ERDC/CHL TR-20-12

Coastal and Hydraulics Laboratory

US Army Corps
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Investigation of Shoaling in the Federal Navigation Channel, Waukegan Harbor, Illinois

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Final report

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Abstract

Persistent and excessive shoaling occurs in the Outer Harbor and Approach Channel of the Waukegan Harbor, Illinois. This report describes a numerical modeling study performed for the US Army Corps of Engineers, Chicago District, to evaluate the existing harbor and 11 structural alternatives for three crest elevations. This report provides details of numerical modeling study, analysis of field data, and estimates of shoaling. The focus of the study is the investigation of a variety of structural solutions intercepting and/or diverting sediments to reduce shoaling in the navigation channel. These include breakwaters, groins, spurs, and structural extensions with varying length and crest elevation connecting to the north beach and existing north breakwater. Estimates of both shoaling volume and height are developed with and without project using an integrated wave-flow-sediment transport numerical modeling approach. Quantitative reduction estimates are provided for each structural alternative investigated.

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Preface

This study was conducted for the US Army Corps of Engineers (USACE), Chicago District (LRC), Program Element No. 280H46, and performed by the Coastal and Hydraulics Laboratory (CHL) of the US Army Engineer Research and Development Center (ERDC).

At the time the study was completed, Mr. Eddie Wiggins was the Technical Director of the Navigation Program. The general administrative supervision was provided by Mr. James Gutshall, Chief, Harbors, Entrances, and Structures Branch, and Dr. Jacqueline Pettway, Chief, Navigation Division.

At the time of publication of this report, Mr. Jeffrey R. Eckstein was the Deputy Director of CHL, and Dr. Ty V. Wamsley was the Director.

COL Teresa A. Schlosser was Commander of ERDC, and the Director was Dr. David W. Pittman.

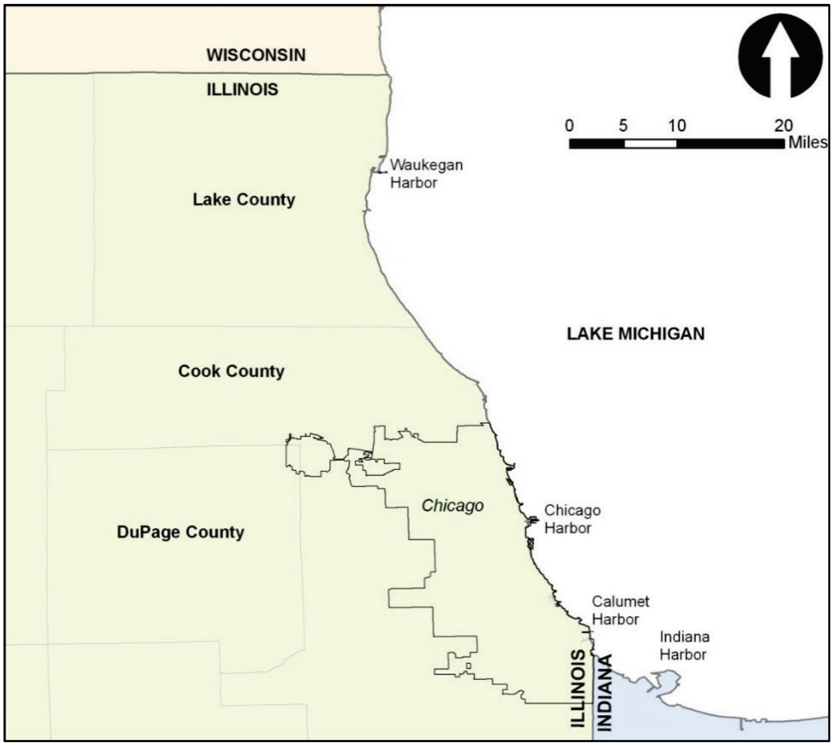
1 Introduction

1.1 Background

1.1.1 Location of study area

Waukegan Harbor, Illinois, is located in Waukegan, Illinois, in Northern Lake County on the western shore of Lake Michigan approximately 64 km[*] (40 miles) north of Chicago, Illinois, and 16 km (10 miles) south of the Illinois-Wisconsin state line. The harbor is approximately 8 km (5 miles) south of Illinois Beach State Park and is used for industrial and recreational activities. It is a federal navigation project maintained by the US Army Corps of Engineers (USACE), Chicago District (LRC). Figure 1-1 shows the location of study area on a map.

Figure 1-1. Location of Waukegan Harbor.



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[*] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

1.1.2 History of site

The US Congress authorized a navigation project for Waukegan Harbor in the Rivers and Harbors Act of 1880 and modified it later through the Rivers and Harbors Acts of 1882, 1902, 1930, 1945, 1965, and 1970. The Waukegan Harbor site development by the USACE started with construction of a breakwater in 1852, and a dredged channel, a basin, and a harbor with pile piers were added in 1880. Substantial improvements made in 1902 included construction of an outer breakwater, a shore connection structure, entrance piers, and inner harbor revetment. After widening and deepening of the harbor and approach channel between 1945 and 1965, the present configuration of harbor and navigation channel have not changed since 1966.

1.1.3 Project description

Figure 1-2 shows four key parts of this harbor: “Inner Harbor,” “Outer Harbor,” “Approach Channel,” and “Advanced Maintenance Area.” These are designated by polygons that show approximate coverage area of each.

Figure 1-2. A sketch of Inner Harbor, Outer Harbor, Approach Channel, and Advanced Maintenance Area of Waukegan Harbor.

Three structures are present in the existing Waukegan Harbor (Figure 1-2). These include two parallel entrance jetties that form a narrow entrance to the interior of harbor. This Inner Harbor section represents the innermost basin of the Waukegan Harbor with a narrow navigation channel protected by two parallel entrance jetties. The Inner Harbor is approximately 915 m (3,000 ft) long, and its narrow channel width ranges from 55 m (180 ft) to 113 m (370 ft). Approximate lengths of the north and south entrance jetties and outer breakwater are 325 m (1,000 ft), 983 m (3,225 ft), and 580 m (1,900 ft), respectively. The Inner Harbor requires little dredging maintenance because it is sheltered from the effects of waves, currents, and sediments. The navigation channel depth in the Inner Harbor is 5.5 m (18 ft) and transitions to 6.7 m (22 ft) in the Outer Harbor and Approach Channel. The outer breakwater was designed to the north of entrance to protect the Outer Harbor and Approach Channel. All depths in this report are referenced to the Lake Michigan low water datum (LWD) (LWD = 176.02 m [577.5 ft]) based on the International Great Lakes Datum of 1985 (IGLD 85).

The Outer Harbor in Figure 1-2 refers to the area outside of the parallel entrance jetties of the inner harbor. The width of the maintained navigation channel in the Outer Harbor increases from 55 m (180 ft) to 137 m (450 ft). The Outer Harbor is approximately 320 m (1,050 ft) long and protected by an outer breakwater, also known as the North Breakwater (NB), to the north. The Outer Harbor connects to the Approach Channel west of the NB, and part of the Approach Channel extends beyond the NB, terminating in Lake Michigan. The Approach Channel is approximately 550 m (1,800 ft) long. It has a uniform channel width that varies from 137 m (450 ft) to 152 m (500 ft). The Advanced Maintenance Area is located north of the Approach Channel and east of the NB. The Advanced Maintenance area is part of the Waukegan Harbor O&M (Operations & Maintenance) plan by LRC.

For Waukegan Harbor to be an economically viable commercial port, it needs periodic maintenance dredging to maintain authorized depths for commercial shipping. Tonnage levels at Waukegan Harbor were relatively steady prior to 2008. However, a significant reduction in tonnage starting in 2010 was attributed to (1) changes in shipping patterns in Lake Michigan and (2) increased shoaling in the Approach Channel and Outer Harbor. Waukegan Harbor has been closed to shipping in recent years due to the Approach Channel being blocked by shoals emerging during storms. Because vessels at Waukegan Harbor were unable to load to their optimal drafts, these closures forced tonnages to be diverted to other harbors or to use of different transportation modes. These unplanned closures increased the number of vessel trips and therefore the cost and risk of shipping as well. If the chronic shoaling in the Approach Channel is not addressed, the present tonnages at Waukegan Harbor will continue to decrease, and remaining tonnage will have to be diverted to more costly waterways or land routes. This is the primary motivation for LRC to initiate the present numerical modeling study to investigate potential causes (environmental forcings) and remedies (structural measures) at Waukegan Harbor as part of a broader Section 107 navigation study.

1.1.4 Channel shoaling

Figure 1-2 shows the existing Waukegan Harbor has a direct exposure to waves and currents of Lake Michigan. Wind-generated waves affect this harbor from the north to south (180 deg) sector of the lake. Sedimentation from north, northeast, east, southeast, and south directions contribute to the channel shoaling. The combination of large waves and strong currents can mobilize excessive sediment volumes, disrupting navigation and port operations. Dredging records from 1977 to 2015 (Table 1-1) indicate a persistent infilling of the approach channel that increases the annual maintenance dredging requirements at Waukegan Harbor. The average annual dredging is approximately 30,600 m^3/yr (40,000 cy/yr).

Table 1-1. Dredging volumes at *Waukegan* Harbor (1977–2015).

Year	Volume (cy)	Year	Volume (cy)	Year	Volume (cy)
2015	125,998	2002	48,623	1991	79,482
2013	63,000	2001	56,194	1990	49,513
2012	107,703	2000	56,275	1988	100,996
2011	4,000	1999	61,675	1985	26,180
2010	60,890	1998	40,000	1984	81,000
2009	67,820	1997	29,000	1982	85,396
2008	71,790	1996	53,515	1977	130,000
2005	30,142	1994	44,879		
2003	30,712	1993	66,597		
Cumulative Volume, cy (1977-2015)		1,571,000			
Average Annual Dredging, cy/yr (1977-2015)		41,000			
Average Annual Dredging, cy/yr (2008-2015)		71,000			

A recent historical sediment budget and shoreline evolution study of Waukegan Harbor (Morang et al. 2019) reported that the fillet beach to the north has migrated lakeward by approximately 305 m (1,000 ft) since the 1950s. The migration stopped in the last 10 years because the fillet beach has no storage capacity remaining. Consequently, sediments can move easily into the Advanced Maintenance Area, Approach Channel, and Outer Harbor. There are no physical barriers to intercept, divert, or stop sand transported by waves and currents into these areas. Insufficient and unmaintained depths in the approach channel due to channel infilling do not allow for normal levels of waterborne commerce, increasing the navigation risk and limiting the utilization of Waukegan Harbor.

1.1.5 Expected benefits of modifications

Shoaling in the Approach Channel and Outer Harbor has significantly increased over the past decade, impacting the harbor’s ability to reliably provide sufficient depths for commercial navigation. The chronic shoaling has been persistent and excessive in recent years and caused a significant reduction in commercial navigation, requiring periodic dredging of these two areas for safe navigation. This has hindered the harbor's reliability for commercial navigation and significantly reduced its use. Increased shoaling now requires more dredging volumes to maintain the channel for a safe navigation. Consequently, properly designed structural modifications (alternatives) are in consideration for this Section 107 navigation project to improve safety and sustainability of commercial navigation that can provide significant long-term cost savings. Effective sediment trapping by appropriately positioned structures is expected to increase reliability of channel depths to allow sustained navigation at Waukegan Harbor.

The types of modifications should involve fewer unknowns and challenges such as the use of rubble-mound extensions to the existing north breakwater. Rubble-mound breakwaters have been implemented successfully by USACE at many other harbors in Great Lakes. Carefully designed extensions to the outer breakwater can be especially beneficial for safe and efficient passage of vessels accessing the harbor. The proposed modifications need to address both present and future expected commerce needs of Waukegan Harbor. A process-based evaluation of structural modifications requires a combined wave and circulation modeling system with morphodynamics and sediment transport. The modeling domain should include the adjacent north and south beaches and surrounding lake areas to east, north, and south of Waukegan Harbor. This will ensure interactions between the harbor, and its surroundings are considered to assess safe passage of vessels moving through the Approach Channel and Outer Harbor to access the Inner Harbor.

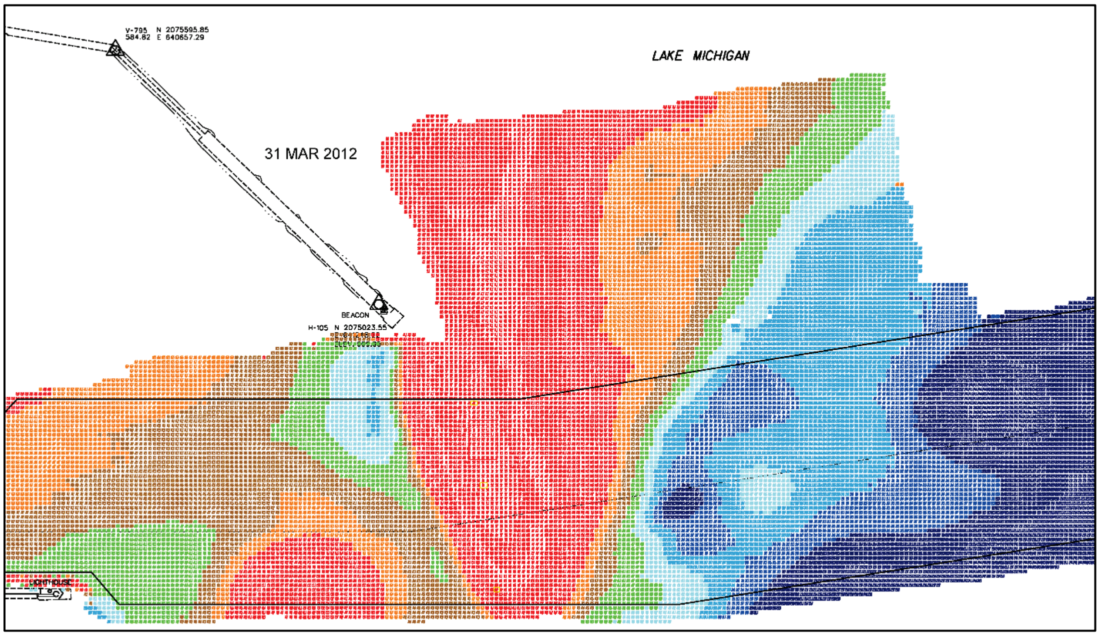
LRC has considered three modifications to mitigate the shoaling problem in the Approach Channel and Outer Harbor. Figure 1-3 shows the shapes and locations of three structures proposed by LRC, which are designated as Alt 1, Alt 2, and Alt 3. The Alt 1 involves excavation of the updrift fillet beach. Alt 2 is a structural breakwater modification for increasing sediment trapping capacity. Alt 3 requires installation of an updrift perpendicular groin sediment trap offsite to the north of the north beach. While these alternatives trap littoral sediments affecting the harbor, a future maintenance-dredging plan is required to ensure their long-term sediment trapping effectiveness. In addition to these three alternatives, several other modifications were investigated in the present study. Chapter 3 provides details of all structures evaluated in this study.

Figure 1-3. Three initial LRC alternatives (Alt 1, Alt 2, and Alt 3).

The sediment accumulation pattern of sands encroaching into the Approach Channel and Outer Harbor from north becomes an important consideration for selecting effective modifications. A survey in March 2012 (Figure 1-4) suggests that neither far-field solutions (e.g., Alt 1 and Alt 3) nor using a short structural modification (e.g., Alt 2) can prevent or alleviate the chronic shoaling occurring in the Approach Channel and Out Harbor. For this reason, the present modeling study was focused on *near-field solutions* that offer the greatest protection to the impacted areas. The near-field solutions include sufficiently long groins, breakwaters, jetties, or spurs. These measures providing maximum protection to the Approach Channel and Outer Harbor are necessary to improve effectiveness of near-field structural modifications.

The preferred location of such modifications becomes an important consideration, the closer to the Approach Channel and Outer Harbor, the better. Ideally, a protection situated along the north edge of Approach Channel would be the best. These modification structures must extend eastward sufficiently into the lake to be effective. The dimensions, cost, and constructability of structures will ultimately determine which types of structural extension are affordable and viable solutions. A proposed near-field solution has to provide adequate protection to affected areas by essentially sheltering them from the effects of waves, currents, and sediments. If appropriately positioned, sediment-intercepting structures can effectively block or redirect littoral transport into the Approach Channel and Outer Harbor. Protection structures must redirect or bypass sediments presently reaching the Waukegan Harbor entrance area.

Figure 1-4. Recent sedimentation pattern in the Approach Channel and Outer Harbor.



1.2 Objectives

- Evaluate alternatives to improve navigation in the Approach Channel and Outer Harbor of Waukegan Harbor.
- Investigate the efficacy of proposed solutions to increase harbor utilization by reducing shoaling in the Approach Channel and Outer Harbor.
- Provide estimates of waves, currents, water levels, morphology change for planning, design, operation and maintenance needs at Waukegan Harbor, and determine change relative to the existing harbor configuration (Alt 0).

1.3 Approach

A reconnaissance-level evaluation of potential alternatives was conducted by LRC in 2017. It was part of a Section 107 investigation at Waukegan Harbor for the Federal Interest Determination (FID) study. The FID recommended a refined coastal analysis to determine effectiveness of potential solutions capable of reducing shoaling in the channel.

Federal navigation designation areas in Waukegan Harbor are marked on Figure 1-2. These are the Inner Harbor, Outer Harbor, Approach Channel, and Advanced Maintenance Area. LRC sought the ERDC expertise to identify the type of tools and analysis methods required for a comprehensive investigation of the shoaling problem.

High wave energy in Lake Michigan can move sediments into the harbor entrance area. Large infilling rates in the Approach Channel in recent years have significantly increased the volume of Waukegan Harbor annual maintenance dredging. Prior to 2010, the fillet beach to the north of Waukegan Harbor had progressively migrated lakeward. The migration appears to have stopped in the last 10 years (Morang et al. 2019). If the fillet beach has little or no storage capacity remaining, more sediments can move into the designated Advanced Maintenance Area, Approach Channel, and Outer Harbor. Additional physical barriers can intercept, divert, and stop sediment coming into the approach channel during storms. Insufficient and unmaintained depths in the channel resulting from channel infilling will interrupt the normal use of waterborne commerce, greatly increase navigation risk, and severely limit the overall utilization of Waukegan Harbor.

A critical assessment of the existing harbor infrastructure modification is required to address present and future navigation needs of Waukegan Harbor. Consequently, the evaluation of modifications by numerical modeling should be centered on means of extending the existing breakwater for safe and efficient passage of waterborne commerce to/from the harbor. This requires a combined wave and circulation modeling with sediment transport and morphodynamics of the study area that includes adjacent beaches and Lake Michigan to the north, east, and south of Waukegan Harbor. The modeling will help to evaluate safety of vessels passing through the Approach Channel and Outer Harbor to access the Inner Harbor.

The updrift fillet beach to the north of the harbor has reached its maximum trapping capacity over the past decade (Figure 1-2). This is partly the reason for a significant increase in sediment load entering the Approach Channel. The shoaling has reduced sufficient depths for commercial navigation and substantially increased annual maintenance dredging requirements, thus posing a threat to the long-term sustainability of the Waukegan Harbor as a commercial port. LRC requested technical assistance in a feasibility-level study to evaluate appropriate measures and benefits that can address long-term shoaling at Waukegan Harbor. An outline of the proposed modeling study plan follows.

1.3.1 Modeling approach

The ERDC Coastal and Hydraulics Laboratory (CHL) proposed a two-phase numerical modeling study with the Phase 1 focused on a detailed investigation of the two new near-field solutions proposed by CHL (Alt 4 and Alt 5) for protecting the Approach Channel and Outer Harbor areas from the combined effects of waves, currents, and sedimentation. The extent of protection was determined in terms of reduction of waves and currents and resulting shoaling in the Approach Channel and Outer Harbor. Short- and long-term numerical simulations identified the merits of proposed modifications for navigation (e.g., available depth for commercial vessel traffic) into Waukegan Harbor during normal operational conditions and following storm events. Using the latest bathymetry, wind, wave, and water level data available, benefits of alternatives (modifications) were quantified in terms of extent of changes in waves, water levels, and sediment volumes in the Approach Channel and Outer Harbor relative to the existing harbor configuration (Alt 0).

The scope of Phase 2 study was determined based on findings of the Phase 1 investigation. A total of four alternatives were investigated during Phase 2. The alternatives were evaluated based on reduction of wave energy and sedimentation in the Approach Channel and Outer Harbor. The two-phase modeling plan was closely coordinated with the LRC team members.

1.3.2 Modeling tools

Hydrodynamics, waves, and sedimentation estimates were developed for channel infilling in the Approach Channel and Outer Harbor using the Coastal Modeling System (CMS). The CMS has been applied in Great Lakes to coastal navigation applications for channels, inlets, bays, and estuaries. Details of the CMS and its verification and validation are available in the References section of this report (Demirbilek et al. 2015a–d; Demirbilek and Rosati 2011). The CMS includes a two-dimensional (2D) wave model (CMS-Wave) and flow/sedimentation model (CMS-Flow). Nearshore processes affecting access and utilization of this harbor were simulated using an analysis of metocean climate for normal conditions and storms. Morphological changes were determined using fine resolution grids to represent features of harbor infrastructure to properly model coastal processes. The modeling included wave breaking, dissipation, diffraction, reflection, transmission, and overtopping of structures, wave-infrastructure, and wave-current interactions inside the enclosed harbor complex.

1.3.3 Study tasks

The following tasks were used to implement the modeling study plan:

Task 1. Develop lake forcing for Waukegan Harbor (winds, waves, water levels). Because the entrance to Waukegan Harbor is exposed to Lake Michigan, wind, wave, and water level inputs were included in the CMS. The lake wind and wave forcing information is available from the Wave Information Studies (http://wis.usace army.mil/). National Data Buoy Center (NDBC) database (https://www.ndbc.noaa.gov/), additional sources of National Oceanic and Atmospheric Administration (NOAA) coastal wind and water level data (https://tidesandcurrents.noaa.gov/), and field data available from other government agencies, academic institutes, and local airports in the region.

Task 2. Assemble bathymetry and sediment grain size data for numerical model grids. Assemble hydrographic survey data including bathymetry, shorelines, sediments, and ancillary data to develop grids for numerical models covering details of Waukegan Harbor. Obtain the latest data and local hydrographic surveys available for the study site of the Approach Channel, Outer Harbor, and Inner Harbor and deepwater bathymetry data from the NOAA Digital Elevation Maps (https://www.ngdc.noaa.gov/mgg/ coastal/) and other sources. Develop CMS grids with variable size cells that cover details of the Approach Channel, Outer Harbor, Inner Harbor, surrounding land and water boundaries of navigation channel, and the rest of the harbor complex. Perform test runs to check the adequacy of grids and selection of computational parameters.

Task 3. Set up of models with a selected subset of hydrodynamic conditions for fact-finding about alternatives and *as is* harbor. Develop hydrodynamic input data required for numerical modeling including winds, waves, water levels, storms, bathymetry, sediments, and ancillary data. Select a set of hydrodynamic conditions for setting up wave and hydrodynamic models. Perform the CMS modeling for the existing harbor configuration (Alt 0). Use Alt 0 results as the base to compare and evaluate relative merits of each alternative, starting with the Alt 4 and Alt 5. Perform sensitivity tests for optimal structure geometric dimensions (e.g., type, location, length, orientation, and water depth). Make appropriate adjustments to alternatives based on modeling study results.

Task 4. Production runs - modeling sedimentation and morphology change in the Approach Channel and Outer Harbor. Calculate water level, wave, and morphology changes for each alternative with the CMS. The Illinois Department of Natural Resources provided the latest bathymetry of the project site, collected grab samples, and conducted analysis of grain size distribution used in the present study. Simulate wave and flow processes from the entrance through the inner harbor including wave shoaling, refraction, breaking, diffraction, reflection, runup/overtopping protective structures, sediment transport, morphology change, and channel infilling rates. Develop estimates of shoaling and sedimentation for each alternative relative to the existing harbor. Identify depositional and erosional areas in the navigation channel (including the Inner Harbor and Outer Harbor) and the impacts of corresponding sedimentation on adjacent beaches. Perform short- and long-term (e.g., monthly, seasonal, and annual) simulations for channel shoaling to identify potential depositional and erosional areas for proposed modifications.

Task 5. Structural design calculations. LRC agreed to perform this task upon the completion of modeling using structural design methods available in the Coastal Engineering and Eurotop manuals. Wave and hydrodynamic information is required for these estimates to determine stable stone sizes, damage progression, run-up, and overtopping and transmission for structures evaluated. The analysis involves structural cross-section calculations, including crest elevation, crest width, side slopes, and armor stone sizes. The effects of sea level rise, local soil subsidence due to weight of structure, and regional settlement in Lake Michigan are also considered in this analysis. The modeling results will assist the LRC team to perform its structural design.

Task 6. Modeling study results and documentation. This technical report provides details of modeling study and results. It describes elements of the modeling study, evaluation (comparison and ranking) of alternatives, and recommendations.

This study is subject to “3x3x3 Smart Planning requirements,” necessitating completion of a large amount of modeling work within a 15-month time period. The modeling study started in Quarter 1/Fiscal Year 18 (Q1/FY18) upon receipt of partial funding and was completed in Q4/FY19. The scope of study changed and expanded as the study progressed and modeling results revealed pros/cons of proposed solutions, and suggested consideration of others. This change in strategy resulted in investigation of 12 alternatives (including the existing harbor) instead of the 5 total alternatives (3 by LRC, and Alt 4 and Alt 5 by CHL) alluded to in the aforementioned work plan.

The layout of this report is as follows: In Chapter 1, the introduction provides history and background, including description of the problem and proposed solutions and summary of a comprehensive modeling study plan. Chapter 2 describes data used in the present study. Chapter 3 provides description of alternatives investigated. Chapter 4 provides details of CMS modeling conducted. Chapter 5 provides results and discussion of modeling study. Chapter 6 provides summary and conclusions of the study.

2 Data for the Study

2.1 Topography, bathymetry, and coastline data

The bathymetry for the exterior and interior of harbor, channels, structures (outer breakwater, jetties, seawalls, etc.), and shorelines was obtained from different sources, including the bathymetry data for entire Lake Michigan from three Lidar data in 2007, 2008, and 2012. Figure 2-1 shows the Lidar coverage areas from 2007 (land only), 2008 (bathymetry data only), and 2012 (bathymetric and land data). Figures 2-2 and 2-3 show the contour maps of combined land and water of the region and local areas around Waukegan Harbor.

Figure 2-1. Lidar coverage polygons from 2007 (yellow), 2008 (red) and 2012 (white).

