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Regional Sediment Management (RSM) Program

Sediment Budget for the North Illinois Shore from the Wisconsin Border to Wilmette Harbor

Andrew Morang, Lauren M. Dunkin, David F. Bucaro, John A. Wethington, Michael J. Chrzastowski, and Ethan J. Theuerkauf

August 2019

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Sediment Budget for the North Illinois Shore from the Wisconsin Border to Wilmette Harbor

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Abstract

A sediment budget for the North Illinois Shore was developed to evaluate littoral processes and provide a regional sand management decision support tool. This study time frame covers the 1990s to 2017. The North Shore of Illinois is a highly dynamic and diverse coastline with littoral processes complicated by coastal infrastructure, commercial harbors, and uncoordinated shoreline management. Longshore sediment transport along the North Illinois Shore is predominately from north to south, and the volume in the system varies greatly. The best available data were used for the computations in this sediment budget. However, some fluxes had to be inferred (i.e., from dredging records), and some were not considered (i.e., aeolian transport, offshore flux).

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Preface

This investigation was conducted by the U. S. Army Corps of Engineers (USACE), Regional Sediment Management (RSM) Program, which is funded by the Operation and Maintenance Navigation Business Line of Headquarters (HQ), USACE (Funding Account Code U4362913; AMSCO Code 008303). The RSM Program is administered by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS, under the Navigation Program of USACE. At the time this study was conducted, Mr. Jeffrey A. McKee was the HQUSACE Navigation Business Line Manager. The work was performed by the Navigation Division, Coastal Engineering Branch, of the ERDC CHL.

At the time of publication of this report, Dr. Katherine Brutsche, Coastal Engineering Branch, was USACE National RSM Program Manager. The ERDC Technical Director for Navigation was Mr. Charles E. Wiggins, CHL. Ms. Lauren Dunkin was Chief, Coastal Engineering Branch; and Dr. Jacqueline S. Pettway was Chief, Navigation Division, CHL.

COL Ivan P. Beckman was the Commander of ERDC, and Dr. David W. Pittman was the Director of ERDC.

1 Introduction

Background

The North Shore of Illinois is a highly dynamic and diverse coastline with littoral processes complicated by coastal infrastructure, commercial harbors, and uncoordinated shoreline management. Historically, coastal management has not been conducted using a coordinated regional approach, which hindered the efficiency and effectiveness of management activities. The newly established Illinois Coastal Management Program (ICMP) is developing a comprehensive plan for shoreline management. The development of a regional sediment budget will support the ICMP and provide a valuable tool for federal, state, and local decision makers.

To date, the ICMP has not developed a comprehensive quantitative analysis of the littoral processes along the North Shore. A large amount of coastal data and analyses are available but is housed by a variety of agencies and municipalities. There are also gaps in the available data, such as mid-twentieth century bathymetry surveys.

Objective

This investigation will evaluate available coastal data and develop a comprehensive sediment budget for the region. A regional sediment budget is a valuable tool for supporting regional and federal planning efforts and for enabling more effective and cost-efficient sediment management informed by coherent and consistent information. Among the goals of developing a sediment budget are as follows:

- Gaining a better understanding of littoral transport in the area
- Identifying effects of harbor structures on littoral transport
- Identifying sources, sinks, and pathways of sediment.

By incorporating goals of Regional Sediment Management (Lillycrop et al. 2011), sediment will be treated as a resource to benefit the entire system rather than as a nuisance to be eliminated regardless of the consequences on the coastal environment. Managing sediment to benefit a region potentially saves money, allows use of natural processes to solve engineering problems, and improves recreation potential and habitat.

Approach

This analysis of littoral transport covers the reach between the Illinois-Wisconsin border and the City of Wilmette (Figure 1; Background map by Environmental Systems Research Institute [ESRI©] Maps and Data). This report summarizes the results of the sediment budget developed by the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, (ERDC-CHL), and the U.S. Army Engineer District, Chicago (LRC), and describes the following:

- Data sources applicable to the study area
- Assumptions and limitations
- Recommendations for continued refinement.

Most units in this report are stated in English units, in correspondence with original data collection and with contemporary use for dredging volumes (cubic yards).

Figure 1. Study area, northern Illinois shore of Lake Michigan. Red outlines show sediment budget cells used in this analysis. (Cell WI-1 from Kenosha, WI, to North Point Marina was not used in this analysis.) Background map from ESRI Maps and Data.

2 Study Area and Physical Processes

Setting and management issues

The North Shore is the northern half of the 63-mile Illinois shoreline on Lake Michigan (Figure 1). This is the most urbanized and populous section of coast along any of the Great Lakes. While the southern (Chicago) shore is almost entirely engineered and artificial, the North Shore, extending from the Illinois-Wisconsin state line to Wilmette, exhibits a diversity of geologic and engineered conditions. The presence of numerous large in-lake structures (e.g., harbors, jetties, detached breakwaters) has created significant littoral barriers. These barriers trap sediment, leaving major sections of coast sand-depleted and vulnerable to erosion via beach and bluff recession and lakebed downcutting. It is a major management challenge to maintain the effectiveness of coastal infrastructure while preserving the stability and integrity of the overall shore. This is further complicated by the shared responsibility for coastal management: the federal government, State of Illinois, local municipalities, and private landowners collectively manage portions of the shoreline.

The Illinois North Shore is diverse politically, geologically, and ecologically. Twelve communities face Lake Michigan as well as federal, state, and municipal infrastructure (Table 1). Ecological and recreational resources include the Adeline Jay Geo-Karis Illinois Beach State Park (IBSP), operated by the Illinois Department of Natural Resources (IDNR) and numerous municipal parks and beaches. Adding to the complexity is the presence of more than a hundred parcel-scale shore protection structures, many decades old and in various states of disrepair.

The North Shore is defined by three distinct coastal geomorphic divisions: the Zion beach-ridge plain, the glacial till bluff coast, and the Chicago lake plain (Figure 1). From north to south, the shoreline changes from a low sandy plain to a high bluff/ravine system (near Waukegan) to a low bluff/beach system (near Winnetka).

The northernmost 6 mi of the study area are in the Zion beach-ridge plain and are part of the IBSP. Beach-ridge plains consist of linear, generally coast-parallel ridges of sand and gravel that are formed by wave action and that extend the coast outward into the adjacent ocean or lake as long as sufficient sediment supply is available (Chrzastowski and Frankie 2000).

Table 1. Major coastal features and infrastructure, Illinois North Shore.

Feature (North-South)	Ownership	Coastal Structure
Prairie Harbor Yacht Club, Runaway Bay, WI	Private	Channel and rubblemound north jetty
North Point Marina, Winthrop Harbor, IL	IDNR	Rubblemound breakwaters and shore armor
Illinois Beach State Park	IDNR	Natural sand beach with limited sheet pile and groins
Zion Nuclear Power Station (closed)	Exelon Nuclear	Rip rap behind natural sand beach
Waukegan Electric Generating Station	Midwest Generation	Intake and outlet canals with sheetpile training wall
Waukegan Harbor	City of Waukegan	Parallel piers and a shore-connected timber crib north breakwater
U.S. Naval Station Great Lakes	U.S. Navy	Rubblemound jetties enclosing harbor
Prospect Ave., Lake Forest	City of Lake Forest	Misc. shore-parallel rubblemound breakwaters
Spruce Ave., Forest Park	City of Lake Forest	Misc. shore-parallel rubblemound breakwaters
Forest Park, Lake Forest Harbor	City of Lake Forest	Shore-parallel rubblemound breakwaters, small harbor
Fort Sheridan	Private	Misc. groins
Park Ave. boat ramp, Highland Park	Park Dist. Highland Park	Sheetpile rectangle protruding into lake
Glencoe Beach, Glencoe	Park Dist. Glencoe	Sheetpile terminal groin holding beach
Winnetka Power Generating Sta. outfall	Village of Winnetka	Concrete piers and canal
Lloyd Park, Winnetka	Village of Winnetka	Sheetpile "L"-shaped pier
Wilmette Park/Gillson Park	Park Dist. Wilmette	Sand beach held by rubble terminal groin
Wilmette Harbor (mouth of North Shore Channel)	Village of Wilmette	Rubblemound and sheetpile piers, south pier deteriorated

This is the only remaining area along the north shore that has not been heavily altered by urbanization and coastal engineering. The park supports 14 natural communities and provides habitat for more than 500 plant and 300 animal species, including several threatened and endangered species. However, because of a lack of new sediment in the system, beach erosion has caused serious shoreline retreat over the decades.

The bluff coast consists of glacial bluffs with elevations above lake level upwards of 80 feet (ft). Many of the bluffs have been armored with revetments, bulkheads, and seawalls of varying condition. Because of the armoring, it is believed that minimal sediment is now supplied to the littoral environment. Silts and clay come down some of the creeks and washes but do not deliver any significant amount of sand-sized sediment.

The Chicago lake plain in the south is emergent former lake bottom, with minor gradient change in the offshore topography (Bretz 1955). Much of the shoreline in this section has been armored and artificially modified, especially from Evanston, IL, to Gary, IN, and will not be considered in this report. There is essentially no longshore transport in this zone.

Given the diversity of this 32-mile reach, shoreline management is a significant challenge for both governmental and non-governmental entities. Considerable sediment management is occurring at a site-specific basis by government and private entities. In January 2012, the State of Illinois entered the National Oceanic Atmospheric Administration (NOAA) Coastal Zone Management program and is currently in the process of coordinating with the various stakeholders to develop a plan for the coastline that establishes regional coastal management and implementation priorities.

