- Description:
  - Reconstruct to +10’ NAVD88 crest elevation
    - Approx. highest existing elv. at breakwater
    - Matches northeast BFE Zone AE El. 10’
  - Engineered cross section (armor, core, bedding layers, slope)
  - Consider revetment expansion at shoreline for protection from runup, overtopping, & scouring (not modeled)



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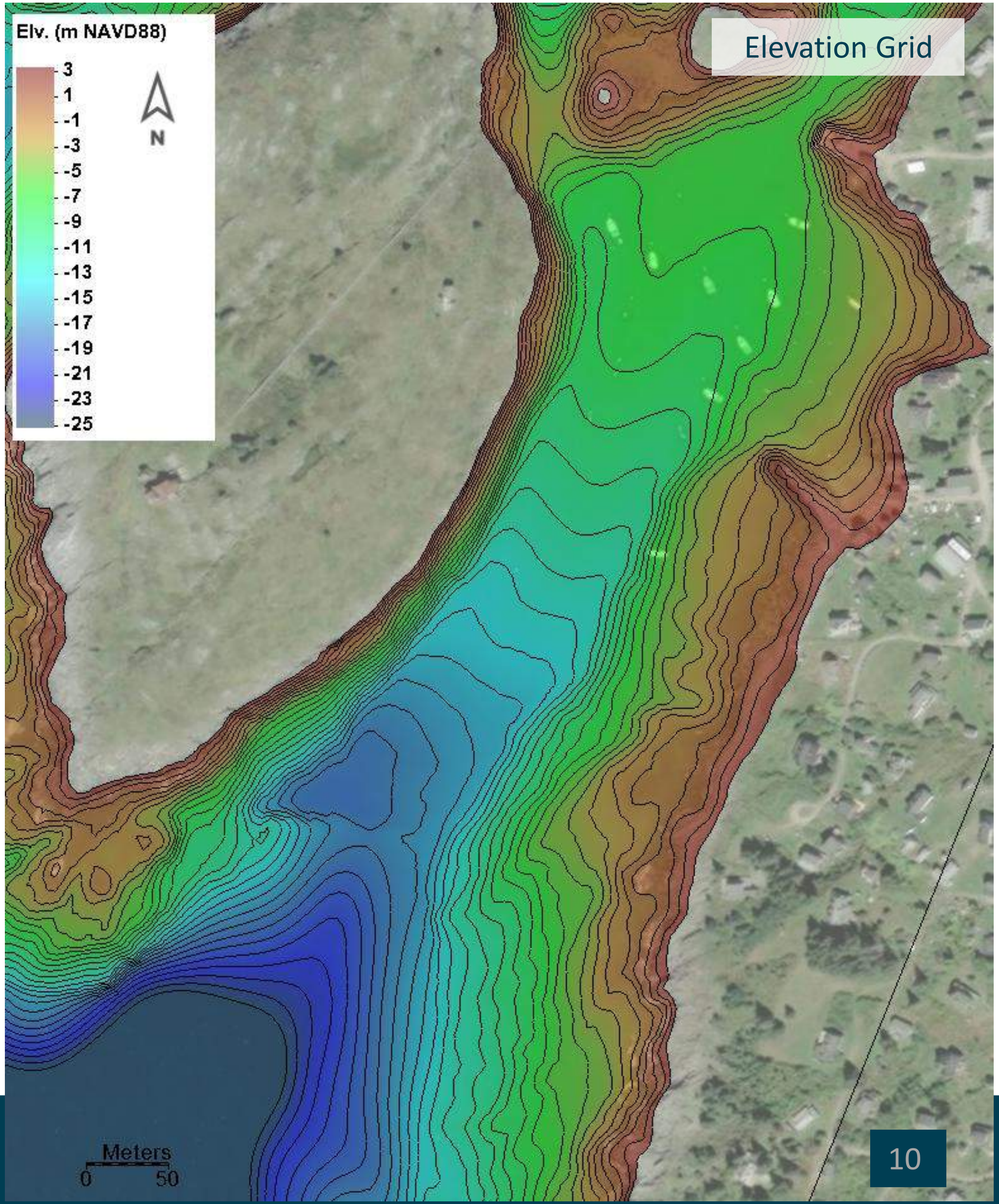
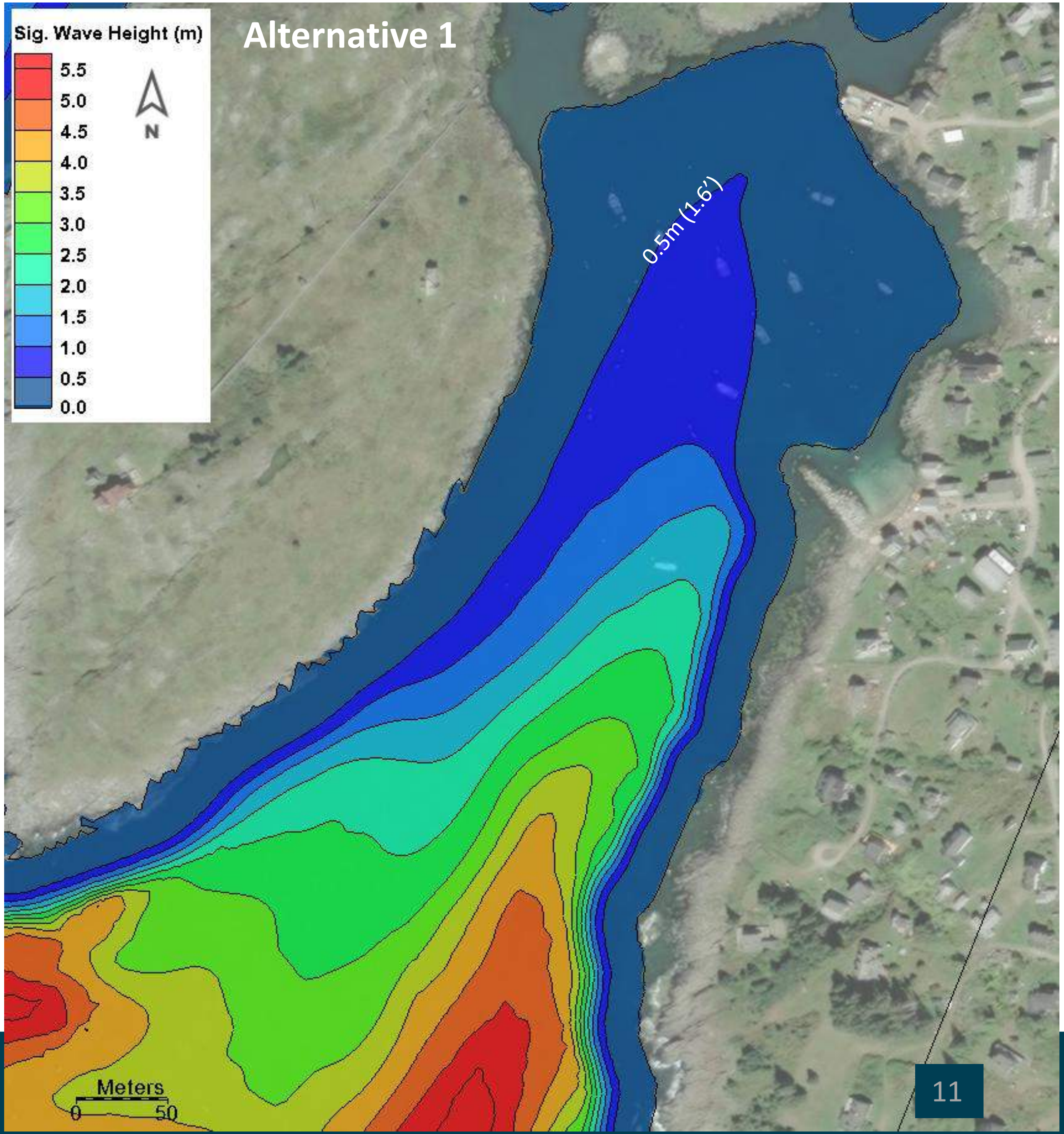
    - Matches northeast BFE Zone AE El. 10’
  - Engineered cross section (armor, core, bedding layers, slope)

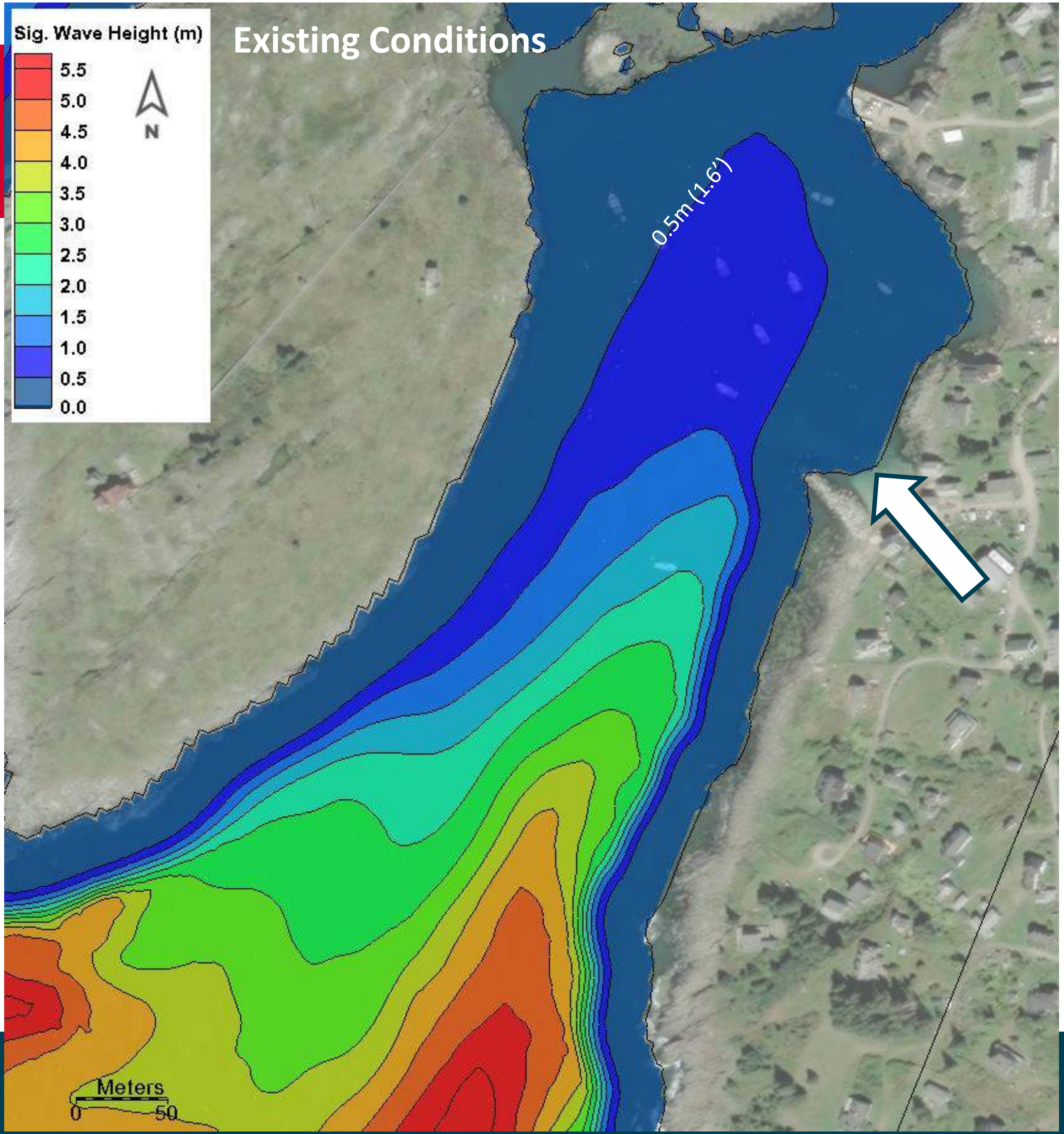


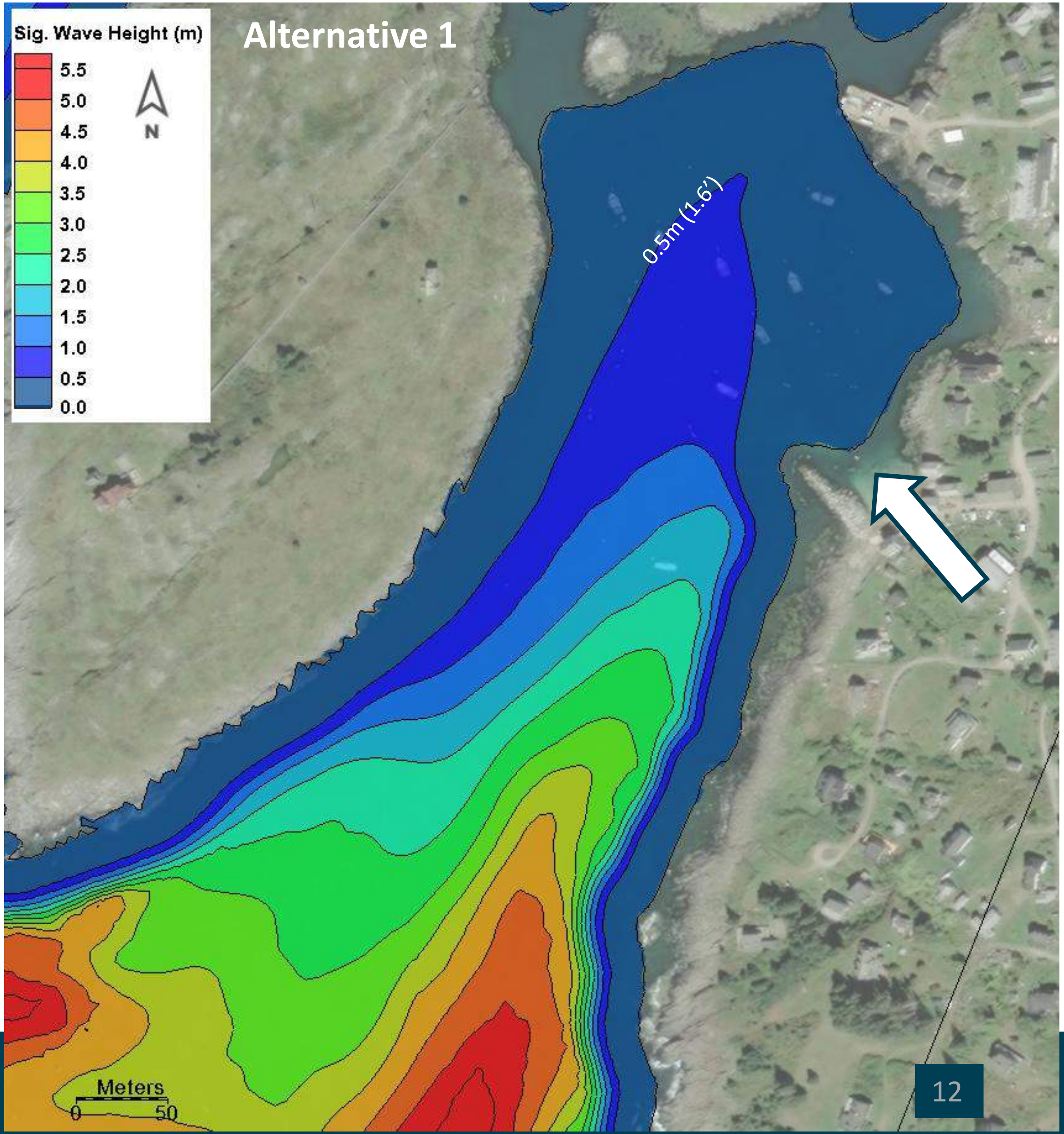
Proposed Alternative 1

Alternative 1

- Model Results: Irene Storm Event
  - Protection still mostly limited to Area 1
- Anticipated additional benefits:
  - Improved structure resiliency during storm events
  - Less frequent maintenance
  - Reduce damage to local properties and backwash-induced scour