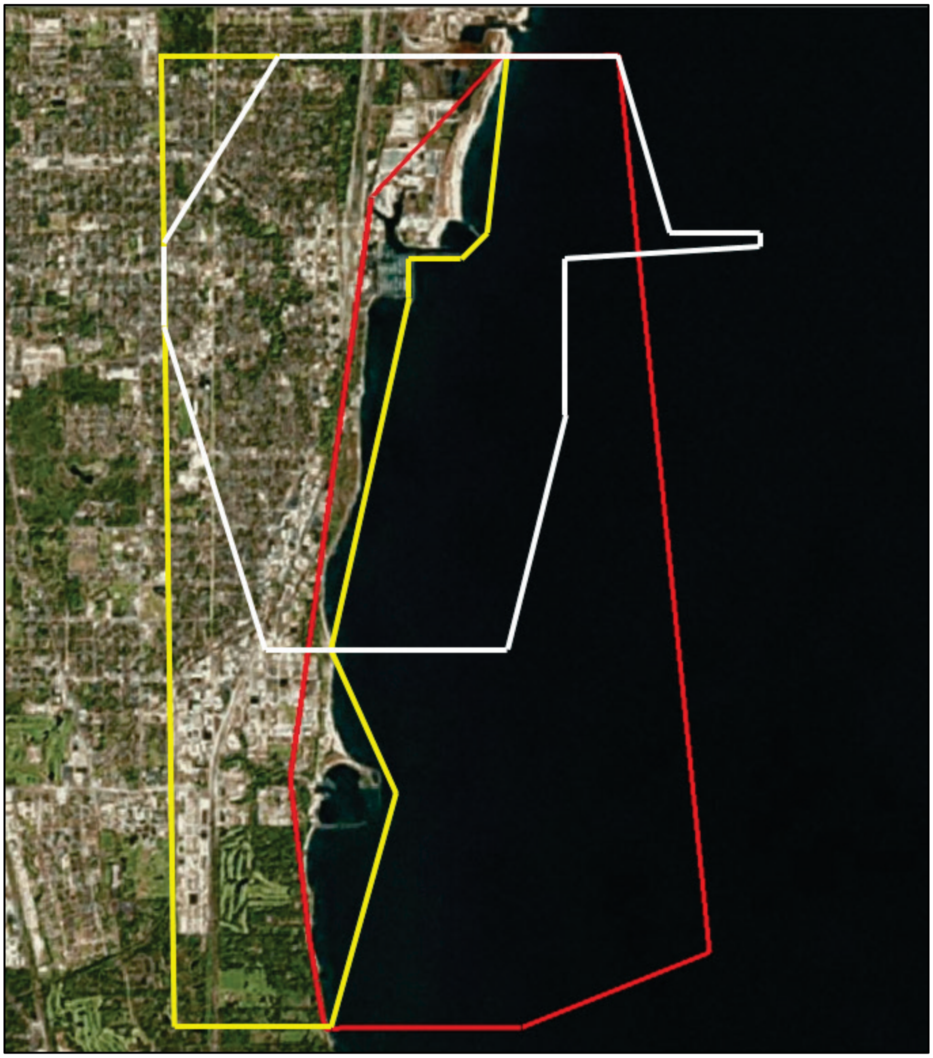


Figure 2-2. Contours of Lidar 2008–2012 data (regional).

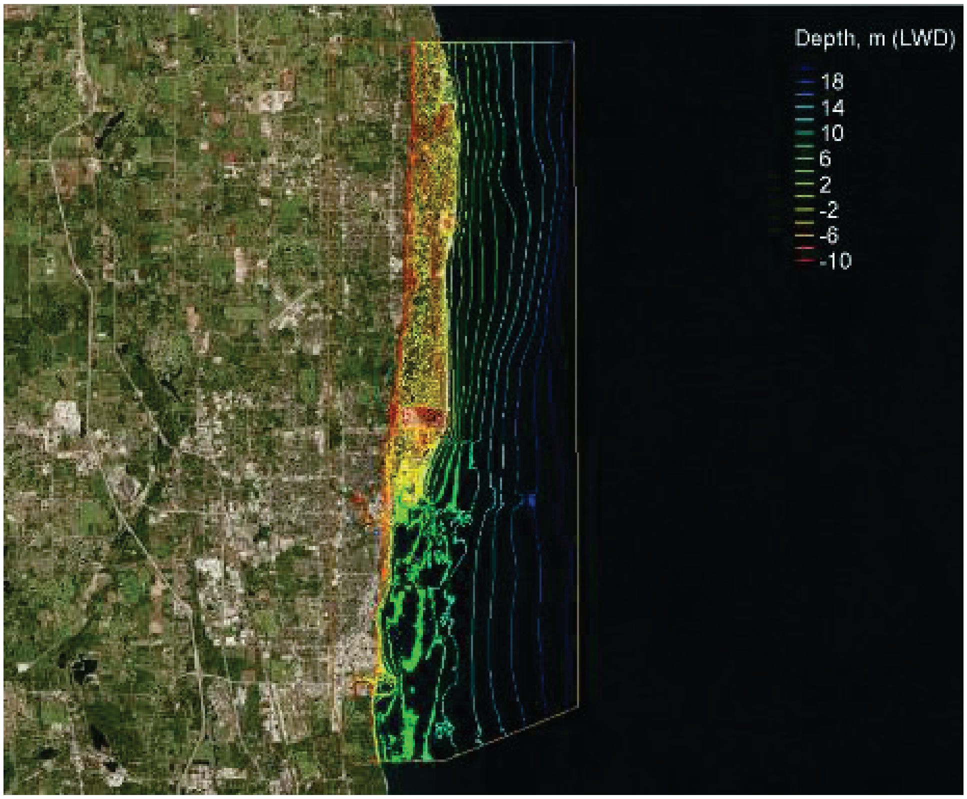
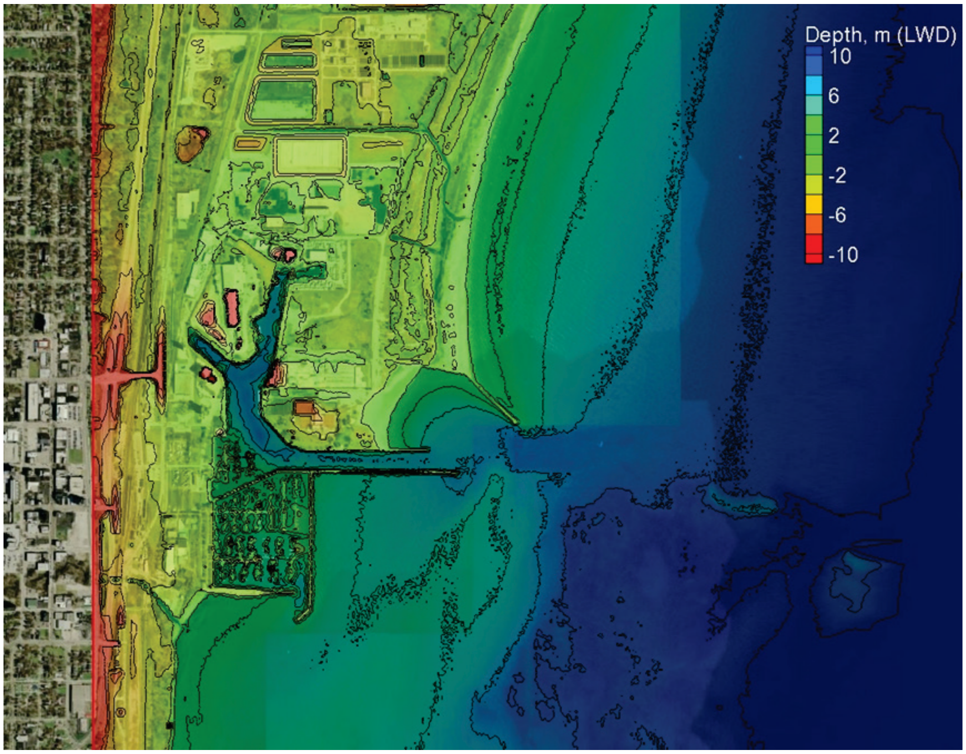


Figure 2-3. Contours of Lidar 2007–2012 data (local zoom).



The Illinois State Geological Survey (ISGS) at the University of Illinois at Urbana-Champaign has conducted nearshore bathymetry surveys outside the harbor in 2017 and 2018 using a single beam echo-sounder system Estimated accuracy of the lakebed bathymetry is approximately 3 cm (0.1 ft). Bathymetry data for the offshore area in the present study was extracted from the National Geophysical Data Center (NGDC) Geophysical Data System (GEODAS) database (https://www.ngdc.noaa.gov/mgg/greatlakes/erie.html). Coastline data were extracted from the NGDC database (http://www.ngdc.noaa.gov/mgg/ shorelines/) and augmented with georeferenced image files downloaded from Google Earth Pro (http://earth.google.com). All geospatial datasets were converted to Lake Michigan's LWD of 176.02 m (577.5 ft) (https://www.lre.usace.army.mil/Portals/69/docs/GreatLakesInfo/docs/IGLD/BrochureOnTheInternationalGreatLakesDatum1985.pdf). Figure 2-4 shows the contour map of combined Lidar 2007–2008–2012 and GEODAS datasets. Figure 2-5 shows details of topography and bathymetry at immediate vicinity of the Approach Channel and Outer Harbor based on the combined Lidar 2007–2008–2012 NGDC dataset. Figure 2-6 shows the dredged Approach Channel at authorized depth of 7.6 m (25 ft).

Figure 2-4. Contour map of combined Lidar 2007–2008–2012 and GEODAS datasets.

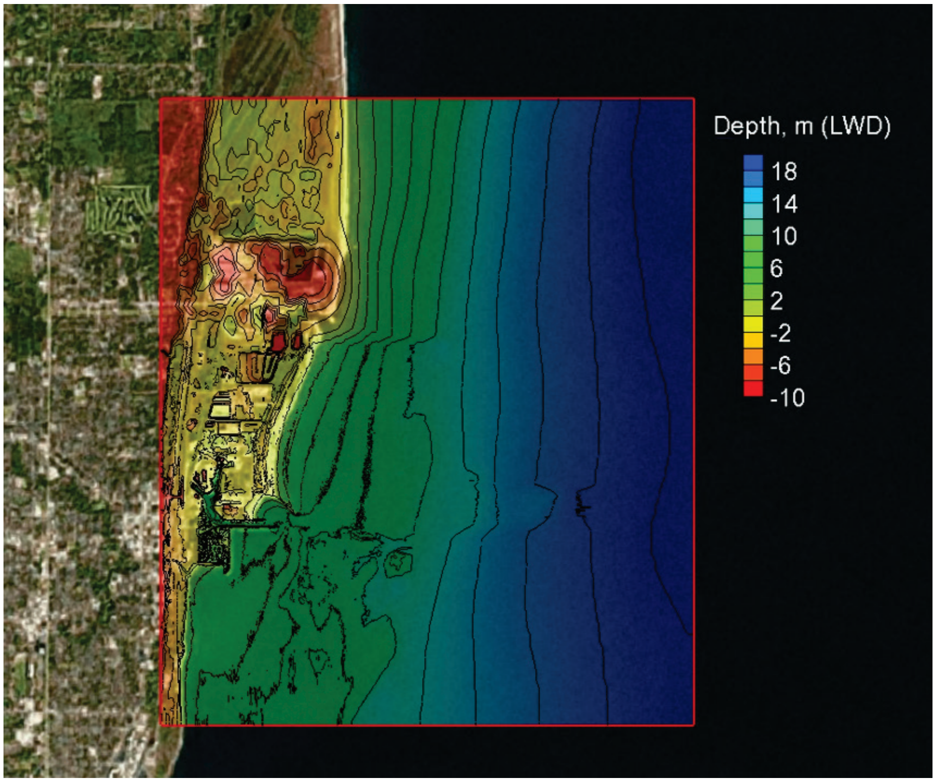


Figure 2-5. Details of topography and bathymetry at vicinity of approach channel and outer harbor.

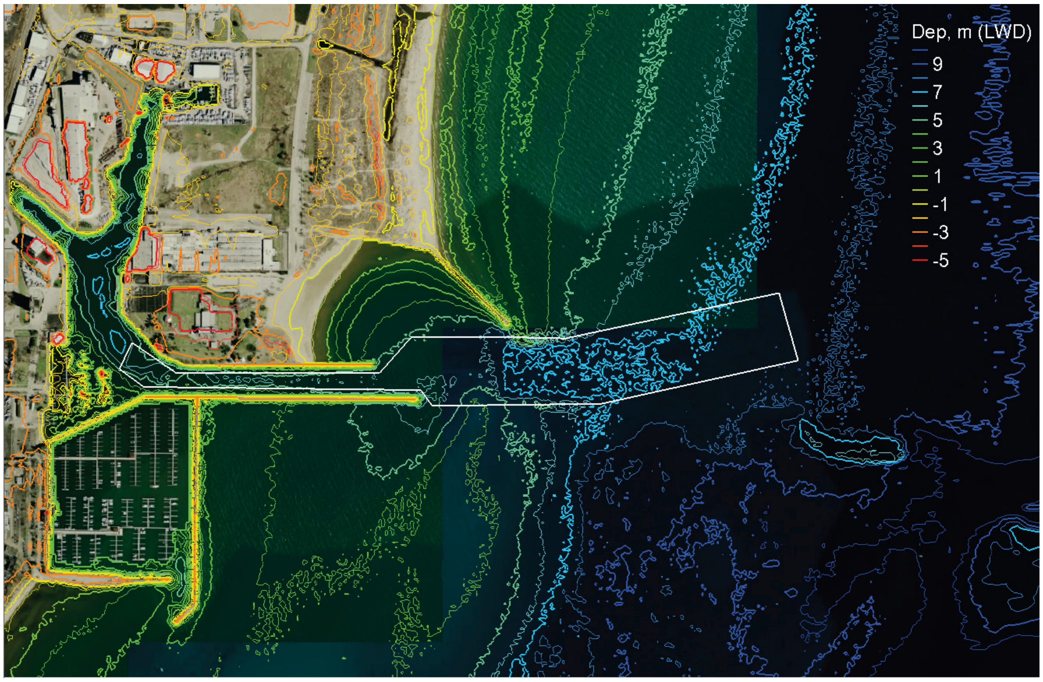


Figure 2-6. Dredged Approach Channel at 7.6 m (25 ft) authorized depth.

2.2 Water level data

Long-term water level data were available from two close-by NOAA coastal stations at Calumet Harbor, IL (Station ID: 9087044 or CMTI2; 41° 43.8' N, 87° 32.3' W) and Milwaukee, WI (Station 9087057; 43° 0.1' N, 87° 53.2' W) and (https://tidesandcurrents.noaa.gov). Figure 2-7 shows the location map of these two NOAA coastal stations. Figure 2-8 shows hourly water level data in Lake Michigan from NOAA 9087044 and 9087057 for 2015. The lake water level is usually higher in summer to fall months due to ice melting and precipitation while lower in winter and spring seasons. Fluctuations of water level are stronger at Calumet Harbor (9087044) as the wind-induced seiching is more significant around the southern end of Lake Michigan.

Figure 2-7. Location map of NOAA coastal stations.

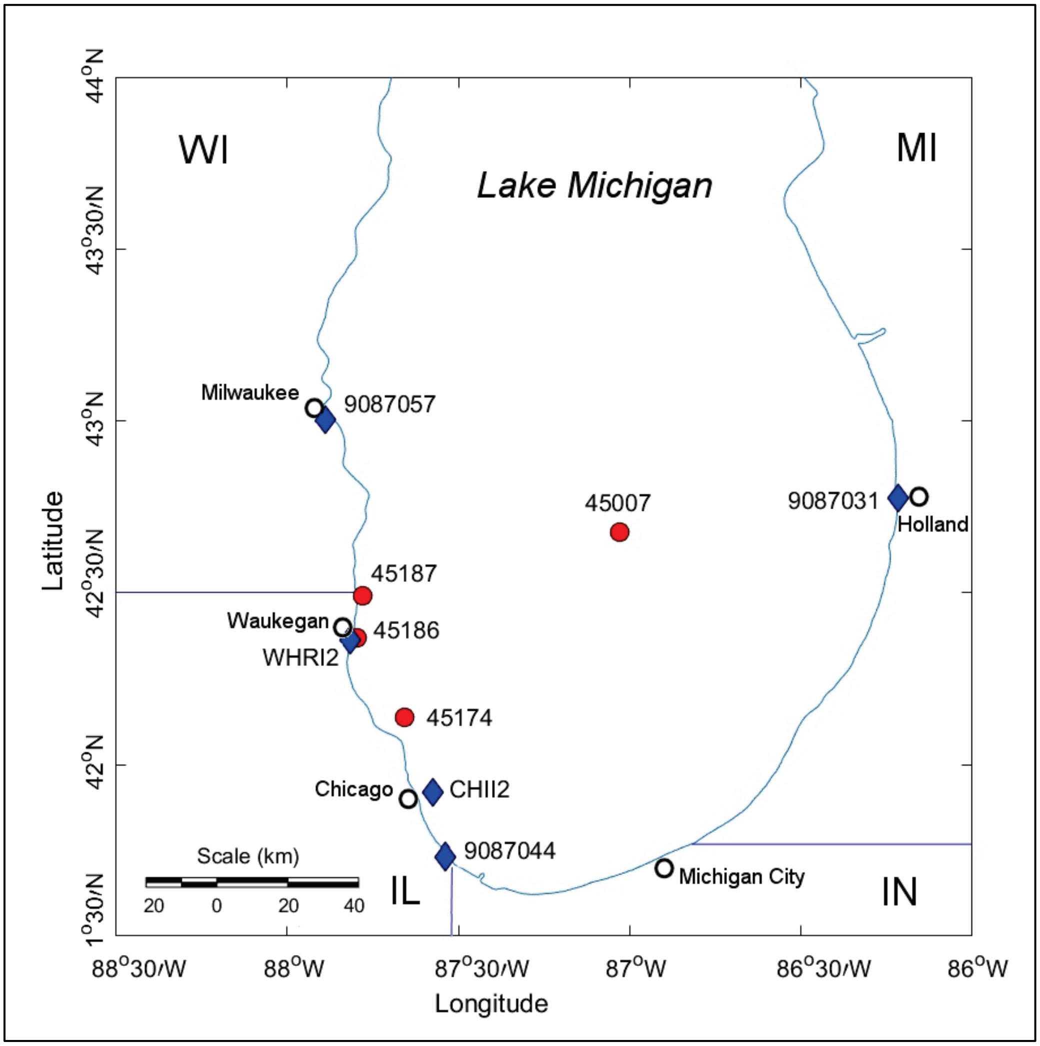
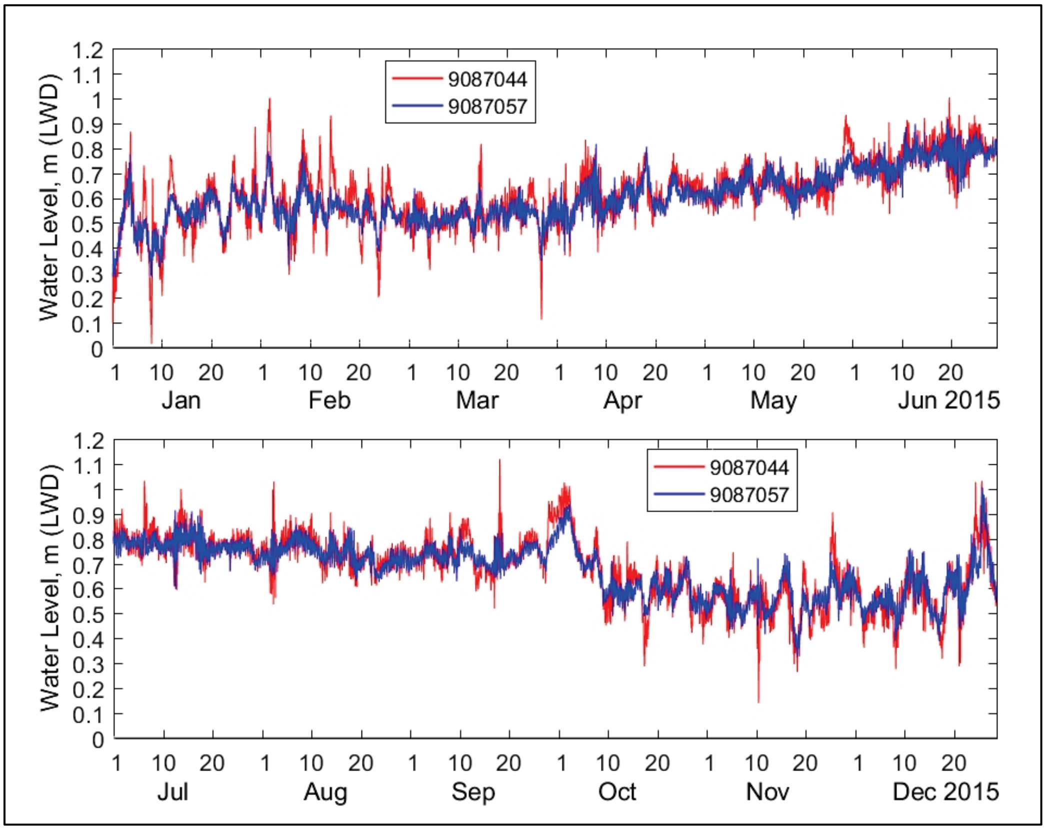


Figure 2-8. Water level time series at Milwaukee for 2015.



The ISGS installed two nearshore wave and water level gauges, G1 and G2, for short-term water level measurements at Waukegan Harbor in various duration from November 2017 to October 2018. Figure 2-9 shows the locations of the ISGS gauges. Table 2-1 presents the location and data duration of ISGS gauges in Waukegan Harbor. Figure 2-10 shows the water level data collected at ISGS gauges G1/G2 versus NOAA Station 9087057 in July to October 2018. The difference in water levels between G1/G2 and NOAA 9087057 is caused by variation of atmospheric (barometric) pressure over Lake Michigan during the period of water level measurements. The water level data from NOAA Station 9087057 were the exact surface level measurements while the water level data from G1/G2 gauges were transferred from under water pressure measurements, which were affected by the water surface atmospheric pressure variation.

The G1/G2 gauges were RBR Compact Tide and Wave Loggers and were bottom mounted using a concrete frame and anchors. These pressure sensors utilize pressure (i.e., water depth) to sample wave height, period, and water level. The pressure sensor reported accuracy is ±0.05% full scale, and the full scale of this sensor is 0.2 m/0.5 m. This results in a vertical accuracy of wave and water level measurements of 0.15 m. Figure 2-11 shows water surface atmospheric pressure data from NOAA Station 9087044 at Calumet Harbor in the distant south of Chicago Harbor and NOAA station 9087031 at Holland, MI, on the east side coast of Lake Michigan (Figure 2-7). The comparison of surface pressure indicates a small spatial change between the two stations but significant temporal change on a daily basis. The influence of surface pressure on G1/G2 measurements for water levels is obviously not linear and difficult to remove from the G1/G2 measurements to correct the water surface elevation. For the same reason, estimates of wave height and period from the G1/G2 measurements are affected by the surface pressure variation.

Table 2-1. ISGS water level gauge locations and data duration in Waukegan Harbor.

Gauge ID	Location	Data Duration
G1	42° 21.81' N, 87° 48.28' W	9 July – 18 October 2018
G2 (a)*	42° 21.64' N, 87° 48.84' W	6 November – 31 December 2017
G2 (b)*	42° 21.76' N, 87° 48.86' W	15 July – 18 October 2018

* G2 was initially installed at Location (a) near the east end of South Breakwater and later reinstalled at Location (b) in the embayment by the Recreational Beach.

Figure 2-9. Location map of ISGS gauges G1, G2(a), and G2(b).

Figure 2-10. NOAA 9087057 and ISGS G1/G2 water levels, July–October 2018.

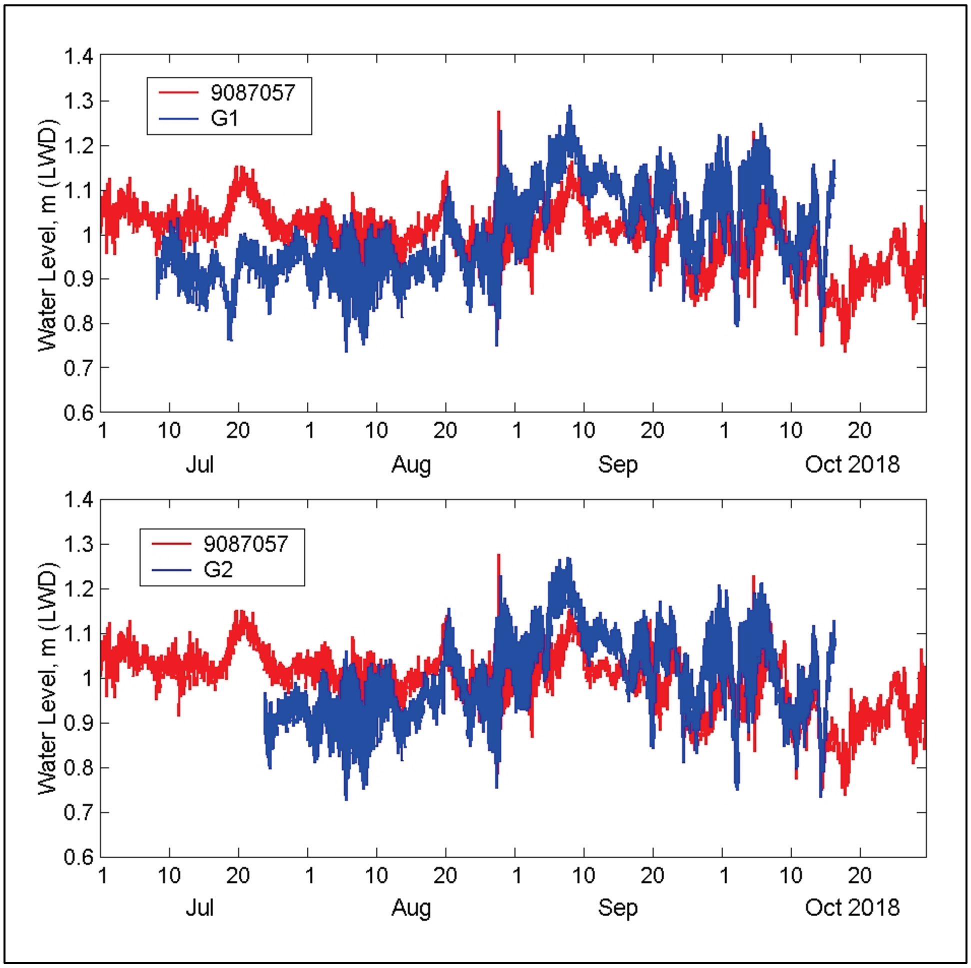
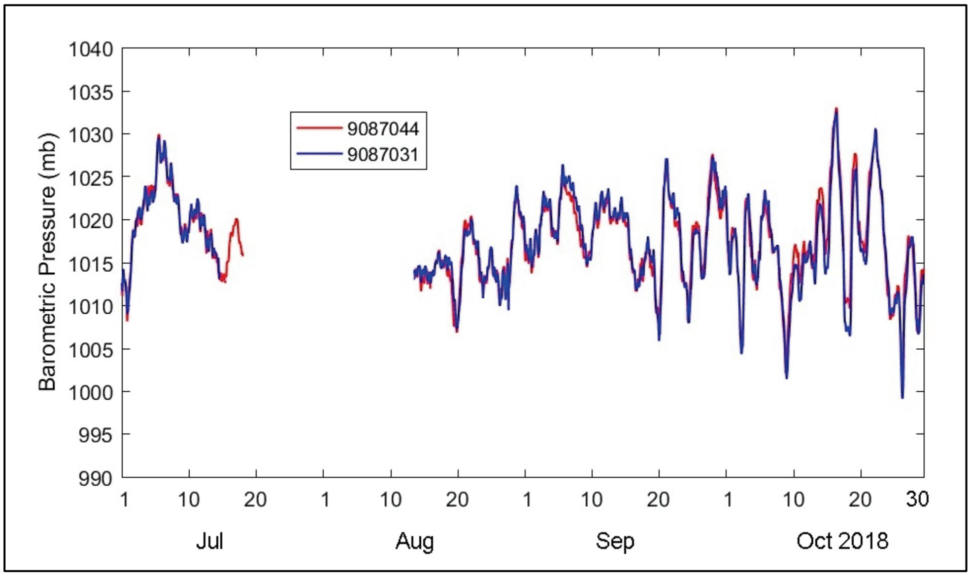


Figure 2-11. Atmospheric pressure from NOAA 9087044 and 9087031.



2.3 Wind and wave data

Long-term coastal wind and wave data in the study area were available from various sources. Field wave measurements were available from NDBC Buoys 45007 (South Michigan), 45174 (Wilmette, IL), 45186 (Waukegan Harbor, IL), and 45187 (Winthrop Harbor, IL). Wind data were available from NDBC 45007, 45174, WHRI2 (Waukegan Harbor), and CHII2 (Chicago, IL). Figure 2-12 shows the locations of these stations. Table 2-2 presents the NDBC station location and data type. ISGS G1/G2 collected short-term wave data for the present study.

Table 2-2. NDBC Station locations and available wind/wave data.