Planning for the best uses of sediment within the system is important because much of the coast exhibits sediment-starved conditions. In this region, the net direction of the littoral drift is from north to south. Based on historical profile data, in the early part of the twentieth century, the littoral transport rate was 90,000 cubic yards per year (yd^3/year) in the Zion beach-ridge area and 57,000 yd^3/year along the bluff coast (USACE 1953). It is unknown why the rate of 90,000 for the Zion beach-ridge region is less than the current computed value for the region north of Waukegan Harbor (to be discussed below). This discrepancy requires further investigation beyond the scope of this study; however, it is potentially a function of the data sources or measurement methods used in the 1953 study, impacts from updrift littoral barriers, or the result of natural geologic processes (i.e., southward migration of the Zion Beach Ridge Plain). Over the past century, the construction of numerous in-lake structures (e.g., harbors and jetties) has created littoral barriers that trap large volumes of littoral sediment, leaving downdrift (south) areas exposed and vulnerable to erosion. Illinois Beach State Park, the most significant ecological resources along this reach has experienced long-term erosion rates as high as 10 ft/year.

Sediments and littoral transport

A fundamental question pertaining to sand management along the Illinois shore is “Where does beach sand come from?” Sand on southern Lake Michigan beaches in Indiana historically was supplied from bluff and lake bed erosion and to a lesser degree, intermittent stream input (Shabica and Pranschke 1994). Along the Michigan shoreline, bluff erosion is the primary contributor of sand with elevations up to 80 ft.

However, along the Illinois shore, the bluffs, often up to 70 or 80 ft high, contain only minor amounts of sand and gravel. The bluffs consist of high, lake-terrace deposits underlain by Pleistocene Wadsworth Till of the Highland Park Moraine and contain approximately 85% clay and 15% clastic materials (i.e., sand, gravel, cobbles, and boulders [Shabica et al. 2010]). Lineback (1974) reported 10% sand. Recent borings reveal that in some areas, the percentage of coarse material is less. Figure 2 and Figure 3 show the locations of borings at Fort Sheridan and Rosewood Beach. The material within the cores was averaged to produce a single pie chart. The cores collected on the bluffs contain 100% till with only trace amounts (<5%) of gravel and sand. The samples on the beach contain a sand wedge with clay till underneath. Data were compiled from unpublished contractor reports provided to LRC (Soil and Material Consultants, Inc., Chicago Testing Laboratory, Inc., and AECOM).

Streams along the Illinois shore supply mostly fine-grain material by means of ravines cut into the bluffs. A lag of cobble and gravel line many of these streams, now often augmented by limestone and other material placed to reduce ravine downcutting (Shabica et al. 2010). At U.S. Naval Station Great Lakes, Pettibone Creek has delivered so much clay and silt to the old boat basin and the inner harbor that they became almost unusable and required dredging in 2009-2011 (North Wind 2011a,b,c).

Therefore, if the local geology did not supply sand to the littoral system, the source must be farther north. The IBSP is a major beach ridge complex, with its southern terminus just north of Waukegan. The major sand and gravel deposit on which Illinois Beach State Park resides is likely a large glacial-fluvial deposit that originally was a sub-glacial delta. The source area may have been Wind Point, Wisconsin (Figure 1). This sub-glacial deposit resided to the south of Wind Point until the lake reached the Nippising level approximately 5,500 years before present. Wave action then transported the sand southward. The Zion Beach Ridge Plain

(Kenosha to Waukegan) is the present manifestation of this sand accumulation. In the geologic past, this sand body was farther north and was wider (east-to-west) and shorter (north-to-south), but has been translating southward through time by littoral transport.

Figure 2. Borings at Fort Sheridan, IL, showing the preponderance of clay in the till bluffs. Numbers represent the boring identification and total boring depth. Photo by ESRI Maps and Data.

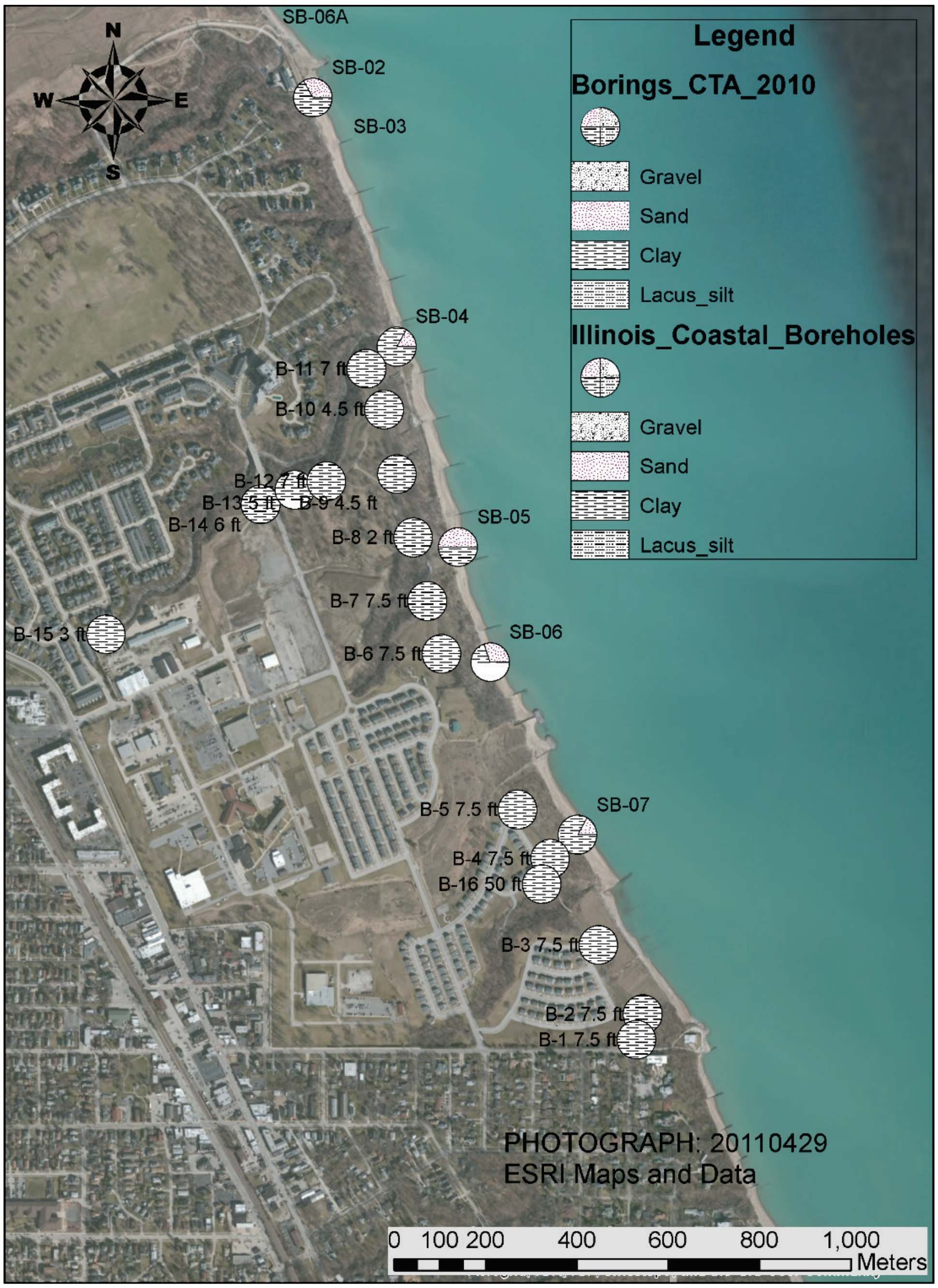
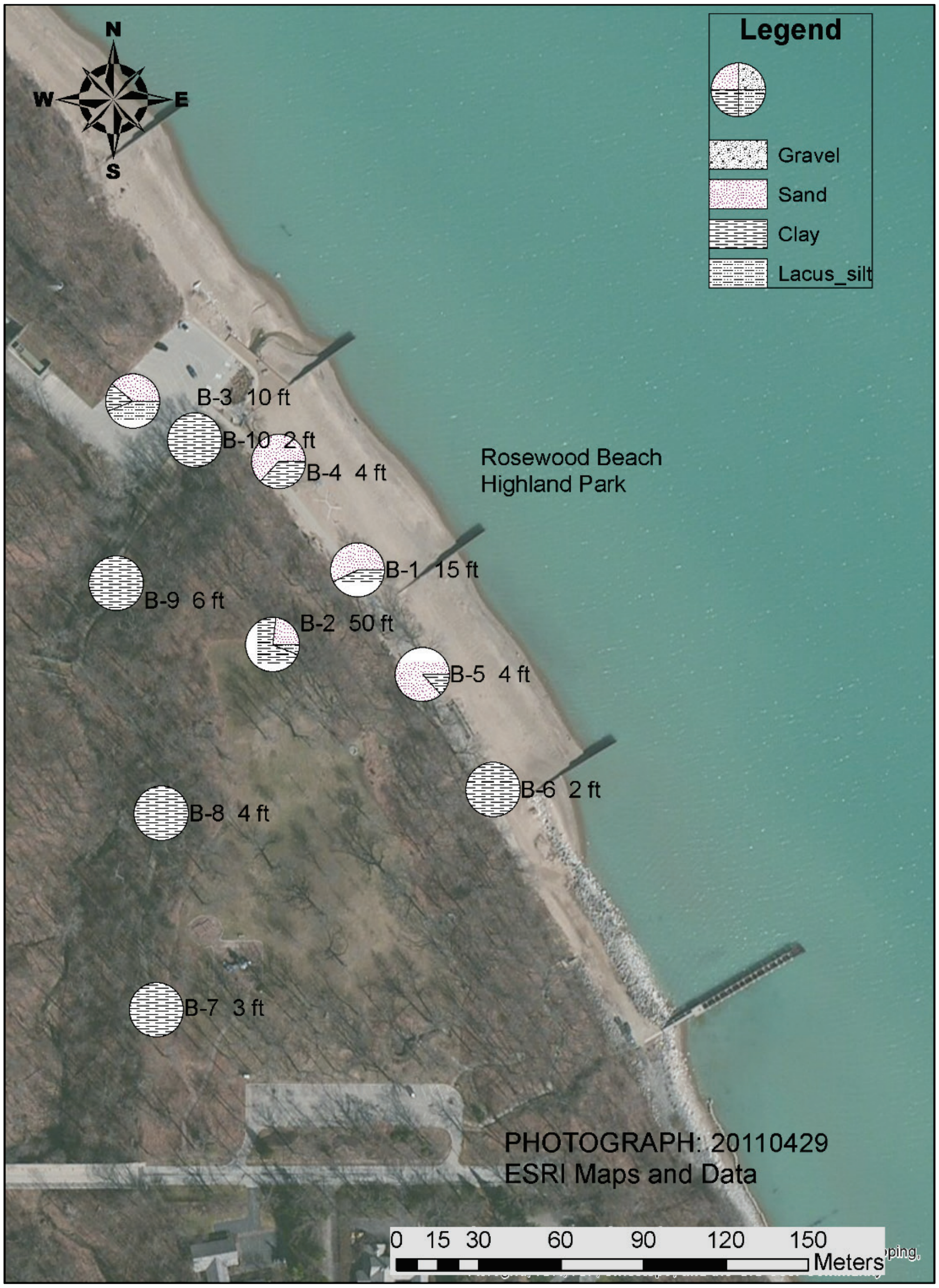


Figure 3. Borings at Rosewood Beach in Highland Park, IL. Clay is the predominant material at most sites, although boring B-2 (50 ft long) contained close to 25% sand. The average percent of sand for the core borings was approximately 5%. Photo by ESRI Maps and Data.