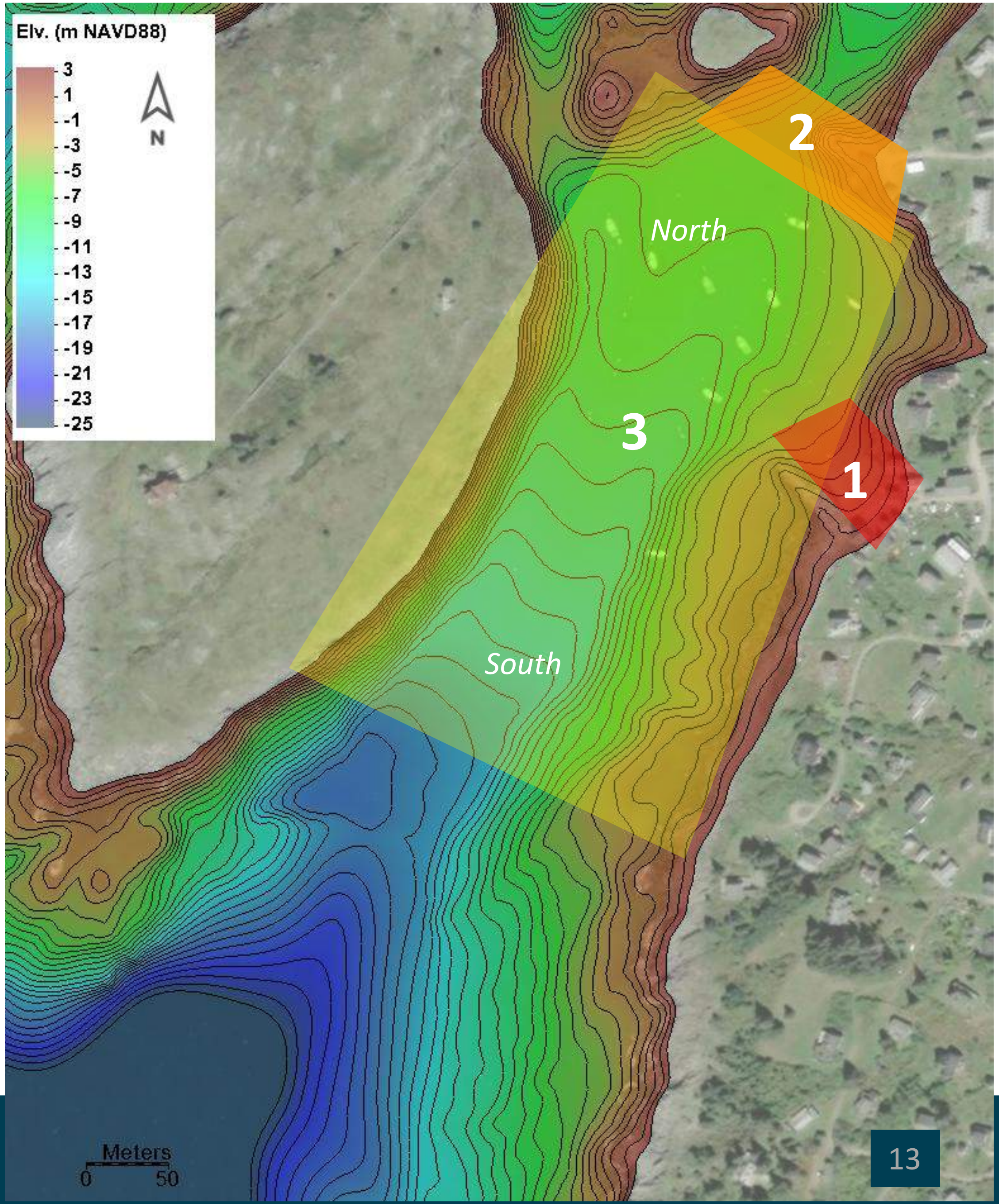

Existing Conditions
Sig. Wave Height (m)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
N
0.5m (1.6')
Meters
0
50


Alternative 1
Sig. Wave Height (m)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
N
0.5m (1.6')
Meters
0
50

Proposed Alternative 2

Alternative 2

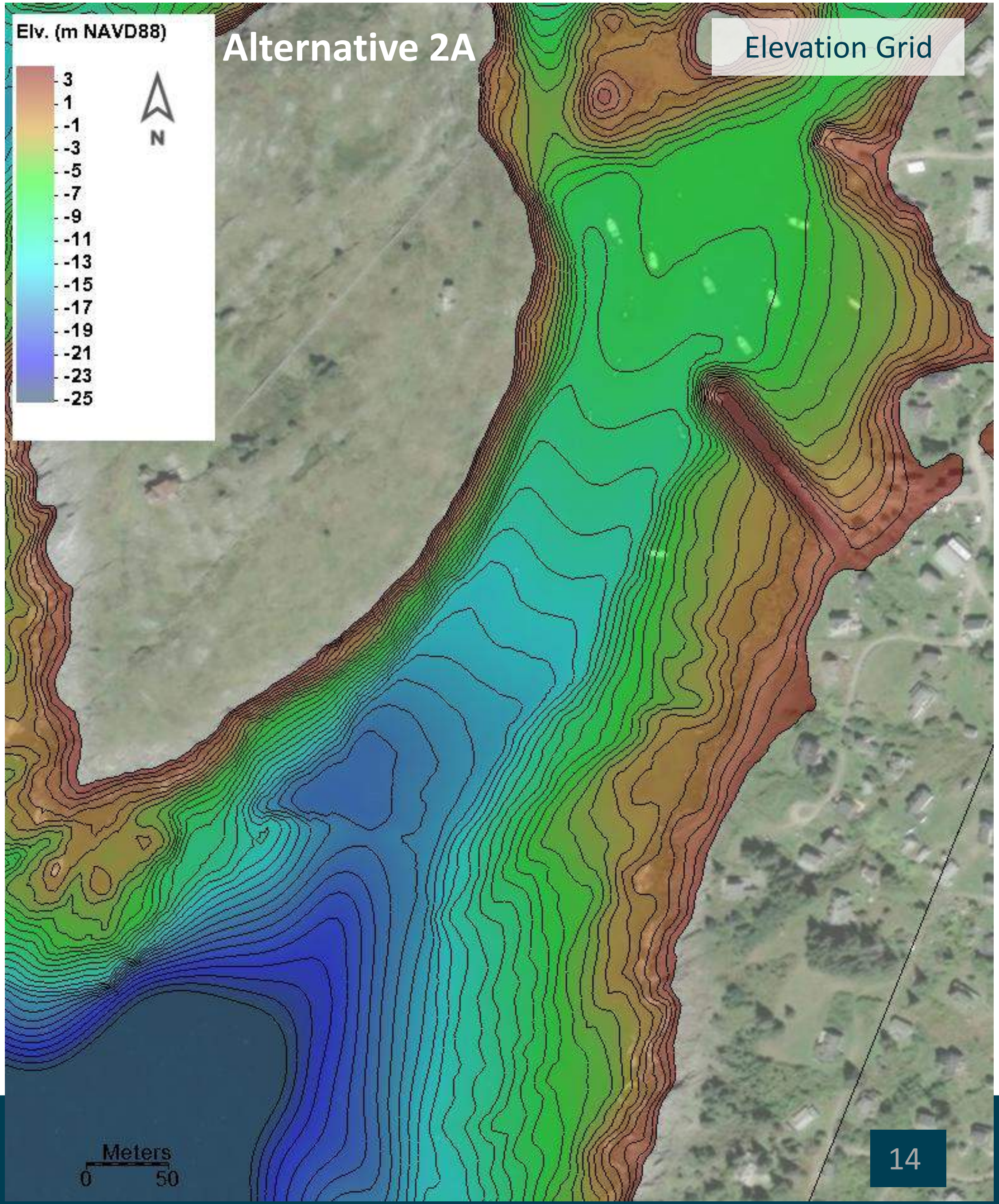
- Objective:
  - Create larger area of reduced wave energy
- Description:
  - Construct new breakwater to +15’ NAVD88 crest elevation
    - Matches southeast BFE Zone VE El. 15’
  - Engineered cross section (armor, core, bedding layers, slope)
  - Three sub-alternative concepts (A, B, C) to improve protection to Areas 2 and 3



Proposed Alternative 2A

Alternative 2A

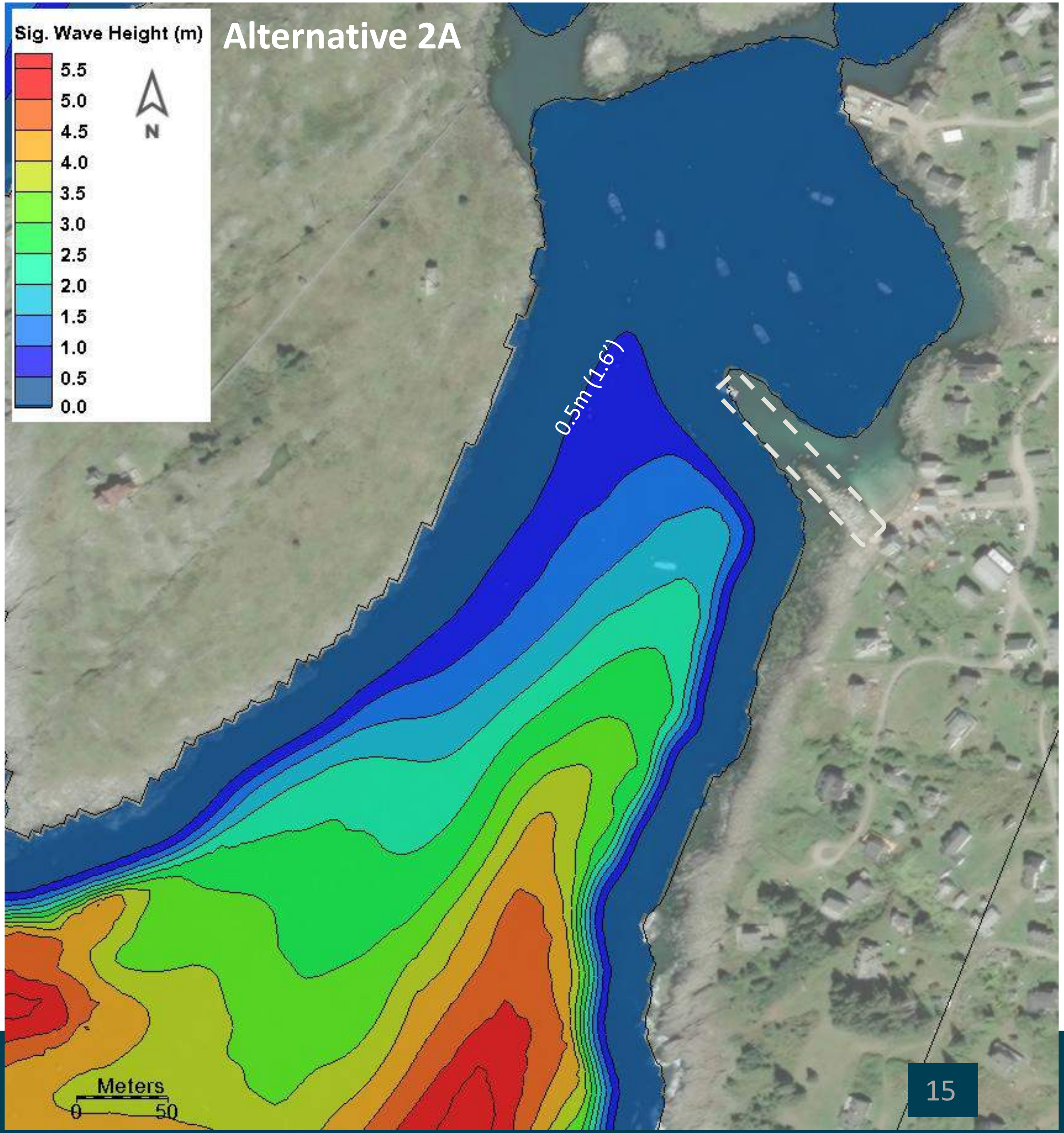
Alt.	Description	Anticipated Key Pros	Anticipated Key Cons
2A	Extend breakwater to increase protected area at existing location.	Lower cost than B & C. Uses location of existing breakwater.	Conflicts with mooring field. Limited area of improved protection. Restricts approach into cove from the south.