Station ID	Location	Wind Data	Wave Data
45007	42° 40.42' N, 87° 1.57' W	x	x
45174	42° 8.10' N, 87° 39.30' W		x
45186	42° 22.10' N, 87° 47.68' W		x
45187	42° 29.45' N, 87° 46.73' W		x
CHII2	41° 54.97' N, 87° 34.33' W	x	
WHRI2	42° 21.63' N, 87° 48.80' W	x	

Long-term wind wave hindcast information for the Great Lakes is available from the USACE Wave Information Studies (WIS) database (http://wis.usace.army.mil/). For Lake Michigan, the WIS wind wave database covers the years from 1960 to 2014. Long-term wave nowcast information for Great Lakes is available from NOAA Great Lakes Coastal Forecasting System (GLCFS) (https://www.glerl.noaa.gov/res/glcfs/).

Figure 2-12 shows a sample time series of wind and wave information from NDBC Buoys 45007 and 45174 and GLCFS at Waukegan offshore (42° 21.6' N, 87° 45.0' W) for March to November 2015. NDBC normally retrieves the buoys in the Great Lakes during early December and redeploys around April to May to avoid icy conditions during the winter months. Figure 2-13 shows the sample time series of wind speed and direction from CHII2 (Chicago Harbor) and WHRI2 (Waukegan Harbor) for March to November 2015. Winds at CHII2 and WHRI2 are overall moderate to strong during the period from March to November. Larger waves are more likely to occur from September to November than from March to August.

Figure 2-12. Wind wave data from NDBC 45007, 45174 and GLCFS, March–November 2015.

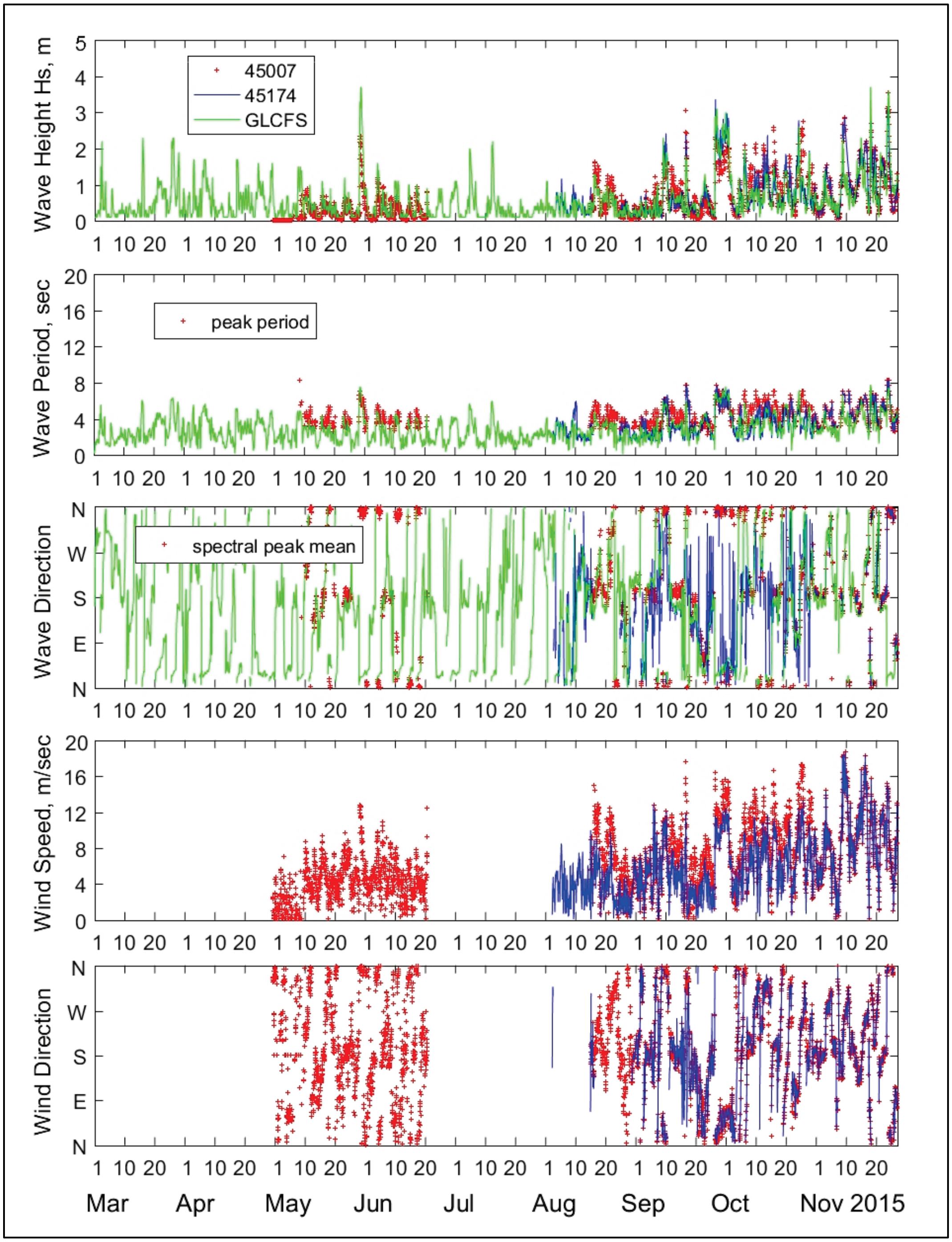
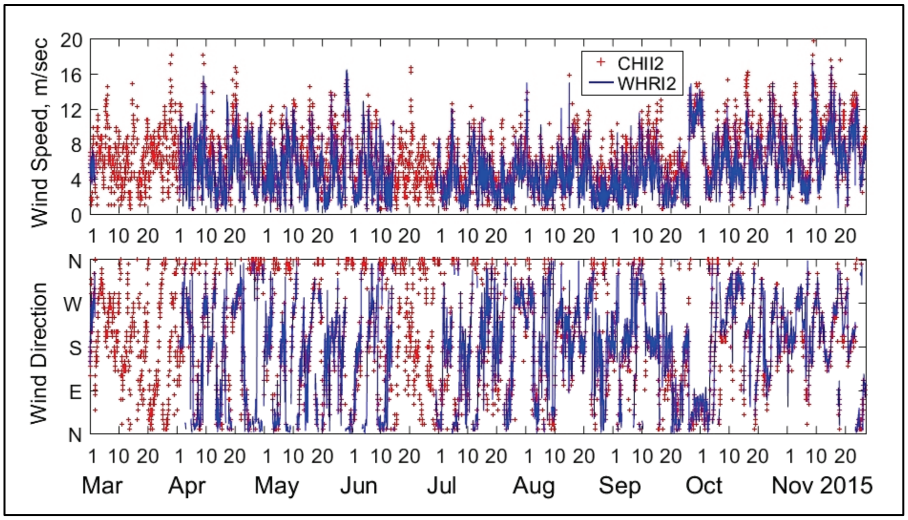


Figure 2-13. Hourly wind data from NOAA Stations CHII2 and WHRI2, March–November 2015.



2.4 Sediment data

Sediment properties in and around Waukegan Harbor are available from the Waukegan Harbor Dredged Material Management Plan report*. ISGS has collected 12 grab samples using a ponar grab sampler along the harbor entrance, Outer Harbor, and Approach Channel as shown in Figure 2-14. Table 2-3 presents the sample location, sediment content, and median grain size (D50).

Table 2-3. ISGS grab sample location, sediment content, and median grain size.

Sample ID	Latitude (N)	Longitude (W)	% sand	% silt	% clay	D50 (mm)
WH01	42.36119	-87.8208	12.23	80.73	7.04	0.16
WH02	42.36123	-87.81902	27.28	67.93	4.79	0.27
WH03	42.36123	-87.81781	62.07	35.59	2.35	0.17
WH04	42.36127	-87.81699	100	0	0	0.28
WH05	42.36127	-87.81634	92.96	6.88	0.16	0.26
WH06	42.36121	-87.81473	71.93	27.00	1.07	0.17
WH07	42.36116	-87.81275	13.27	83.26	3.47	0.23
WH08	42.36228	-87.81375	90.69	9.31	0	0.16
WH09	42.3624	-87.81537	95.64	4.36	0	0.17
WH10	42.36353	87.81448	99.08	0.92	0	0.23
WH11	42.3625	-87.81167	88.03	11.26	0.71	0.26
WH12	42.36143	-87.81004	97.58	2.42	0	0.22

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* USACE. 2012. Waukegan Harbor DMMP, Appendix C – Geotechnical Engineering. Chicago District (LRC).

Figure 2-14. ISGS grab sample location map.

3 Alternatives Investigated

3.1 Alternatives considered

Twelve structural alternatives, including the existing harbor, were investigated in this study for reducing shoaling in the Approach Channel of Waukegan Harbor. The alternatives are divided into two groups based on their distance to the approach channel. Those within a 1 km (0.62 miles) distance of harbor are the *near-field* alternatives while others are the *far-field* alternatives. The far-field alternatives were expected to have less effect on channel shoaling but could reduce channel shoaling by intervening with other far-distance sources that ultimately reach the harbor entrance. Previous sediment budget analyses and regional sediment management studies[*] (Morang et al. 2019) have concluded that the north beach is the largest sediment source supply to Waukegan Harbor. Consequently, a main objective of each alternative was to alter or reduce contribution of this primary supply source. Figure 3-1 shows examples of three potential solutions to minimize shoaling in the approach channel. These solutions proposed by LRC included removal or excavation of the up-drift fillet beach and construction of structural breakwaters and groins as sediment traps.

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[*] USACE. 2014. Illinois Beach State Park, Lake County, Illinois, Section 204 Beneficial Use of Dredged Material, Detailed Project Report, Regional Sediment Management Plan and Environmental Assessment, Chicago District (LRC).

Figure 3-1. A sketch illustrating three general solutions for Waukegan Harbor shoaling problem.

3.2 Description of alternatives

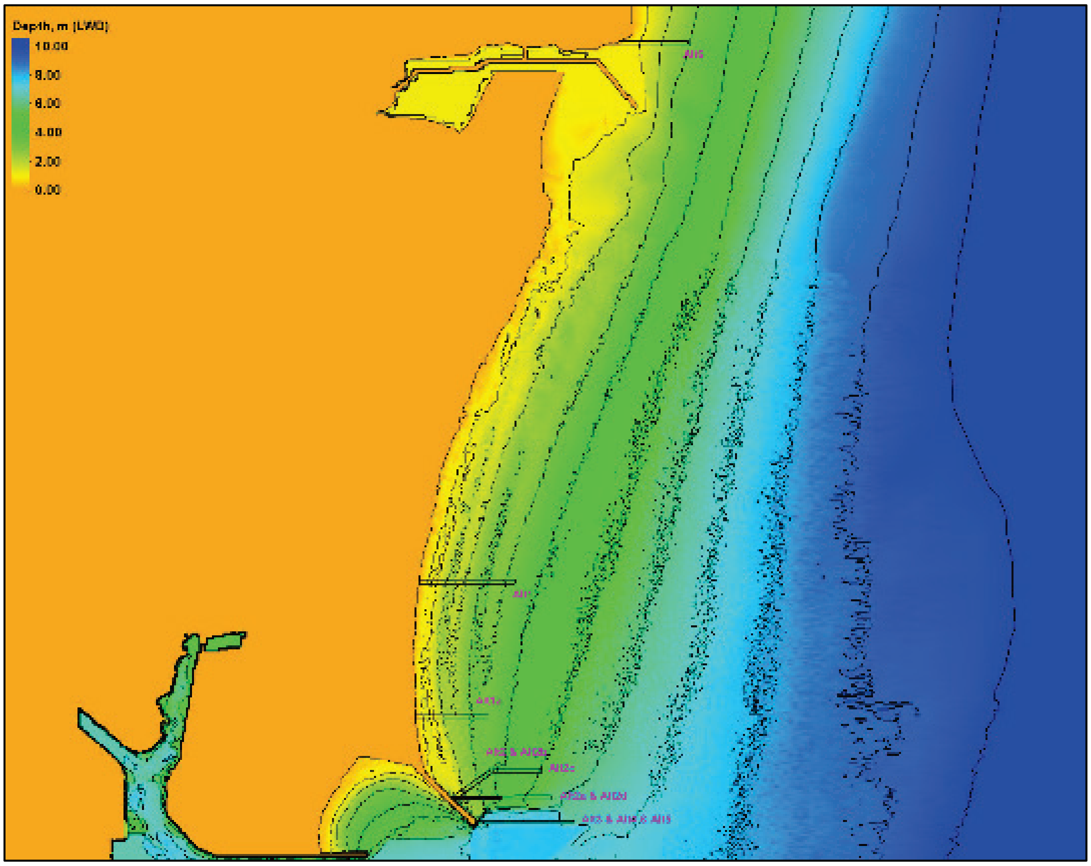
Twelve structural alternatives were selected for modeling and evaluation in this study. Table 3-1 provides a list of alternatives with a brief description of each. Figure 3-2 is a sketch that shows location and shape of these structures. Each alternative includes a modification to Alt 0 (the existing harbor without project). Details of alternatives and associated modifications are described following Figure 3-2.

Table 3-1. List of twelve alternatives.

Alternative	Description
Alt 0	Existing harbor without project
Alt 1	305 m (1000 ft) groin connected to the North Beach
Alt 1a	244 m (800 ft) groin connected to the North Beach
Alt 2	152 m (500 ft) angled spur connected to the Outer Breakwater
Alt 2a	152 m (500 ft) eastward spur connected to the Outer Breakwater
Alt 2b	183 m (600 ft) angled spur connected to the Outer Breakwater
Alt 2c	305 m (1000 ft) dogleg spur connected to the Outer Breakwater
Alt 2d	305 m (1000 ft) eastward spur connected to the Outer Breakwater
Alt 3	228 m (750 ft) eastward extension to the Outer Breakwater
Alt 4	152 m (500 ft) eastward extension to the Outer Breakwater
Alt 5	305 m (1000 ft) eastward extension to the Outer Breakwater
Alt 6	305 m (1000 ft) groin connected to the NB at the Power Plant

Some of the proposed alternatives were expected to reduce sediment build up near the trunk area and along northeast face of the outer breakwater. The position and dimensions (length, orientation, and crest height) of each alternative determine the extent of sediment accumulating in the impoundment area. All structures included in these alternatives are assumed to be rubble-mound construction. Figures 3-3 to 3-14 depict alternatives Alt 0 to Alt 6 and the associated water depth contours around the structure. Some alternatives may require additional maintenance dredging for a long-term sediment trapping effectiveness.

Figure 3-2. Map of the location and shape of structural alternatives.



Alt 0, the existing harbor configuration, represents the baseline geometry without any alternative structure. The shoaling rate in all other alternatives is compared and referenced to Alt 0. Figure 3-3 shows the Alt 0 configuration covering the vicinity of harbor and entrance channel. The authorized depth of the Approach Channel is 7.5 m (25 ft). The bathymetry is based on a 2018 survey of the post-dredge channel according to the authorized depth.

Alt 1 includes a 305 m (1,000 ft) long straight groin (Figure 3-4), located approximately 366 m (1,200 ft) north of outer breakwater, that extends eastward from North Beach into Lake Michigan. The water depth at the tip of Alt 1 structure is 3.5 m (11.5 ft). The sediment diversion and trapping by this structure is expected to reduce sediment build up occurring near the trunk and along the northeast face of the Outer Breakwater.

Figure 3-3. The existing harbor approach channel bathymetry (Alt 0).

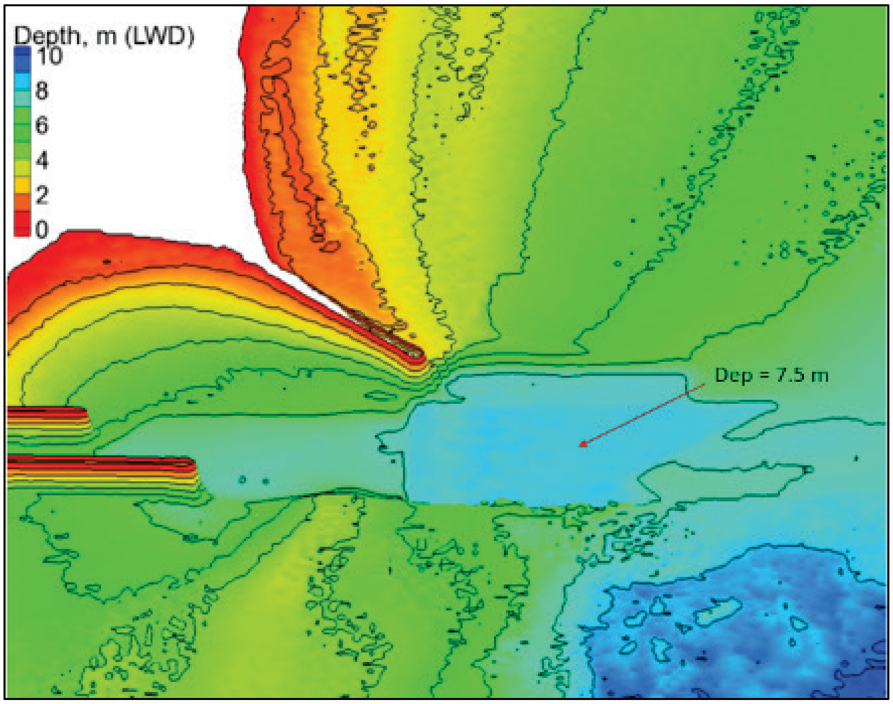
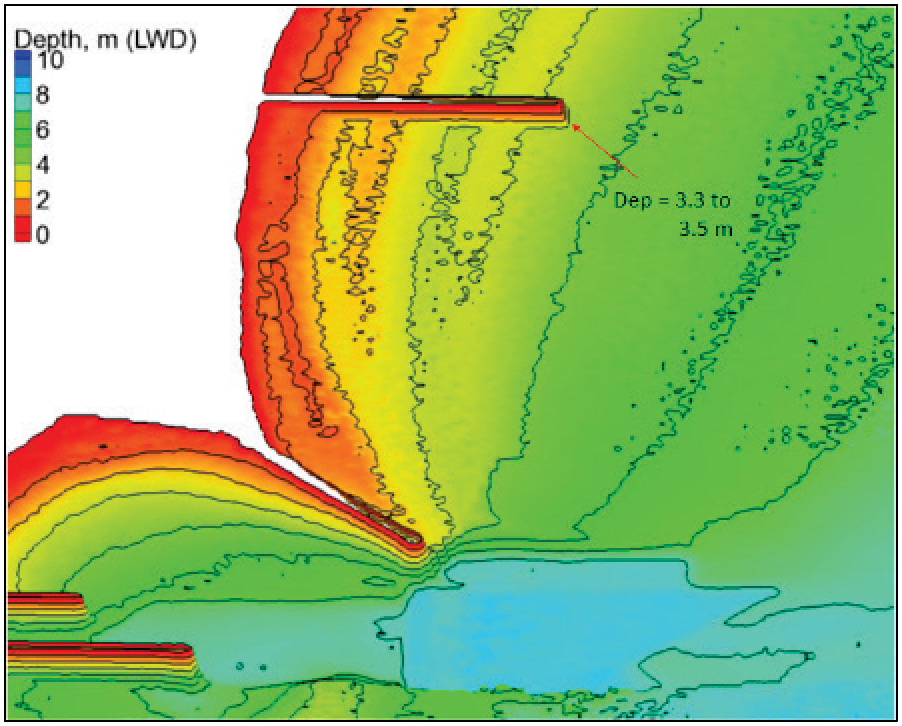
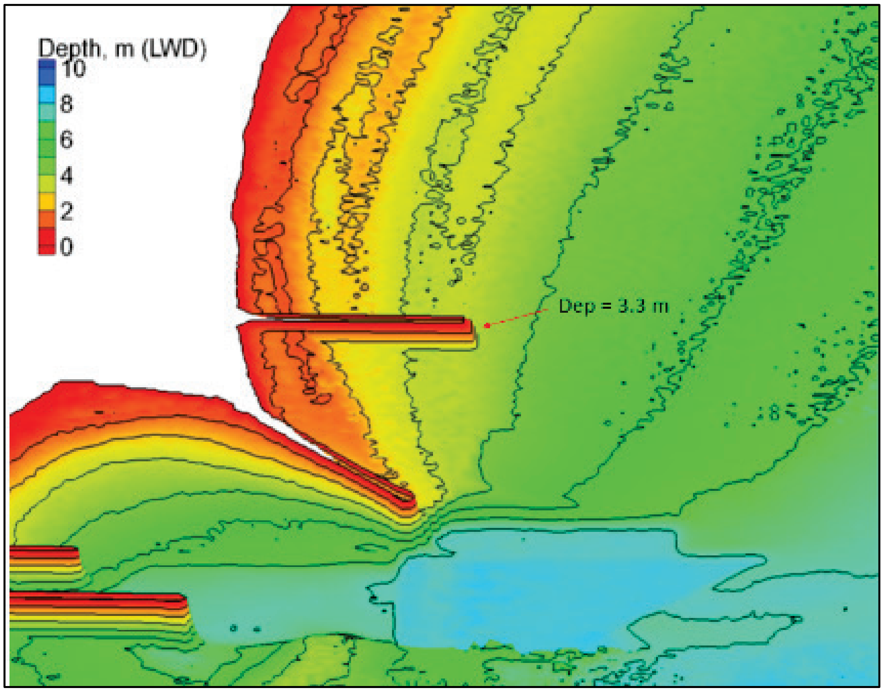


Figure 3-4. A 305 m (1000 ft) groin structure at the North Beach (Alt 1).



Alt 1a includes a 244 m (800 ft) long straight groin, located approximately 92 m (300 ft) north of the outer breakwater; it is attached to the north beach (Figure 3-5). The depth at the tip of Alt 1a groin is 3.3 m (11 ft).

Figure 3-5. A 244 m (800 ft) long groin attached to the North Beach (Alt 1a).



Alt 2 includes a 152 m (500 ft) long, angled spur connected to the outer breakwater (Figure 3-6). The spur points to northeast at a 40 deg angle. The depth at the tip of the groin is 3.5 m (11.5 ft). Sediment is likely to be trapped in the smaller impoundment area between the spur, trunk of the outer breakwater, and the north beach.

Alt 2a is similar to Alt 2 but reorients the 152 m (500 ft) long spur eastward into the lake (Figure 3-7). The Alt 2a groin terminates at 4.5 m (15 ft) depth. Alt 2b is similar to Alt 2 but extends the angled spur by 30 m (100 ft) to approximately the 4 m (13 ft) depth contour (Figure 3-8).

Alt 2c is similar to Alt 2 but extends the length of the groin eastward by 152 m (500 ft) into the lake (Figure 3-9). The depth at the tip of this dogleg groin is 5 m (16 ft).

Alt 2d is similar to Alt 2a but extends the groin by 152 m (500 ft) for a total length of 305 m (1000 ft) into the lake (Figure 3-10). This straight groin extends to a water depth of 5.7 m (18.7 ft).

Figure 3-6. A 152 m (500 ft) angled spur attached to the Outer Breakwater (Alt 2).

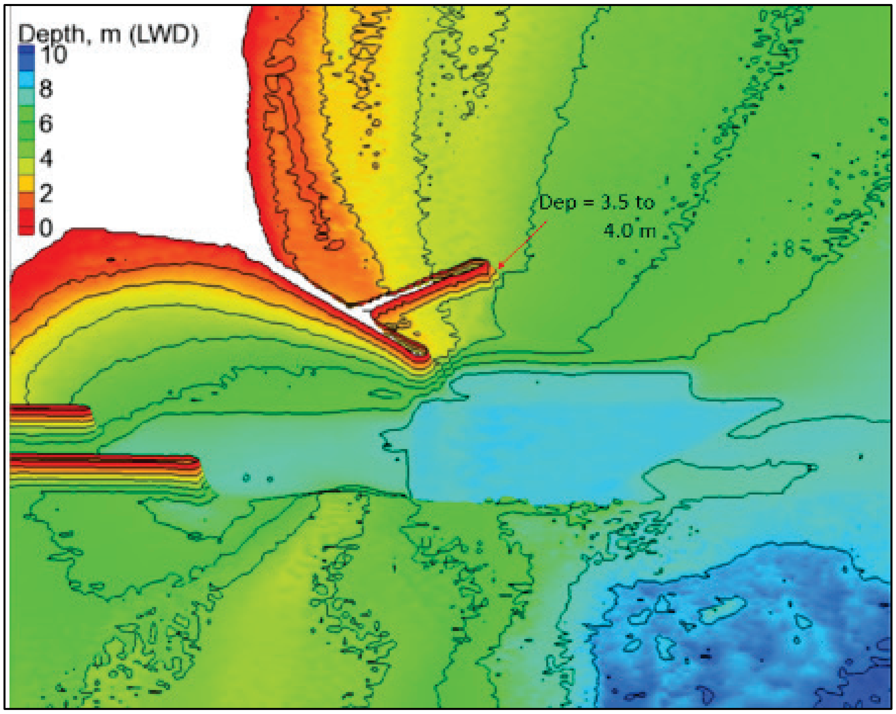


Figure 3-7. A 152 m (500 ft) straight spur attached to the Outer Breakwater (Alt 2a).

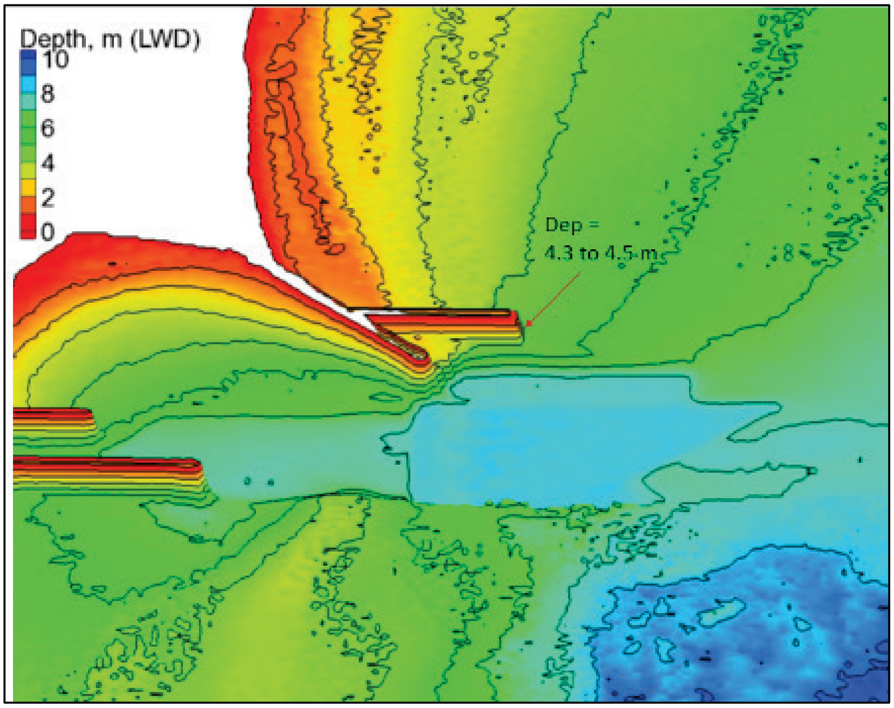


Figure 3-8. A 182 m (600 ft) angled spur attached to the Outer Breakwater (Alt 2b).

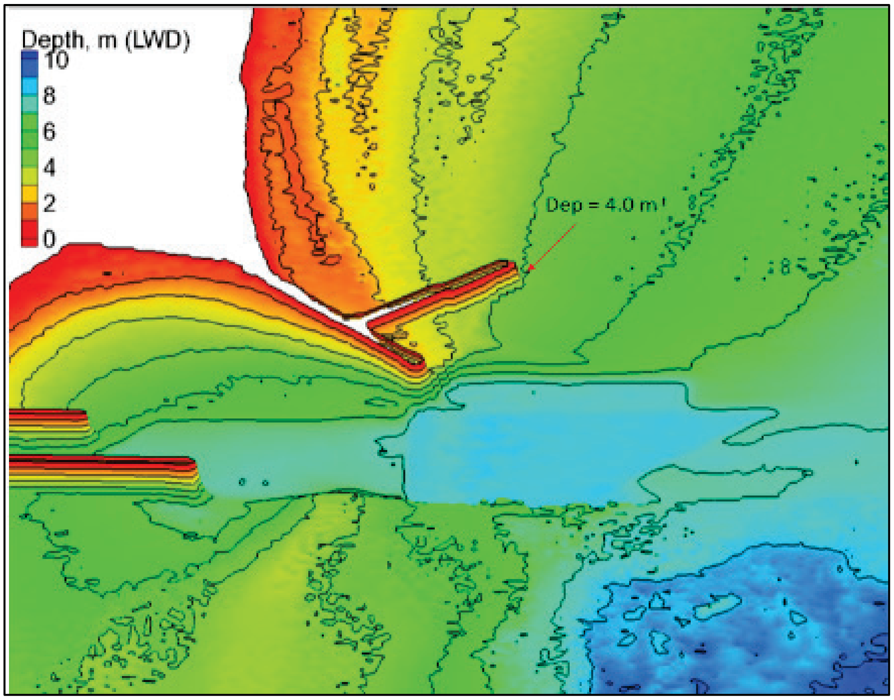


Figure 3-9. A 305 m (1000 ft) dogleg spur attached to the Outer Breakwater (Alt 2c).