The sand plain is not a closed sediment system. Erosion on the north and deposition on the south contributed to the southward translation, and some sand clearly moves southward beyond the southern limit of the plain. This is demonstrated by the persistent need to dredge Waukegan Harbor entrance (discussed in the sediment removal and placement section of the report below). In the pre-engineered state, the Illinois coast was the southern end of a littoral transport pathway that began along the Wisconsin coast at least as far north as Sheboygan (86 miles north of the Wisconsin-Illinois border) and likely as far north as Manitowoc (110 miles north of the border). The evidence for this is the southward deflection of stream mouths recorded in the early mapping of streams along western Lake Michigan. Even along the Wisconsin coast, sand is limited in the bluff stratigraphy. Thus, coarse-grain material from glacial fluvial deposits was likely the source of sand along the Illinois shore.

Since the late-1800s to mid-1900s, most bluffs along the Illinois lakeshore have been protected with steel, concrete, timber, rubble, and stone armor. Limited unprotected sections of till bluffs are found in Highland Park and Lake Forest, but otherwise, the coast south of Waukegan is about 95% engineered and stable (Shabica et al. 2004). Compounding the problem, structures like the jetties and breakwaters at Waukegan, Great Lakes, and Wilmette almost totally interrupted the movement of sediment to the south. Therefore, a comprehensive sand management plan for the North Shore will require managing and recycling the sand that is presently in the system, while anticipating minimal new supply coming in from the north.

3 Previous Studies

The Illinois North Shore of Lake Michigan has been extensively studied over the past century. The effects of coastal erosion and accretion in this area were first recognized in the late 1800s as part of the construction of the Waukegan Harbor breakwater jetties. Two comprehensive studies of shore erosion along the entire Illinois coast were completed first by USACE in 1953 (USACE 1953) and then by the State of Illinois Division of Waterways in 1958 (State of Illinois 1958). These two studies utilized shore position and nearshore bathymetry data from 1872 to 1873, 1909 to 1911, 1937 to 1938, 1946 to 1947, and 1955 to map coastal change along the Illinois lakeshore. These two studies provided a benchmark for further study by the State of Illinois in the late 1970s and again by USACE in 1989 (USACE 1989). The Illinois State Geological Survey (ISGS) conducted a series of coastal studies along the Illinois North Shore in the 1990s and early 2000s in conjunction with the construction of North Point Marina near the border with Wisconsin (Chrzastowski et al. 1993, 1996; Chrzastowski 2003). These studies provide the most recent documentation of coastal erosion and accretion trends and associated littoral transport rates.

4 Data Sources, Management, and Organization

Software

Spatial data were organized and displayed in ESRI ArcMap™ Geographic Information System (GIS) software, version 10.1. Data were projected in State Plane Illinois East Zone, U.S. feet, North American Datum 1983 (NAD83). Features specifically related to an elevation are referenced to International Great Lakes Datum (IGLD) of 1985 (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1992).

Dredge volumes have been reported in cubic yards, as per common usage for dredging and engineering projects in this area.

Sediment volumes have been entered into the USACE Sediment Budget Analysis System software, which plots the cells and fluxes within the ArcMap environment (Dopsovic, Hardegree, and Rosati 2002; Rosati and Kraus 2001)

Contemporary aerial photography

Contemporary aerial photography of southern Lake Michigan and the surrounding states is available online from ESRI Maps and Data via the ArcGIS Map service. The World Imagery photography is dynamically scaled as needed. For the project area, maximum resolution was 0.3 meter (m) (≈13 inches). For most of the study area, the latest photography was 29 April 2011. It was primarily used for visual reference of topographic and man-made (anthropogenic) features. On the fillet north of Waukegan Harbor, the contemporary (photograph) shoreline was compared to historic shorelines to compute sediment accumulation.

2012 Lidar data

Light detection and ranging (lidar) data were collected along the coast of Illinois during the summers of 2008 and 2012 under the USACE National Coastal Mapping Program (NCMP) by the Joint Airborne Lidar Bathymetry Technical Center of Expertise using the Compact Hydrographic Airborne Rapid Total Survey system (Macon 2009; Wozencraft and Millar 2005; Wozencraft and Lillycrop 2006). Coverage typically extended from the waterline 1,600 ft (500 m) inland and offshore 3,300 ft (1,000 m) or to laser extinction. The NOAA Coastal Services Center supplies the USACE lidar data in various formats as requested by the user.

To measure the amount of bluff recession, historical bluff edge data collected by the ISGS were compared with the 2012 lidar data. The lidar was processed by NOAA with a contour interval of 1 m, with horizontal and vertical datum of NAD83 Illinois State Plane east zone, Federal Information Processing Standard (FIPS) 1201 and North American Vertical Datum of 1988 (NAVD88), respectively. Figure 4 plots the 2012 lidar data in Highland Park along with the older ISGS data shown as colored points. In this example, the 1987 bluff locations are slightly behind (landward) of the contemporary bluff edge, which is likely an artifact of the data given that it is not possible for the bluff to have advanced unless landowners constructed retaining walls and added fill. The discrepancy may be a result of an interpretation error or original source material. The 1987 bluff edge position was interpreted from aerial photography using optical methods. If the photographs had been flown during partial or full foliage, it may have been difficult to determine the exact edge. The older bluff dates were from charts, which may have survey or printing errors. The conclusion for this area is that the bluffs have not retreated since 1987 because of armoring and bluff protection measures undertaken by property owners.

To measure changes in offshore bathymetry, the 2012 lidar data were used in the form of GeoTiff files with elevations in feet, NAVD88, and horizontal datum of NAD83 Illinois State Plane east zone, (Federal Information Processing Standard, Publication 1201 [FIPS 1201]). This was gridded data with cell size of 10×10 ft (Figure 5). The 2012 lidar dataset had data gaps in some areas along the coast. The 2008 dataset was used to fill some of the gaps that were occurring in turbid areas possibly as a result of runoff or storms suspending sediment during the airborne survey timeframe. The percentage of data gaps within each sediment budget cell is less than 10%, so the 2012 lidar dataset was used as the principle dataset with 2008 coverage filling in the missing bathymetry data. One exception was in Cell 12, which used the 2008 dataset to cover over 75%, so for this cell, the sediment budget calculations used 2008 for the end year.

Figure 4. Elevation contours derived from lidar data collected in 2012 compared with historical bluff edge points from ISGS, Highland Park, IL. Closely spaced contours indicate steep bluffs or ravines. Photo by ESRI Maps and Data.