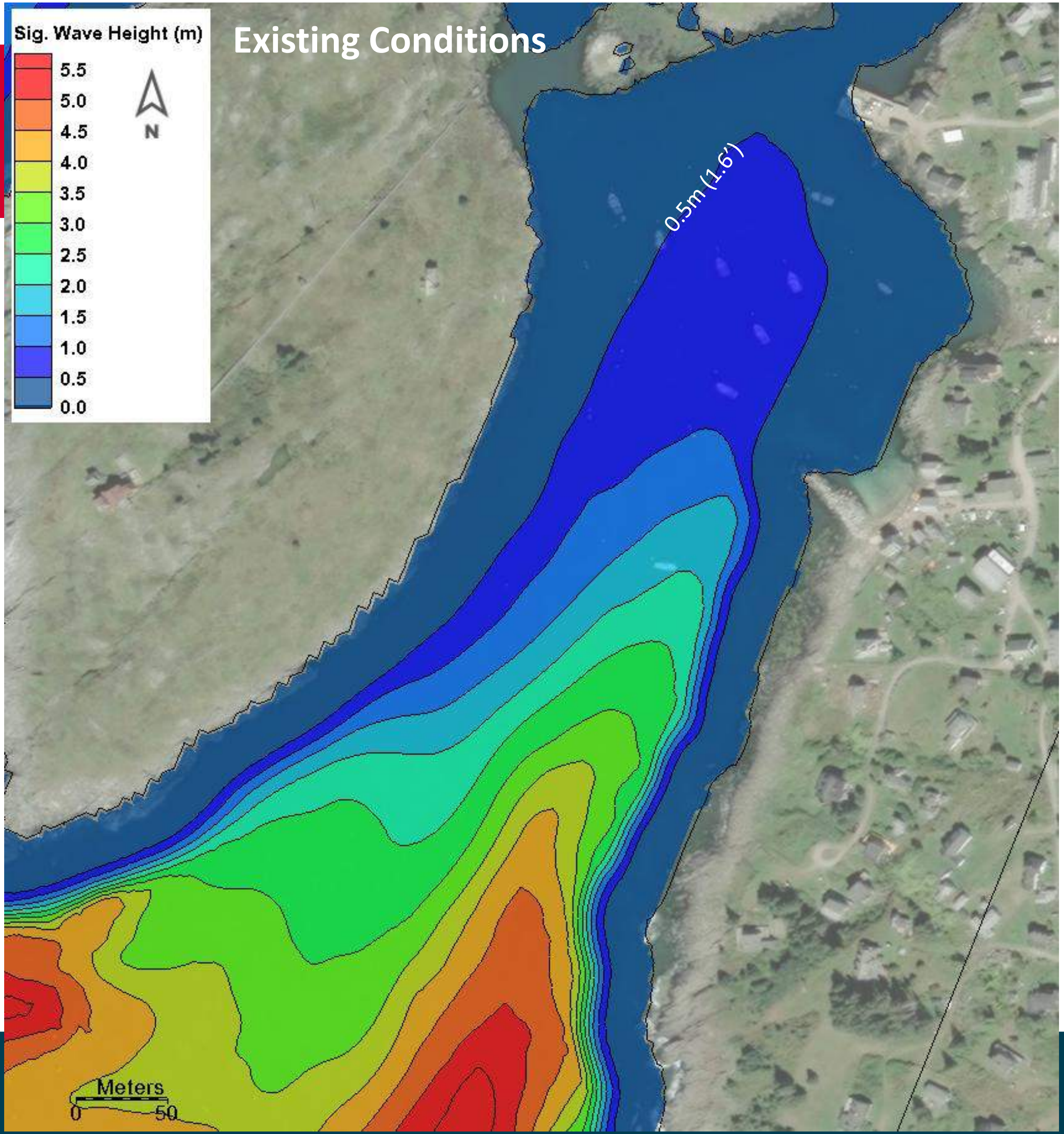


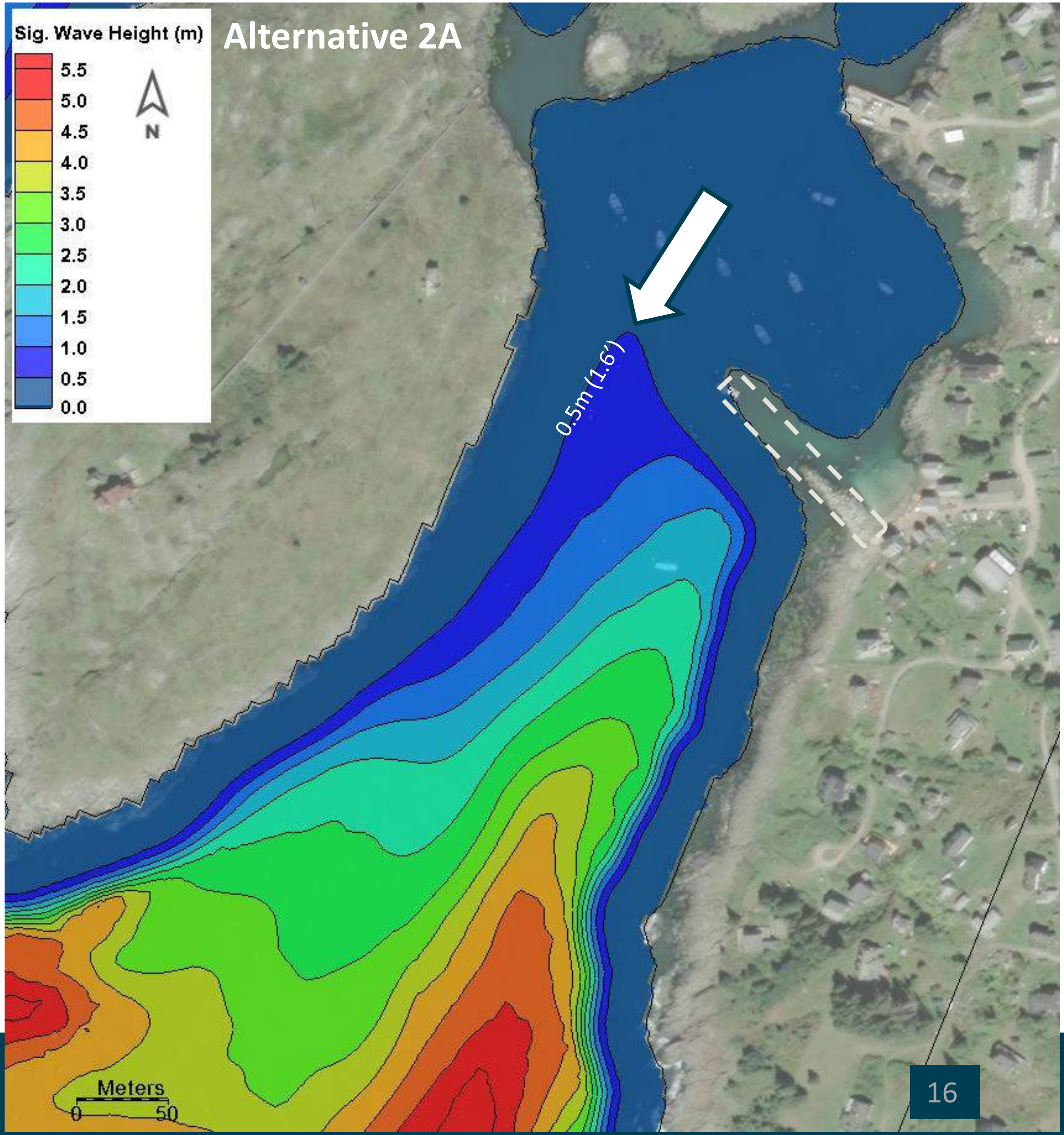
Proposed Alternative 2A

Alternative 2A

- Model Results: Irene Storm Event
  - Protection improved for Areas 1, 2, and 3 North



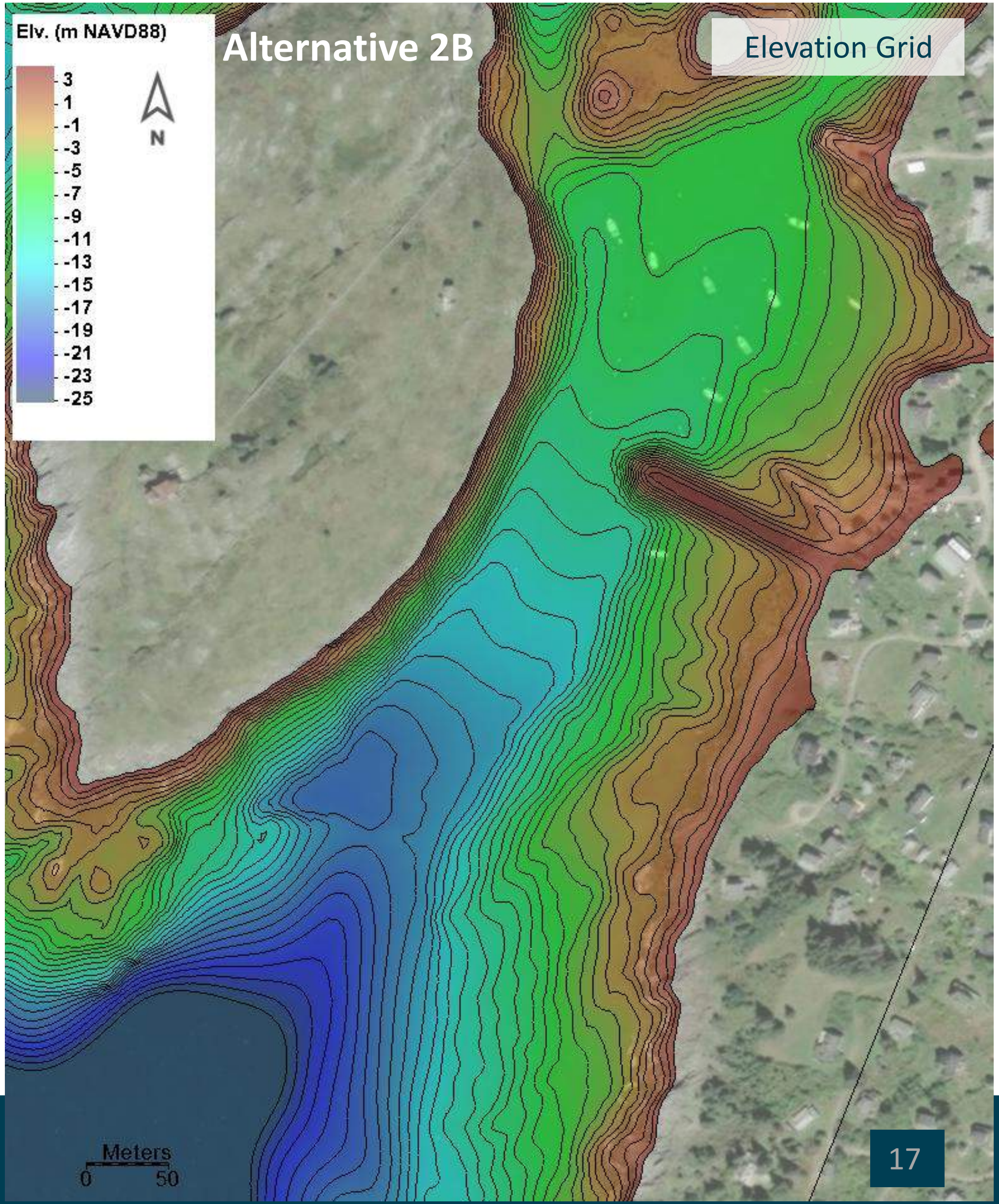

Sig. Wave Height (m)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
N
Existing Conditions
0.5m (1.6')
Meters
0
50


Sig. Wave Height (m)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
N
Alternative 2A
0.5m (1.6')
Meters
0
50

Proposed Alternative 2B

Alternative 2B

Alt.	Description	Anticipated Key Pros	Anticipated Key Cons
2B	Relocate breakwater to increase protected area.	Less conflict with mooring field than A. More room for moorings in protected zone than A. May be extended to increase protection.	Visually unappealing and impractical to have 2 adjacent rock structures. Makes existing breakwater obsolete. Permitting and right, title, interest (RTI).



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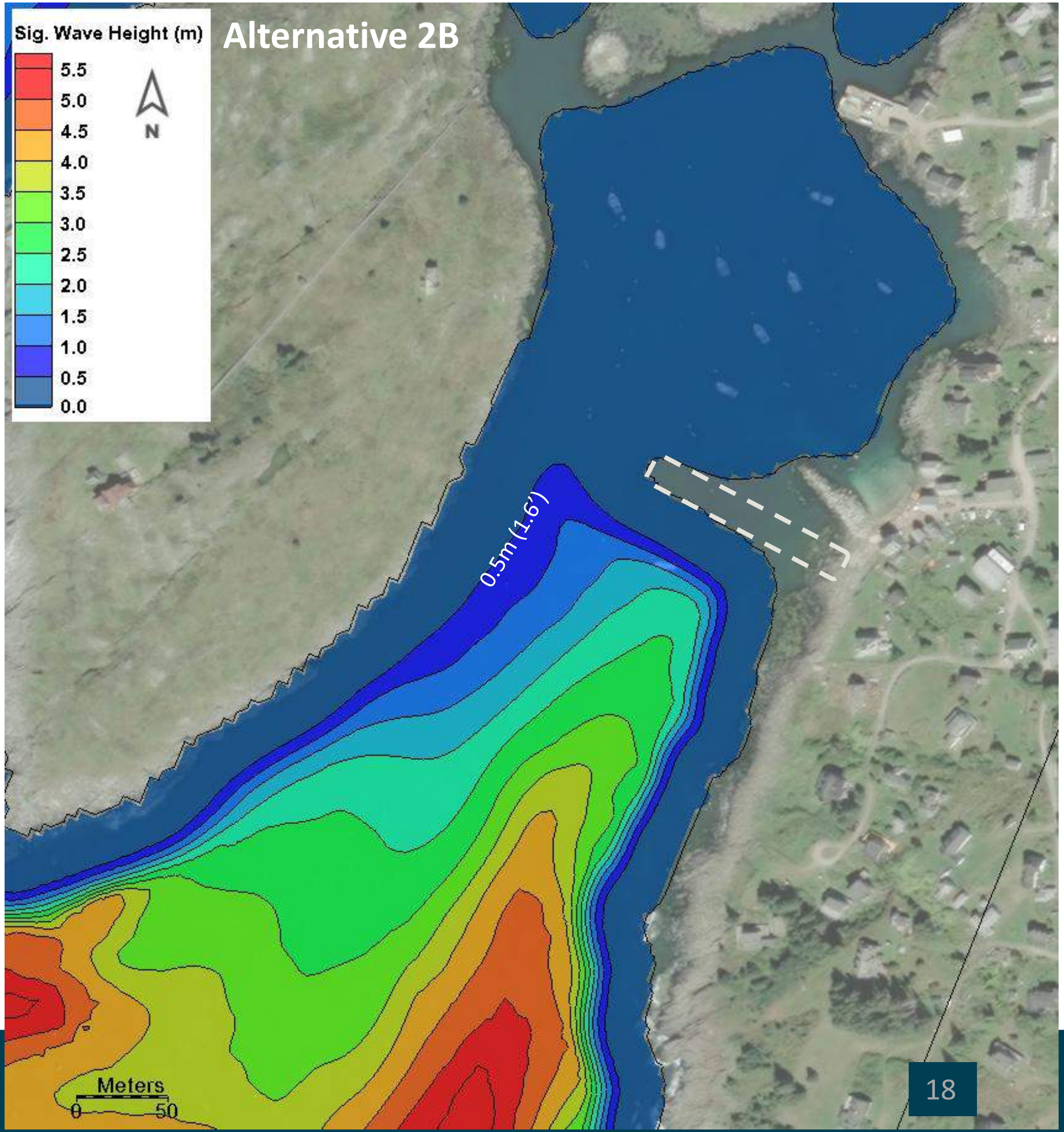
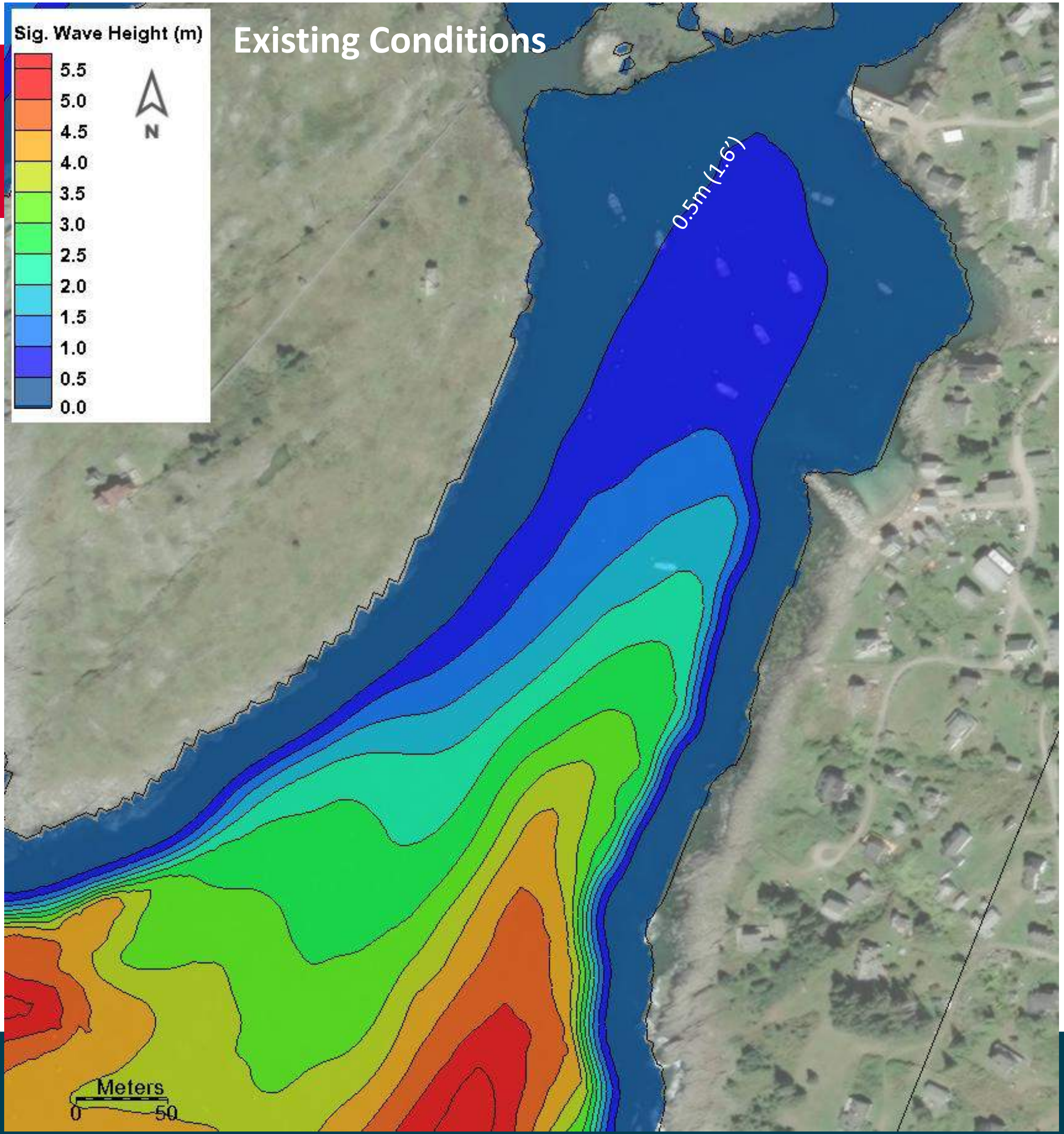
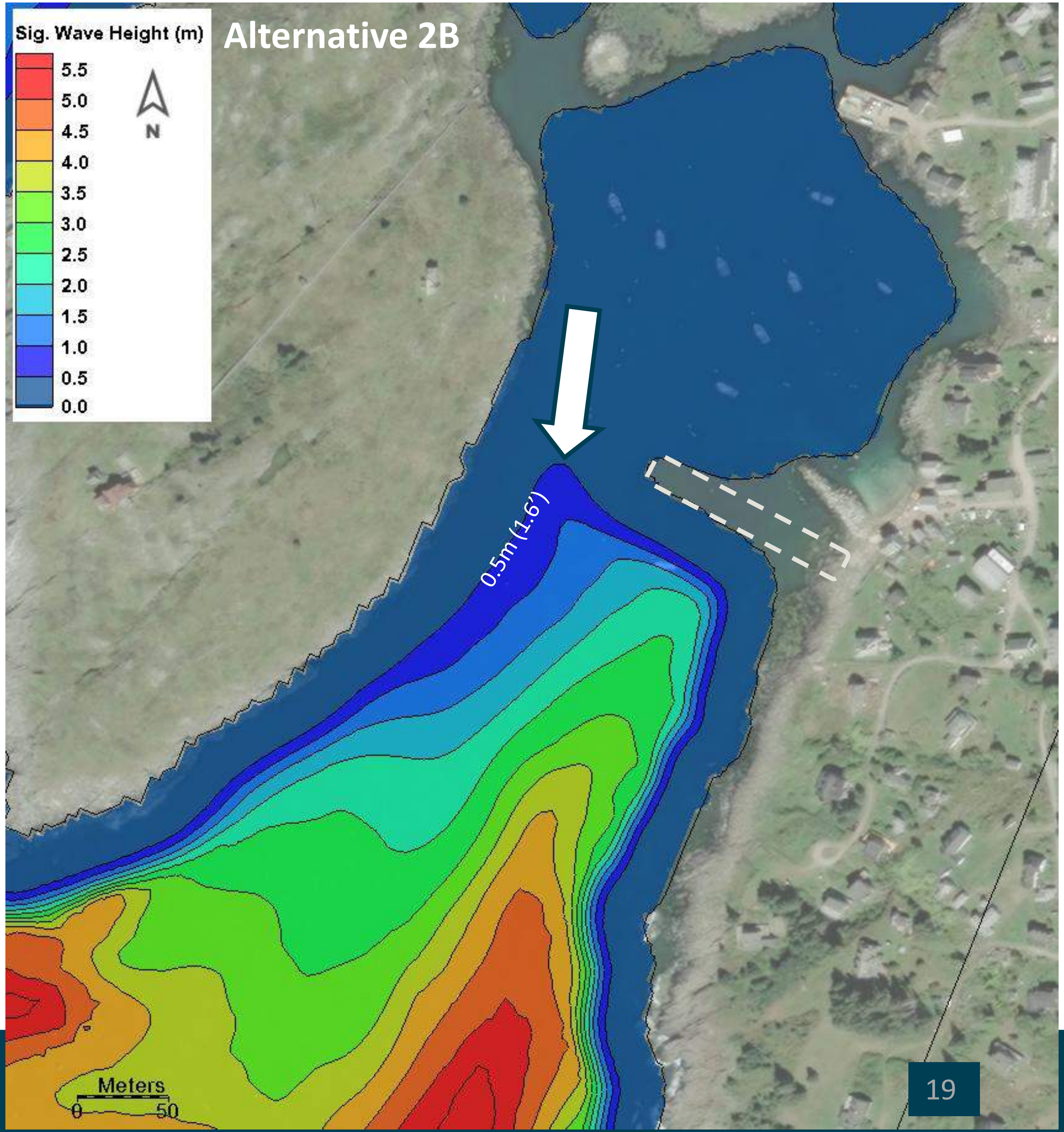
Proposed Alternative 2B