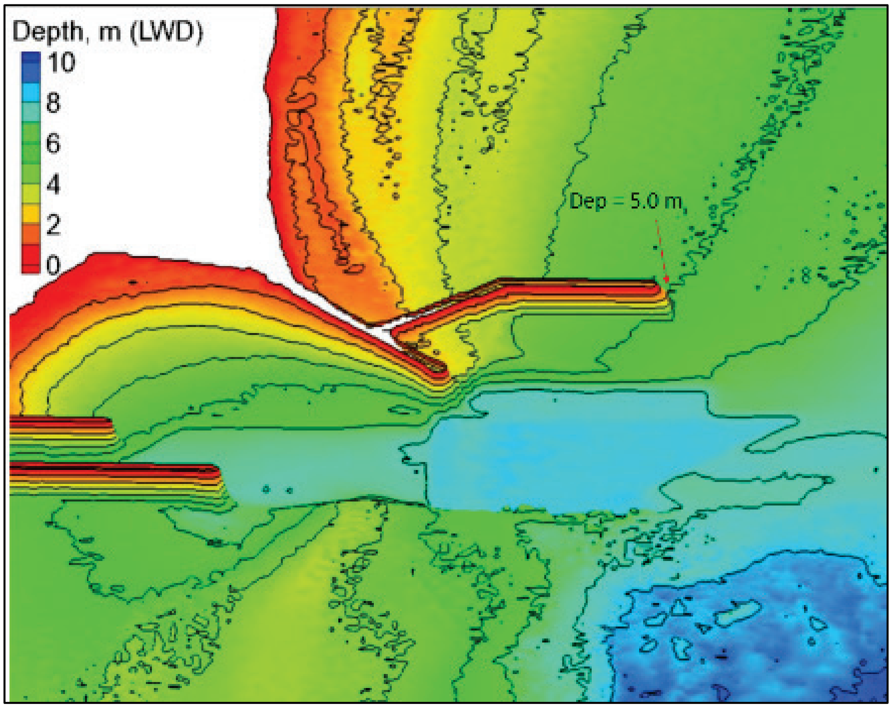
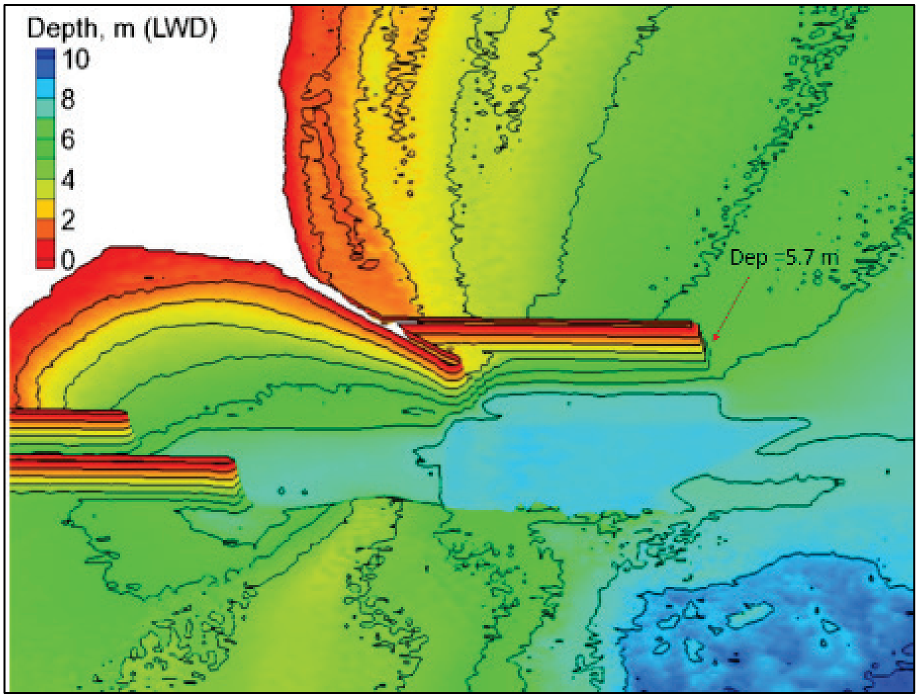


Figure 3-10. A 305 m (1000 ft) straight spur attached to the Outer Breakwater (Alt 2d).



Alt 3 is a 230 m (750 ft) eastward extension of the outer breakwater. The straight extension terminates at 7.5 m water depth (Figure 3-11).

Alt 4 is a 152 m (500 ft) eastward extension of to the outer breakwater. This extension terminates at the 7.4 m water depth (Figure 3-12).

Alt 5 is a 305 m (1000 ft) eastward extension of to the outer breakwater. This extension terminates at the 7.5 m water depth (Figure 3-13).

Alt 6 is a 305 m (1000 ft) long straight groin located north of the Power Plant (Figure 3-4) that terminates at approximately the 3 m water depth.

Figure 3-11. A 230 m (750 ft) eastward extension of the Outer Breakwater (Alt 3).

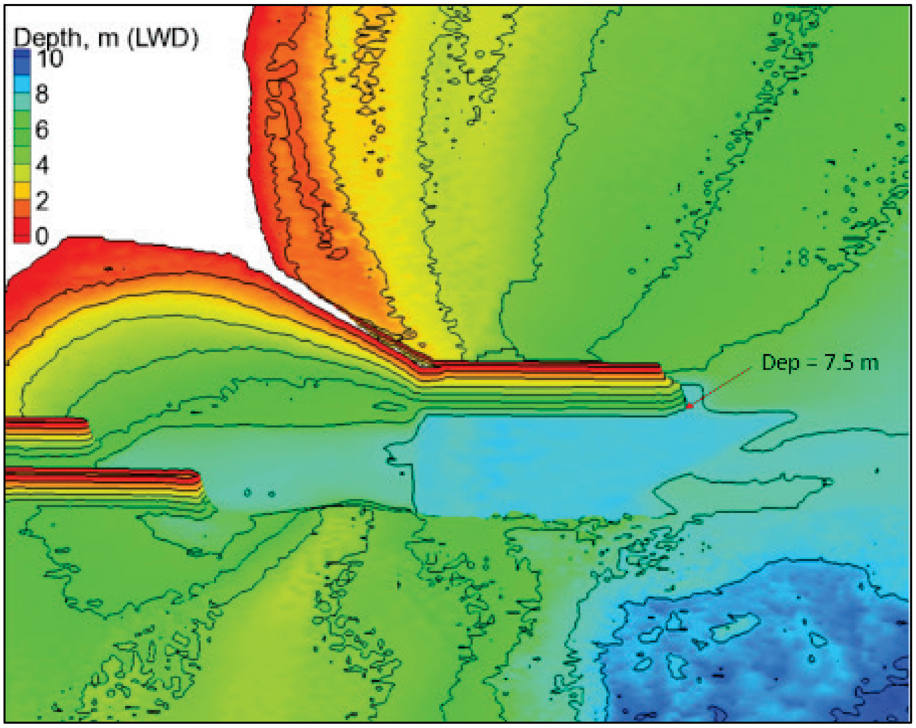


Figure 3-12. A 152 m (500 ft) eastward extension of the Outer Breakwater (Alt 4).

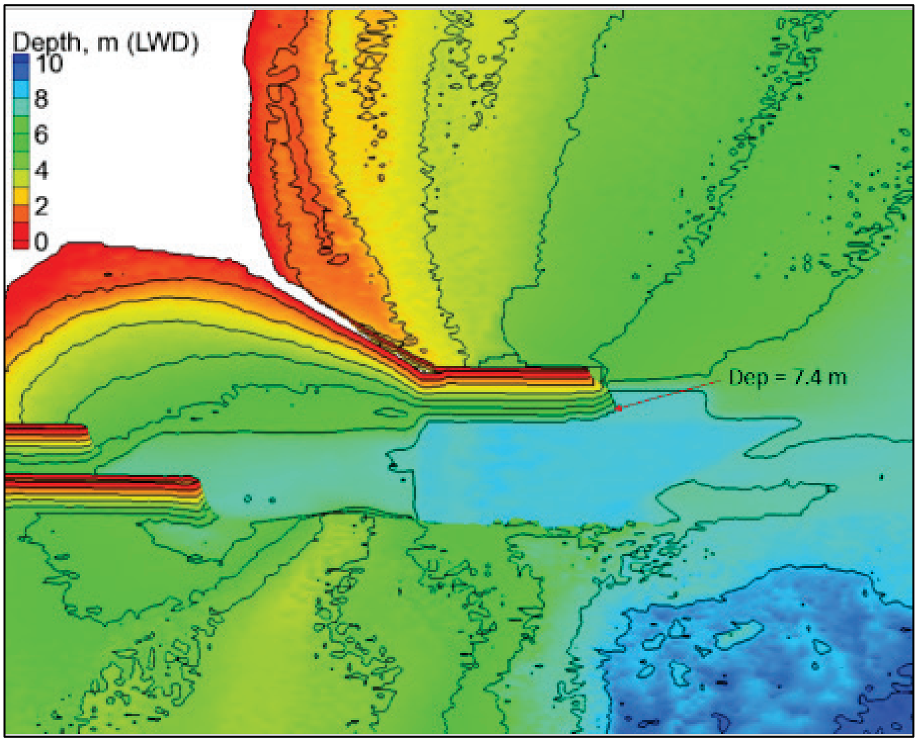


Figure 3-13. A 305 m (1000 ft) eastward extension of the Outer Breakwater (Alt 5).

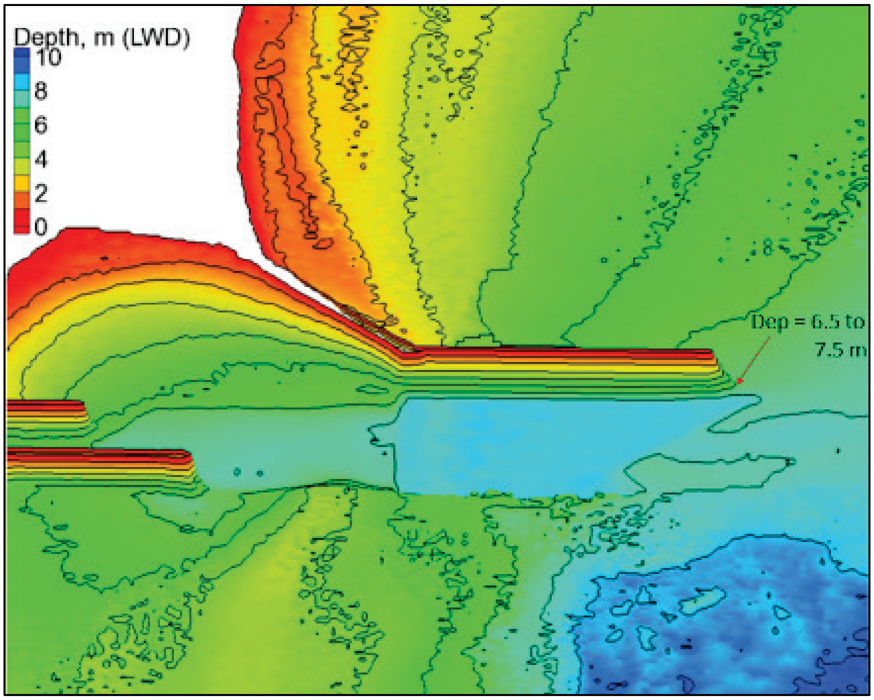
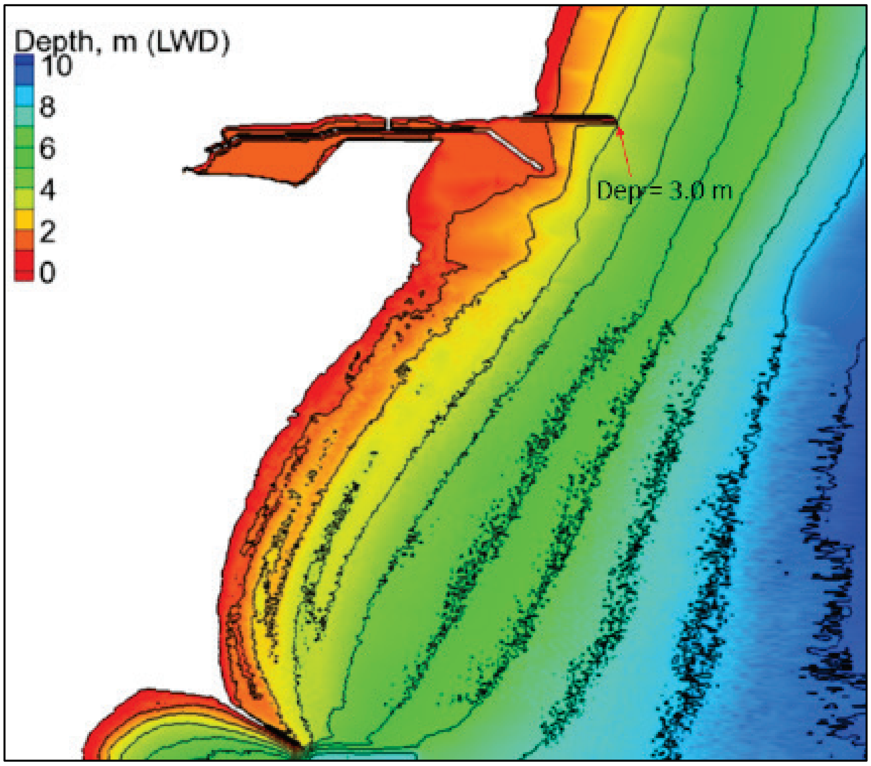


Figure 3-14. A 305 m (1000 ft) straight groin located north of the Power Plant (Alt 6).



4 Coastal Modeling System (CMS) Modeling

4.1 Description of model

This modeling study used an integrated CMS developed for coastal and inlet processes in USACE navigation projects (http://cirp.usace.army.mil/products/cms.php). The CMS simulates nearshore waves, currents, water levels, sediment transport, morphology change, salinity, and temperature on desktop computers. It is designed for coastal inlets and navigation studies involving channel performance and sediment exchange between inlets and adjacent beaches.

The Surface-water Modeling System (SMS) (www.aquaveo.com/products) interface of the CMS is used for grid generation, model setup, and post-processing (Demirbilek et al. 2007; Zundel 2006). The CMS Verification and Validation (V&V) tests with analytical solutions, idealized examples, and laboratory and prototype applications have been documented in four technical reports (Demirbilek and Rosati 2011; Lin et al. 2011a,b; Sanchez et al. 2011a,b). Additional information about the CMS is available in technical notes, journal papers, wiki pages, and from the Coastal Inlets Research Program (CIRP) website: http://cirp.usace.army.mil/wiki/CMS; https://cirpwiki.info/wiki/CMS/ValidationTestCases; https://cirpwiki.info/wiki/Test_Cases.

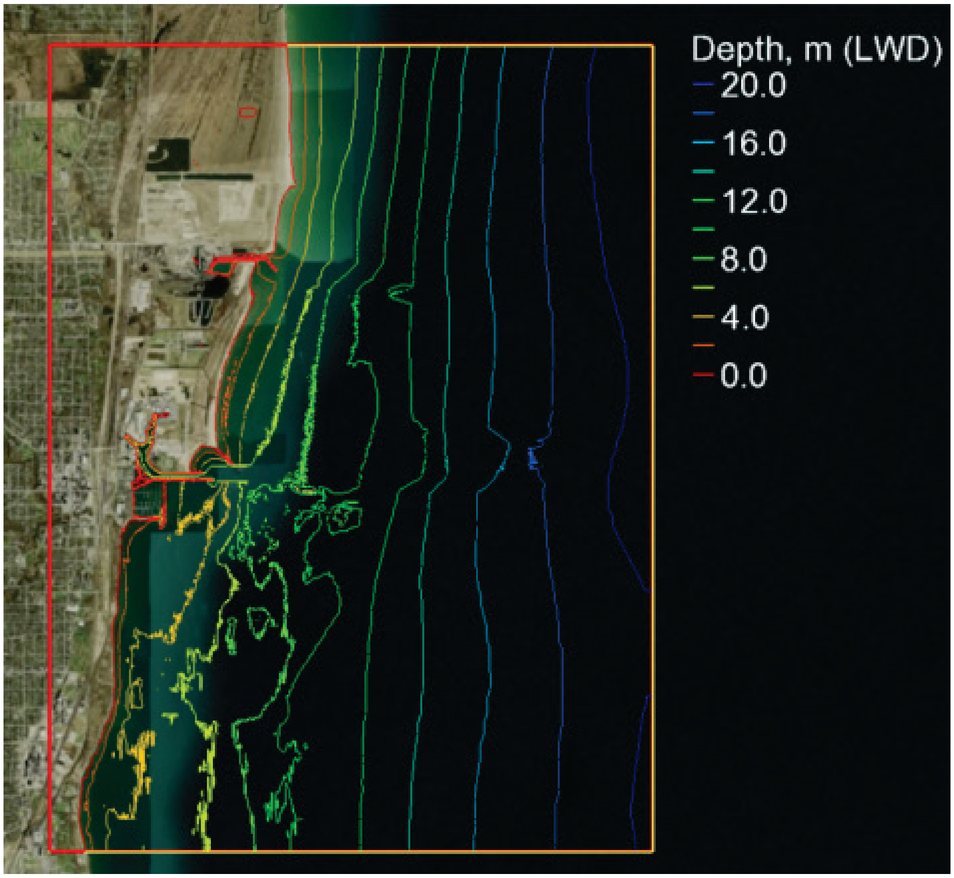
Wave-current interactions and variation in water levels affect hydrodynamics and the resulting sediment transport and morphological changes at Waukegan Harbor. The CMS consists of a spectral wave model, CMS-Wave (Lin and Demirbilek 2012; Lin et al. 2011a,b; Lin et al. 2008; Demirbilek et al. 2007) and a shallow-water equations based flow model (CMS-Flow) that includes sediment transport and morphodynamic calculations. The appendix of this report provides a detailed description of the CMS. The References section of this report includes several recent field applications of the CMS (e.g., Demirbilek et al. 2018, 2017, 2016a,b; 2015a,b,c,d).

CMS-Wave is a steady-state 2D spectral wave model (Lin et al. 2008; Lin et al. 2011a,b) capable of simulating wave processes including wave generation and growth with ambient currents at coastal inlets, harbors, and navigation channels. It uses the wave-action balance equation that includes the following wave processes: wave propagation, refraction, shoaling, diffraction, reflection, breaking, and dissipation. Deeper water incident waves in Lake Michigan were transformed to the project site using CMS-Wave to develop nearshore wave estimates outside and inside Waukegan Harbor. The computational efficiency of CMS-Wave and recently improved capabilities of the model (Lin and Demirbilek 2012; Lin et al. 2011a,b; Demirbilek and Rosati 2011) allowed for simulating a large spatial domain and a number of wave conditions in this application. The dynamic coupling of CMS-Wave with CMS-Flow and WaveNet/TideNet were used in the modeling of nearshore coastal processes.

4.2 Model grid

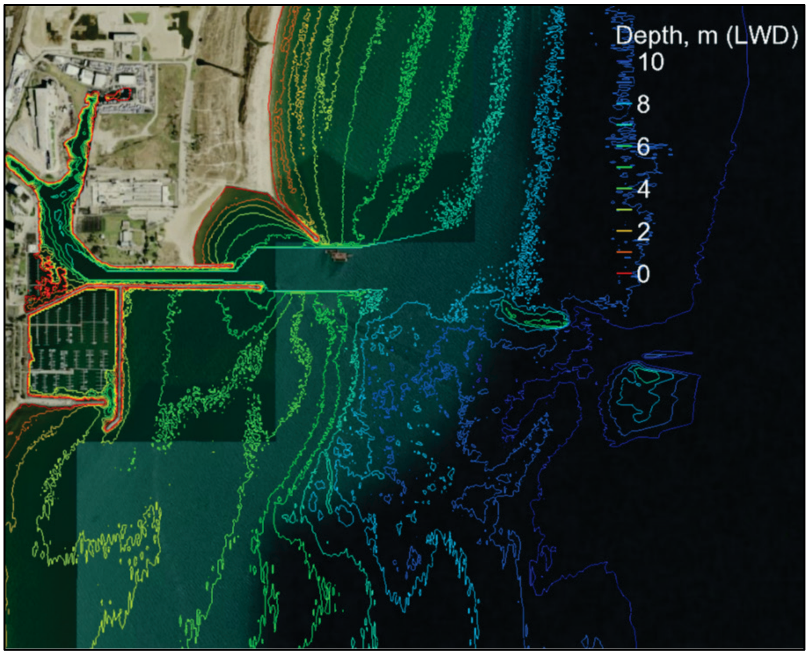
Figure 4-1 shows the numerical model domain with bathymetric contours superimposed on a Google Maps background image. The CMS modeling covers a rectangular area of 6.8 km (easting) × 9.1 km (northing) with higher cell resolution of 5 m around the harbor channel and lower resolution of 150 m away from the harbor.

Figure 4-1. Final numerical model grid domain used in CMS simulations.



The extent of grid domain and grid resolution affects the run time and computing resources (memory and disk space) required. Ultimately, the sediment transport and morphology change with a longer simulation determined the final modeling grid specifications (e.g., grid dimensions, grid resolution, and length of simulation). Figure 4-2 provides a closer view of the grid and bathymetry encompassing the Waukegan Harbor complex, and details of the topography/bathymetry in the immediate vicinity of the Approach Channel and Outer Harbor.

Figure 4-2. Details of final CMS grid around vicinity of Waukegan Harbor.



4.3 Model settings

Available nearshore wind, wave, and water level measurements at and near the project site from Milwaukee to Chicago were used in the model. The wave diffraction intensity was set to 4 (default) for the maximum diffraction allowed in CMS-Wave. A constant Darcy-Weisbach coefficient of 0.005 and a constant reflection coefficient of 0.3 (default) were applied for bottom friction and forward reflection calculations, respectively (Demirbilek et al. 2018, 2017, 2015a–d). Incident wave spectra were specified with 40 frequency bins (covering the range of 0.06 to 0.45 Hz at 0.01 Hz increment) and 35 direction bins (covering a half-plane for incoming wave direction in the range of 0 to 180 deg azimuth with 5 deg increment). Wave runup on breakwaters and infra-gravity wave options were activated in simulations.

The CMS-Flow explicit-solver version was used in the coupling with CMS-Wave. A time-varying water level was specified along the CMS-Flow offshore boundary. The hydrodynamic time-step is set to 0.25 sec while sediment transport and morphology time steps are equal to 2 and 4 sec, respectively. The non-equilibrium formulation and a median grain size of 0.2 mm were used in the model sediment transport and morphology change. The bed load and suspended load factors are set to 1.5 and 0.2, respectively. For bottom friction, a constant Mannings coefficient of 0.015 was specified in the model simulation (Demirbilek et al. 2018, 2017, 2015a–d).

The model was run on the same grids used in CMS-Wave. The coupled CMS-Wave and CMS-Flow simulations used a 3 hr interval. There is a two-way feedback between the wave and flow models using the *steering* framework in the SMS. This includes using wave radiation stress fields computed from the CMS-Wave as wave forcings to CMS-Flow and using the current and water level fields computed from the CMS-Flow as feedback to CMS-Wave. The wave radiation stresses from two consecutive CMS-Wave runs are linearly applied in the CMS-Flow simulation.

Wave model results were saved over the entire computational domain. These included significant wave height, peak period, and mean direction. Model results were saved (e.g., wave parameters and spectra) from CMS-Wave grid at the points of interest along the north beach and in/around the harbor entrance.

Figure 4-3 shows model wave height field in color scaling and current vector fields for one southeast (SE) storm event on 29 March 2015 @ 2100 Greenwich Mean Time (GMT) (Hs = 1.7 m, Tp = 5.7 sec, θwave = 157 deg, Uw = 15. 3 m/sec, θwind = 190 deg). Figure 4-4 shows model wave height and current fields for a northeast (NE) storm condition on 9 April 2015@ 0000 GMT (Hs = 1.0 m, Tp = 4.1 sec, θwave = 33 deg, Uw = 8.1 m/sec, θwind = 33 deg). Figure 4-5 shows a severe NE storm occurring on 31 May 2015 @ 0600 GMT (Hs = 3.5 m, Tp = 7.5 sec, θwave = 23 deg, Uw = 16 m/sec, θwind = 12 deg). The wind speed ranged from 8 m/sec to 16 m/sec in this simulation. Model results indicated waves breaking along the shallow depths of north and south beaches. Wave heights at the harbor entrance were generally less than 1 m.

Figure 4-3. Wave height and current vector fields (29 March 2015 @ 2100 GMT).

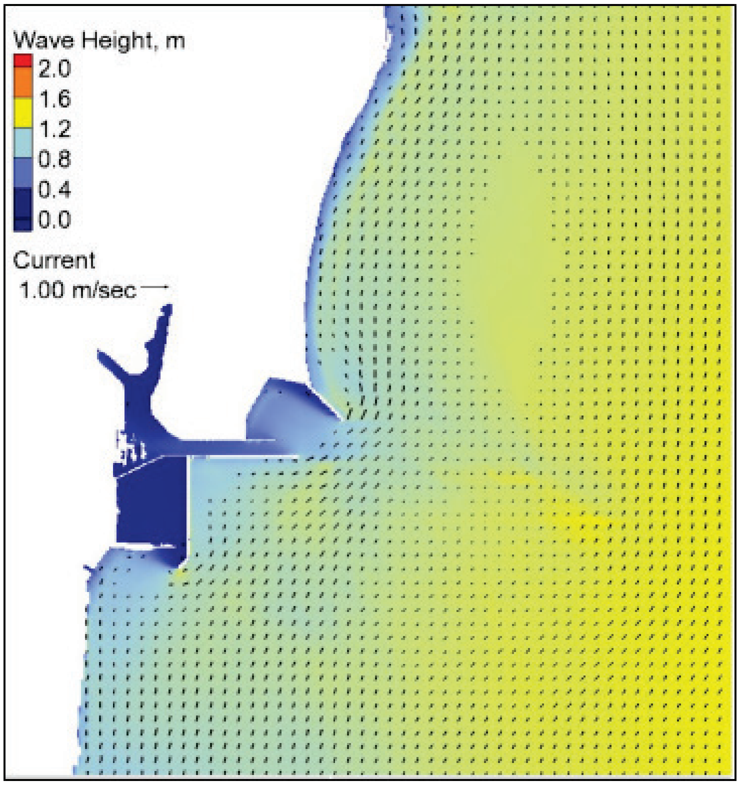


Figure 4-4. Wave height and current vector fields (9 April 2015 @ 000 GMT).