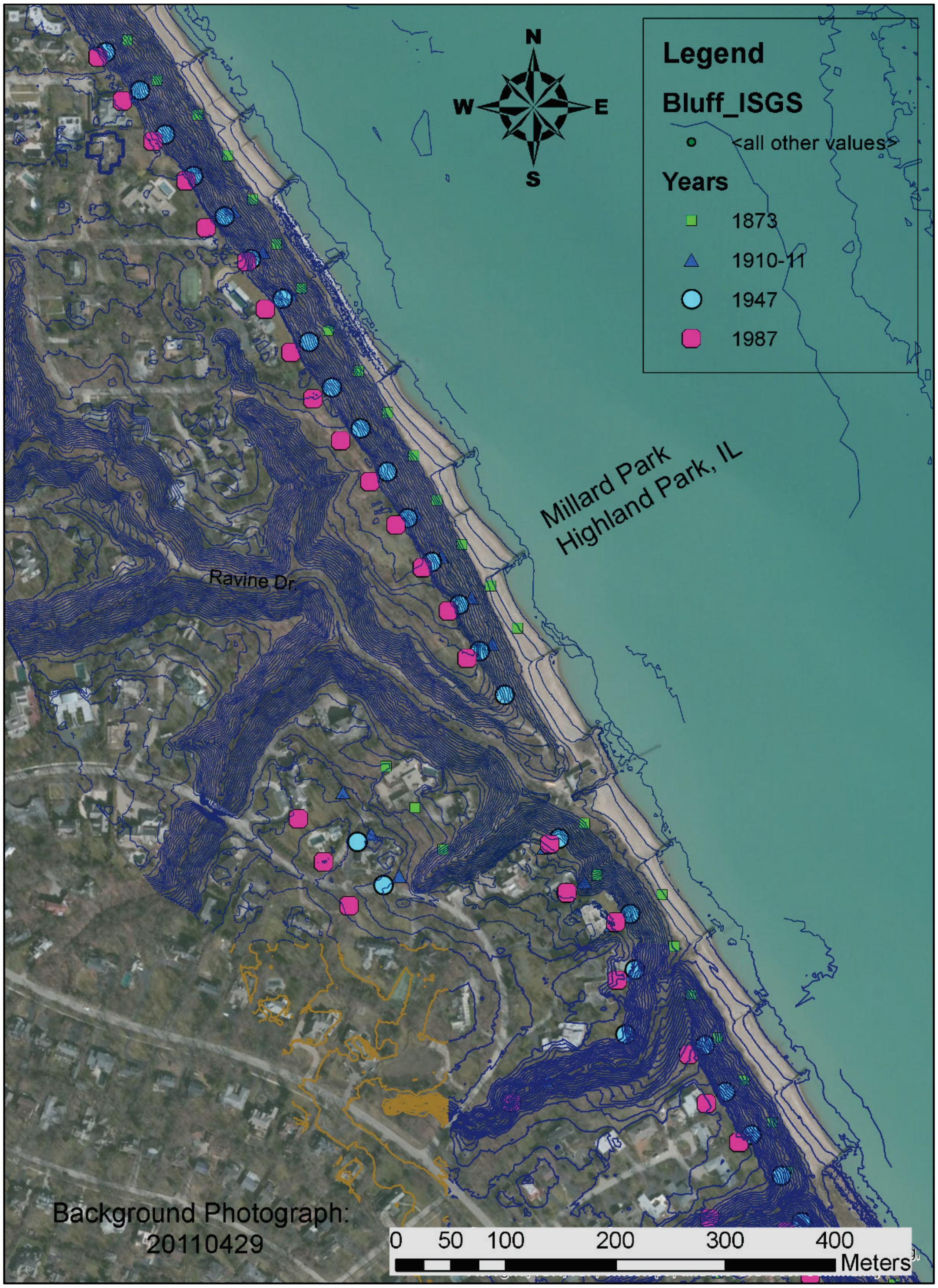
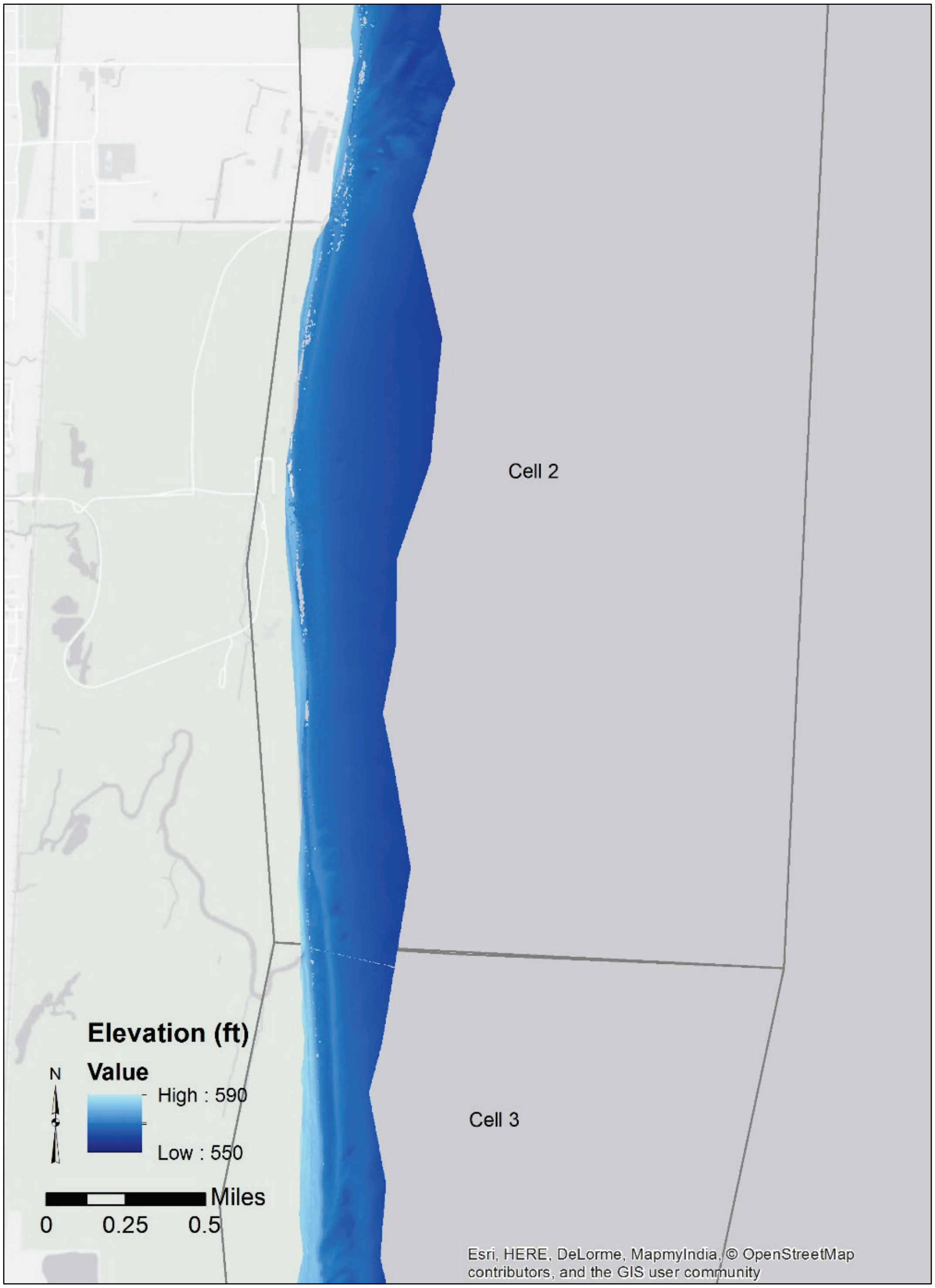


Figure 5. Nearshore bathymetry from 2012 lidar data, gridded at 10 ft × 10 ft cell size. Background map from ESRI Maps and Data.



Nearshore bathymetry mid-1970s

The ISGS prepared an Illinois coastal atlas based on nearshore bathymetry surveys conducted by the agency in the 1970s (ISGS 1988). The atlas is unpublished, but the 1988 version was supplied to ERDC-CHL for this study. This was the only mid-century bathymetry available for the shallow offshore waters along the Illinois coast. Digital data from NOAA were too far offshore and too sparse to be useful for this study. Eighteen of the ISGS sheets were geo-referenced to fit to the correct locations along the shore. Figure 6 is an example of charts 10 and 11 from Waukegan. The isobaths (bottom contours) were based on surveys run during 1974-1976, adjusted to a hypothetical lake level of 581.0 ft IGLD 1955 (NOAA 1980). The zero contour shown on the maps represents the April 1988 shoreline. The contours were digitized and stored as shapefiles. The contours were adjusted from IGLD 1955 to NAVD88 and used to construct a Triangular Irregular Network (TIN) surface with ESRI ArcMap software. The TIN surface was then converted into a grid with 10 ft x 10 ft cells to permit direct comparison with the 2012 lidar grids.

Figure 7 shows the comparison of the mid-1970s bathymetry with the 2012 lidar data. The data show that most of the lakebed off the IBSP lost sediment over the years, but sand accumulated in the fillet north of the jetties at Waukegan Harbor. Some of the lakebed loss might consist of till, but the portion of the shore off IBSP is more sand rich than the lakebed south of Waukegan because of the presence of the ancient beach ridge plain. South of Waukegan, the lakebed consisted of glacial till with a sand content of approximately 5% (per analysis of bluff core data, shown in Figure 3). Therefore, only 5% of the sediment volume change of the lakebed and bluffs was included in the sediment budget. The remaining 95% consists of fine-grained silt and clay, which is lost in the surf zone and does not contribute to the littoral transport. This process underscores a fundamental difference between a bluff coast and a sandy shore. The sandy beach can erode and recover depending on sand supply, whereas weathering and erosion of a bluff shore is a one-way process. Once the till bluff is cut back, no contemporary hydrodynamic process can rebuild the clay/silt/sand matrix.

Figure 6. Map frames 10 and 11 from ISGS 1988 Illinois coastal atlas. Isobaths were based on surveys completed during 1974-1976, adjusted to a hypothetical lake level of 581.0 ft IGLD 1955. Background map from ESRI Maps and Data.