Alternative 2B

- Model Results: Irene Storm Event
  - Protection improved for Areas 1, 2, and 3 North



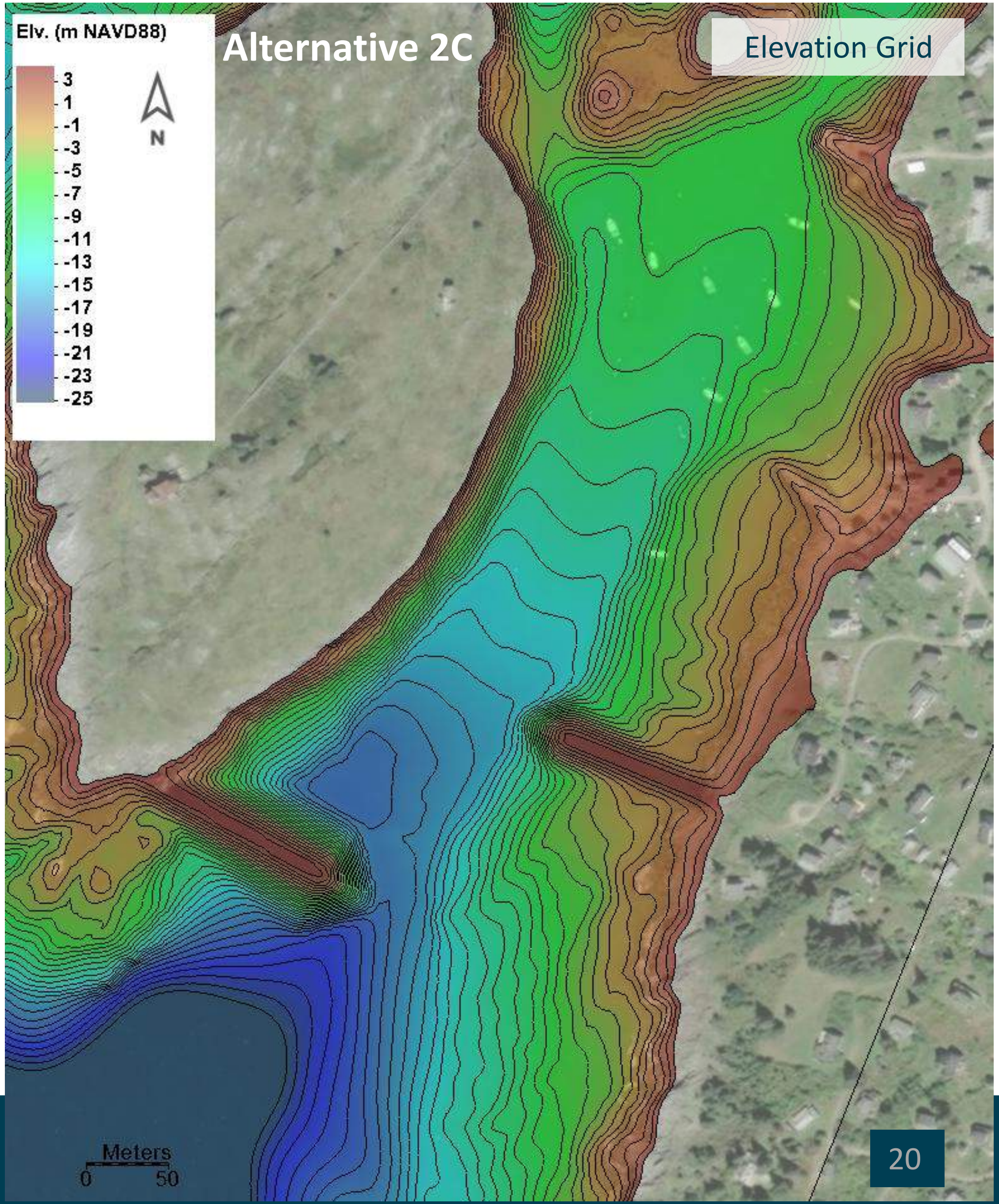

Sig. Wave Height (m)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
N
Existing Conditions
0.5m (1.6')
Meters
0
50


Sig. Wave Height (m)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
N
Alternative 2B
0.5m (1.6')
Meters
0
50

Proposed Alternative 2C

Alternative 2C

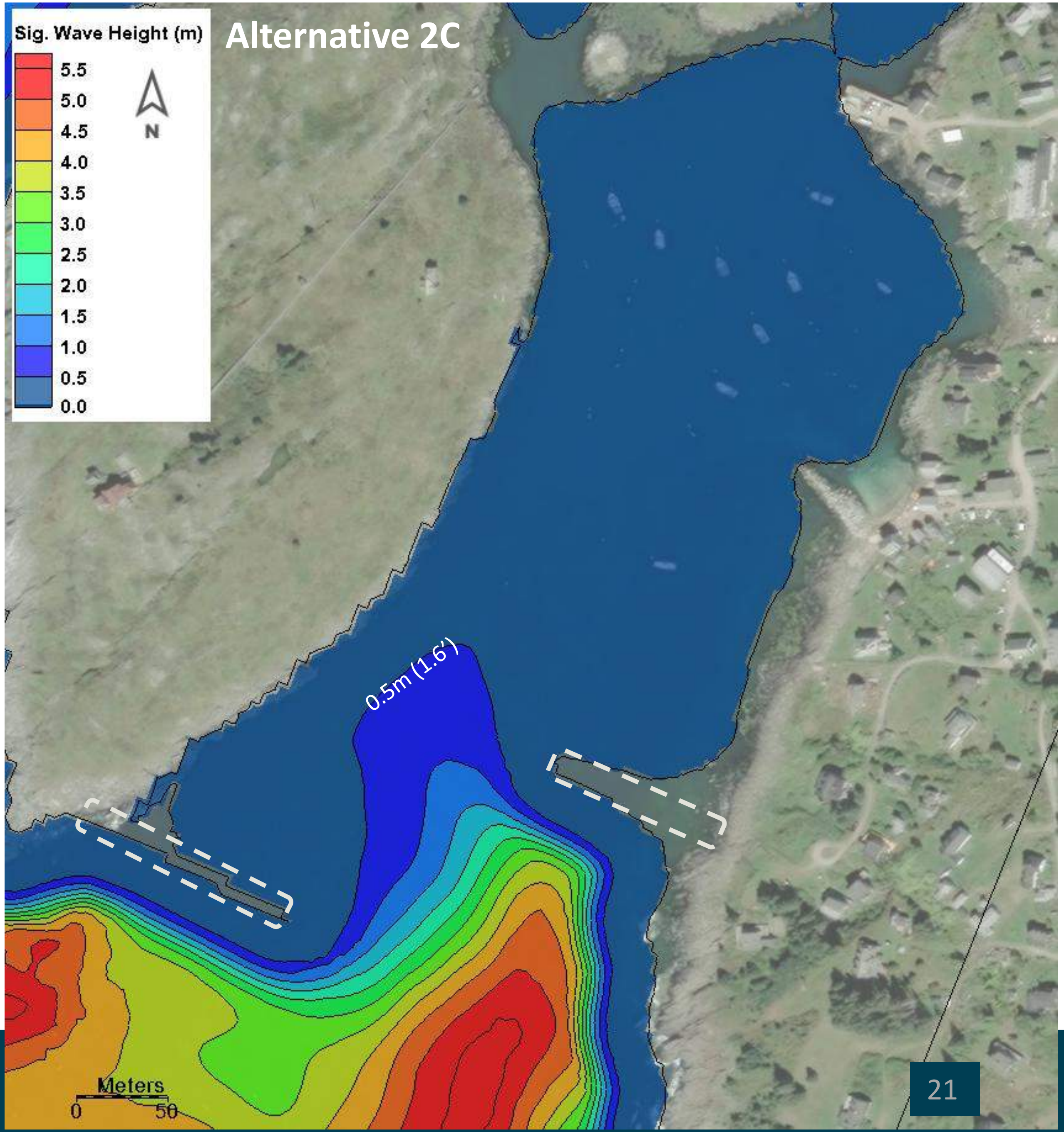
Alt.	Description	Anticipated Key Pros	Anticipated Key Cons
2C	New harbor entrance breakwater system to create largest protected area.	Wave protection to overall harbor. Secondary protection at cove with remaining existing breakwater.	Highest cost. Construction in deepest waters. Permitting and right, title, interest (RTI).