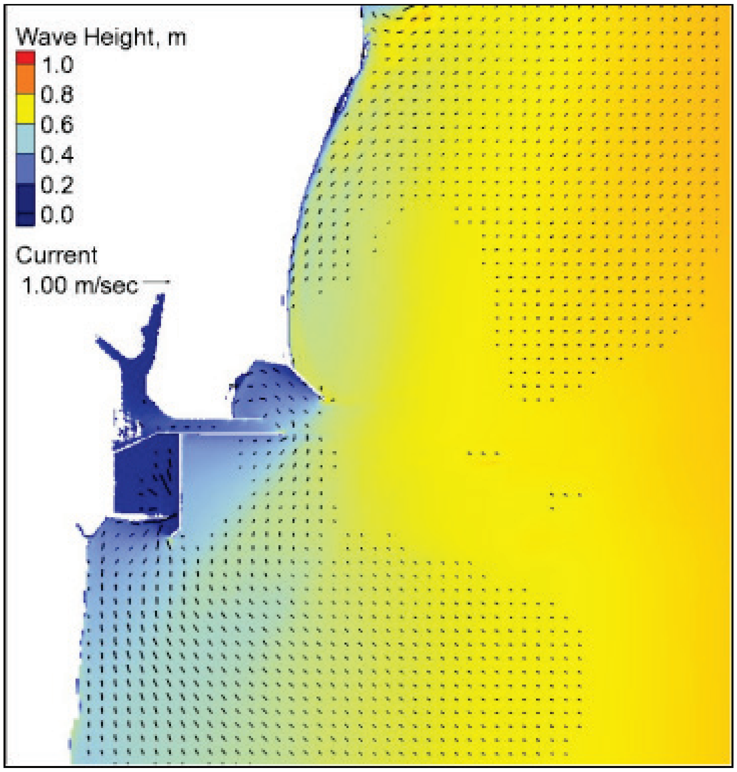
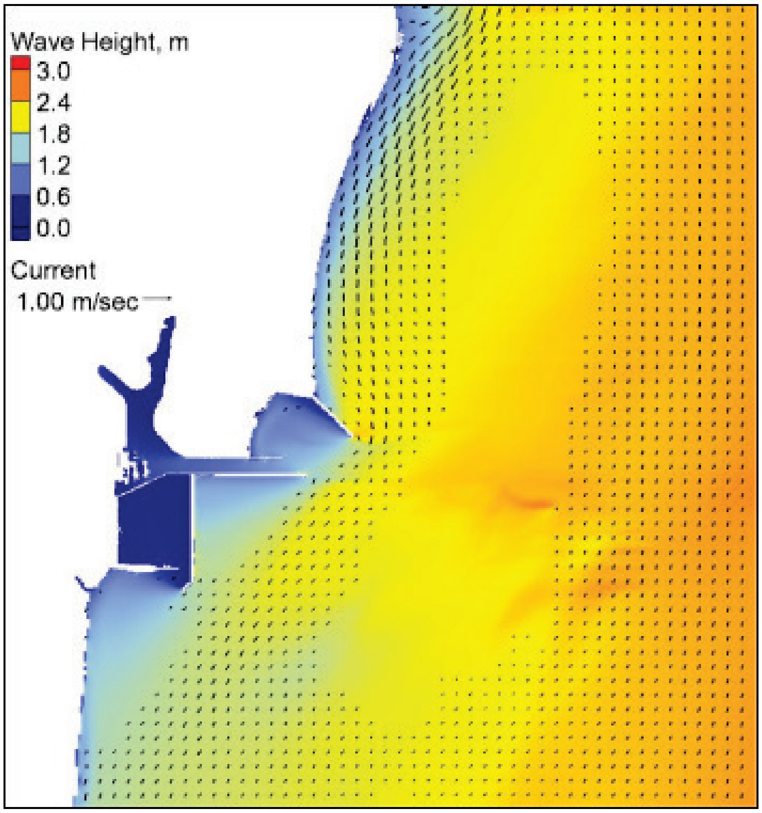


Figure 4-5. Wave height and current vector fields (31 May 2015 @ 0600 GMT).



4.4 Model calibration and validation

The calibration and validation of model waves were conducted for July–August and September–October 2018, respectively. Model forcing included offshore incident waves from NOAA Buoy 45187 (Winthrop Harbor, IL), local water levels from NOAA Station 9087057 (Milwaukee, WI), and surface wind data from WHRI2 (Waukegan Harbor). Model channel shoaling rates were compared to survey data for 2015.

Model waves were compared to the measurements at NDBC Buoy 45186 (Waukegan Harbor) and ISGS Gauges G1 and G2. Figures 4-6 to 4-8 show model calibration of wave heights and periods versus data at Buoy 45186, Gauge G1, and Gauge G2, respectively, for 20-31 July 2018. Figures 4-9 to 4-11 show model waves versus data at Buoy 45186, Gauge G1, and Gauge G2, respectively, for August 2018. For G1 and G2, apparent strong surface atmospheric (barometric) pressure disturbance has caused high noise in wave measurements. Accordingly, a significant amount of wave data in G1 and G2 were affected and removed for comparison with model waves. Conversely, model wave results used the incident wave input from NDBC Buoy 45187, located 10 miles north of Waukegan Harbor. The local wind data from NOAA Station WHRI2 used as input may also affect model results as the data may not represent the over-water winds well for modeling.

Figure 4-6. Model wave results versus data at Buoy 45186 for 20–31 July 2018.

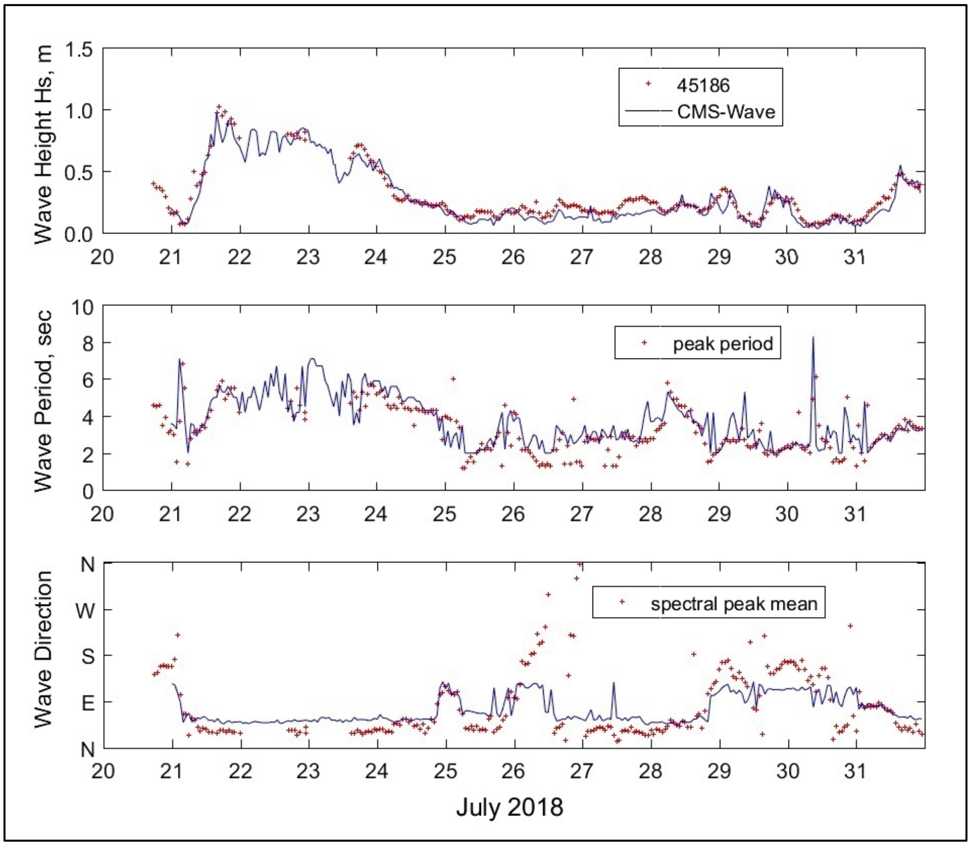


Figure 4-7. Model wave results versus data at ISGS G1 for 20–31 July 2018.

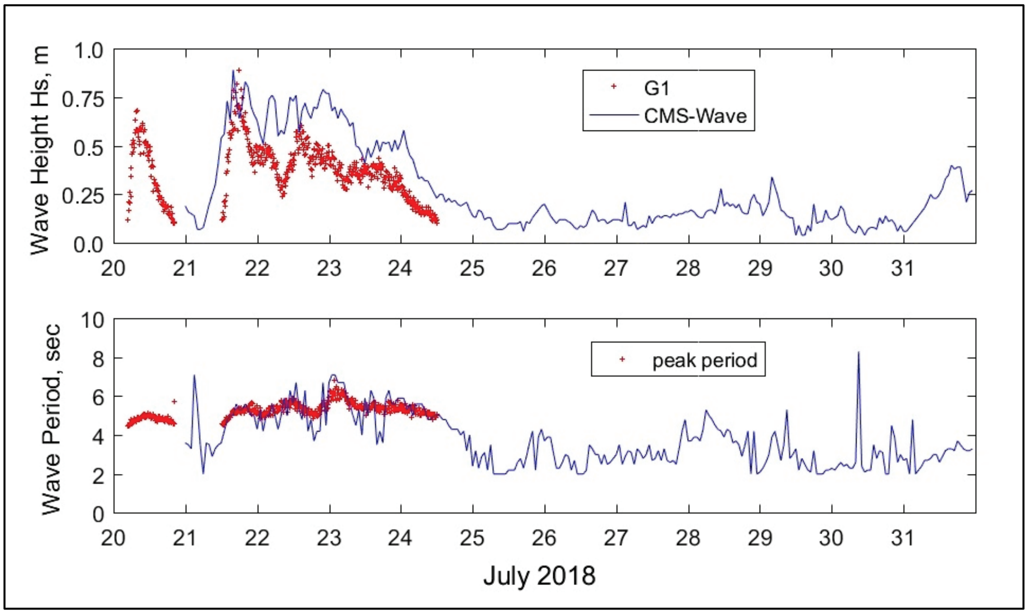


Figure 4-8. Model wave results versus data at ISGS G2 for 20–31 July 2018.

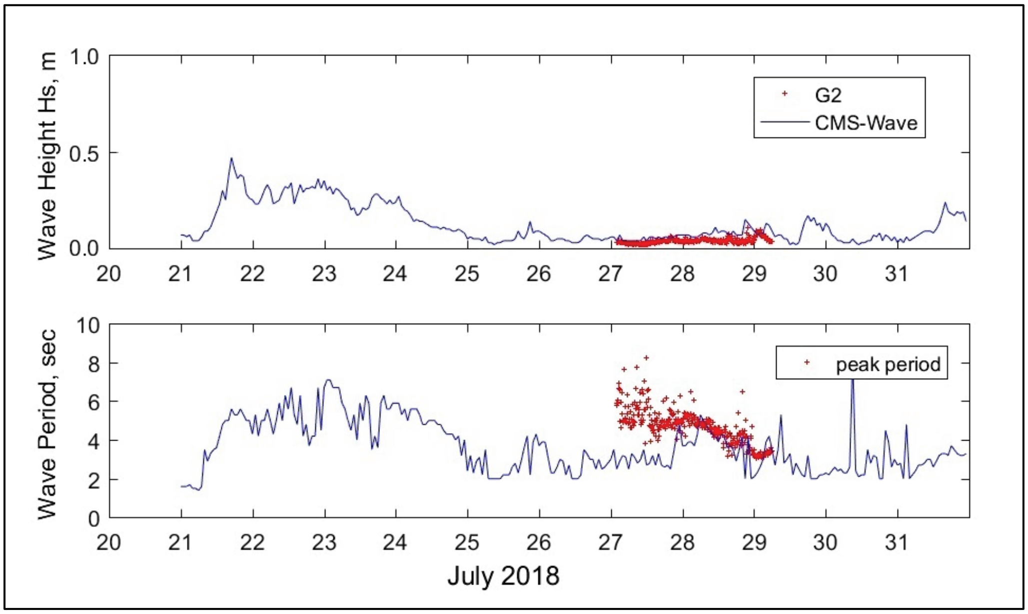


Figure 4-9. Model wave results versus data at Buoy 45186 for August 2018.

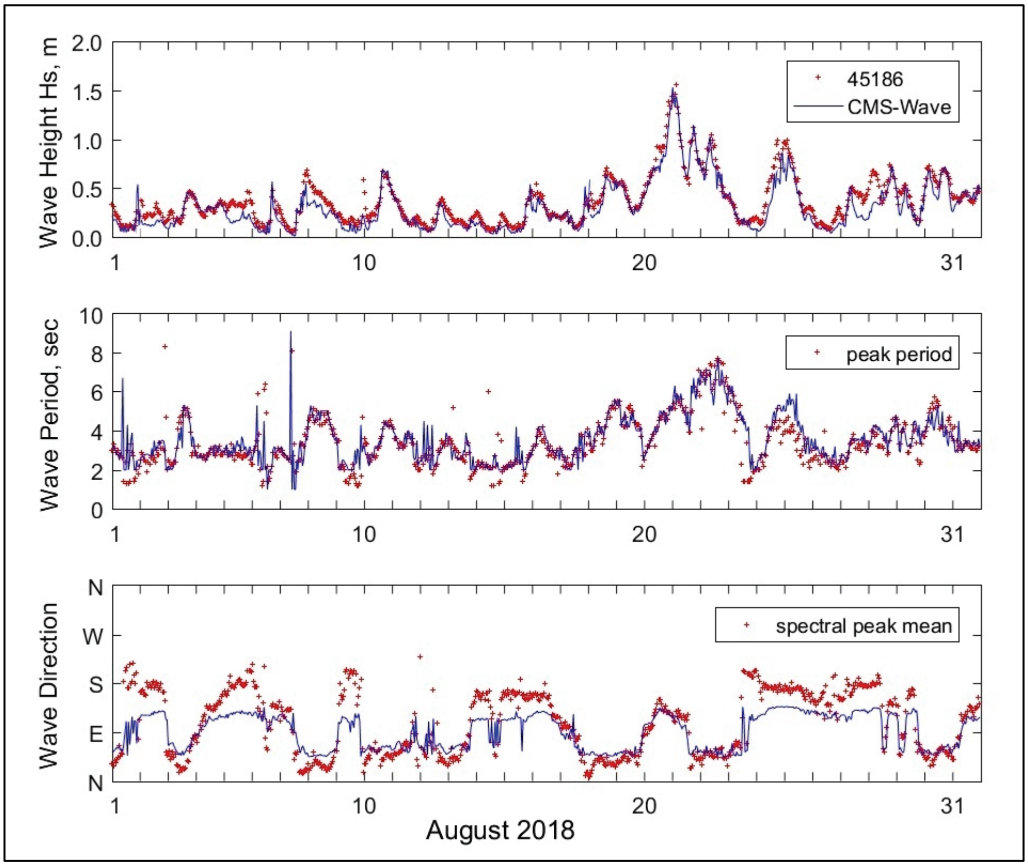


Figure 4-10. Model wave results versus data at ISGS G1 for August 2018.

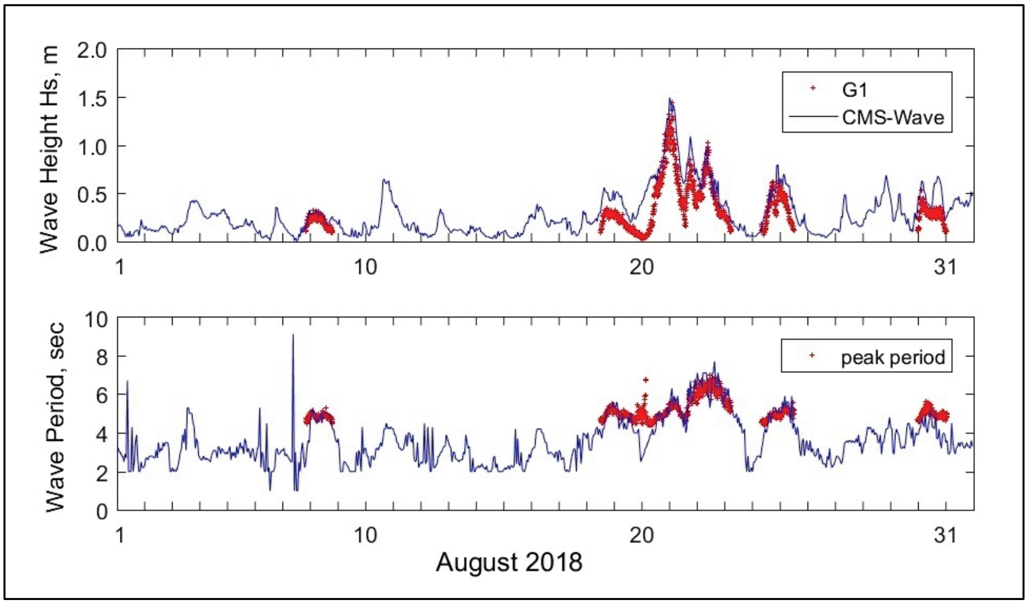
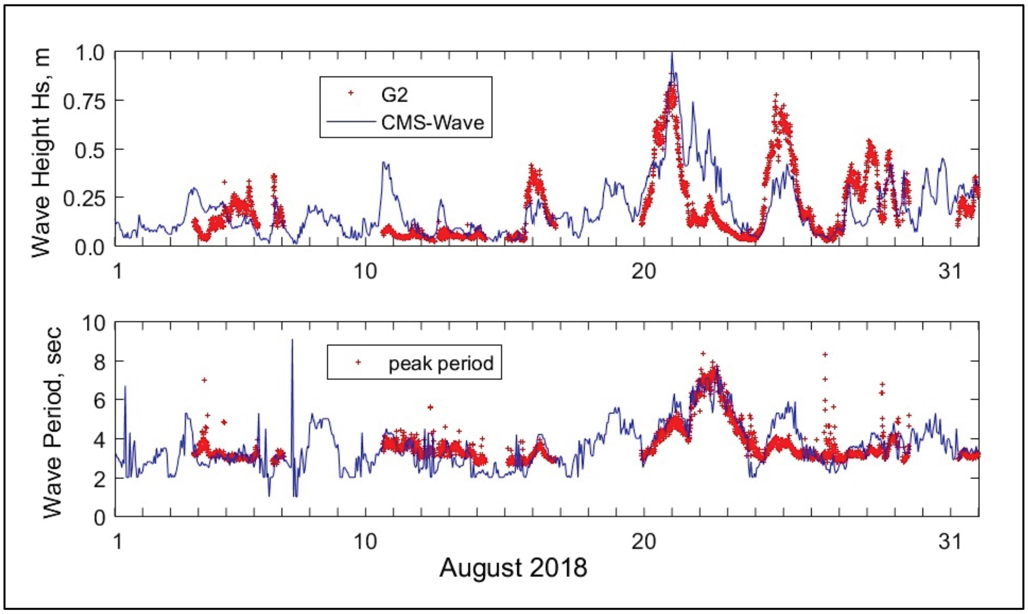


Figure 4-11. Model wave results versus data at ISGS G2 for August 2018.



Figures 4-12 to 4-14 show model verification of wave heights and periods versus data at Buoy 45186, Gauge G1, and Gauge G2, respectively, for September 2018. Figures 4-15 to 4-17 show model waves versus data at Buoy 45186, Gauge G1, and Gauge G2, respectively, for 1–20 October 2018. A significant portion of wave data at G1 and G2 were removed in the comparison with model waves as the data were contaminated by strong surface pressure variations that occurred during wave measurements.

Figure 4-12. Model waves versus data at Buoy 45186 for September 2018.

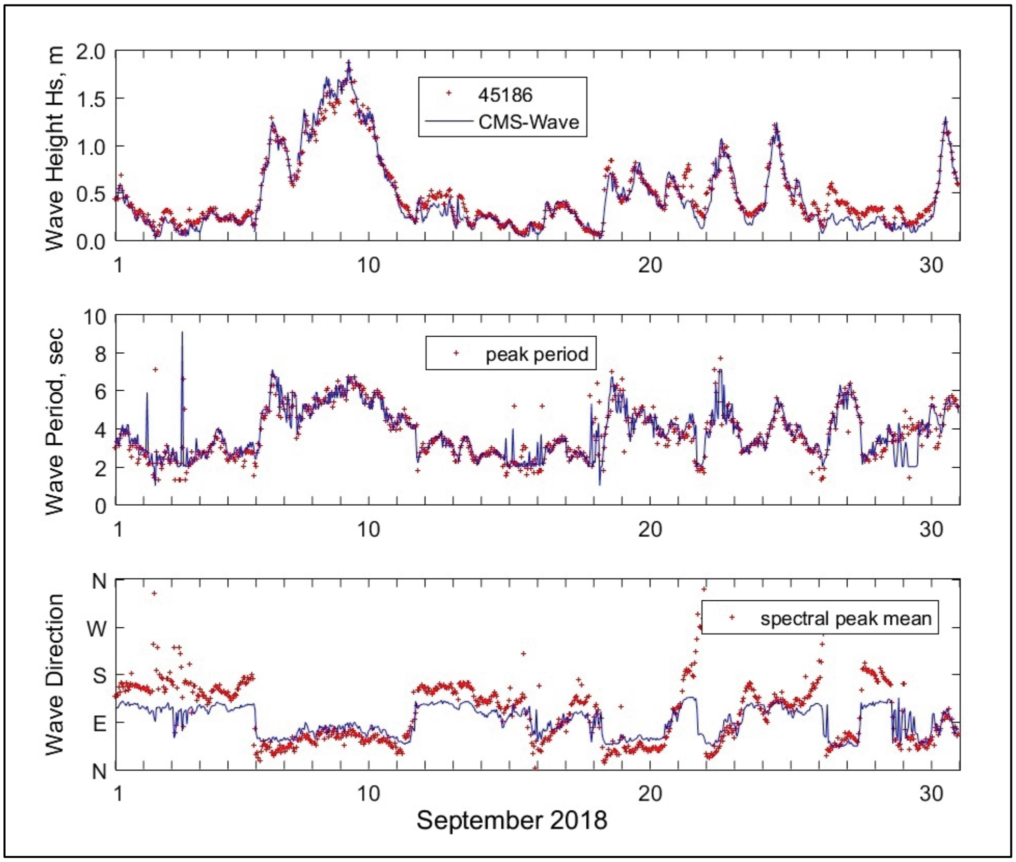


Figure 4-13. Model waves versus data at ISGS G1 for September 2018.

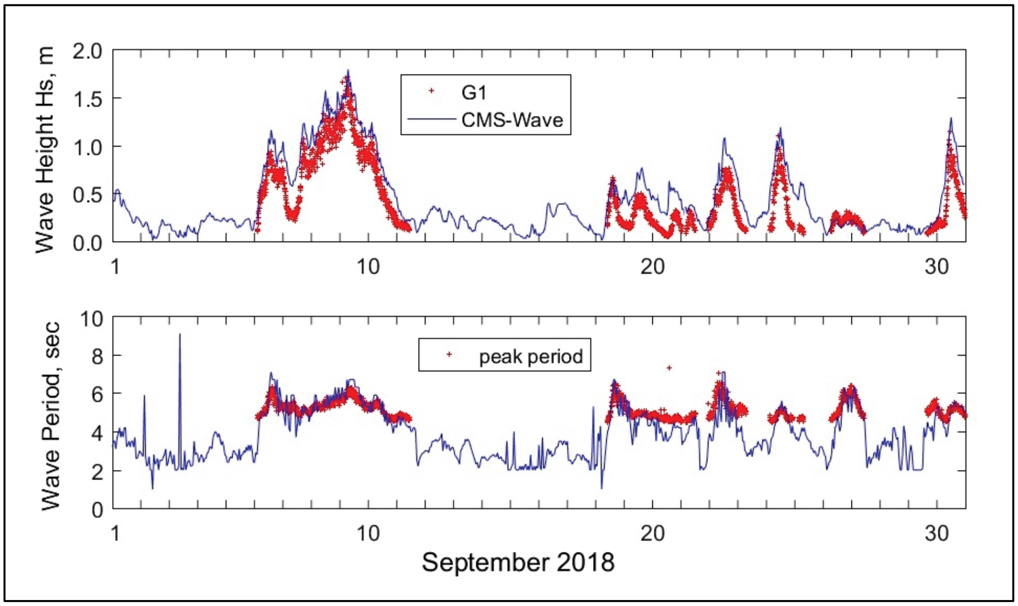


Figure 4-14. Model waves versus data at ISGS G2 for September 2018.

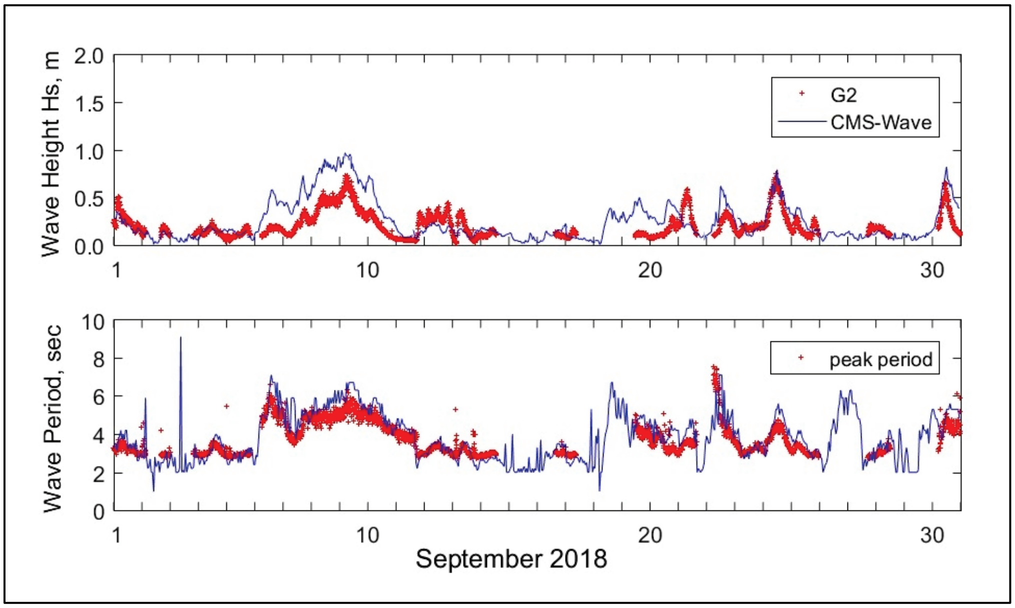


Figure 4-15. Model waves versus data at Buoy 45186 for 1–20 October 2018.

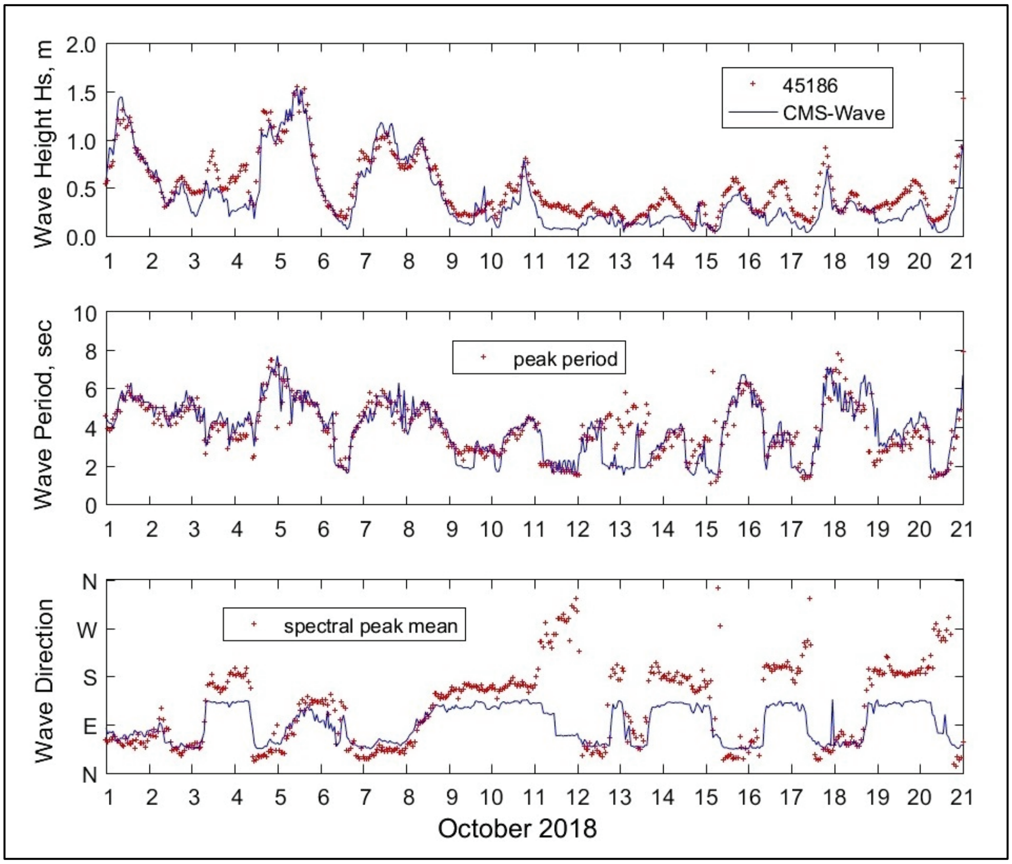


Figure 4-16. Model waves versus data at ISGS G1 for 1–20 October 2018.