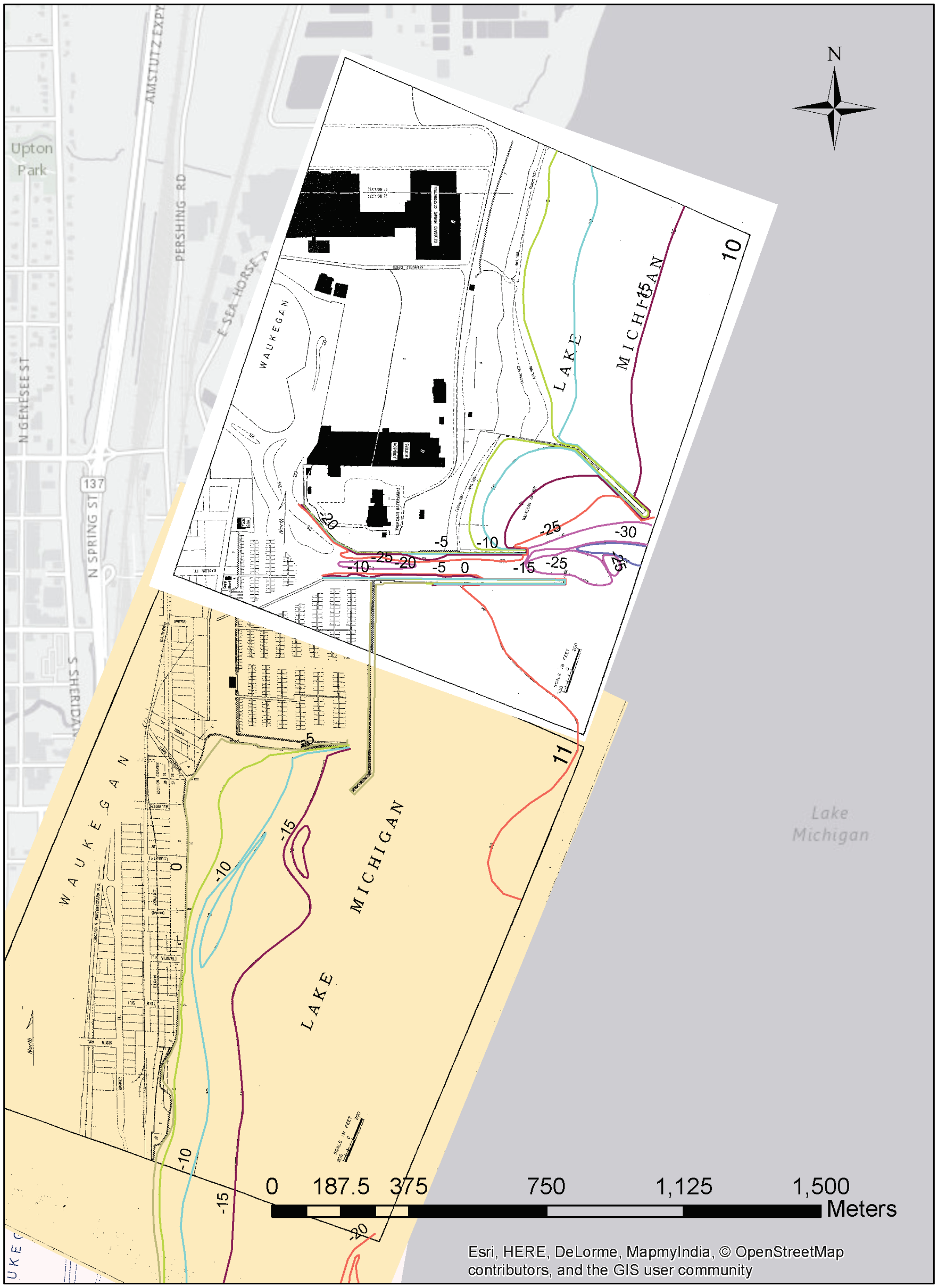
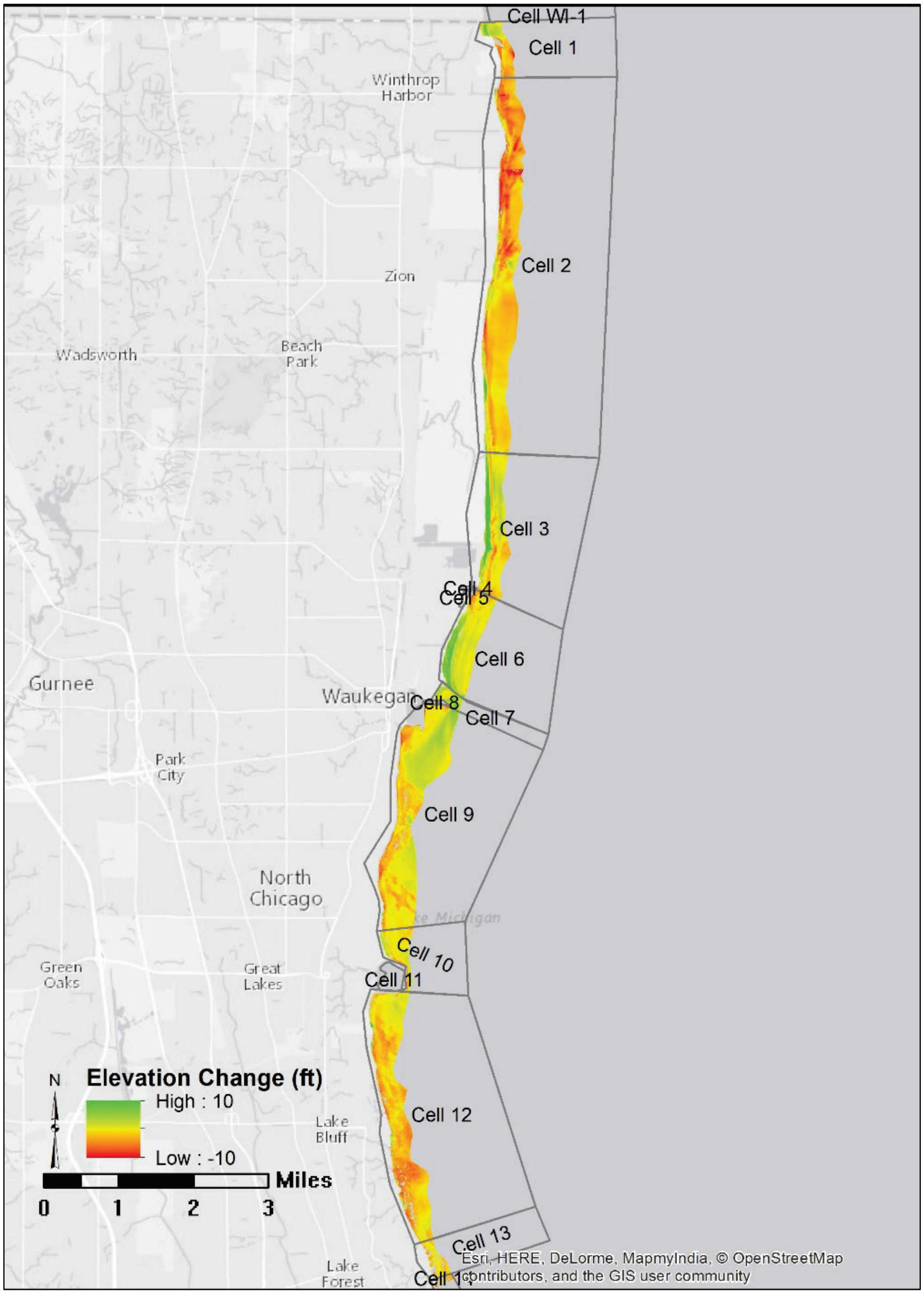


Figure 7. Lakebed comparison between mid-1970s acoustic and 2012 lidar bathymetry. Contours were traced from the ISGS coastal atlas (1988 publication date but containing 1974-1976 data). Background map from ESRI Maps and Data.



5 Sediment Budget Cells

A sediment budget is a tallying of sediment gains and losses, or sources and sinks, within a specified control volume (or cell), or series of connecting cells, over a given time. Cells are defined by geologic features or natural geomorphic boundaries, data resolution, coastal structures, and knowledge of the site. Sediment may pass from one cell to another, either naturally by wave and current-induced transport or artificially via dredging and placement. Note that sediment movement from one cell to the next cell downdrift is not 100% efficient because some sediment can be transported offshore or onshore. Along this coast, areas with seawalls or shore protection have minimal onshore sediment transport except in the rare cases where storm waves break high enough to deposit water and sand over the top of the walls. Rosati (2005) provides a more complete description of sediment budget methodology.

The basic sediment budget equation can be expressed as follows:

$$\sum Q_{source} - \sum Q_{sink} - \Delta V + P - R = Residual$$

where:

Q_{source} and Q_{sink} = the sources and sinks to the control volume, respectively
ΔV = the net change in volume within the cell
P = the amounts of material placed in the cell
R = the amounts of material removed from the cell (usually dredging)
Residual = the degree to which the cell is balanced.

The term *Residual* needs explanation:

- It is the remainder from the accounting of defined sources and sinks including ΔV, and for a balanced cell, the residual is zero.
- A cell may have *Residual* = 0 if all sources and sinks are accounted, but the cell may still have net sediment gain or net loss because of a flux in or out.
- *Residual* = 0 does not mean that all the fluxes in each littoral cell are understood or all sources and sinks of the system (Q_{source} and Q_{sink}) and artificial intervention (P and R) have been resolved perfectly. However, all terms were adjusted to ensure *Residual* = 0 in the calculation.

For a region consisting of many contiguous cells, such as the North Illinois study area, the budgets for individual cells must algebraically balance to achieve a balanced budget for the entire regional system.

Table 2 summarizes sediment gains and losses that may apply to a Lake Michigan budget cell. Not all of these are applicable today. For example, sand mining is no longer conducted, although gravel was mined from the Illinois Beach State Park on an industrial basis in the early twentieth century. Offshore flux to deep water and aeolian transport are not accounted for in this budget because no accurate estimates for these processes currently exist. For most of the study area, aeolian transport is assumed to be zero because in a developed terrain consisting of suburbia, there is no source of sand. An exception is a loss of sand from the dredge pile at the Waukegan power plant (discussed below). Flux to deep water can be included in a future refinement of the budget. Figure 1 shows the budget cells considered for this study. These are similar to the cells used by Chrzastowski and Trask (1996a) for the USACE Illinois Shoreline Erosion Interim IV study, but some of the 1996 cells have been subdivided into smaller units (for example, the intake canal at Waukegan Electric Generating Station and the sand pile on land are treated as two cells).

Table 2. Sediment gains and losses for budget calculation.

Gains	Losses
Longshore transport into cell	Longshore transport out of cell
Riverine supply (minimal in N. Illinois)	Offshore transport (to deep water)
Bluff erosion	Wind transport inland or out to lake
Wind transport onto the beach	Transport into dredged navigation channels
Onshore transport	Beach mining or other anthropogenic causes (no longer applicable)
Beach nourishment	
Dumping of debris (no longer applicable)	

Accretion *(ΔV)* is entered as a positive value while erosion is a negative. Longshore sediment transport from updrift is shown as a flux into the cell while sediment moving downdrift is a flux out of the cell. The fluxes are inferred mathematically based on dredging or volumetric changes; they have not been measured with sediment traps or other in situ methods. The budget is presented as an annual flux rate, resulting in a time-averaged net transport (not gross). The flux rate during any given year may be different for climatological reasons:

- Flux rate may be seasonal or even reverse direction.
- Storms are likely to alter the flux rates, and a given year with more or fewer storms will result in different magnitudes of transport.
- Alongshore vs. across-shore transport will also be dependent on storminess. Increased storminess could result in enhanced overwash (in the Illinois Beach State Park area) or offshore loss of sediment.

Construction of shore protection between the analysis dates, 1974 and 2012, may have altered the flux, but it is not possible to examine the effect. However, much of this shore south of Waukegan has been heavily armored for decades, and this budget is largely an examination of sediment flux along a developed shore.

Artificial sediment movement out of the cell, such as the dredging from the intake canal at the Waukegan Electric Generating Station, is not shown as a flux but rather is entered as a positive number for the term *R* (for removal). Artificial placement, such as beach nourishment at IBSP, is entered as a positive number for term *P* (placement).