Proposed Alternative 2C

Alternative 2C

- Model Results: Irene Storm Event
  - Protection improved for all Areas



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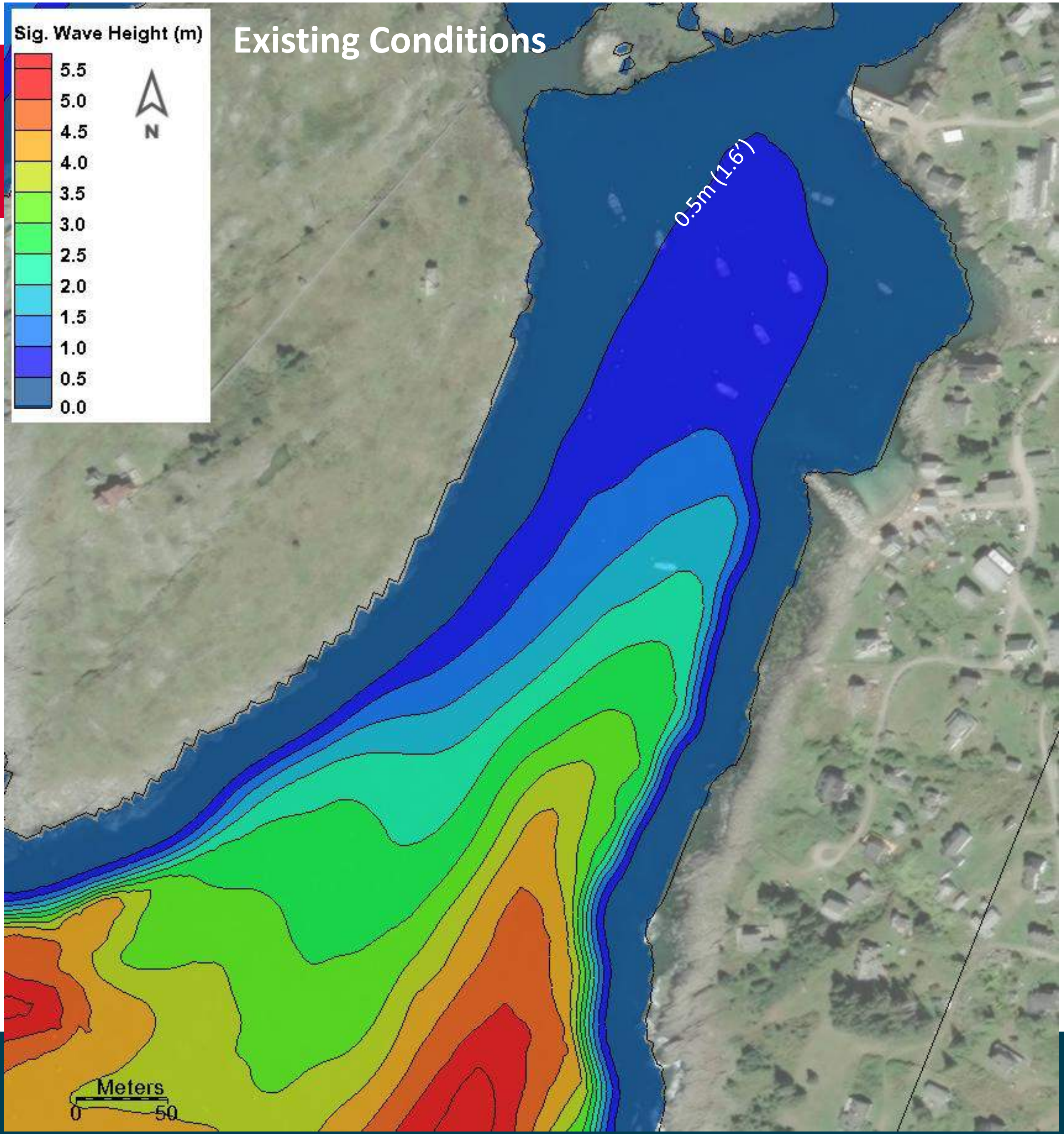
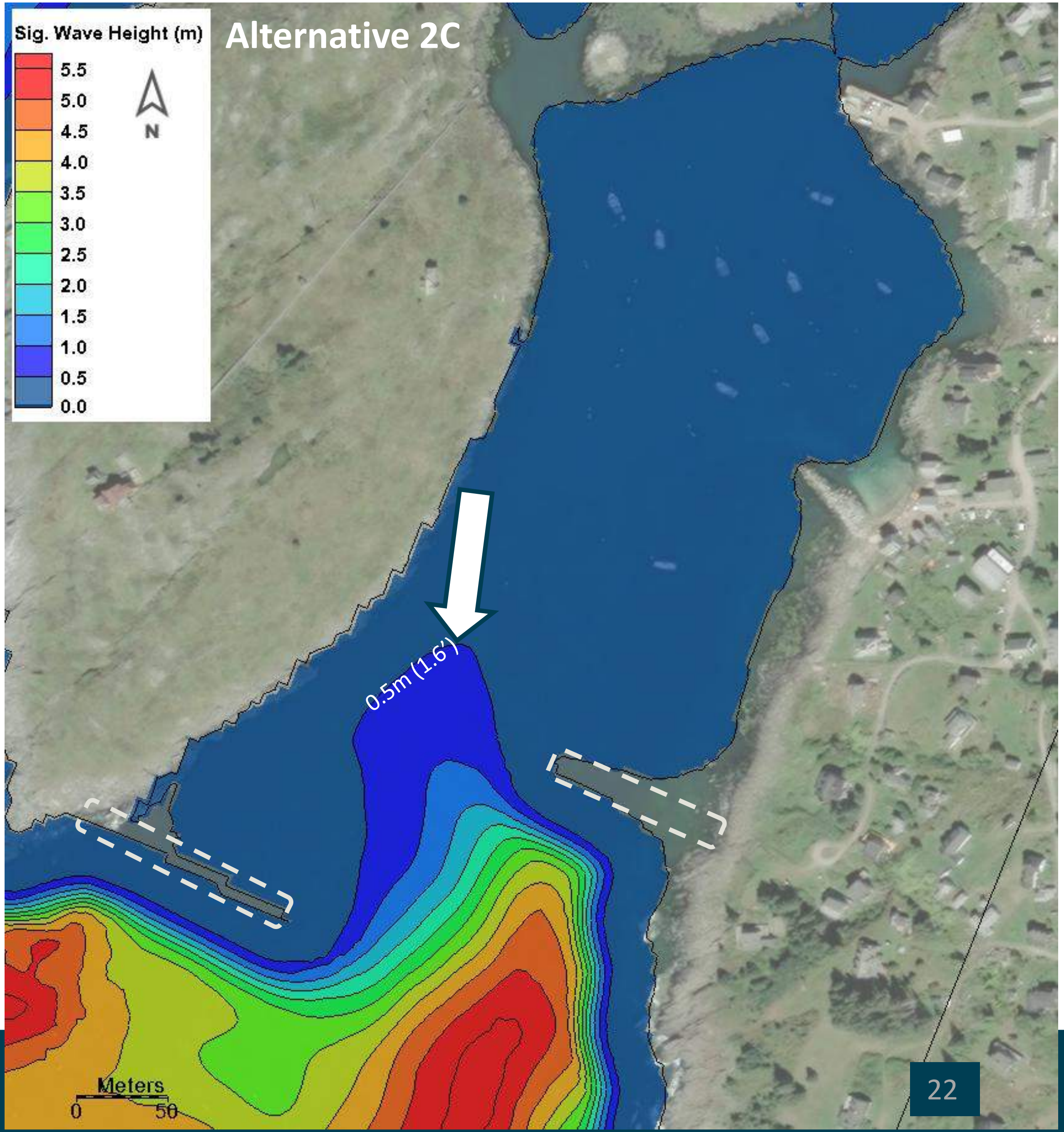
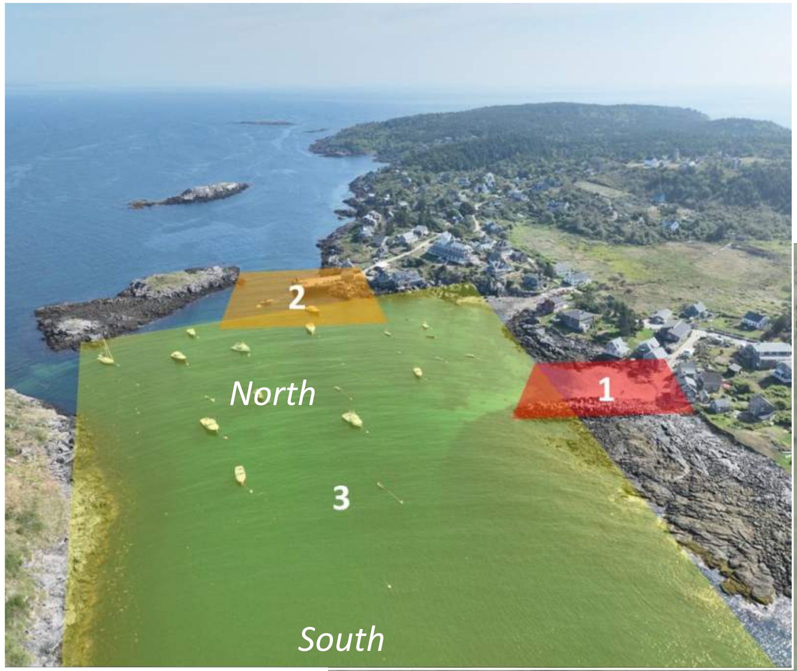

Sig. Wave Height (m)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
N
Existing Conditions
0.5m (1.6')
Meters
0
50

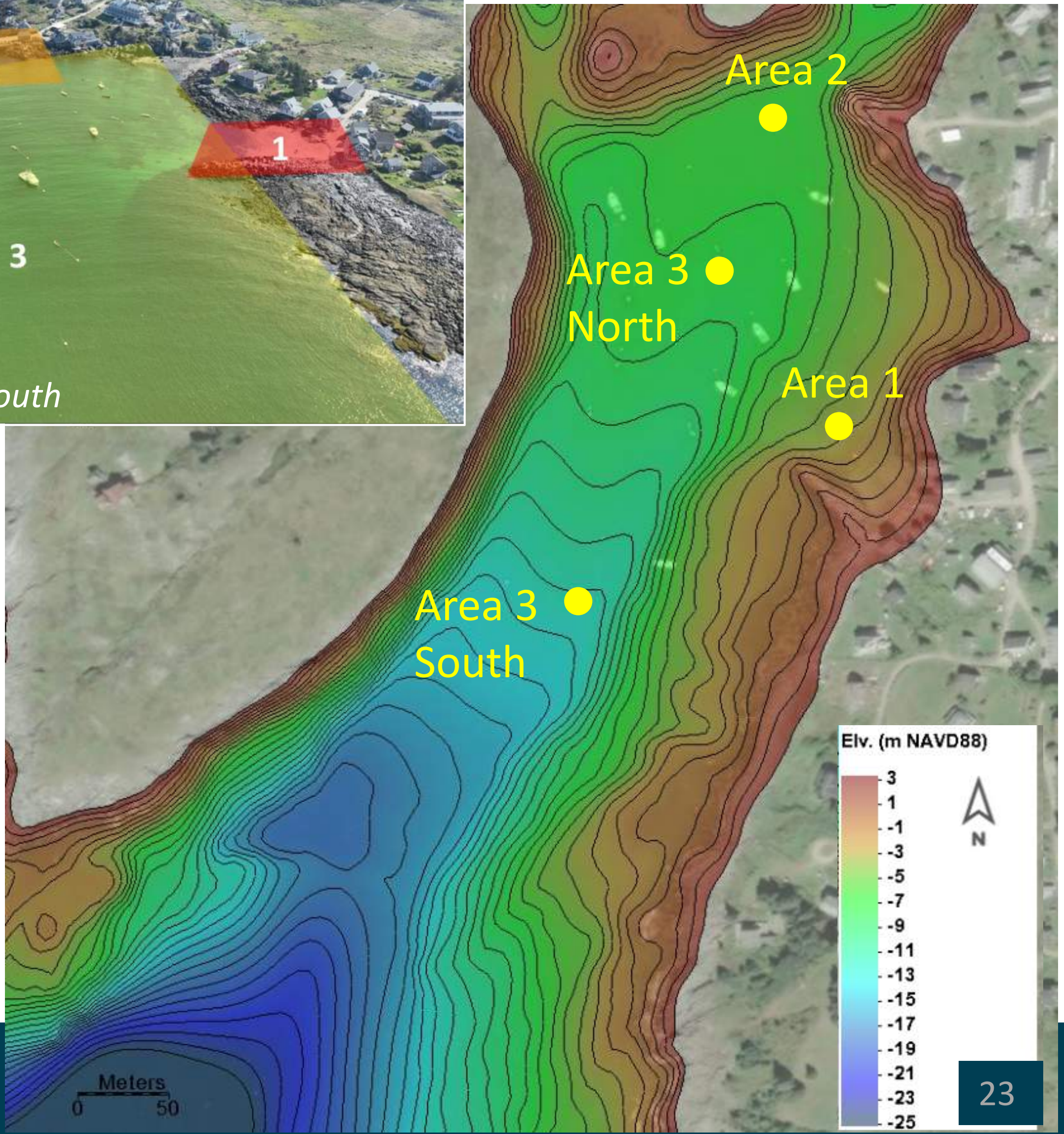

Sig. Wave Height (m)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
N
Alternative 2C
0.5m (1.6')
Meters
0
50

Relative Comparison of Sig. Wave Heights

Relative comparison of resulting significant wave heights (ft) among alternatives at Area "observation points"



"Observation points"



Significant Wave Height (ft)

Observation Point	Existing Conditions	Alt 1	Alt 2A	Alt 2B	Alt 2C
Area 1	0.2	0.1	<0.1	<0.1	<0.1
Area 2	1.3	1.1	0.4	<0.1	0.1
Area 3 North	2.1	1.9	0.5	0.1	0.2
Area 3 South	5.2	5.0	5.0	5.0	0.8

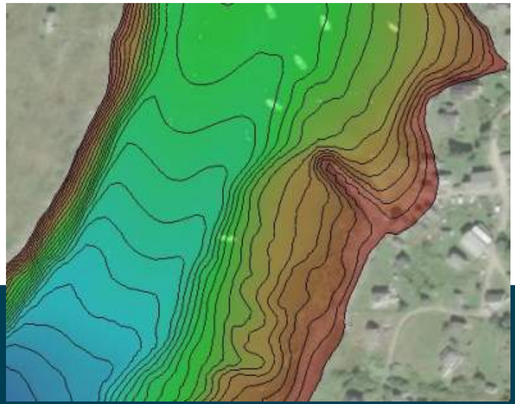
(light green)	>50% reduction in Sig. Wave Height compared to Existing Conditions
(green)	>80% reduction in Sig. Wave Height compared to Existing Conditions

Summary of Findings

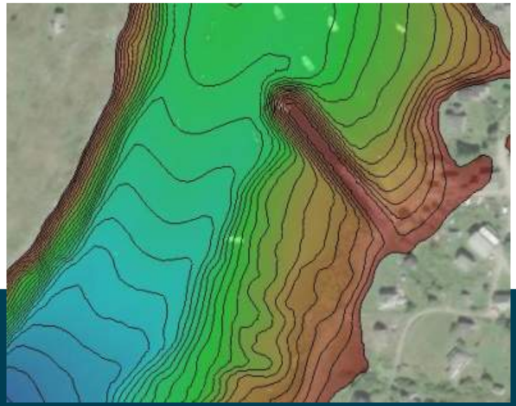
Discussion of Findings by Area

- **Area 1:** all Alts. provide mostly similar wave protection
- **Areas 2 & 3 North:** wave protection is most improved by the Alt. 2s (A, B, & C)
- **Area 3 South:** wave protection is only improved with Alt 2C