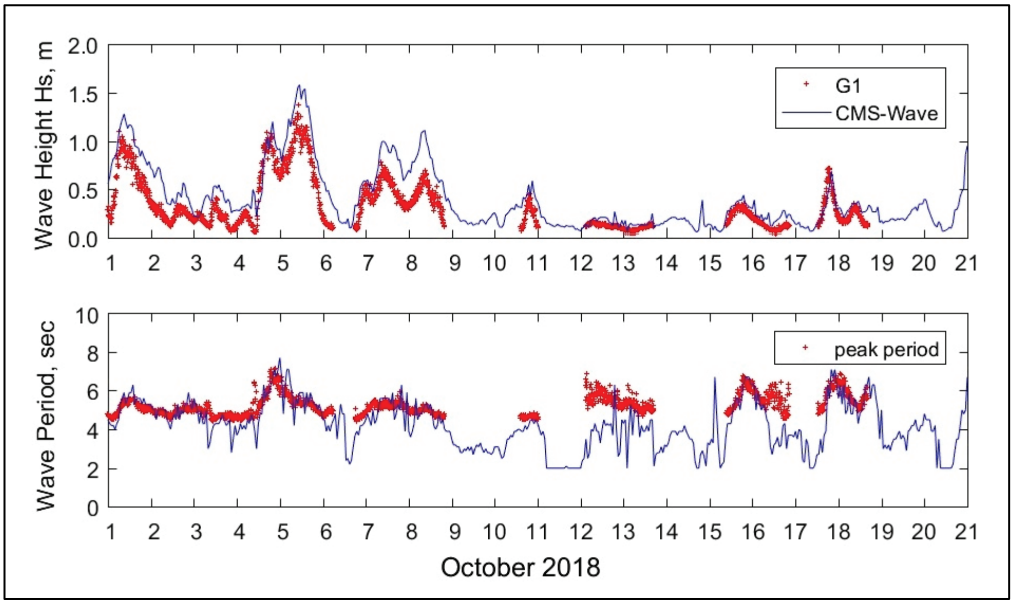
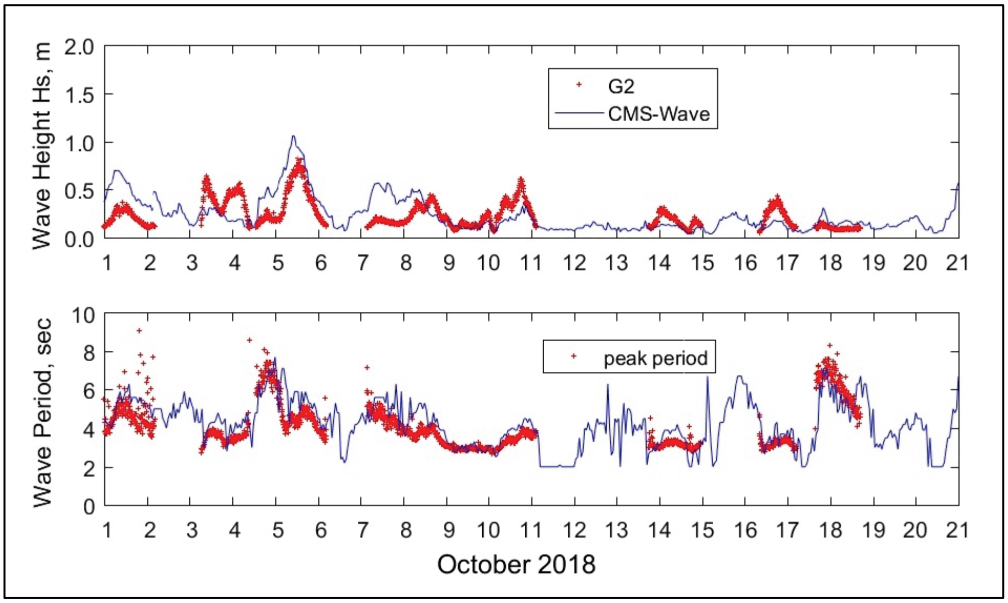


Figure 4-17. Model waves versus data at ISGS G2 for 1–20 October 2018.



5 Results and Discussion

5.1 Description of simulations

This chapter describes shoaling estimates for each investigated alternative based on model-calculated sediment transport and morphology changes. Numerical simulations were performed for 12 alternatives including the existing harbor described in Chapter 3 for a year-long time period. The year 2015 was selected as a recent average climate year for 9-month (March–November 2015) simulations, excluding ice conditions during winter months. These simulations helped to determine the sensitivity of shoaling rates occurring during different times of the year.

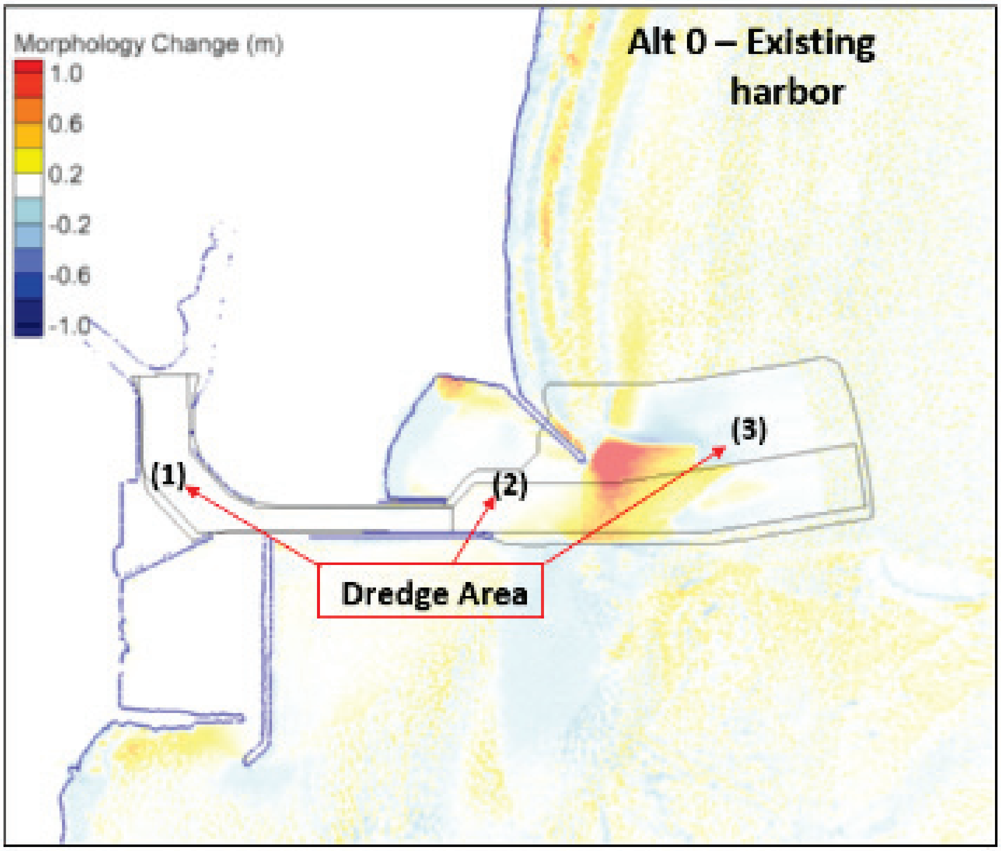
5.2 Phase 1 study shoaling estimates for Waukegan Harbor

The sediment transport and morphology change is for a 9-month (March–November 2015) simulation with combined CMS wave and hydrodynamics models. Estimates of the shoaling volume and the sediment accumulation hotspots were made for three areas of interest:

- Area 1: Inner Harbor (IH)
- Area 2: Outer Harbor (OH) + Approach Channel (AC)
- Area 3: Advance Maintenance (AM) area.

Figure 5-1 shows the boundaries of these areas in the existing harbor configuration (Alt 0). Hereafter, these areas are referred to as “Area 1”, “Area 2,” and “Area 3.” Area 2 covers only the navigable (dredged) sections of the OH and AC. Area 3 included Area 2 and part of the impoundment area along the outer breakwater.

Figure 5-1. Three polygons used to define shoaling areas at Waukegan Harbor.



Figures 5-2, 5-3, and 5-4 show the 2D maps of morphology change for all alternatives investigated. In these figures, the vertical variation at each model grid point represents the morphology change. This change represents sediments moved by waves and currents. The channel shoaling, denoted by yellow and red, increases if more sediments reach a grid point and remain there. Because morphology change is relative to the initial depth at a grid point, it represents the time-varying depth change at the end of a simulation. Thus, the morphology change is the depth difference at any grid point between the start and end times of a simulation. The 9-month simulation time represents the entire year of 2015 excluding a 3-month (December, January, and February) period during which the lake might have ice.

Simulations were performed on desktop Windows 10 personal computers with 16 to 32 GB memory and 12 to 48 processors. The computer run time for a 9-month simulation ranged from 17 days to 21 days. The coupled CMS-Wave and CMS-Flow (explicit model) simulations required the use of a *steering* module available in version 11.0 of the SMS (SMS 11.0). The SMS was also used for grid generation, pre-/post-processing of model inputs and outputs, generating 2D spatial images to show variation of morphology change, and generating the tabulated modeling results in this chapter.

A positive value of the morphology change in these plots denotes sediment accretion (deposition) or areas gaining material while a negative value signifies erosional areas loosing material. Red and yellow indicate accretion areas and blue signifies erosion. The intensity of colors represents severity (magnitude) of the morphology change. For each alternative, these 2D contour maps display the spatial distribution of sedimentation at the end of the 9-month simulation. The morphology change maps are provided for three groups, each group with four alternatives: Group 1 (Alt 1, Alt 1a, Alt 2, Alt 6) shown in Figure 5-2; Group 2 (Alt 2a, Alt 2b, Alt 2c, Alt 2d) in Figure 5-3; and Group 3 (Alt 0, Alt 3, Alt 4, Alt 5) in Figure 5-4. Chapter 3 provides detailed information about each alternative. The sketch of each alternative super-imposed on a 2D map shows its location and geometry (shape). These maps also depict locations of the hot spot areas created by each alternative.

Figure 5-2. Morphology change for Alt1, Alt1a, Alt2, and Alt6 (March–November 2015).

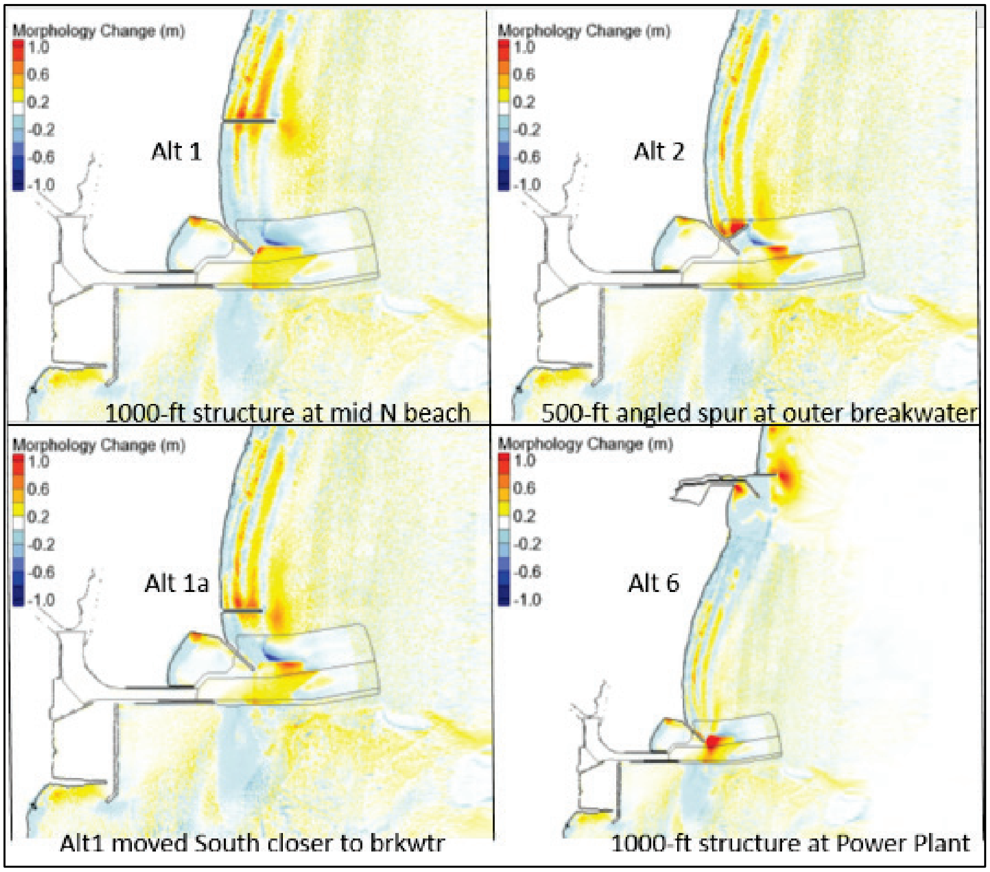


Figure 5-3. Morphology change for Alt2a, Alt2b, Alt2c, and Alt2d (March–November 2015).

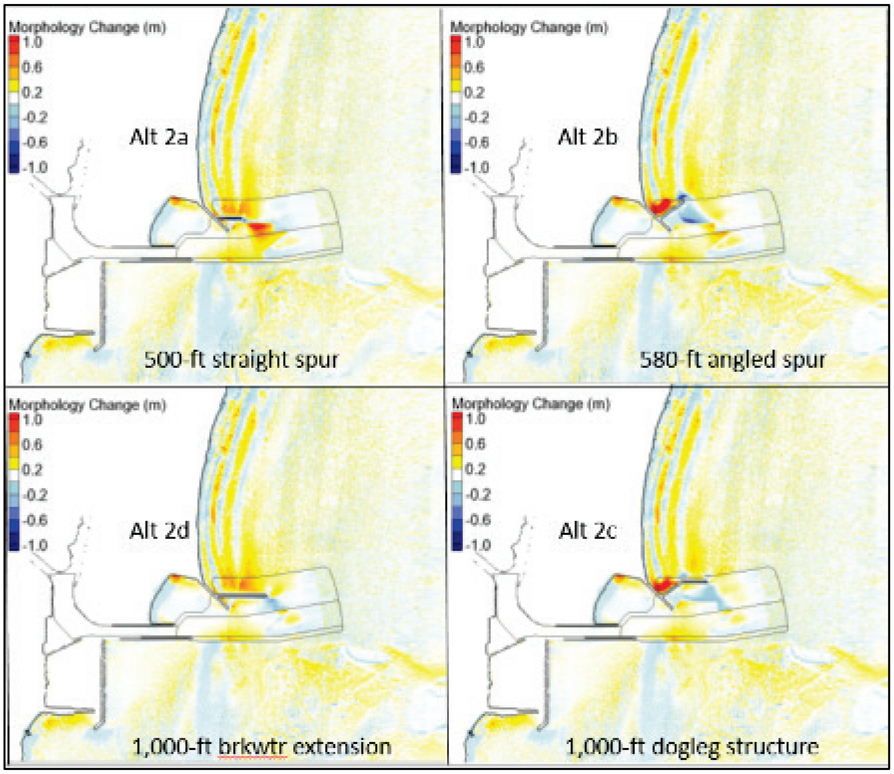


Figure 5-4. Morphology change for Alt0, Alt3, Alt4, and Alt5 (March–November 2015).

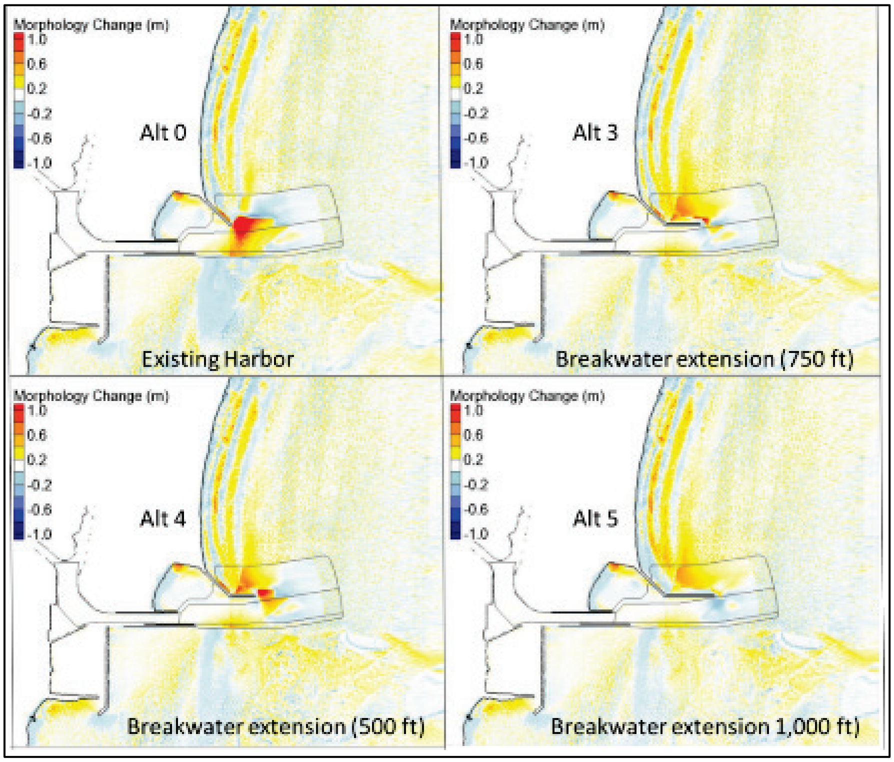


Table 5-1 presents the summary of 9-month (March–November 2015) morphology change estimates for all alternatives in the three polygon areas shown in Figure 5-1. Shoaling volume estimates in Area 1, Area 2, and Area 3 are provided in cubic meter (m^3) and cubic yards (cy). Existing Harbor (Alt 0) serves as the baseline without project condition and is used to evaluate effectiveness of other alternatives. Alt 1a, Alt 2b, Alt 2c, and Alt 2d are marked in bold in Table 5-1. These were not in Phase 1 study and added later as Phase 2 study. All alternatives involved certain modifications to the existing harbor in order to reduce chronic channel shoaling.

Table 5-1. Morphology change for all alternatives (March–November 2015).

	9-Month Morphology Change** (m^3)		
Alternatives (Groins, spurs and brkwtr extensions)	Area 1 (Inner Harbor)	Area 2 (Outer harbor + Approach channel)	Area 3 (Area 2 + Advance maintenance dredge area)
Alt 0 w/o project (as is)	130 (170*)	14,000 (18,300)	39,800 (52,000)
Alt 1 1000-ft N groin	150 (195)	9,100 (11,900)	19,000 (24,850)
Alt 1a*** **1000 ft S groin**	**140** **(180)**	**9,800** **(12,800)**	**20,600** **(26,950)**
Alt 2 500 ft angled spur	80 (105)	9,050 (11,840)	26,500 (34,660)
Alt 2b*** **580 ft angled spur**	**130** **(170)**	**8,000** **(10,460)**	**24,100** **(31,520)**
Alt 2c*** **1000 ft dogleg spur**	**144** **(188)**	**5,700** **(7,450)**	**19,795** **(25,870)**
Alt 2a 500 ft E-W ext	140 (180)	9,500 (12,425)	29,800 (38,975)
Alt 2d*** 500 ft E-W ext	141 (184)	4,673 (6,107)	20,933 (27,360)
Alt 3 750 ft E-W ext	120 (160)	4,300 (5,620)	27,100 (35,420)
Alt 4 500 ft ext	130 (170)	6,550 (8,560)	29,100 (37,900)
Alt 5 1000 ft ext	130 (170)	2,650 (3,500)	20,800 (27,200)
Alt 6 1000 ft groin @power station	130 (170)	13,300 (17,400)	38,800 (50,750)

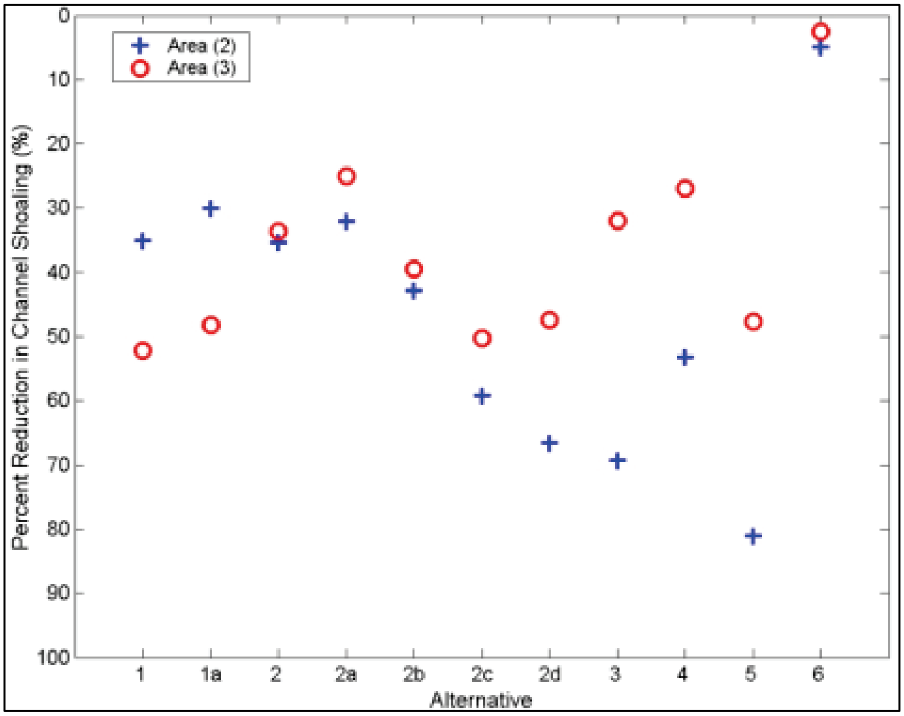
*Quantity shown in parentheses is cubic yard (cy)

**CMS with D50 = 0.2 mm and n = 0.015

***New alternatives

Sensitivity tests were performed with different sediment grain sizes and Manning's coefficients to check model results. The sediment grain size of D50=0.2 mm and Manning's coefficient of n=0.015 yielded the best match to dredging data. The performance ranking of the 12 alternatives is presented in Figure 5-5 based on the data in Table 5-1. Blue and red markers represent percent reduction in the shoaling volumes in Area 2 and Area 3, respectively. Among all alternatives, Alt 5, Alt 3, Alt 2c, and Alt 2d performed the best with a percent reduction ranging from 60% to 85%. Alt 4 with a 55% reduction follows these top performers. Other alternatives (Alt 1, Alt 1a, Alt 2, Alt 2a, and Alt 2b) achieved a lower percent of reduction from 30% to 40%. Alt 6, a far-field solution located near the Waukegan Power Plant produced no reduction and did not affect harbor shoaling. Figure 5-5 indicates the distance of an alternative to the harbor entrance is one of the controlling factors for effectiveness of sand-trapping structural alternatives.

Figure 5-5. Percent reduction of shoaling in Area 2 and Area 3.



5.3 Phase 2 study shoaling estimates for three crest elevations

LRC developed cost estimates for the 12 alternatives investigated based on modeling results summarized in Table 5-1 for high-crest structural elevation of 1.98 m (6.5 ft). Among all alternatives, Alt 5, Alt 3, Alt 2c, and Alt 2d were the top four performers (Figure 5-5). This group was selected for additional investigation in the Phase 2 modeling study with two specific objectives in mind: (1) to evaluate the sensitivity of cost estimates to the structural crest elevation and (2) to investigate the seasonal variation of channel shoaling as a function of the length of simulation.

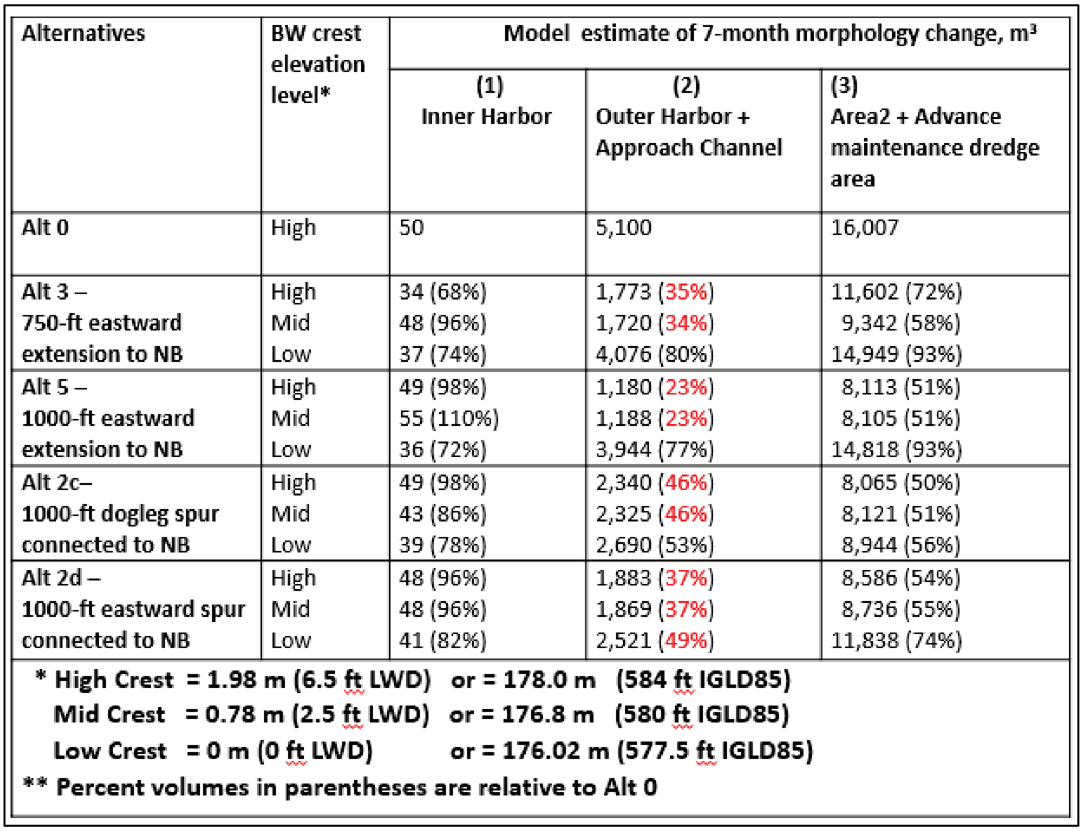
In the Phase 2 study, three structural crest elevations (high, middle, and low) and three simulation lengths (7-month, 2-month, and 9-month) were further investigated. The *high-crest* elevation of 1.98 m (6.5 ft LWD) corresponds to a vertical datum of 178 m (584 ft) IGLD85 representing a 50-year return period water level for Lake Michigan. The *mid-crest* elevation of 0.78 m (2.5 ft LWD) corresponds to 176.8 m (580 ft) IGLD85 and a 20-year design water level for Lake Michigan. The *low-crest* elevation of 0 m (0 ft LWD) corresponds to a vertical datum of 176.02 m (577.5 ft) IGLD85.

Numerical simulations were performed for three time lengths: 7 month (March–September 2015), 2 months (October–November 2015), and 9 months (March–November 2015). These simulations helped to determine the sensitivity of shoaling rates occurring during different times of the year. A particular interest was in the 2-month (October–November 2015) simulation because the largest storms generally occurred during these months. Model results indeed confirmed greater shoaling volume estimates during these 2 months relative to the first 7 months (March–September 2015).