Each cell represents a geomorphic unit that includes the beach and the shallow nearshore zone. The dimension alongshore represents the linear extent of the cell, but the shore-perpendicular width does not represent a specific or fixed value. The depth of the nearshore zone is unspecified but is intended to include the active sediment zone (approximately 20-25 ft water depth). Cells have been drawn with exaggerated cross-shore dimension for display purposes on the figures.

Flux arrows shown in figures in this report indicate the direction of net sediment movement, but the lengths of the arrows have not been scaled to indicate magnitude. Magnitudes and other values are listed in Table A-1 in Appendix A.

6 Sediment Removal (Dredging) and Placement

Table 3 lists dredging from the North Point Marina[1].

Table 3. Dredging, North Point Marina.

Date	Volume (yd^3)	
6/1/1995		Initial marina date used for calculations
1995-1996	24,000	Foyle and Chrzastowski (1997, p. 19)
6/1/1997	15,000	From David L. Suthard, General Manager, North Point Marina, 8/21/14
6/1/1999	15,000	‘’
3/21/2003	8,423	‘’
5/31/2007	7,553	‘’
7/31/2007	16,552	‘’
11/20/2008	20,150	‘’
9/29/2009	15,006	‘’
4/30/2010	4,229	‘’
8/31/2011	8,859	‘’
5/31/2012	5,529	‘’
5/31/2013	31,645	‘’
Total	**171,946**	
Years	**17.999**	
Annual	**9,553**	Avg. 1995-2013

[1] David L. Suthard, General Manager, North Point Marina, personal communication, 21 August 2014.

Table 4 lists sand dredged from the intake canal at the Waukegan Electric Generating Station.

Table 4. Dredging, intake canal, Waukegan Electric Generating Station.

Date	Volume (yd^3)
1958	120,000
1961	125,000
1963	50,000
1965	100,000
1968-69	120,000
1972	100,000
1973	103,000
1976	78,700
1977	149,000
1981	20,000
1983	42,000
1984	90,000
1986	102,700
1987	80,000
1988	7,000
1990	35,600
1992	114,700
1995	20,000
1997	20,000
1999	11,000
2000	50,000
2003	38,573
2003/2004	63,492
2004/2005	93,850
2005 (12/16 - 12/31)	28,595
2006 (1/3 - 1/19)	84,510
2007 (1/1 - 1/24)	160,900
2008 (1/08 - 2/08)	80,990
2009 (2/24 - 2/26)	39,420

Date	Volume (yd^3)
2010 (1/4 - 1/6)	66,225
2011 (1/3 - 1/31)	91,400
2012 (1/1 - 1/31)	74,280
2013 (1/1 - 1/31)	66,410
2014 (1/02 - 3/31)	50,790
Total	2,478,135
Years (2-year interval in 1950s)	58
Average annual	42,726
Total Volume 1995-2014	1,040,435
Years (assume 1-year interval)	20
Average 1995-2014	52,022

Source: Frederick Veenbaas, NRG Energy Services, LLC, 2/4/2015

Table 5 lists dredging from the approach channel and advance maintenance area of Waukegan Harbor. This is a federal navigation channel, and work was performed by contract plant for LRC or by federal plant (data from internal LRC documents). Dredge requirements have increased significantly since the late-2000s as the fillet beach to the north has reached capacity and sand wraps around the north jetty and enters the channel. The 1995-2013 value is used in this sediment budget.

Table 5. Dredging, Waukegan approach channel and advanced maintenance area.

Year	Volume (yd^3)	Placement
1889	17,805	Offshore
1890	63,069	Offshore
1892	9,714	Offshore
1893	50,292	Offshore
1897	128,862	Offshore
1898	58,249	Offshore
1900	33,650	Offshore
1903	26,722	Offshore
1905	280,900	Offshore
1906	5,004	Offshore
1907	9,129	Offshore
1908	6,426	Offshore
1909	14,866	Offshore
1910	53,453	Offshore
1912	7,791	Offshore
1913	10,220	Offshore
1914	31,929	Offshore
1915	31,163	Offshore
1916	37,106	Offshore
1917	19,600	Offshore
1918	28,880	Offshore
1919	50,510	Offshore
1920	16,837	Offshore
1921	36,750	Offshore
1922	59,500	Offshore

Year	Volume (yd^3)	Placement
1923	30,000	Offshore
1924	50,000	Offshore
1925	41,700	Offshore
1926	60,498	Offshore
1927	73,622	Offshore
1928	77,359	Offshore
1930	111,485	Offshore
1931	90,164	Offshore
1933	28,500	Offshore
1934	29,000	Offshore
1936	18,746	Offshore
1937	89,871	Offshore
1939	23,917	Offshore
1947	56,041	Offshore
1950	29,640	Offshore
1958	108,200	Offshore
1960	12,629	Offshore
1961	39,900	Offshore
1963	47,191	Offshore
1964	50,812	Offshore
1965	41,279	Offshore
1966	49,370	Offshore
1967	32,491	Offshore
1969	33,456	Offshore
1974	10,000	Unknown
1975	48,369	Offshore
1976	34,691	Offshore
1977	130,000	Shallow-South
1982	85,396	Offshore
1984	81,000	Shallow-South
1985	26,180	Shallow-South
1988	100,996	Shallow-South
1990	49,513	Shallow-South
1991	79,482	Shallow-South

Year	Volume (yd³)	Placement
1993	66,597	Shallow-South
1994	44,879	Shallow-South
1996	53,515	Shallow-South
1997	29,000	Shallow-South
1998	40,000	Shallow-South
1999	61,675	Shallow-IBSP
2000	56,275	Shallow-IBSP
2001	56,194	Shallow-IBSP
2002	48,623	Shallow-IBSP
2003	30,712	Shallow-South
2005	30,142	Shallow-IBSP (8,300) & South (21,842)
2008	71,789	Shallow-IBSP (60,000) & South (11,789)
2009	67,820	Shallow-IBSP
2010	60,890	Shallow-IBSP (29,000) & South (31,890)
2011	4,000	Shallow-South
2012	105,422	Shallow-IBSP(36,300) & South (69,122)
2013	73,000	Shallow-IBSP (63,000) & South (10,000)
Total Volume 1889-2013	**3,860,458**	
Avg Annual 1977-2013	**39,273**	
Avg Annual 1995-2013	**43,836**	
Avg Annual 2008-2013	**76,584**	

Note: missing years indicate no dredging in that year or data unrecoverable.

Table 6 lists dredging in the harbor at U.S. Naval Station Great Lakes. Large areas of the harbor shoaled soon after construction in the early twentieth century. In recent years, the harbor serves the U.S. Coast Guard and privately owned recreational boats. The entrance channel area was dredged in 2010-2011 to allow boats to reach the marina area. Volume data about previous dredging are unavailable, but during a site visit in February 2015, ERDC representatives were told the previous work was in the early 1970s. No records exist for the 1970s work.

Table 6. Dredging, U.S. Naval Station Great Lakes.

Date	Area	Volume (yd^3)	Disposal	Notes
12/1/2009	2007A	4,706	Barge to NASCO in Chicago	North Wind 2011a
8/23/2010	2007B	22,327	Barge to NASCO in Chicago	North Wind 2011a
5/21/2011	FY2008	19,871	Barge to Buffington	North Wind 2011b
6/9/2010	FY2009A	31,612	Landfill - fine grained, contaminants	Not used in coastal budget; North Wind 2011c
4/7/2011	FY2009D	5,350	Barge to NASCO in Chicago	North Wind 2011c
5/3/2011	FY2009B	1,962	Barge to NASCO or Buffington	North Wind 2011c
5/31/2011	FY2009C	12,518	Barge to Buffington dock, Gary	North Wind 2011c
Total Coastal Sediment		**66,734**	**Open coast (littoral) source**	
Years		**40**	**Previous dredging in ≈1970s**	
Average		**1,700**		

Table 7 lists sand dredged from the boat ramp at Forest Park (data supplied by the Parks Supervisor, City of Lake Forest).

Table 7. Dredging, Forest Park boat ramp.

Year	Volume (yd^3)
1995	2,400
1996	2,750
1997	2,950
1998	3,150
1999	2,800
2000	2,750
2001	2,580
2002	2,800
2003	2,450
2004	2,600
2005	2,449
2006	2,700
2007	2,450
2008	2,875
2009	2,500
2010	2,780
2011	2,420
2012	2,650
2013	2,865
2014	1,652
Total:	**52,571**
Years:	**20**
Average:	**2,629**

Source: Rich Paulsen, Parks Supervisor, The City of Lake Forest, 2/11/15.

Table 8 lists sand dredged from the Wilmette Harbor. All amounts reflect spring dredging.

Table 8. Dredging, Wilmette Harbor.

Year	Volume (yd^3)
1998	0
1999	19,950
2000	7,500
2001	16,138
2002	14,000
2003	8,142
2004	6,160
2005	9,800
2006	15,100
2007	14,685
2008	15,000
2009	15,073
2010	13,924
2011	14,700
2012	15,000
2013	11,400
2014	10,200
2015	10,500
Total:	217,272
Years:	17
Annual:	12,781

Source: Sabine Herber, Executive Director, Wilmette Harbor Association, 11/12/2014 and 8/12/15.