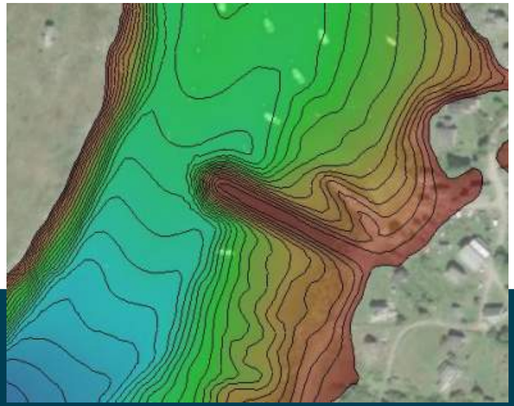
Alt 1



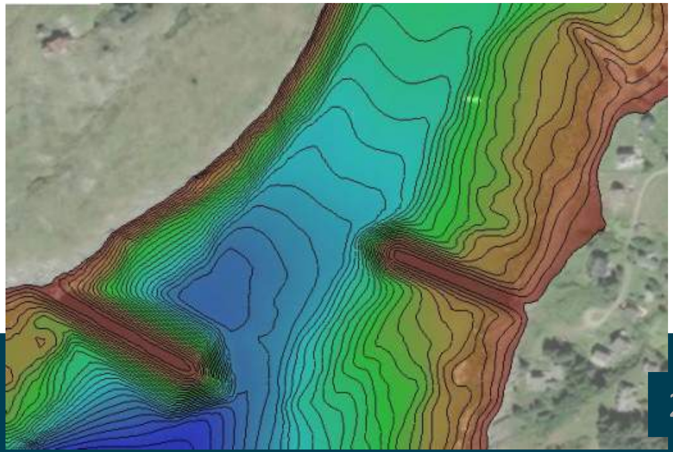
Alt 2A



Alt B



Alt 2C

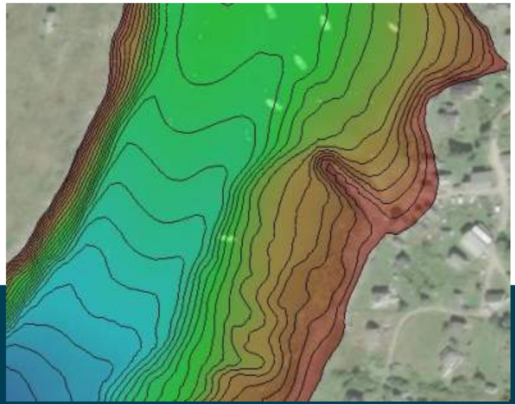


Summary of Findings

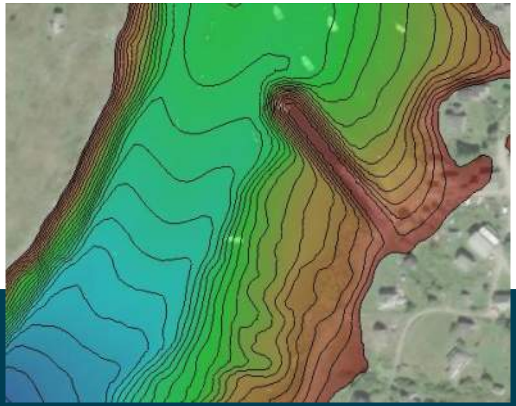
Discussion of Findings by Alternative

- **Alt 1:** wave protection is similar to existing conditions
- **Alt 2A:** mostly improves protection for Area 1 with additional benefits of protection improvement for Areas 2 & 3 North
- **Alt 2B:** provides significant protection improvement to Areas 1, 2, and 3 North
- **Alt 2C:** provides significant protection improvement to all Areas

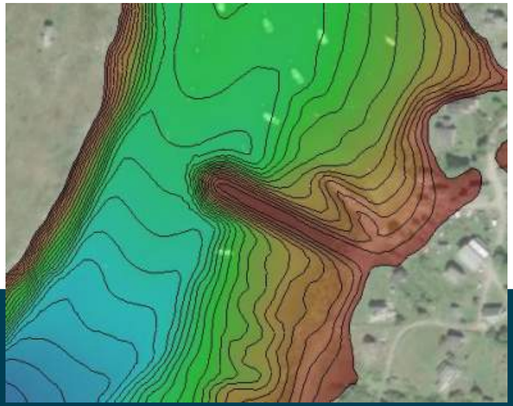
Alt 1



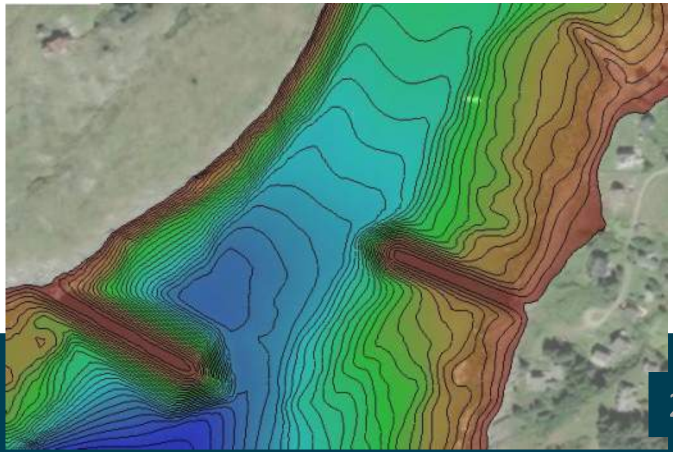
Alt 2A



Alt B



Alt 2C

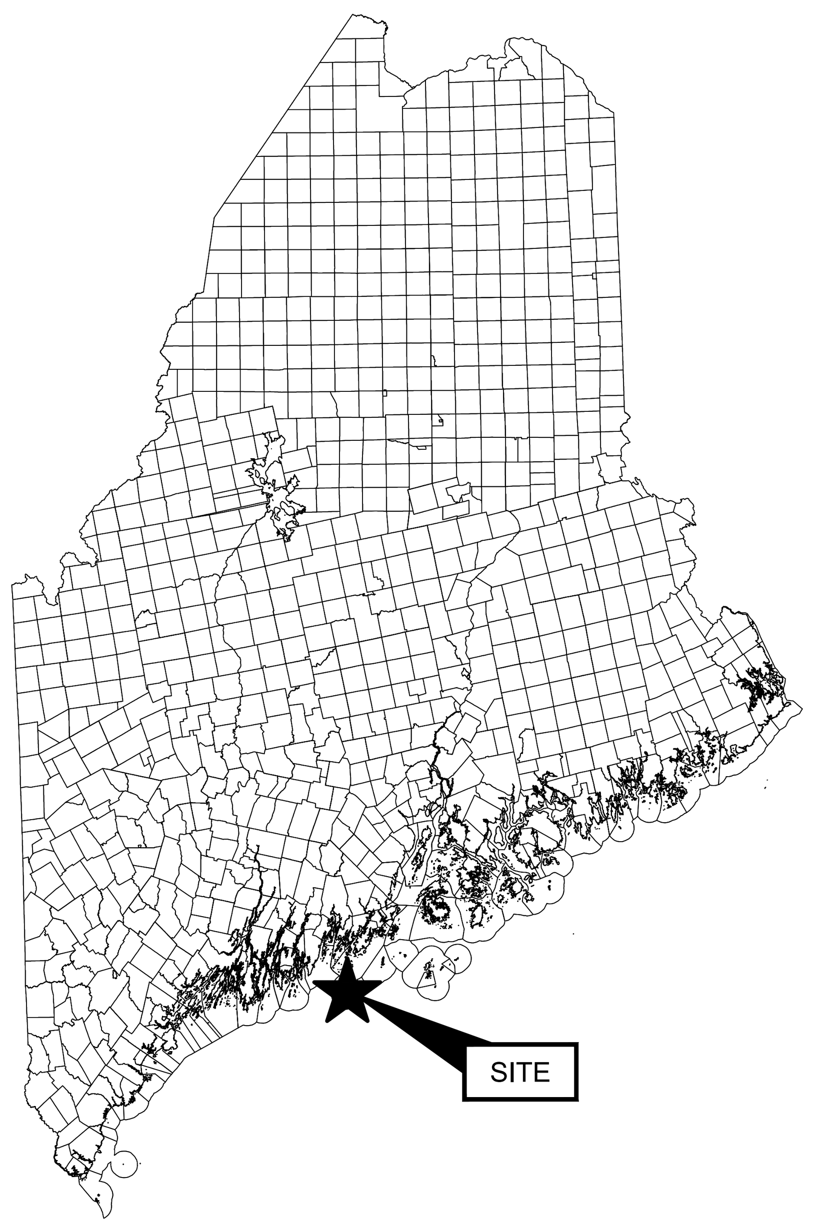


Questions?

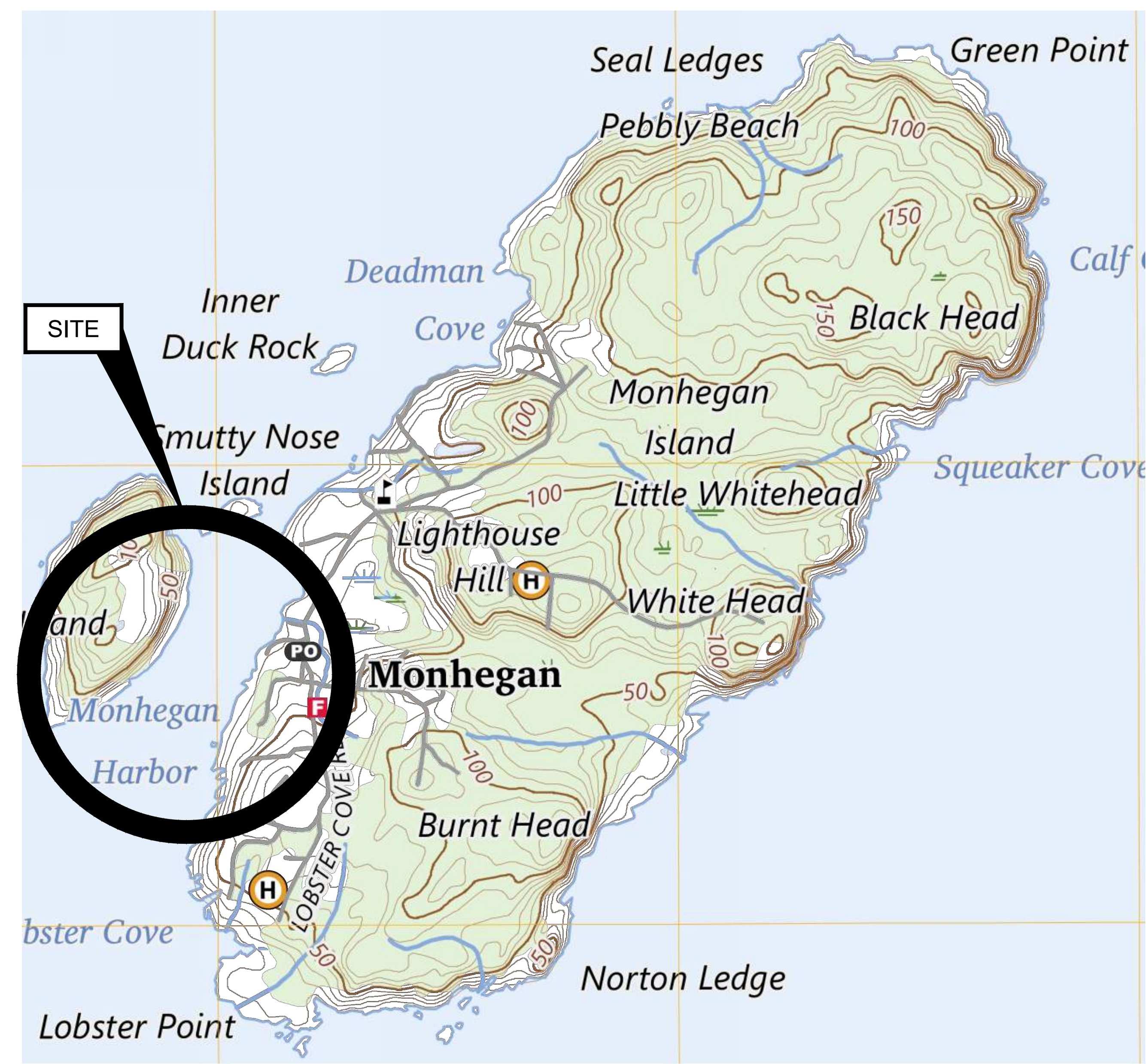
Appendix B Concept Design Plans

MONHEGAN PLANTATION
BREAKWATER CONCEPTS

MONHEGAN ISLAND, MAINE



STATE MAP
(NOT TO SCALE)



SOURCE:
2024 USGS MONHEGAN QUADRANGLE

SITE LOCATION MAP
(NOT TO SCALE)

SHEET INDEX

SHEET NO.	DRAWING NO.	TITLE
1	G-01	COVER SHEET
2	C-01	EXISTING CONDITIONS
3	C-02	BREAKWATER ALTERNATIVES
4	C-03	BREAKWATER MITIGATION PLAN - ALT 1
5	C-04	BREAKWATER PLAN - ALT 2A
6	C-05	BREAKWATER PLAN - ALT 2B
7	C-06	BREAKWATER PLAN - ALT 2C
8	C-07	TYPICAL BREAKWATER SECTIONS

PREPARED FOR:

MONHEGAN PLANTATION
MONHEGAN ISLAND, MAINE

PREPARED BY:

GEI CONSULTANTS, INC.
5 MILK STREET
PORTLAND, ME 04101
(207)797-8901

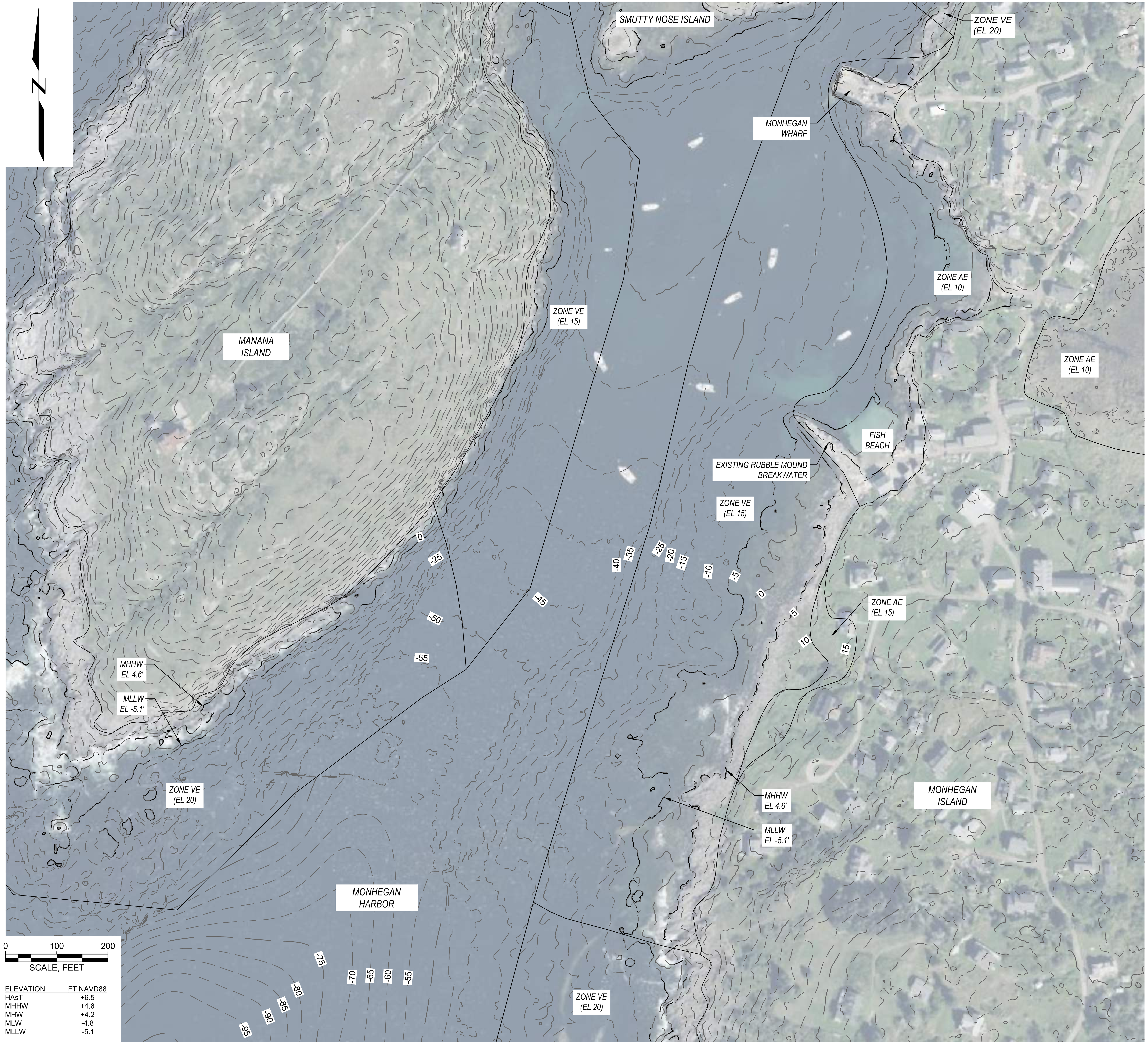
GEI Consultants

CONCEPTUAL

GEI PROJECT NO. 2505689

NO.	DATE	ISSUE/REVISION	APP
0	3/5/2026	DRAFT WORKING	

SHEET NO.
G-01



ELEVATION	FT NAVD88
HAsT	+6.5
MHHW	+4.6
MHW	+4.2
MLW	-4.8
MLLW	-5.1

* PROJECT DATUM

ELEVATION DATA

1. TOPOGRAPHIC AND BATHYMETRIC ELEVATION DATA IS MERGED SURFACE COMPRISED OF THE FOLLOWING SOURCES:
   1.1. NOAA CONTINUOUSLY UPDATED DEM
   1.2. TOPOGRAPHIC AND BATHYMETRIC SURVEY OF BREAKWATER PERFORMED BY LITTLE RIVER LAND SURVEYING IN JANUARY 2025
2. ALL ELEVATIONS ARE IN FEET NAVD88 VERTICAL DATUM.