Table 5-2 and Table 5-3 present shoaling volume estimates for 7-month (March–September 2015) and 9-month (March–November 2015) periods, respectively. A continuous 9-month simulation was conducted for comparison of combined results from 7-month and 2-month simulations. This showed that volume estimates from two consecutive shorter simulations might be linearly added to provide an approximate projection for a longer timeframe. Such a projection should be verified before it can be used in practice. The spatial change in the shoaling height (e.g., the height of accretion or erosion) did not follow a linear superposition of results from two consecutive shorter simulations. Modeling results revealed comparatively greater shoaling occurring in the last 2 months (October–November 2015), indicating a correlation between the channel shoaling and large storms during these 2 months.

For each alternative listed in Tables 5-2 and 5-3, values in parentheses are the percent estimates (e.g., divided by the Alt 0 estimate) expressing the estimate as a percentage of the Alt 0 estimate. The total estimates from the 9-month simulation are not necessarily a linear sum of results from the 7 month and 2-month simulations.

Table 5-2. The shoaling estimates over a 7-month time (March–September 2015).

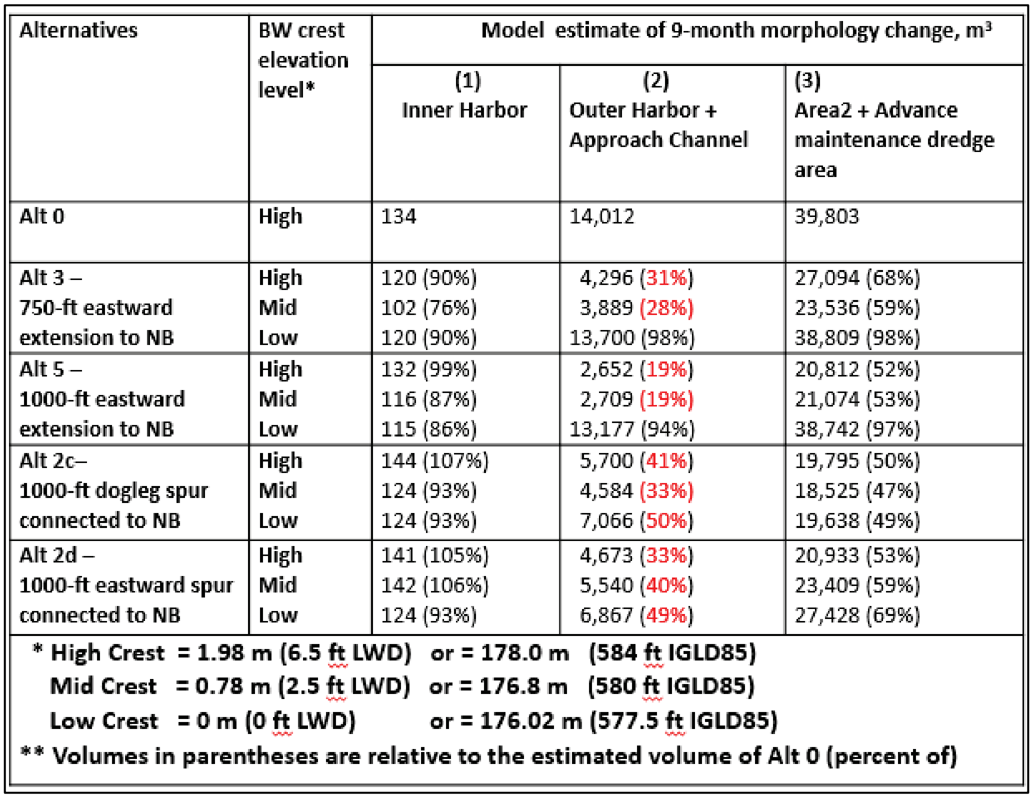


Alternatives	BW crest elevation level*	Model estimate of 7-month morphology change, m^3		
		(1) Inner Harbor	(2) Outer Harbor + Approach Channel	(3) Area2 + Advance maintenance dredge area
Alt 0	High	50	5,100	16,007
Alt 3 – 750-ft eastward extension to NB	High	34 (68%)	1,773 (35%)	11,602 (72%)
	Mid	48 (96%)	1,720 (34%)	9,342 (58%)
	Low	37 (74%)	4,076 (80%)	14,949 (93%)
Alt 5 – 1000-ft eastward extension to NB	High	49 (98%)	1,180 (23%)	8,113 (51%)
	Mid	55 (110%)	1,188 (23%)	8,105 (51%)
	Low	36 (72%)	3,944 (77%)	14,818 (93%)
Alt 2c– 1000-ft dogleg spur connected to NB	High	49 (98%)	2,340 (46%)	8,065 (50%)
	Mid	43 (86%)	2,325 (46%)	8,121 (51%)
	Low	39 (78%)	2,690 (53%)	8,944 (56%)
Alt 2d – 1000-ft eastward spur connected to NB	High	48 (96%)	1,883 (37%)	8,586 (54%)
	Mid	48 (96%)	1,869 (37%)	8,736 (55%)
	Low	41 (82%)	2,521 (49%)	11,838 (74%)

*** High Crest = 1.98 m (6.5 ft LWD) or = 178.0 m (584 ft IGLD85)**
Mid Crest = 0.78 m (2.5 ft LWD) or = 176.8 m (580 ft IGLD85)
Low Crest = 0 m (0 ft LWD) or = 176.02 m (577.5 ft IGLD85)
**** Percent volumes in parentheses are relative to Alt 0**

In Tables 5-2 and 5-3, the performance of Alt 3, Alt 5, Alt 2c, and Alt 2d has been quantified as a scaled percentage relative to Alt 0 (w/o project condition). This metric defines the effectiveness of an alternative. The shoaling volume estimates less than 50% are marked in red. The percent reduction in shoaling for each alternative is calculated from the scaled percentages. Because either volumes or percent reduction estimates can be used in engineering practice, both estimates are provided for the three structural crest elevations. Although structures with the high-crest elevation performed the best, because the construction cost is directly proportional to the size of a structure (length, width, height and water depth), the mid- and low-crest structures have become of particular interest to this project for reducing structural design costs.

Table 5-3. The shoaling estimates over a 9-month time (March–November 2015).

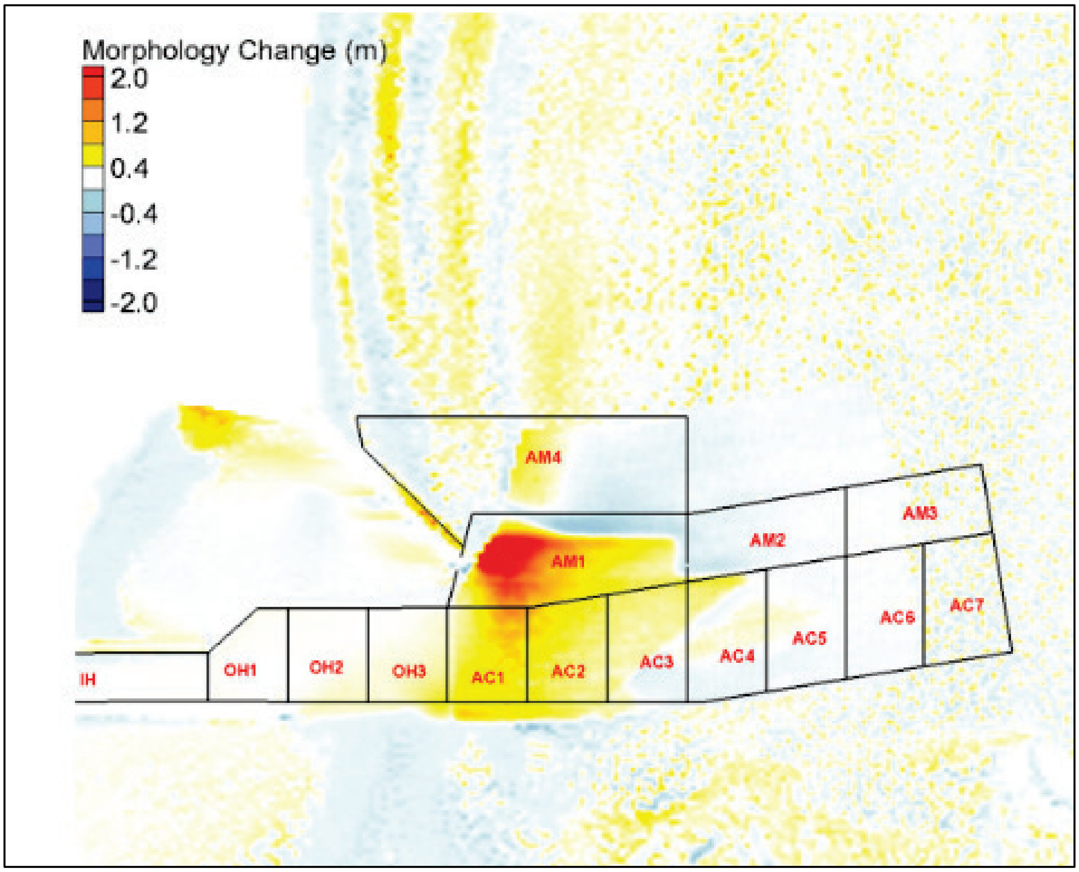


Alternatives	BW crest elevation level*	Model estimate of 9-month morphology change, m^3		
		(1) Inner Harbor	(2) Outer Harbor + Approach Channel	(3) Area2 + Advance maintenance dredge area
Alt 0	High	134	14,012	39,803
Alt 3 – 750-ft eastward extension to NB	High	120 (90%)	4,296 (31%)	27,094 (68%)
	Mid	102 (76%)	3,889 (28%)	23,536 (59%)
	Low	120 (90%)	13,700 (98%)	38,809 (98%)
Alt 5 – 1000-ft eastward extension to NB	High	132 (99%)	2,652 (19%)	20,812 (52%)
	Mid	116 (87%)	2,709 (19%)	21,074 (53%)
	Low	115 (86%)	13,177 (94%)	38,742 (97%)
Alt 2c– 1000-ft dogleg spur connected to NB	High	144 (107%)	5,700 (41%)	19,795 (50%)
	Mid	124 (93%)	4,584 (33%)	18,525 (47%)
	Low	124 (93%)	7,066 (50%)	19,638 (49%)
Alt 2d – 1000-ft eastward spur connected to NB	High	141 (105%)	4,673 (33%)	20,933 (53%)
	Mid	142 (106%)	5,540 (40%)	23,409 (59%)
	Low	124 (93%)	6,867 (49%)	27,428 (69%)

*** High Crest = 1.98 m (6.5 ft LWD) or = 178.0 m (584 ft IGLD85)**
Mid Crest = 0.78 m (2.5 ft LWD) or = 176.8 m (580 ft IGLD85)
Low Crest = 0 m (0 ft LWD) or = 176.02 m (577.5 ft IGLD85)
**** Volumes in parentheses are relative to the estimated volume of Alt 0 (percent of)**

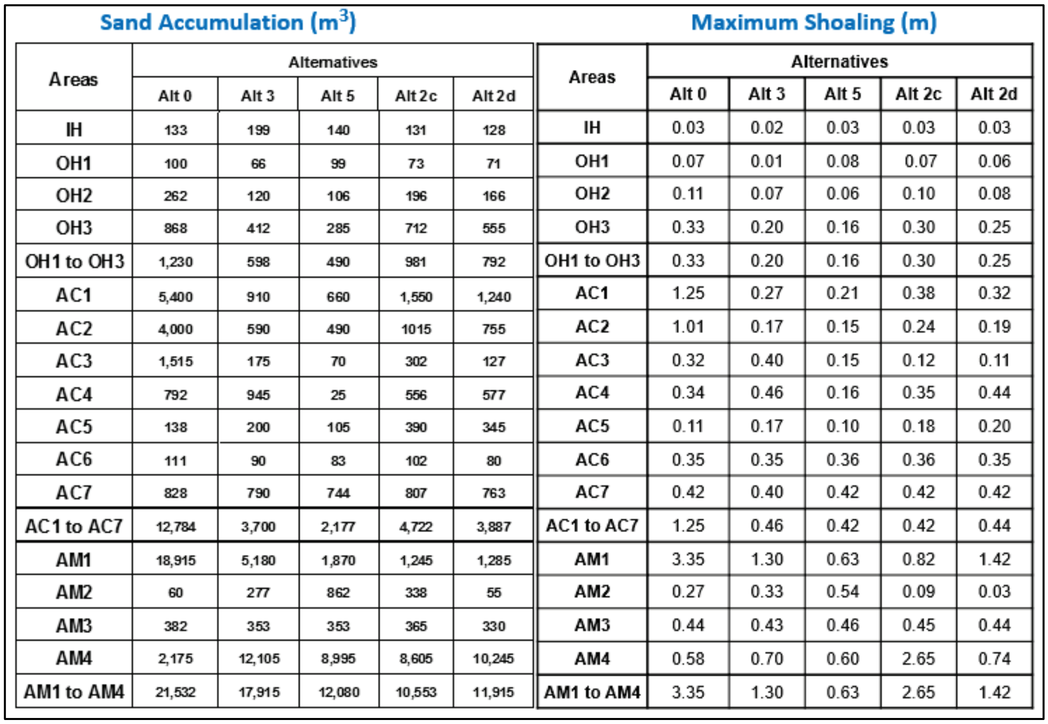
Tables 5-2 and 5-3 provide an overall summary for four alternatives: Alt 5, Alt 3, Alt 2c, and Alt 2d. In addition, a detailed analysis was performed for the morphological change in two areas of interest (Area 2 and Area 3). This required dividing each area into a number of smaller polygons shown in Figure 5-6. Area 2 was divided into ten 100 m long sub-polygons. These are marked in Figure 5-6 as OH1 to OH3 and AC1 to AC7. Area 3 was divided into four sub-polygons marked as AM1 to AM4, where AM1 covers the existing advanced maintenance area while AM2, AM3, and AM4 extend beyond the acreage of Area 3. These extended advanced maintenance areas are greater than the original area. Note that the estimates for Area 1 (IH) used only one polygon because the amount of shoaling in the IH was negligible and did not warrant sub-dividing Area 1 into sub-polygons.

Figure 5-6. Sub-polygons for detailed analysis of morphology change.



Tables 5-4, 5-5, and 5-6 provide sediment shoaling volumes (m^3) and height of the accumulation (m) for Alt 5, Alt 3, Alt 2c, and Alt 2d for high-, mid-, and low-crest elevations, respectively. Volume estimates and maximum shoaling heights are tabulated in the left and right sides, respectively, of these tables. The estimates are provided for each sub-polygon within Areas 2 and 3 followed by the total estimate for each area. The estimates for Alt 0 (w/o project) are also shown for comparison purposes. The high-crest structural elevation produced the lowest total sand accumulation volumes in Area 2. The largest volume of 4,722 m^3 for Alt 2c in AC is less than 33% of Alt 0. This corresponds to a 67% reduction in the AC shoaling volume. The maximum shoaling of 0.46 m in Area 2 is nearly 30% of the Alt 0 maximum shoaling of 1.25 m. These results clearly show the high effectiveness of these four alternatives with high-crest elevation for significantly reducing the shoaling in Area 2.

Table 5-4. Results for high-crest elevation structures (March–November 2015).



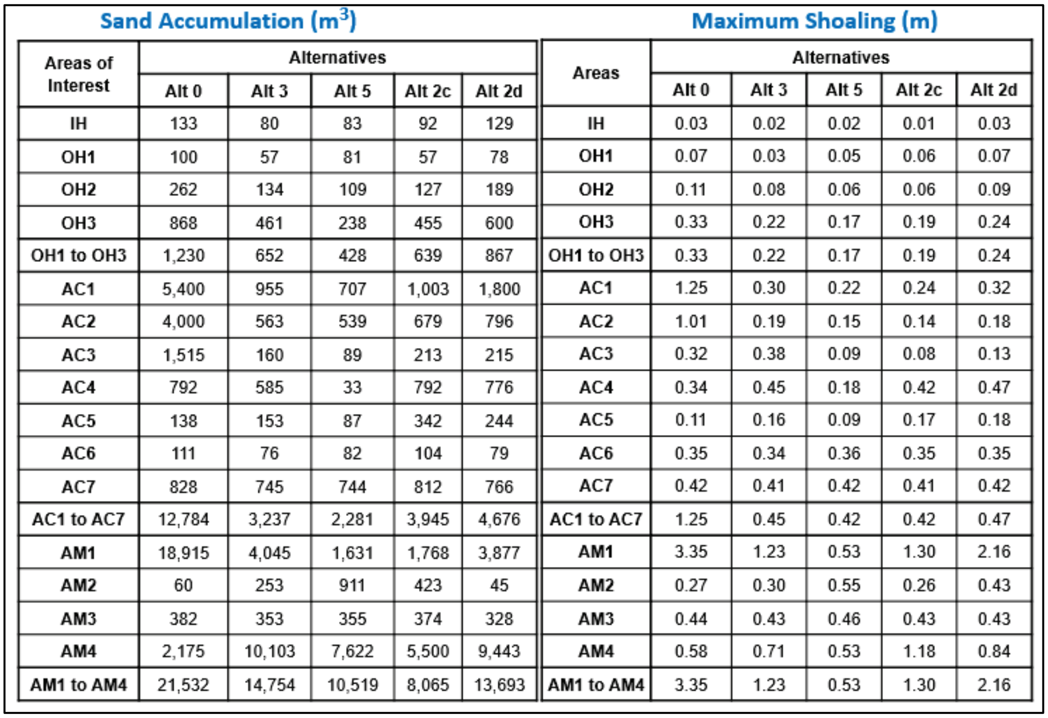
Sand Accumulation (m^3)

Areas	Alternatives				
	Alt 0	Alt 3	Alt 5	Alt 2c	Alt 2d
IH	133	199	140	131	128
OH1	100	66	99	73	71
OH2	262	120	106	196	166
OH3	868	412	285	712	555
OH1 to OH3	1,230	598	490	981	792
AC1	5,400	910	660	1,550	1,240
AC2	4,000	590	490	1015	755
AC3	1,515	175	70	302	127
AC4	792	945	25	556	577
AC5	138	200	105	390	345
AC6	111	90	83	102	80
AC7	828	790	744	807	763
AC1 to AC7	12,784	3,700	2,177	4,722	3,887
AM1	18,915	5,180	1,870	1,245	1,285
AM2	60	277	862	338	55
AM3	382	353	353	365	330
AM4	2,175	12,105	8,995	8,605	10,245
AM1 to AM4	21,532	17,915	12,080	10,553	11,915

Maximum Shoaling (m)

Areas	Alternatives				
	Alt 0	Alt 3	Alt 5	Alt 2c	Alt 2d
IH	0.03	0.02	0.03	0.03	0.03
OH1	0.07	0.01	0.08	0.07	0.06
OH2	0.11	0.07	0.06	0.10	0.08
OH3	0.33	0.20	0.16	0.30	0.25
OH1 to OH3	0.33	0.20	0.16	0.30	0.25
AC1	1.25	0.27	0.21	0.38	0.32
AC2	1.01	0.17	0.15	0.24	0.19
AC3	0.32	0.40	0.15	0.12	0.11
AC4	0.34	0.46	0.16	0.35	0.44
AC5	0.11	0.17	0.10	0.18	0.20
AC6	0.35	0.35	0.36	0.36	0.35
AC7	0.42	0.40	0.42	0.42	0.42
AC1 to AC7	1.25	0.46	0.42	0.42	0.44
AM1	3.35	1.30	0.63	0.82	1.42
AM2	0.27	0.33	0.54	0.09	0.03
AM3	0.44	0.43	0.46	0.45	0.44
AM4	0.58	0.70	0.60	2.65	0.74
AM1 to AM4	3.35	1.30	0.63	2.65	1.42

Table 5-5. Results for mid-crest elevation structures (March–November 2015).



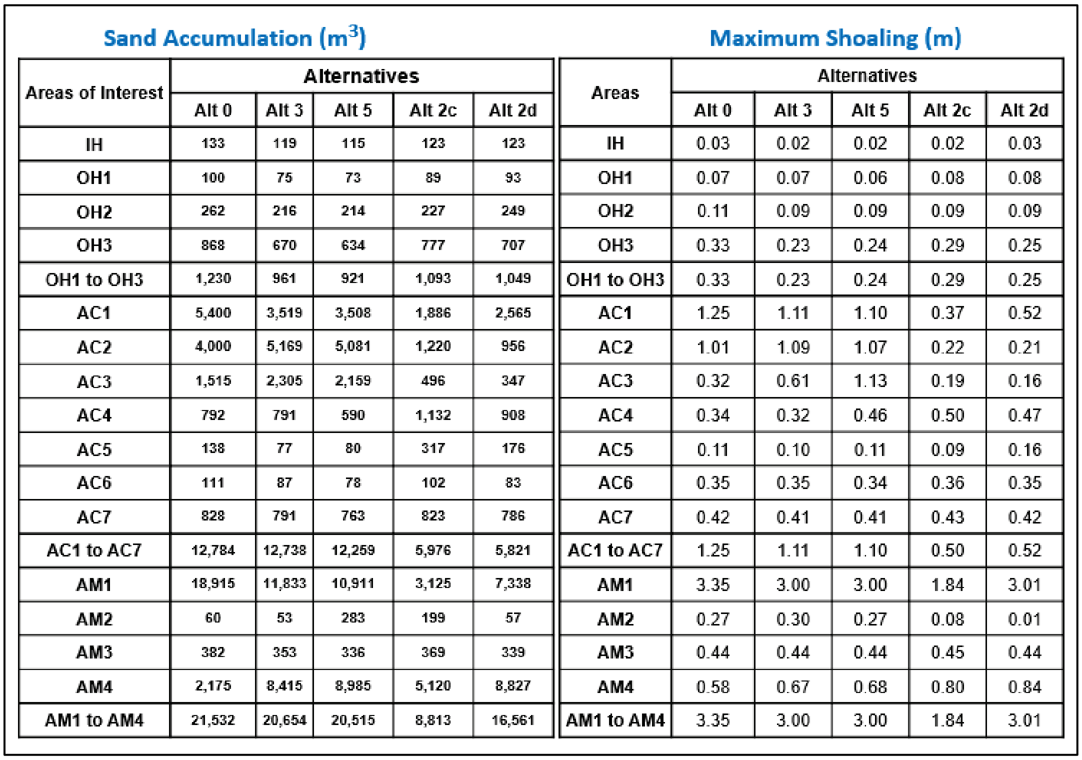
Sand Accumulation (m^3)

Areas of Interest	Alternatives				
	Alt 0	Alt 3	Alt 5	Alt 2c	Alt 2d
IH	133	80	83	92	129
OH1	100	57	81	57	78
OH2	262	134	109	127	189
OH3	868	461	238	455	600
OH1 to OH3	1,230	652	428	639	867
AC1	5,400	955	707	1,003	1,800
AC2	4,000	563	539	679	796
AC3	1,515	160	89	213	215
AC4	792	585	33	792	776
AC5	138	153	87	342	244
AC6	111	76	82	104	79
AC7	828	745	744	812	766
AC1 to AC7	12,784	3,237	2,281	3,945	4,676
AM1	18,915	4,045	1,631	1,768	3,877
AM2	60	253	911	423	45
AM3	382	353	355	374	328
AM4	2,175	10,103	7,622	5,500	9,443
AM1 to AM4	21,532	14,754	10,519	8,065	13,693

Maximum Shoaling (m)

Areas	Alternatives				
	Alt 0	Alt 3	Alt 5	Alt 2c	Alt 2d
IH	0.03	0.02	0.02	0.01	0.03
OH1	0.07	0.03	0.05	0.06	0.07
OH2	0.11	0.08	0.06	0.06	0.09
OH3	0.33	0.22	0.17	0.19	0.24
OH1 to OH3	0.33	0.22	0.17	0.19	0.24
AC1	1.25	0.30	0.22	0.24	0.32
AC2	1.01	0.19	0.15	0.14	0.18
AC3	0.32	0.38	0.09	0.08	0.13
AC4	0.34	0.45	0.18	0.42	0.47
AC5	0.11	0.16	0.09	0.17	0.18
AC6	0.35	0.34	0.36	0.35	0.35
AC7	0.42	0.41	0.42	0.41	0.42
AC1 to AC7	1.25	0.45	0.42	0.42	0.47
AM1	3.35	1.23	0.53	1.30	2.16
AM2	0.27	0.30	0.55	0.26	0.43
AM3	0.44	0.43	0.46	0.43	0.43
AM4	0.58	0.71	0.53	1.18	0.84
AM1 to AM4	3.35	1.23	0.53	1.30	2.16

Table 5-6. Results for low-crest elevation structures (March–November 2015).



Sand Accumulation (m^3)

Areas of Interest	Alternatives				
	Alt 0	Alt 3	Alt 5	Alt 2c	Alt 2d
IH	133	119	115	123	123
OH1	100	75	73	89	93
OH2	262	216	214	227	249
OH3	868	670	634	777	707
OH1 to OH3	1,230	961	921	1,093	1,049
AC1	5,400	3,519	3,508	1,886	2,565
AC2	4,000	5,169	5,081	1,220	956
AC3	1,515	2,305	2,159	496	347
AC4	792	791	590	1,132	908
AC5	138	77	80	317	176
AC6	111	87	78	102	83
AC7	828	791	763	823	786
AC1 to AC7	12,784	12,738	12,259	5,976	5,821
AM1	18,915	11,833	10,911	3,125	7,338
AM2	60	53	283	199	57
AM3	382	353	336	369	339
AM4	2,175	8,415	8,985	5,120	8,827
AM1 to AM4	21,532	20,654	20,515	8,813	16,561

Maximum Shoaling (m)

Areas	Alternatives				
	Alt 0	Alt 3	Alt 5	Alt 2c	Alt 2d
IH	0.03	0.02	0.02	0.02	0.03
OH1	0.07	0.07	0.06	0.08	0.08
OH2	0.11	0.09	0.09	0.09	0.09
OH3	0.33	0.23	0.24	0.29	0.25
OH1 to OH3	0.33	0.23	0.24	0.29	0.25
AC1	1.25	1.11	1.10	0.37	0.52
AC2	1.01	1.09	1.07	0.22	0.21
AC3	0.32	0.61	1.13	0.19	0.16
AC4	0.34	0.32	0.46	0.50	0.47
AC5	0.11	0.10	0.11	0.09	0.16
AC6	0.35	0.35	0.34	0.36	0.35
AC7	0.42	0.41	0.41	0.43	0.42
AC1 to AC7	1.25	1.11	1.10	0.50	0.52
AM1	3.35	3.00	3.00	1.84	3.01
AM2	0.27	0.30	0.27	0.08	0.01
AM3	0.44	0.44	0.44	0.45	0.44
AM4	0.58	0.67	0.68	0.80	0.84
AM1 to AM4	3.35	3.00	3.00	1.84	3.01

Results for the alternatives with the mid-crest elevation are similar to those for the high-crest elevation (e.g., 4,676 m^3 vs. 4,722 m^3 and 0.47 m vs. 0.46m in Area 2). For the low crest elevation, only Alt 2c and Alt 2 provide limited channel shoaling reduction in Area 2. This detailed analysis suggests that the mid-elevation structures, and Alt2c and Alt2 at low elevation, can be considered because of their reasonably good performance (50% to 75%) relative to the high-crest elevation structures. A substantial design cost savings is possible for these mid- or low-crest elevation structures, but long-term maintenance cost could be higher.

Figures 5-7, 5-8, and 5-9 display the pattern of sediment accumulation for four alternatives with three structural crest elevations. These figures are color coded to highlight the hot spot areas where increased sediment accumulation occurs. The hot spot area generally develops adjacent to a structure but the presence of a structure can also impact adjacent areas.

Figure 5-7. Location map of sand accumulation for high-crest structures.