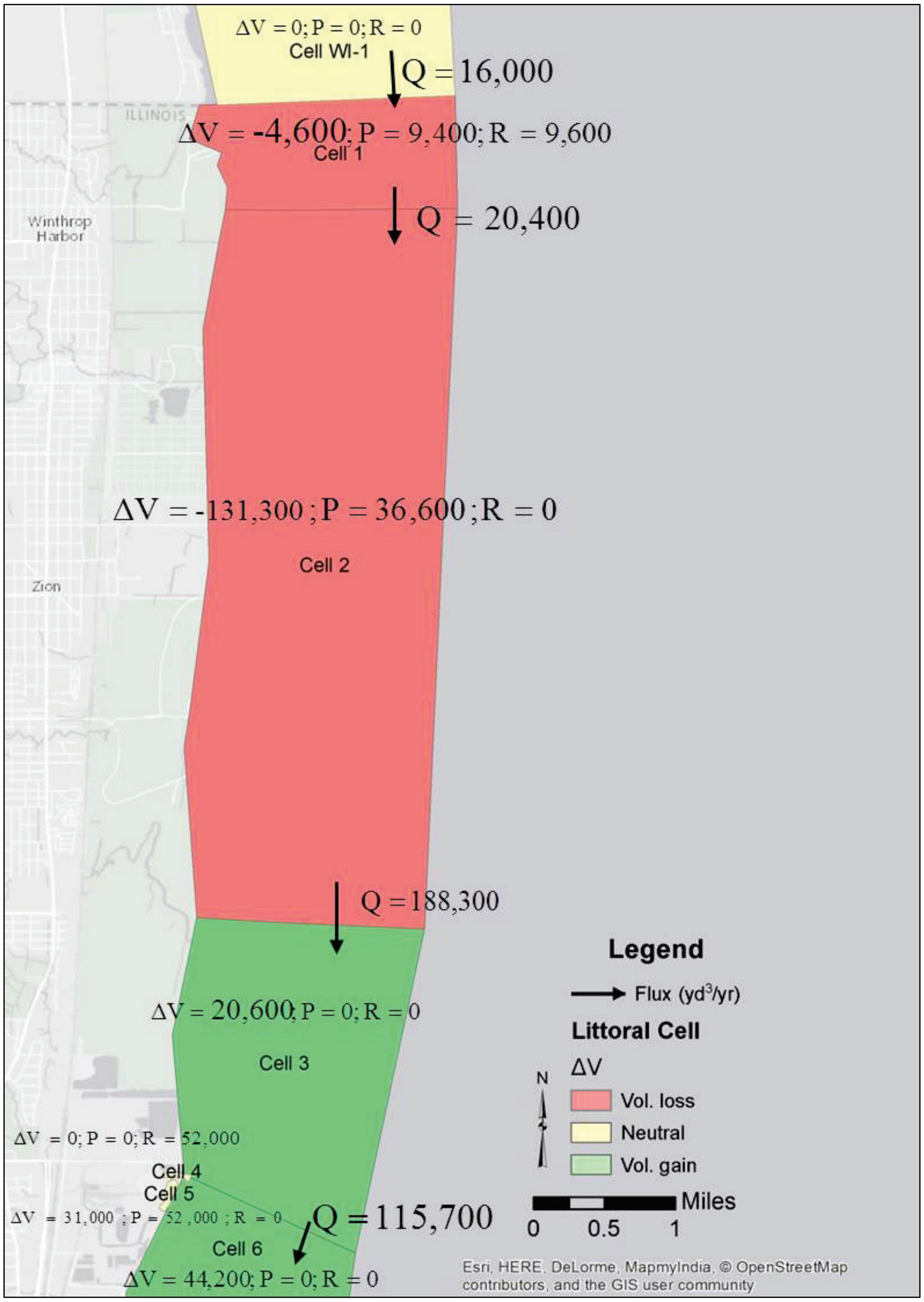
7 Sediment Volumes and Budget

Cell WI-1, Kenosha to North Point Marina[1]

This cell covers the coast north of the Illinois-Wisconsin border (Figure 8). It is outside the study area of this project but has been included because sediment moves south along the Wisconsin shore and enters North Point Marina in Illinois. The source of sediment in the littoral zone is likely beach and nearshore erosion but has not been specifically evaluated. Before development and armoring of the Wisconsin shore, erosion and transport contributed several tens of thousands of cubic yards per year to the littoral transport (Chrzastowski and Frankie 2000). Construction of shore defenses along much of the coast south of Kenosha, and the dredging and removal of littoral sand at the entrances to Kenosha Harbor and Prairie Harbor Marina (constructed in the late-1980s) on the Wisconsin side of the state line have significantly reduced the quantity of littoral sediment reaching the Illinois shore. Foyle, Chrzastowski, and Trask (1998) estimated that only 10,000 yd^3/year of littoral material crossed the state line. Before construction of the North Point Marina, a "best estimate" was considered to be 60,000 to 80,000 yd^3/year, but based on the monitoring of geomorphic changes at North Point Marina, Chrzastowski (2003) estimated that a minimum of 16,000 yd^3/year crossed into Illinois. Based on the monitoring by Chrzastowski (2003), the amount of sand moving south for this budget is also estimated to be 16,000 yd^3/year. This rate is the best available estimate of sediment flux across the state-line. However, this value likely needs to be updated as updrift shore protection structures and sand management activities may have reduced nearshore sand availability. In the future, if the sediment volume crossing the state line is recomputed, the rest of the sediment budget farther south can be adjusted accordingly. The following paragraphs provide additional information about the values included in the sediment budget.

[1] Cell number is used for reference when referring to Appendix A.

Figure 8. Sediment budget north zone, from the WI-IL border to Waukegan Harbor. All units in yd³/year; ΔV = net change in volume within the cell; R = amount of material removed from the cell, usually by dredging; P = amount of material placed in the cell. Details of the Waukegan area are shown in Figure 13. Background map from ESRI Maps and Data.



Cell 1, North Point Marina

The marina is operated by the IDNR and is the largest recreational marina in the Great Lakes. Construction began in 1987, and the project was completed by 1989, making this the most recent major coastal structure to be added to the Illinois coast (Chrzastowski and Trask 1996a; Chrzastowski 2003). Two arcuate rubble-mound breakwaters protect the perimeter of the marina basin, and the north breakwater forms a partial barrier to littoral transport. Sand that bypasses this breakwater accumulates in the marina entrance and is removed with mechanical equipment. The average annual removal is 9,600 yd^3, and the sand is placed downdrift (south) adjacent to the parking lot (Figure 9 and Table 3). Shortly after marina construction, the feeder beach to the south was reassigned to become a parking area. Shore defense was built, and additional sand was imported to serve as a substitute feeder beach. Chrzastowski et al. (1996; p. 17) listed the import of 150,000 yd^3 in 1990, 32,000 yd^3 in 1994, and 53,000 yd^3 in 1995-early-1996. For estimating the P term in the sediment budget, the volume was averaged over the period 1990-2015, amounting to 9,400 yd^3/year.

Offshore, sediment has accumulated north of the north jetty but had been lost adjacent to the marina and to the south (Figure 7). Lakebed change (ΔV) is only -4,600 yd^3/year (see Appendix A for details of this and all other cells).

Figure 9. Sand dredged from the entrance channel at North Point Marina is piled south of the entrance and pushed into the lake. Photograph 17 June 2014.

Cell 2, Illinois Beach State Park north zone

Illinois Beach was legally designated as a state park on 13 July 1953. Prior to park designation, the land had a diverse history and saw a variety of uses. The initial designation as a park was for what is now the South Unit, while the North Unit has existed for approximately 40 years following land acquisitions by the State of Illinois in the 1970s (Chrzastowski and Frankie 2000). As described earlier, this stretch of the Illinois Coast is least anthropogenically disturbed; however, the beach continues to suffer erosion from storm waves (Figure 10). Two cells cover the shore along the IBSP. The northern cell includes the zone with the greatest lakebed sediment loss, with ΔV = -131,300 yd^3/year. USACE has placed an average of 27,000 yd^3/year of dredged material from Waukegan Harbor (1995-2013) in the nearshore area of the Illinois Beach State Park (USACE 2014). Additionally, IDNR has placed 9,600 yd^3/year of dredged material from North Point Marina and brought in additional sources via trucks to a feeder beach that is south of the marina.

Figure 10. Illinois Beach State Park, with scarp formed by storm waves. Photograph 17 June 2014.

Cell 3, Illinois Beach State Park south zone

The southern part of IBSP has experienced minimal lakebed loss with mainly areas of accretion as compared to the north zone, with ΔV = 20,600 yd^3/year. Analysis of dredging histories suggests that from the south end of this cell, 52,000 yd^3/year of sediment enters the cooling water canal at Waukegan Electric Generating Station while 115,700 yd^3/year continues south to the fillet north of the Waukegan Harbor north jetty.

Cell 4, Waukegan Electric Generating Station intake canal

Two canals lead from the Waukegan Electric Generating Station into Lake Michigan. The warm water outlet canal is self-flushing, but the cooling water intake canal requires regular clearing. Annual dredging for the period 1995-2014 was 52,000 yd^3/year. This value has been used in the sediment budget (Figure 8). Because of State of Illinois regulations, presently this sand cannot be returned to the open coast and must be stockpiled on land due to the presence of asbestos fibers sourced from homes that were destroyed by erosion in the area now occupied by North Point Marina.

Cell 5, Waukegan Electric Generating Station sand pile

The sand pile contains approximately 600,000-630,000 yd^3 of sand (Figure 11 and Figure 12). The volume was calculated two ways: (1) geometrically based on the footprint and height and (2) via a sand pile calculator: http://www.had2know.com/garden/calculate-volume-pile-gravel.html. For this analysis, a volume of 620,000 yd^3 total has been used. The pile has compressed over time (F. Veenbaas, NRG Energy, personal communication, 15 July 2015). Over 20 years, ΔV = 31,000 yd^3/year. Because placement has been 52,000 yd^3/year, approximately 21,000 yd^3 is lost annually. A reasonable assumption is that approximately half, or 11,000 yd^3/year, has been lost to Aeolian transport and 10,000 yd^3/year to compression (Figure 13).

Figure 11. Sand pile at Waukegan Generating Station. Photograph 17 June 2014.