TIDAL DATUM AND FLOOD ELEVATIONS

1. TIDAL ELEVATIONS TAKEN FROM NOAA PUBLISHED DATA USING NOAA VDATUM ONLINE TOOL.
2. HIGHEST ASTRONOMICAL TIDE (HAsT) TAKEN FROM THE MAINE DEPARTMENT OF AGIRCULTURE, CONSERVATION, AND FORESTRY, MAINE GEOLOGICAL SURVEY (MGS) PUBLISHED VALUES FOR MONHEGAN ISLAND.
3. FEMA BFE TAKEN FROM FLOOD INSURANCE RATE MAPS OF MONHEGAN ISLAND, EFFECTIVE JULY 16, 2015.

CONCEPTUAL

GEI Consultants
GEI CONSULTANTS, INC.
5 MILK STREET
PORTLAND, ME 04101
(207)797-8901

MONHEGAN PLANTATION

MONHEGAN ISLAND, MAINE

MONHEGAN PLANTATION BREAKWATER CONCEPTS

MONHEGAN ISLAND, MAINE

DRAFT

P.E. No.:	
Approved:	LCV
Checked:	KW
Drawn:	JAG/JLD
Designed:	JAG/KW
GEI Project	2505689

Attention:
0 1"
If this scale bar does not measure 1" then drawing is not original scale.

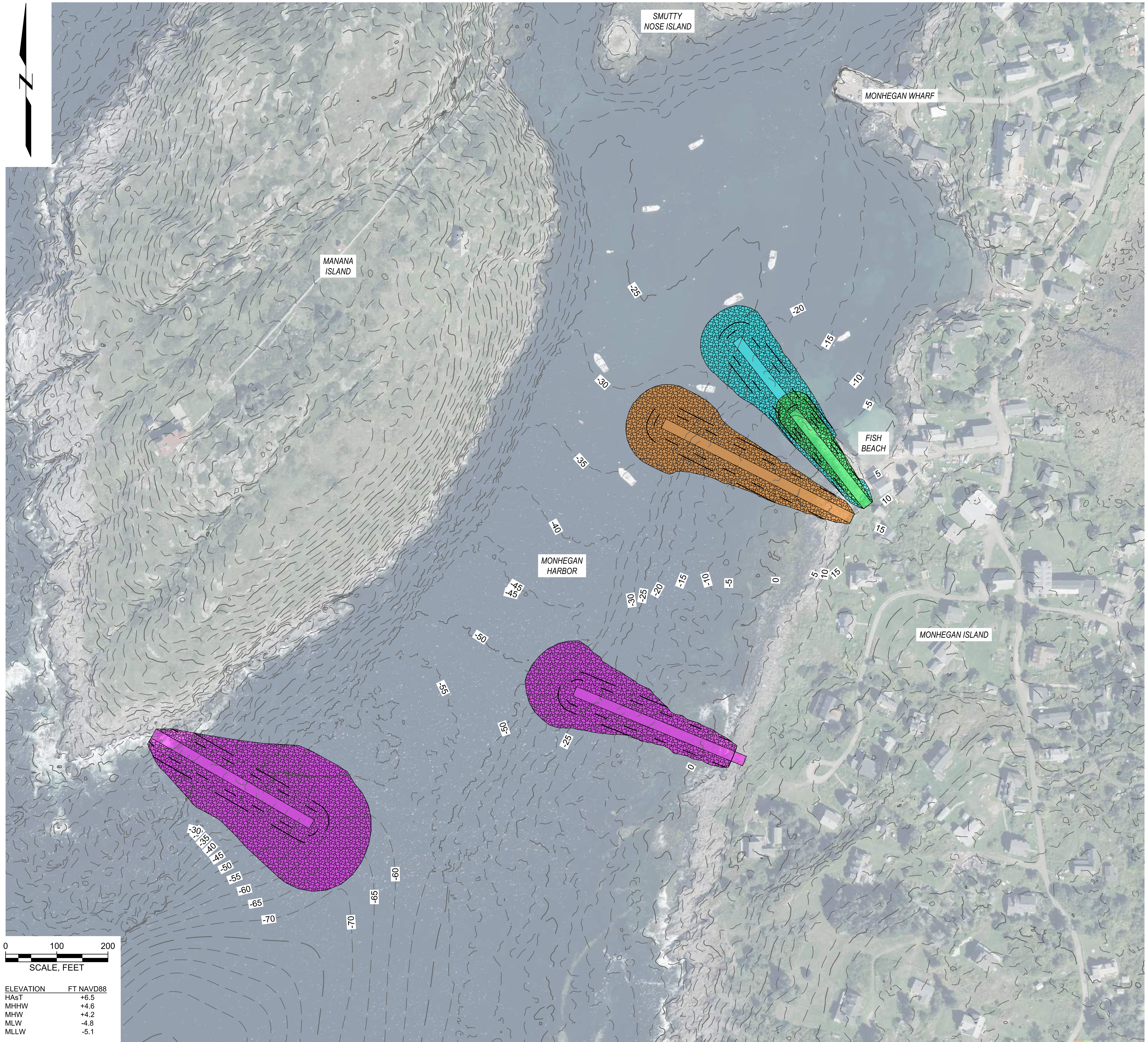
NO.	DATE	ISSUE/REVISION	APP
0	4/29/2026	CONCEPT DESIGN	LCV

SHEET NAME

EXISTING CONDITIONS

SHEET NO.

C-01



ELEVATION	FT NAVD88
HAsT	+6.5
MHHW	+4.6
MHW	+4.2
MLW	-4.8
MLLW	-5.1

* PROJECT DATUM

ELEVATION DATA

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   1.2. TOPOGRAPHIC AND BATHYMETRIC SURVEY OF BREAKWATER PERFORMED BY LITTLE RIVER LAND SURVEYING IN JANUARY 2025
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TIDAL DATUM AND FLOOD ELEVATIONS

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3. FEMA BFE TAKEN FROM FLOOD INSURANCE RATE MAPS OF MONHEGAN ISLAND, EFFECTIVE JULY 16, 2015.

- BREAKWATER ALT 1
- BREAKWATER ALT 2A
- BREAKWATER ALT 2B
- BREAKWATER ALT 2C

GEI Consultants
GEI CONSULTANTS, INC.
5 MILK STREET
PORTLAND, ME 04101
(207)797-8901

MONHEGAN PLANTATION

MONHEGAN ISLAND, MAINE

MONHEGAN PLANTATION BREAKWATER CONCEPTS

MONHEGAN ISLAND, MAINE

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Designed:	JAG/KW
GEI Project	2505689

Attention: 0 1"
If this scale bar does not measure 1" then drawing is not original scale.

NO.	DATE	ISSUE/REVISION	APP
0	4/29/2026	CONCEPT DESIGN	LCV

SHEET NAME

BREAKWATER ALTERNATIVES

SHEET NO.

C-02

CONCEPTUAL

0 20 40
SCALE, FEET

ELEVATION	FT NAVD88
HAsT	+6.5
MHHW	+4.6
MHW	+4.2
MLW	-4.8
MLLW	-5.1

* PROJECT DATUM

NOTES:
1. BREAKWATER DIMENSIONS AND GEOMETRY ARE CONCEPTUAL ONLY, AND SUBJECT TO CHANGE BASED ON FUTURE DETAILED DESIGN EFFORTS.

CONCEPTUAL

GEI Consultants
GEI CONSULTANTS, INC.
5 MILK STREET
PORTLAND, ME 04101
(207)797-8901

MONHEGAN PLANTATION

MONHEGAN ISLAND, MAINE

MONHEGAN PLANTATION BREAKWATER CONCEPTS

MONHEGAN ISLAND, MAINE

DRAFT

P.E. No.:	
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Designed:	JAG/KW
GEI Project	2505689

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0 1"
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NO.	DATE	ISSUE/REVISION	APP
0	4/29/2026	CONCEPT DESIGN	LCV

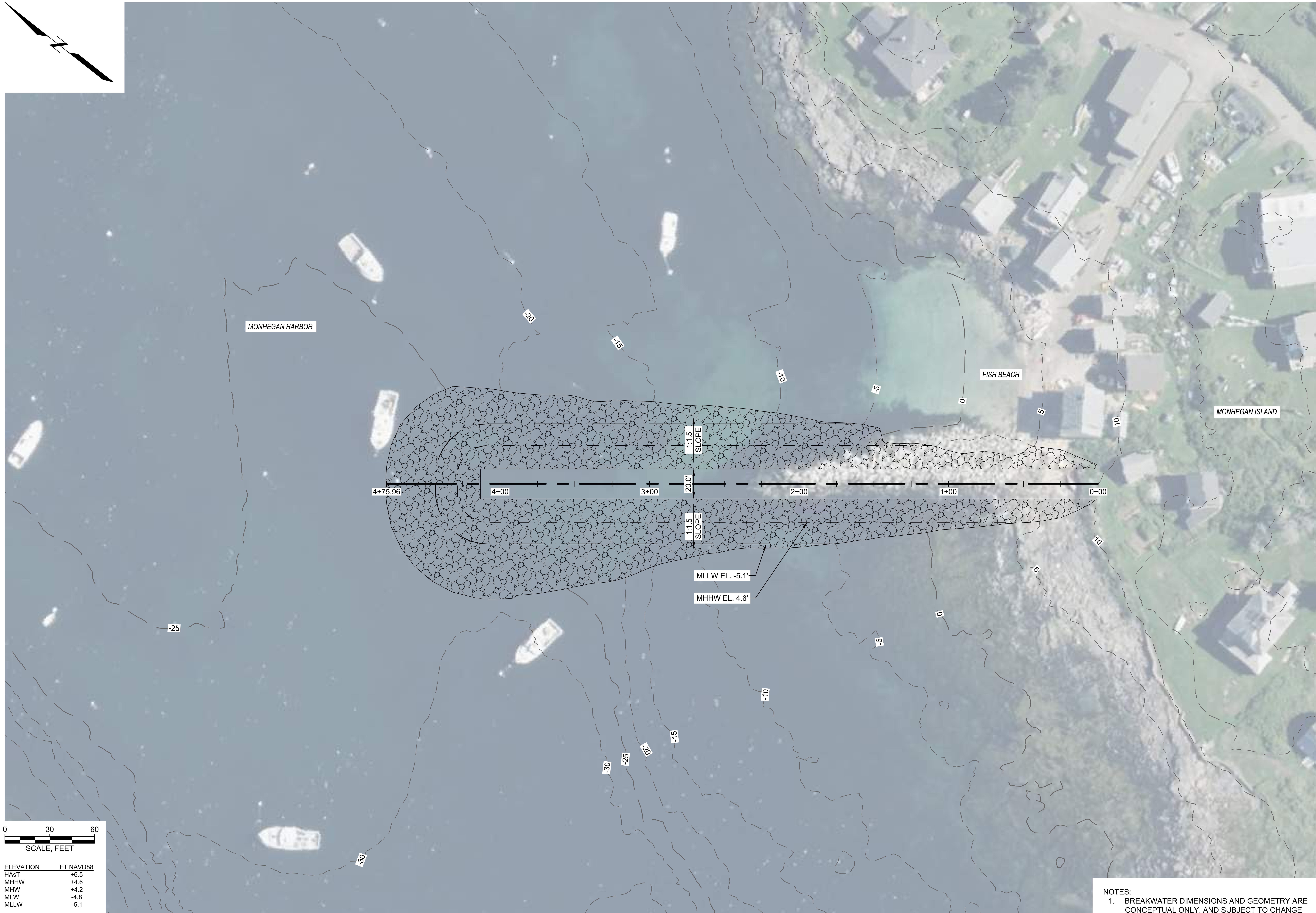
SHEET NAME

BREAKWATER MITIGATION PLAN - ALT 1

SHEET NO.