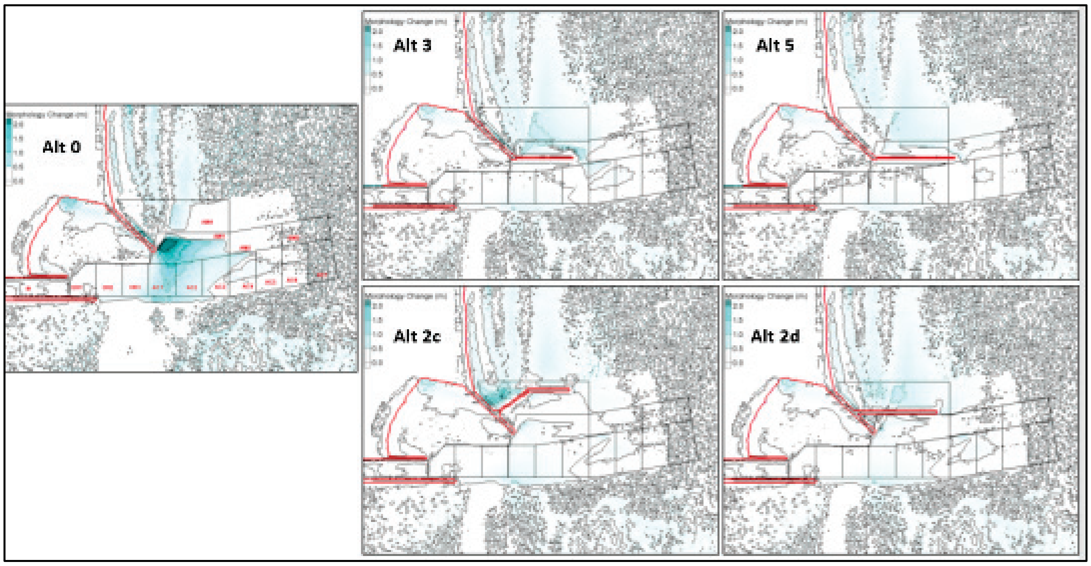


Figure 5-8. Location map of sand accumulation for mid-crest structures.

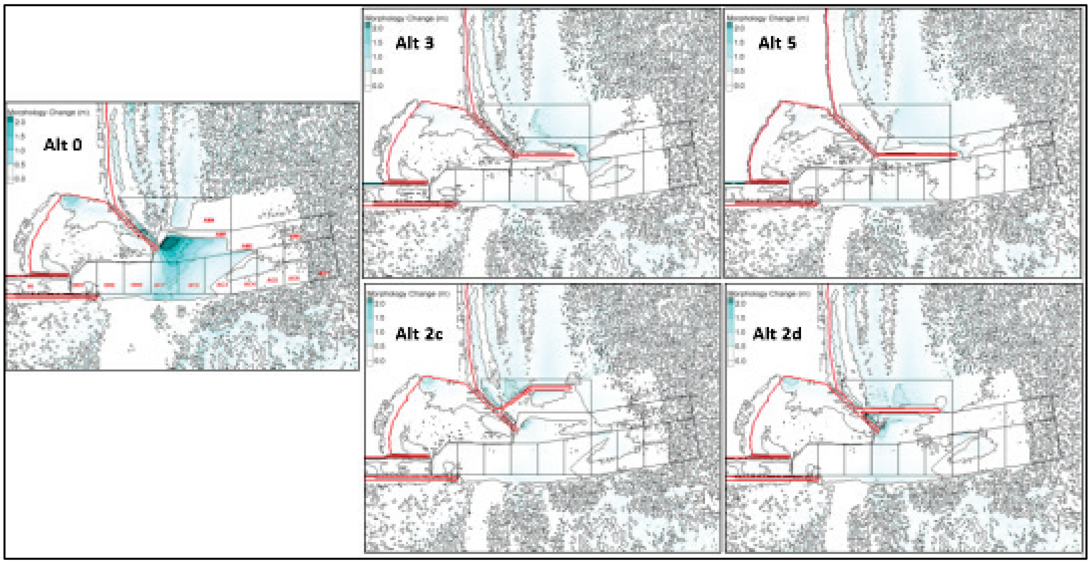
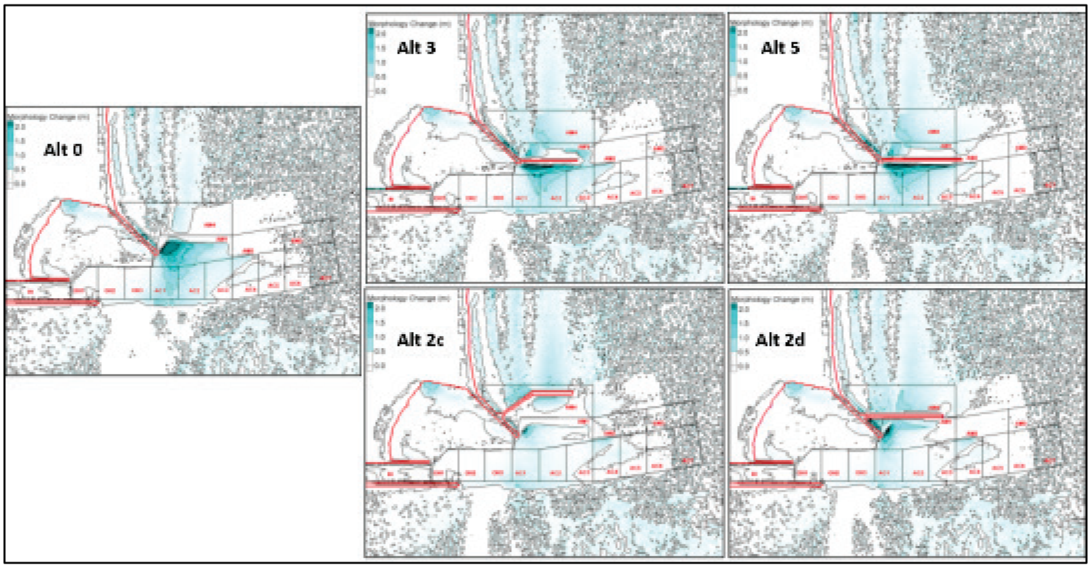


Figure 5-9. Location map of sand accumulation for low-crest structures.

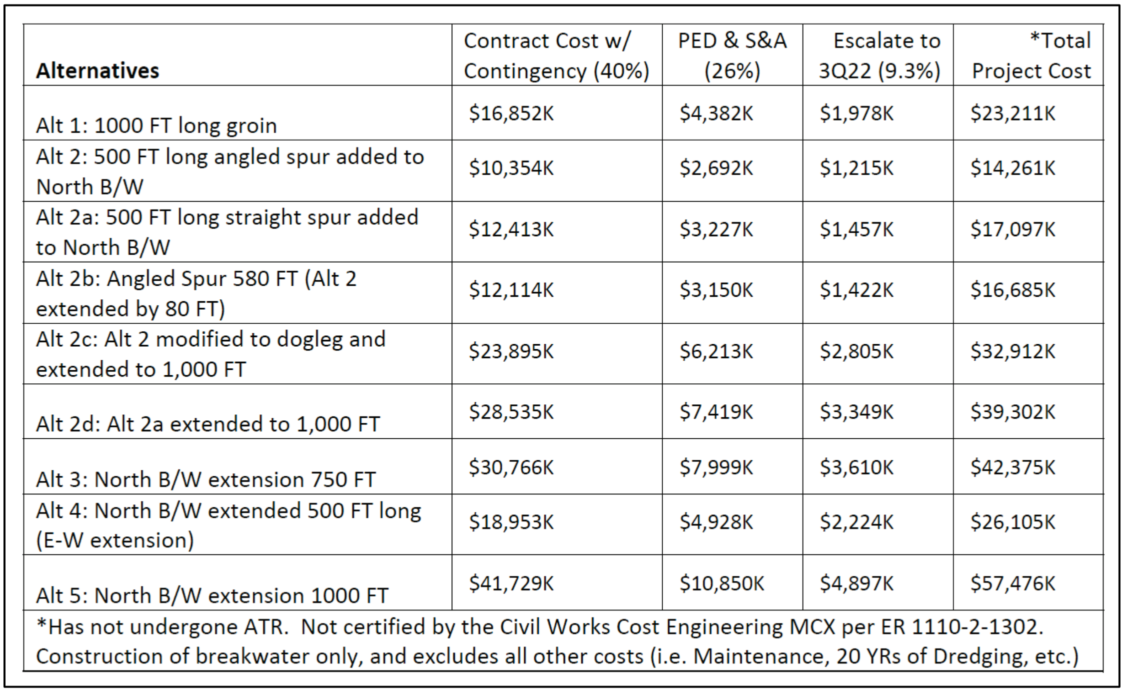


5.4 Cost estimates for high- and mid-crest structures

Based on modeling results investigated in Phase 1 and Phase 2 studies, LRC developed preliminary cost estimates for alternatives. These estimates assumed construction of alternatives structures with 1:2 side slopes as rubble-mound breakwaters using 20-ton A-stone size rocks and a 3.05 m (10 ft) structural subsidence. The estimates increase/decrease if any of these assumptions change or if the geometry of an alternative changes. These costs represent physical construction of the breakwater only and exclude maintenance of the structure, maintenance dredging behind the structure, etc.

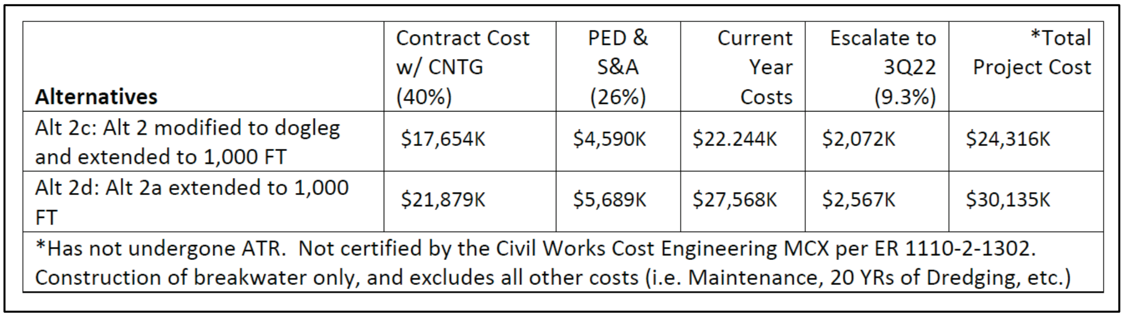
Table 5-7 presents the cost estimates for nine alternatives investigated in the Phase 1 study. These estimates assumed all alternatives had a high-crest elevation (178 m or 584 ft IGLD85). Table 5-8 provides estimates for Alt 2c and Alt 2d, the top-two performing alternatives in the Phase 2 study with mid-crest elevation (176.8 m or 580 ft IGLD85). The cost information provided in this report is only for future reference. Note that the two highest costs ($57.5 million and $42.4 million) are for Alt 5 and Alt 3 with high-crest elevation structures. The costs for Alt 2d and Alt 2c with mid-crest elevation structures are comparatively less ($30 million and $24.3 million).

Table 5-7. Cost estimate for alternatives with a high-crest elevation structure.



Alternatives	Contract Cost w/ Contingency (40%)	PED & S&A (26%)	Escalate to 3Q22 (9.3%)	*Total Project Cost
Alt 1: 1000 FT long groin	$16,852K	$4,382K	$1,978K	$23,211K
Alt 2: 500 FT long angled spur added to North B/W	$10,354K	$2,692K	$1,215K	$14,261K
Alt 2a: 500 FT long straight spur added to North B/W	$12,413K	$3,227K	$1,457K	$17,097K
Alt 2b: Angled Spur 580 FT (Alt 2 extended by 80 FT)	$12,114K	$3,150K	$1,422K	$16,685K
Alt 2c: Alt 2 modified to dogleg and extended to 1,000 FT	$23,895K	$6,213K	$2,805K	$32,912K
Alt 2d: Alt 2a extended to 1,000 FT	$28,535K	$7,419K	$3,349K	$39,302K
Alt 3: North B/W extension 750 FT	$30,766K	$7,999K	$3,610K	$42,375K
Alt 4: North B/W extended 500 FT long (E-W extension)	$18,953K	$4,928K	$2,224K	$26,105K
Alt 5: North B/W extension 1000 FT	$41,729K	$10,850K	$4,897K	$57,476K
*Has not undergone ATR. Not certified by the Civil Works Cost Engineering MCX per ER 1110-2-1302. Construction of breakwater only, and excludes all other costs (i.e. Maintenance, 20 YRs of Dredging, etc.)				

Table 5-8. Cost estimate for Alt 2c and Alt 2d with a mid-crest elevation structure.



Alternatives	Contract Cost w/ CNTG (40%)	PED & S&A (26%)	Current Year Costs	Escalate to 3Q22 (9.3%)	*Total Project Cost
Alt 2c: Alt 2 modified to dogleg and extended to 1,000 FT	$17,654K	$4,590K	$22.244K	$2,072K	$24,316K
Alt 2d: Alt 2a extended to 1,000 FT	$21,879K	$5,689K	$27,568K	$2,567K	$30,135K
*Has not undergone ATR. Not certified by the Civil Works Cost Engineering MCX per ER 1110-2-1302. Construction of breakwater only, and excludes all other costs (i.e. Maintenance, 20 YRs of Dredging, etc.)					

6 Summary and Conclusions

This is a detailed numerical modeling study with field data collection conducted for Waukegan Harbor. The study was performed to better understand the dynamic nature of the harbor-lake system. An expanded comprehensive modeling study can produce rational and scientifically defensible findings to identify alternatives to increase safety and promote sustainable long-term navigability at Waukegan Harbor. The study used findings from previous studies[*][†][‡] (Morang et al. 2019) to focus on evaluation of a number of alternative structural design options.

The dynamic lake setting of the study area requires a thorough understanding of the local metocean forcings to reduce uncertainties and assumptions used in prior studies. The numerical modeling study was tasked to investigate sediment trapping and diversion using shore-connected structural measures. Effectiveness of each modification (alternative) for improving navigation at Waukegan Harbor was examined to identify potential solutions for significant long-term cost savings compared to increased maintenance dredging. The chosen alternatives intercepted and diverted sediments affecting access to the harbor, also benefiting beaches to the north and south. The selected alternatives are compatible with public use of beaches and improve life and public safety, recreation, and beach management and regulatory considerations. The primary purpose of proposed alternatives is to reduce long-term O&M costs of the approach channel, outer harbor, and advanced maintenance areas.

The estimates of morphology change, shoaling volumes, and navigable depth changes inside, outside, and around Waukegan Harbor were developed using an integrated CMS. A combined (coupled) wave, hydrodynamic, and sediment transport modeling was performed to develop estimates for 1-year time period. The year of 2015 was selected because it was an average climate year for which the entire year metocean data (wind, water level, and wave) were available. The modeling study first investigated the sediment trapping capability of

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[*] USACE. 2014. Illinois Beach State Park, Lake County, Illinois, Section 204 Beneficial Use of Dredged Material, Detailed Project Report, Regional Sediment Management Plan and Environmental Assessment, Chicago District (LRC).

[†] USACE. 2016. Waukegan Harbor, Illinois Continuing Authorities Program, Section 107 Federal Interest Determination (FID) Report, Chicago District (LRC).

[‡] USACE. 2017. Waukegan 107 Continuing Authorities Program (CAP) Section 107 Project Management Plan (PMP), Chicago District (LRC).

structures identified by LRC in the Phase 1 study. The study's scope was expanded in the Phase 2 modeling to include additional alternatives. A total of 12 alternatives, including the existing harbor, were modeled to determine potential effects of various structural factors on channel shoaling. These factors influence the efficiency of proposed alternatives to reduce harbor shoaling and included the position, orientation, length, and crest elevation of structures and water depth.

The modeling domain covered a rectangular area of 6.8 km (easting) × 9.1 km (northing) with a 5 m finer cell resolution near the harbor channel and 150 m lower resolution away from the harbor. The Lidar data collected in 2007, 2008, and 2012 by NGDC were used for the bathymetry and shorelines. More recent bathymetric survey data in 2017 by the ISGS University of Illinois at Urbana-Champaign were used to update the CMS modeling bathymetry.

The local metocean forcings data (winds, water levels, waves, and currents) available from NOAA coastal buoys and gauges were used to develop estimates of water levels, waves, currents, and sediment transport and morphology change inside, outside, and around the vicinity area of Waukegan Harbor. The ISGS installed two nearshore gauges, G1 and G2, for short-term water level and wave measurements at Waukegan Harbor in various duration from November 2017 to October 2018. The wave data were used in the model calibration for July–August 2018 and model verification for September–October 2018.

This report describes modeling details of nearshore coastal processes in the exterior and interior areas of Waukegan Harbor and variation at/around the entrance of the harbor. Different type of structural alternatives were introduced into the modeling domain to determine how the shoaling changes in the navigation channel. The modeling of a large domain required using a spectral wave model (CMS-Wave) coupled to a hydrodynamic model (CMS-Flow) for calculating changes in nearshore water levels, waves and currents, sediment transport, and morphology. The use of a constant median grain size of D_{50}=0.2 mm in the modeling is based on grab samples collected by ISGS in 2017. Details of the CMS modeling are provided in Chapter 4, Chapter 5, and the appendix.

Effectiveness of alternatives can be quantified relative to Alt 0 by defining two performance evaluation metrics: a percent shoaling volume estimate and a maximum shoaling height. Table 5-1 and Figure 5-5 provide a summary of results for all alternatives. Overall, alternatives with high-crest elevation structures performed the best by achieving maximum reduction in shoaling in the AC and OH.

Tables 5-2 to 5-6 summarize modeling results for three crest elevations. Estimates of the sediment accumulation volume and maximum shoaling height in the AC, OH, and AM area are provided for these four alternatives. The mid-crest structures also performed well but low-crest structures did not. Alt 3 and Alt 5 with high-crest elevation were top performers achieving approximately 85% reduction in channel shoaling. Higher cost estimates for high-crest elevation structures led to consideration of the mid-crest and low-crest structures. Alt 2c, Alt 2d, Alt 3, and Alt 5 were further modeled for mid- and low-crest elevations due to the potentially reduced design costs of these alternatives.

Because construction cost is proportional directly to the size of a structure (length, width, and height), estimates are also provided for the four alternatives with mid- and low-crest structures. Alt 2c and Alt 2d with mid-crest were the top performers while alternatives with low-crest structures did not perform well. A substantial design cost saving can be realized for the mid- and low-crest structures, but associated long-term maintenance cost can be high.

In addition to the shoaling volumes (accumulated sand) and height of shoaling metrics, Chapter 5 presented a number of 2D maps showing the spatial variation of morphological change in and around Waukegan Harbor. These maps display hot-spot areas developing in each alternative around the navigation channel and in other locations along the north breakwater and north beach. The hot-spot areas are of particular interest because these areas may require expansion (acreage) of the existing AM area.

In summary, Alt 2c, Alt 2d, Alt 3, and Alt 5 provided the best protection to the entrance of Waukegan Harbor by reducing shoaling significantly in navigation channel. Because cost estimates for high-crest structures were high, some mid- and low-crest alternatives were retained for further modeling. Design cost estimates for Alt 2c and Alt 2d with mid- and low-crest elevations were substantially less than those of high-crest elevation. Ultimately, the design and maintenance cost, constructability of a system, as well as potential impacts on environment, will determine the alternative that can best meet future project needs.

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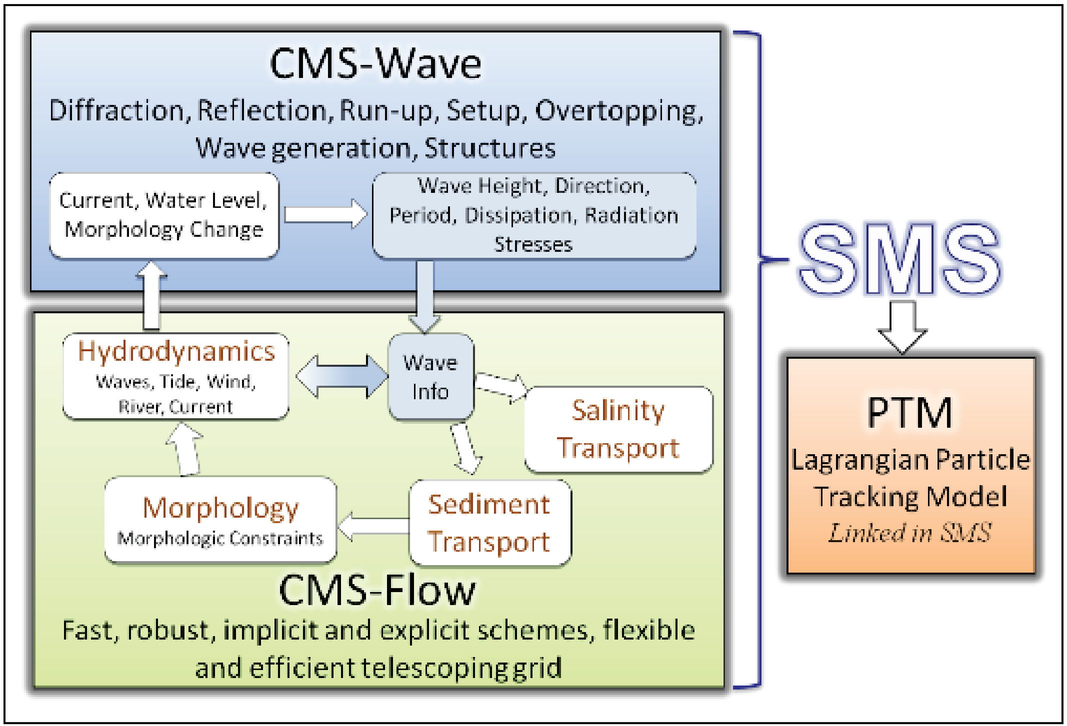
Appendix: Description of the CMS

The CMS was used in this study to provide estimates of waves and water levels in Buffalo Harbor for studies involving repairs of breakwaters and a seawall. A brief description of the CMS is provided here for completeness. Figure A-1 shows the modular framework of the CMS and its components. CMS consists of numerical models for waves, flows, and sediment transport and morphology change in coastal areas. This modeling system includes representation of relevant nearshore processes for practical applications of navigation channel performance and sediment management at coastal inlets and adjacent beaches. The development and enhancement of CMS capabilities continues to evolve as a research and engineering tool for desk-top computers. CMS uses the SMS interface for grid generation and model setup as well as plotting and post-processing. Additional information about CMS is available (Demirbilek and Rosati 2011; Demirbilek et al. 2007a,b,c; Lin and Demirbilek 2012, 2005; Lin et al. 2011a,b, 2008).

Figure A-1. The CMS framework and its components.



CMS uses the SMS interface for grid generation and model setup, as well as plotting and post-processing. The V&V Report 1 (Demirbilek and Rosati 2011) and Report 2 (Lin et al. 2011) have detailed information about the CMS-Wave features and evaluation of model's performance skills in a variety of applications. Report 3 and Report 4 by Sanchez et al. (2011a and 2011b) describe coupling of wave-flow models and hydrodynamic and sediment transport and morphology change aspects of CMS-Flow. The performance of the CMS for a number of applications is summarized in Report 1, and details are described in the three companion V&V Reports 2, 3, and 4.

The CMS-Wave is a spectral wave model and was used in this study given the large extent of modeling domain over which wave estimates were required. Details of the wind-wave modeling are described in Chapter 3 of this report. The main wave processes included in the CMS-Wave are wind-wave generation and growth, diffraction, reflection, dissipation due to bottom friction, white-capping and breaking, wave-current interaction, wave runup, wave setup, and wave transmission through structures. The height and direction of waves approaching the Buffalo Harbor change due to wave shoaling, refraction, diffraction, reflection, and breaking. Waves propagating toward the breakwaters interact with bathymetry, surrounding land features and coastal structures. These features affect waves propagating and reaching the protective structures, waves going over these structures and getting into the interior of harbor, which can affect navigation and utilization of harbor.

CMS-Wave model solves the steady-state wave-action balance equation on a non-uniform Cartesian grid to simulate steady-state spectral transformation of directional random waves at and around the breakwaters in Buffalo Harbor. CMS-Wave is designed to simulate wave processes with ambient currents in navigation channels, coastal inlets, and harbors. The model can be used either in half-plane or full-plane mode for spectral wave transformation (Lin et al. 2008; Demirbilek et al. 2007b). The half-plane mode is the default because in this mode CMS-Wave can run more efficiently as waves are transformed primarily from the lake ward boundary toward shore. See Lin et al. (2011, 2008) for features of the model and step-by-step instructions with examples for application of CMS-Wave to a variety of coastal inlets, ports, structures, and other navigation problems. Publications listed in the V&V reports and this report provide additional information about CMS-Wave and its engineering applications. Additional information about CMS-Wave is available from the CIRP website: http://cirp.usace.army.mil/wiki/CMS-Wave.

Since the flow model was also used in this study, brief information is provided. The CMS-Flow is a 2D shallow-water wave model for hydrodynamic modeling (calculation of water level and current). Both the explicit and implicit versions of flow (circulation) model are available to provide estimates of water level and current given the tides, winds, and river flows as boundary conditions. CMS-Flow calculates hydrodynamic (depth-averaged circulation) sediment transport, morphology change, and salinity due to tides, winds, and waves. It was used in this study with CMS-Wave to check water level changes in the harbor caused by winds, waves, and river flows.

The hydrodynamic model solves the conservative form of the shallow-water equations that includes terms for the Coriolis force, wind stress, wave stress, bottom stress, vegetation flow drag, bottom friction, wave roller, and turbulent diffusion. Governing equations are solved using the finite volume method on a non-uniform Cartesian grid. Finite-volume methods are a class of discretization schemes, and this formulation is implemented in finite-difference for solving the governing equations of coastal wave, flow, and sediment transport models. See the V&V Reports 3 and 4 by Sanchez et al. (2011a,b) for the preparation of the flow model at coastal inlet applications. Additional information about CMS-Flow is available from the CIRP website: http://cirp.usace.army.mil/wiki/CMS-Flow.

Although hydrodynamic, sediment transport, and morphology change modeling were not considered in this study, it is noted for future reference that there are three sediment transport models available in CMS-Flow: a sediment mass balance model, an equilibrium advection-diffusion model, and a non-equilibrium advection-diffusion model. Depth-averaged salinity transport is simulated with the standard advection-diffusion model and includes evaporation and precipitation. The V&V Reports 1 through 4 describe the integrated wave-flow-sediment transport and morphology change aspects of CMS-Flow. The performance of CMS-Flow is described for a number of applications in the V&V reports.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
knots	0.5144444	meters per second
miles per hour	0.44704	meters per second
miles (U.S. nautical)	1.852	kilometers
miles (U.S. statute)	1.609347	kilometers

Acronyms and Abbreviations

2D	two-dimensional
AC	Approach Channel
AM	Advance Maintenance
CHL	Coastal and Hydraulics Laboratory
CIRP	Coastal Inlets Research Program
CMS	Coastal Modeling System
FID	Federal Interest Determination
GLCFS	Great Lakes Coastal Forecasting System
GMT	Greenwich Mean Time
IDNR	Illinois Department of Natural Resources
IGLD 85	International Great Lakes Datum of 1985
IH	Inner Harbor
ISGS	Illinois State Geological Survey
LRC	Chicago District
LWD	low water datum
NB	North Breakwater
NDBC	National Data Buoy Center
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
O&M	Operations & Maintenance
OH	Outer Harbor
Q/FY	Quarter/Fiscal Year
SMS	Surface-water Modeling System
USACE	US Army Corps of Engineers
V&V	Verification and Validation
WIS	Wave Information Studies

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14. ABSTRACT

Persistent and excessive shoaling occurs in the Outer Harbor and Approach Channel of the Waukegan Harbor, Illinois. This report describes a numerical modeling study performed for the US Army Corps of Engineers, Chicago District, to evaluate the existing harbor and eleven structural alternatives for three crest elevations. This report provides details of numerical modeling study, analysis of field data, and estimates of shoaling. The focus of the study is the investigation of a variety of structural solutions intercepting and/or diverting sediments to reduce shoaling in the navigation channel. These include breakwaters, groins, spurs, and structural extensions with varying length and crest elevation connecting to the north beach and existing north breakwater. Estimates of both shoaling volume and height are developed with and without project using an integrated wave-flow-sediment transport numerical modeling approach. Quantitative reduction estimates are provided for each structural alternative investigated.

15. SUBJECT TERMS

Breakwaters, Dredging, Harbors—Design, Navigation, Section 107 Study, Sedimentation and deposition, Sediment transport, Shoaling, Water currents, Water levels, Water waves, Waukegan (Ill.)

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