C-03

GAREAU, JOHN \\geiconsultants.com\data\Data_Storage\Working\MONHEGAN PLANTATION\2505689 Monhegan Breakwater\00_CAD\Design\Sheets\2505689_C-03 BREAKWATER MITIGATION PLAN - ALT 1.dwg - 4/29/2026



0 30 60
SCALE, FEET

ELEVATION	FT NAVD88
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MHHW	+4.6
MHW	+4.2
MLW	-4.8
MLLW	-5.1

* PROJECT DATUM

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CONCEPTUAL

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5 MILK STREET
PORTLAND, ME 04101
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MONHEGAN PLANTATION

MONHEGAN ISLAND, MAINE

MONHEGAN PLANTATION BREAKWATER CONCEPTS

MONHEGAN ISLAND, MAINE

DRAFT

P.E. No.:	
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Checked:	KW
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Designed:	JAG/KW
GEI Project	2505689

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0 1"
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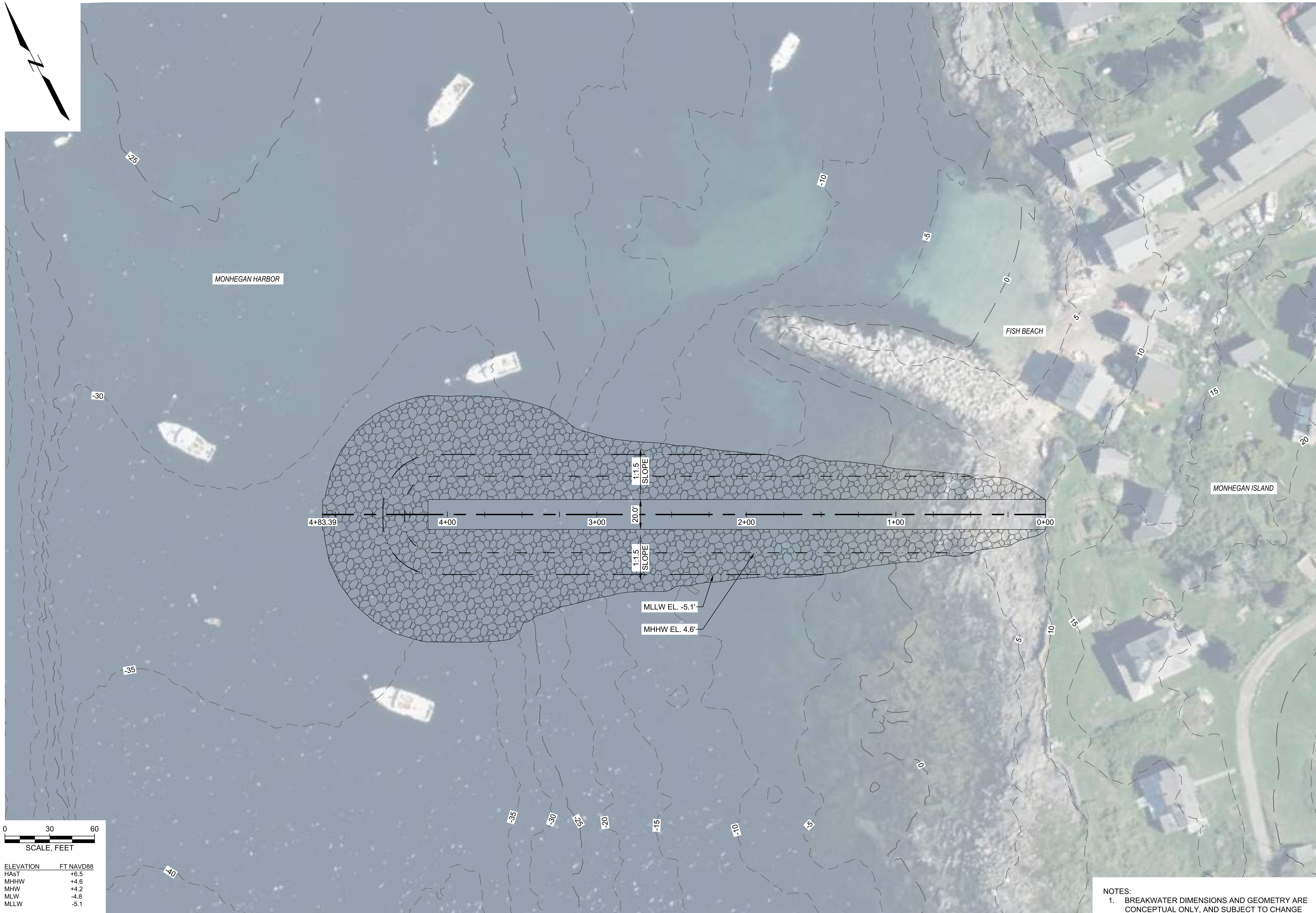
NO.	DATE	ISSUE/REVISION	APP
0	4/29/2026	CONCEPT DESIGN	LCV

SHEET NAME

BREAKWATER PLAN - ALT 2A

SHEET NO.

C-04



0 30 60
SCALE, FEET

ELEVATION	FT NAVD88
HAsT	+6.5
MHHW	+4.6
MHW	+4.2
MLW	-4.8
MLLW	-5.1

* PROJECT DATUM

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5 MILK STREET
PORTLAND, ME 04101
(207)797-8901

MONHEGAN PLANTATION

MONHEGAN ISLAND, MAINE

MONHEGAN PLANTATION BREAKWATER CONCEPTS

MONHEGAN ISLAND, MAINE

DRAFT

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Checked:	KW
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Designed:	JAG/KW
GEI Project	2505689

Attention:
0 1"
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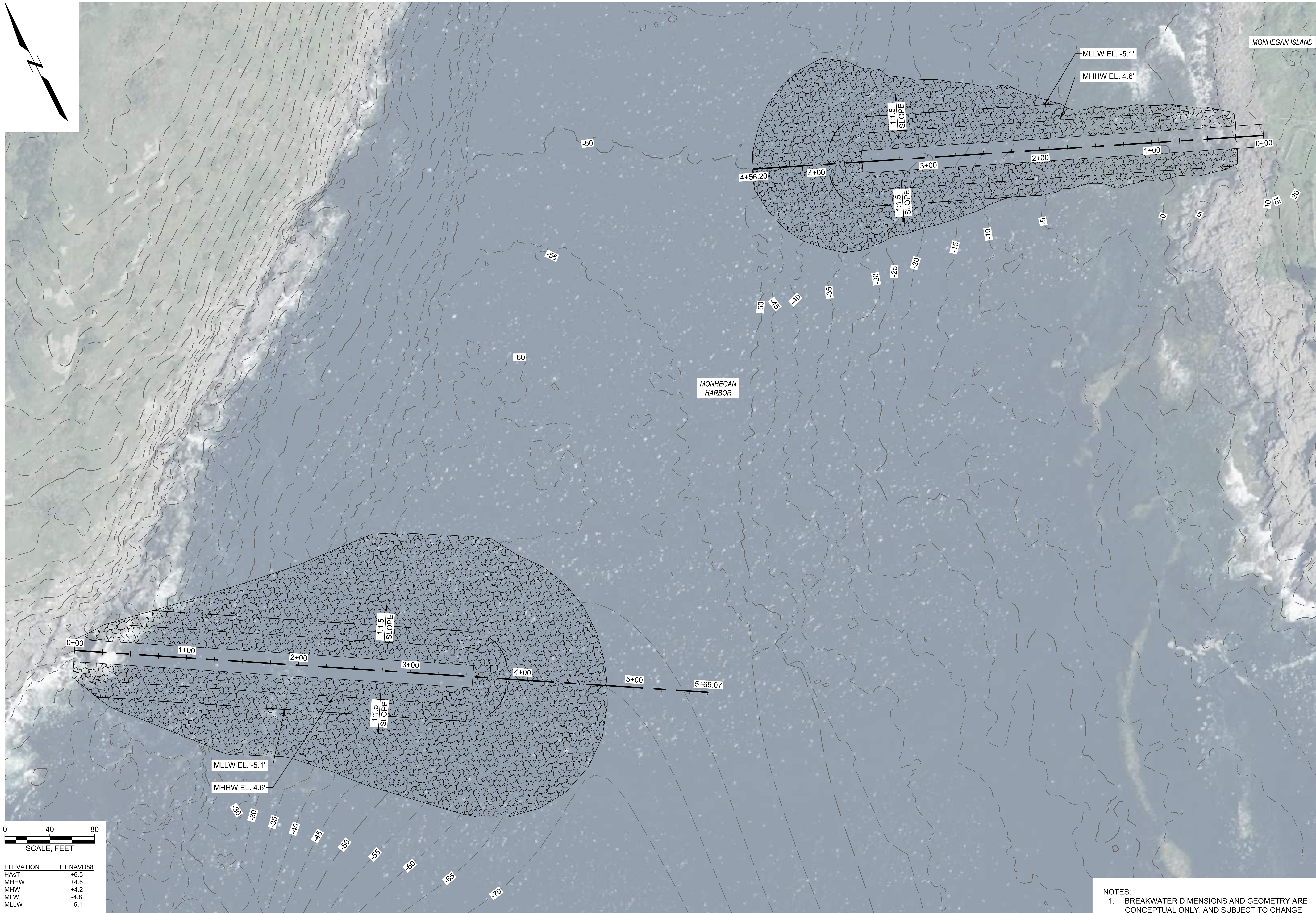
NO.	DATE	ISSUE/REVISION	APP
0	4/29/2026	CONCEPT DESIGN	LCV

SHEET NAME

BREAKWATER PLAN - ALT 2B

SHEET NO.

C-05



0 40 80
SCALE, FEET

ELEVATION	FT NAVD88
HAsT	+6.5
MHHW	+4.6
MHW	+4.2
MLW	-4.8
MLLW	-5.1

* PROJECT DATUM

NOTES:
1. BREAKWATER DIMENSIONS AND GEOMETRY ARE CONCEPTUAL ONLY, AND SUBJECT TO CHANGE BASED ON FUTURE DETAILED DESIGN EFFORTS.

CONCEPTUAL

GEI Consultants
GEI CONSULTANTS, INC.
5 MILK STREET
PORTLAND, ME 04101
(207)797-8901

MONHEGAN PLANTATION

MONHEGAN ISLAND, MAINE

MONHEGAN PLANTATION BREAKWATER CONCEPTS

MONHEGAN ISLAND, MAINE

DRAFT

P.E. No.:	
Approved:	LCV
Checked:	KW
Drawn:	JAG/JLD
Designed:	JAG/KW
GEI Project	2505689

Attention:
0 1"
If this scale bar does not measure 1" then drawing is not original scale.

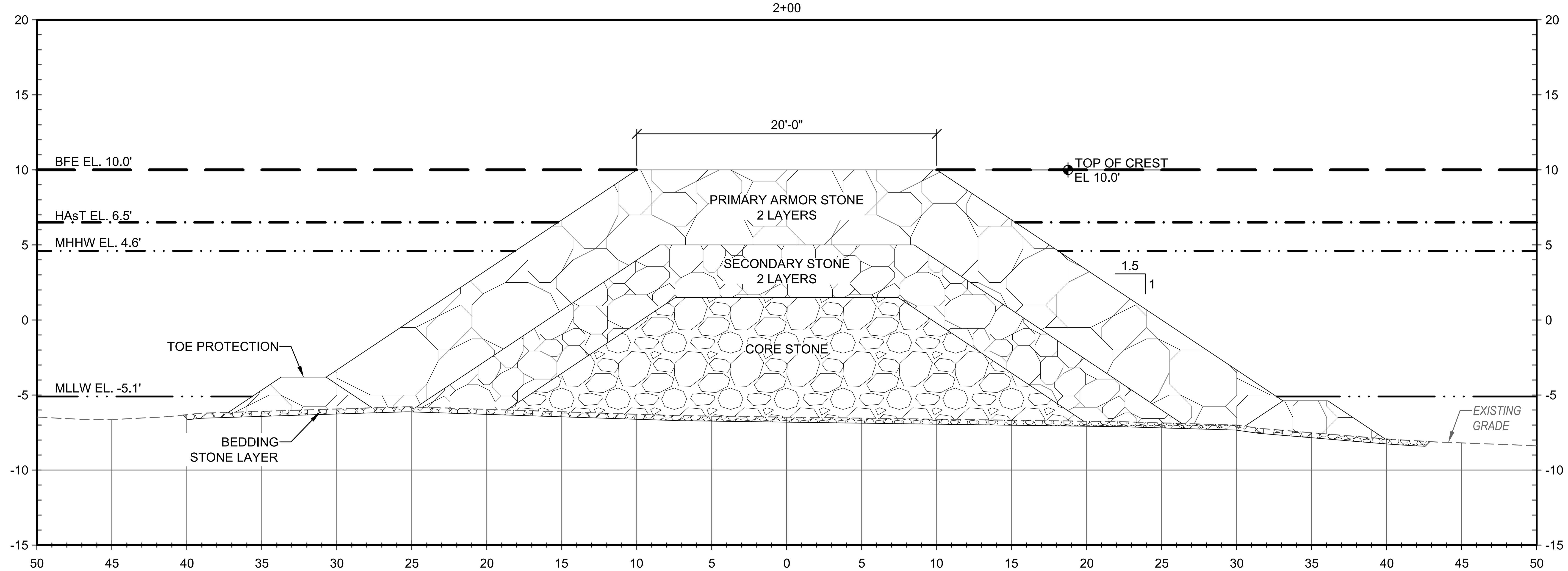
NO.	DATE	ISSUE/REVISION	APP
0	4/29/2026	CONCEPT DESIGN	LCV

SHEET NAME

BREAKWATER PLAN - ALT 2C

SHEET NO.

C-06

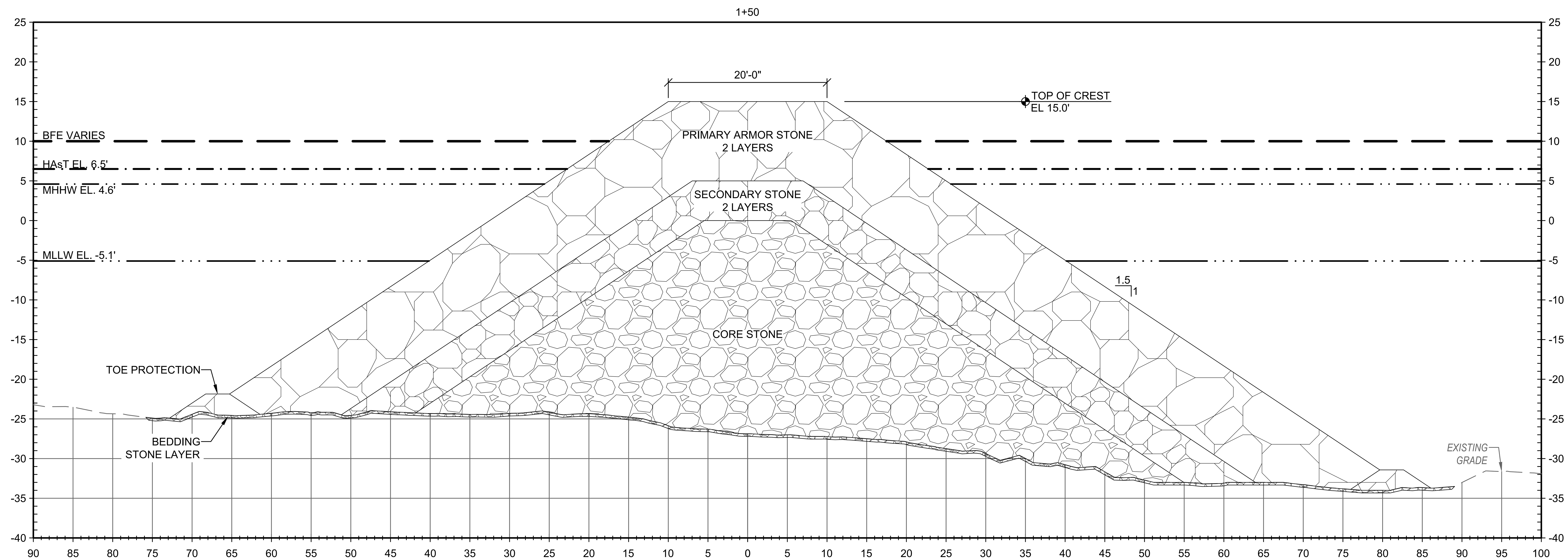


0 2.5 5 10

SCALE, FEET

ALTERNATIVE 1 BREAKWATER

(CREST EL. AT +10 FT NAVD88) SCALE: 1" = 5'



0 4 8 16

SCALE, FEET

ALTERNATIVE 2 BREAKWATER
OPTIONS A, B, C

(CREST EL. AT +15 FT NAVD88) SCALE: 1" = 8'

ELEVATION	FT NAVD88
HAsT	+6.5
MHHW	+4.6
MHW	+4.2
MLW	-4.8
MLLW	-5.1

* PROJECT DATUM

NOTES:
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CONCEPTUAL

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GEI CONSULTANTS, INC.
5 MILK STREET
PORTLAND, ME 04101
(207)797-8901

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Attention:
0 1"
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0	4/29/2026	CONCEPT DESIGN	LCV

SHEET NAME

TYPICAL BREAKWATER SECTIONS

SHEET NO.

C-07