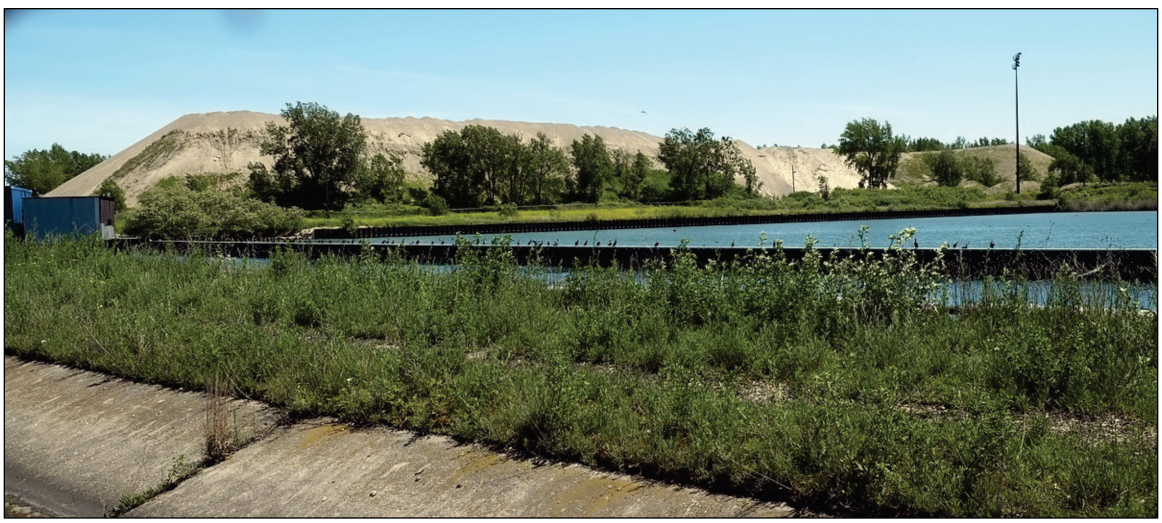
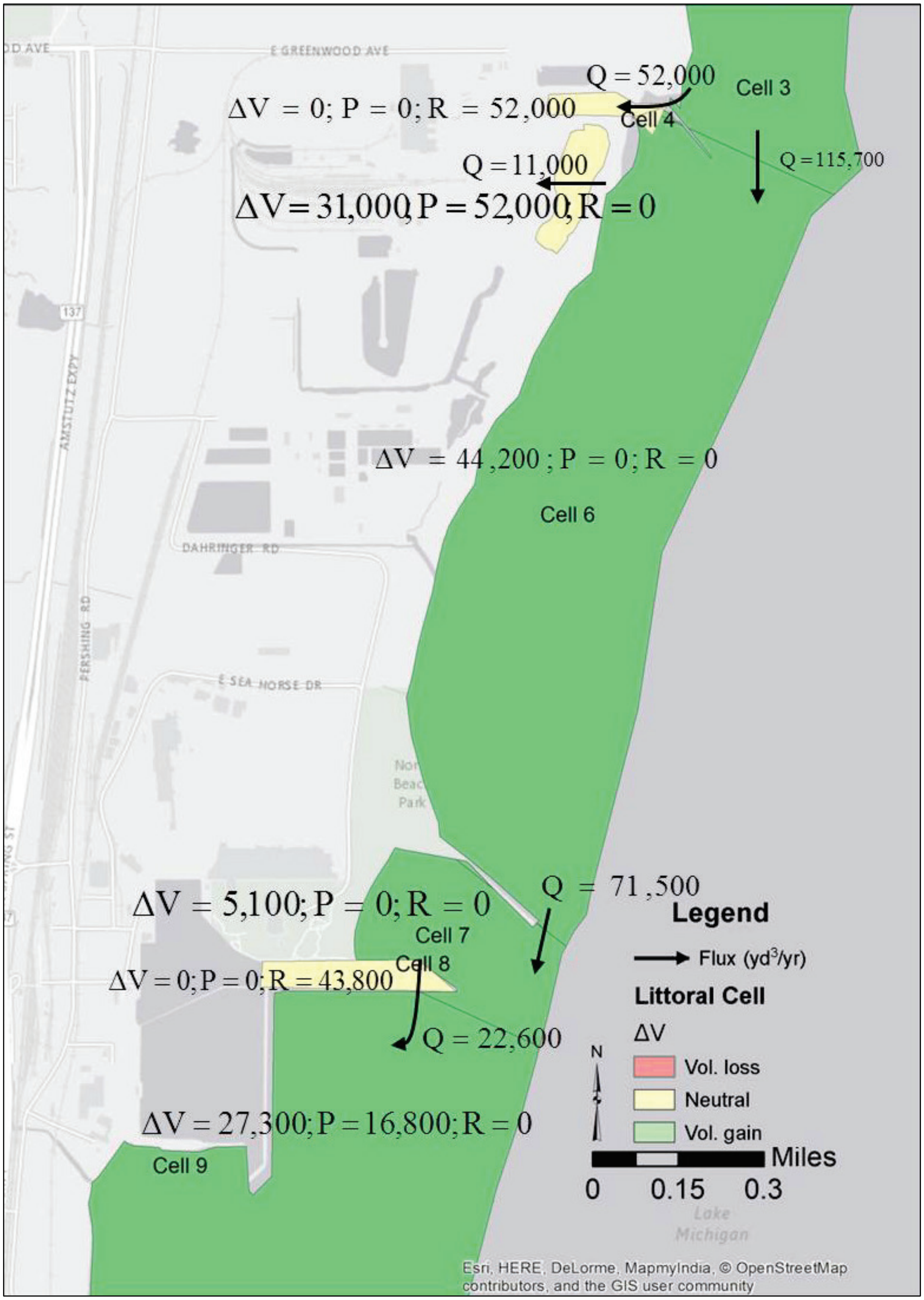


Figure 12. Dredged sand pile at Waukegan Generating Station. Top of the pile is unvegetated.

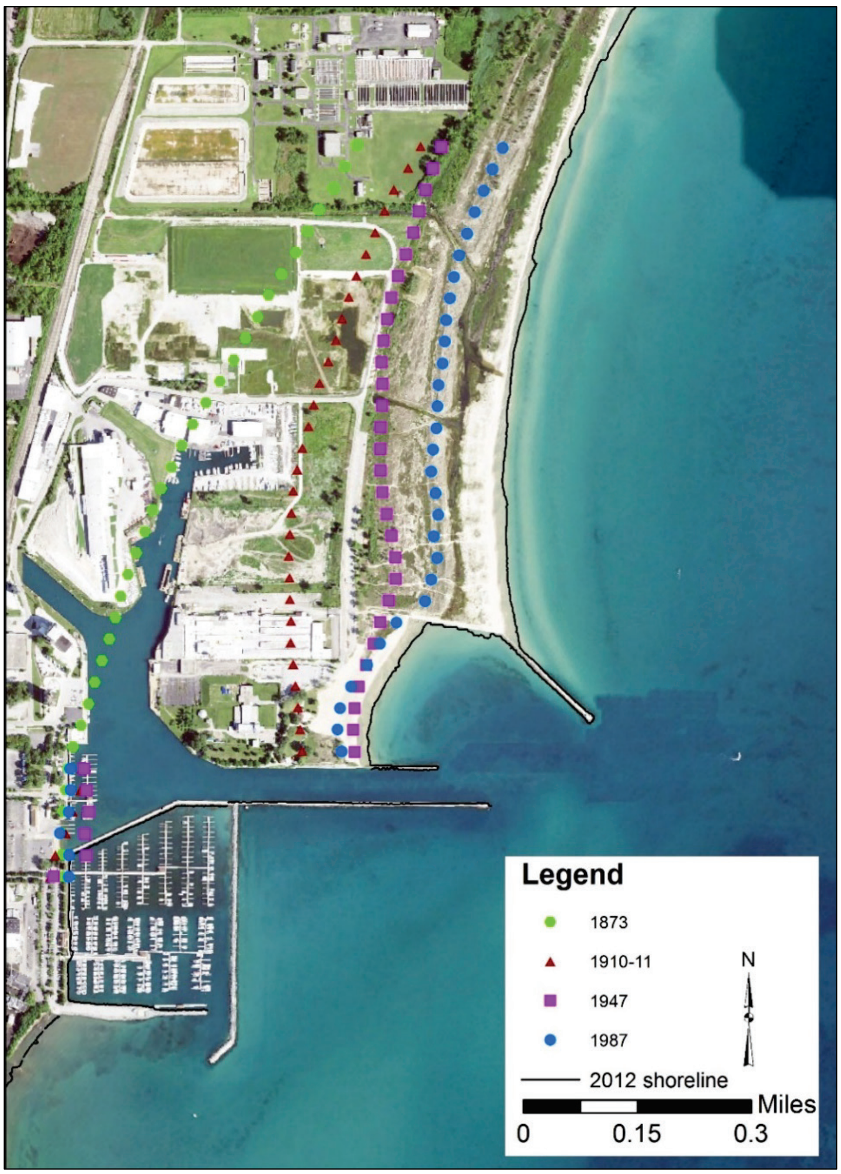
Figure 13. Sediment movement near Waukegan Generating Station and Waukegan Harbor. All units in yd³/year; ΔV = net change in volume within the cell; R = amount of material removed from the cell, usually by dredging; P = amount of material placed in the cell. Background map from ESRI Maps and Data.



Cell 6, Waukegan Electric Generating Station to Waukegan north fillet beach

At ISGS Transect 222, just north of the base of the north jetty (Figure 14), total beach advance since 1873 was 2,700 ft. To determine the recent sediment budget, the 2012 lidar dataset along with 3% of the 2008 cells were compared with the 1976 contour map. This area has predominately accreted, with ΔV = 44,200 yd^3/year. From the south end of this cell, 71,500 yd^3/year of sediment continues south to the Waukegan Harbor beach fillet.

Figure 14. Historical bluff edges north of Waukegan Harbor based on ISGS data. The blue points are a hypothetical 1987 beach shoreline.



Cell 7, Waukegan Harbor beach fillet

The fillet beach north of the jetty has been accumulating sand that has been trapped by the north jetty since the late 1800s. To determine the recent sediment budget, the 2012 lidar dataset along with 5% of the 2008 lidar values were compared with the 1976 contour map. This area has predominately accreted, with ΔV = 5,100 yd^3/year. From the south end of this cell, 22,600 yd^3/year of sediment continues south along the open coast to Cell 9 after an average yearly removal of 43,800 yd^3/year from Waukegan Harbor (Cell 8).

Cell 8, Waukegan Harbor

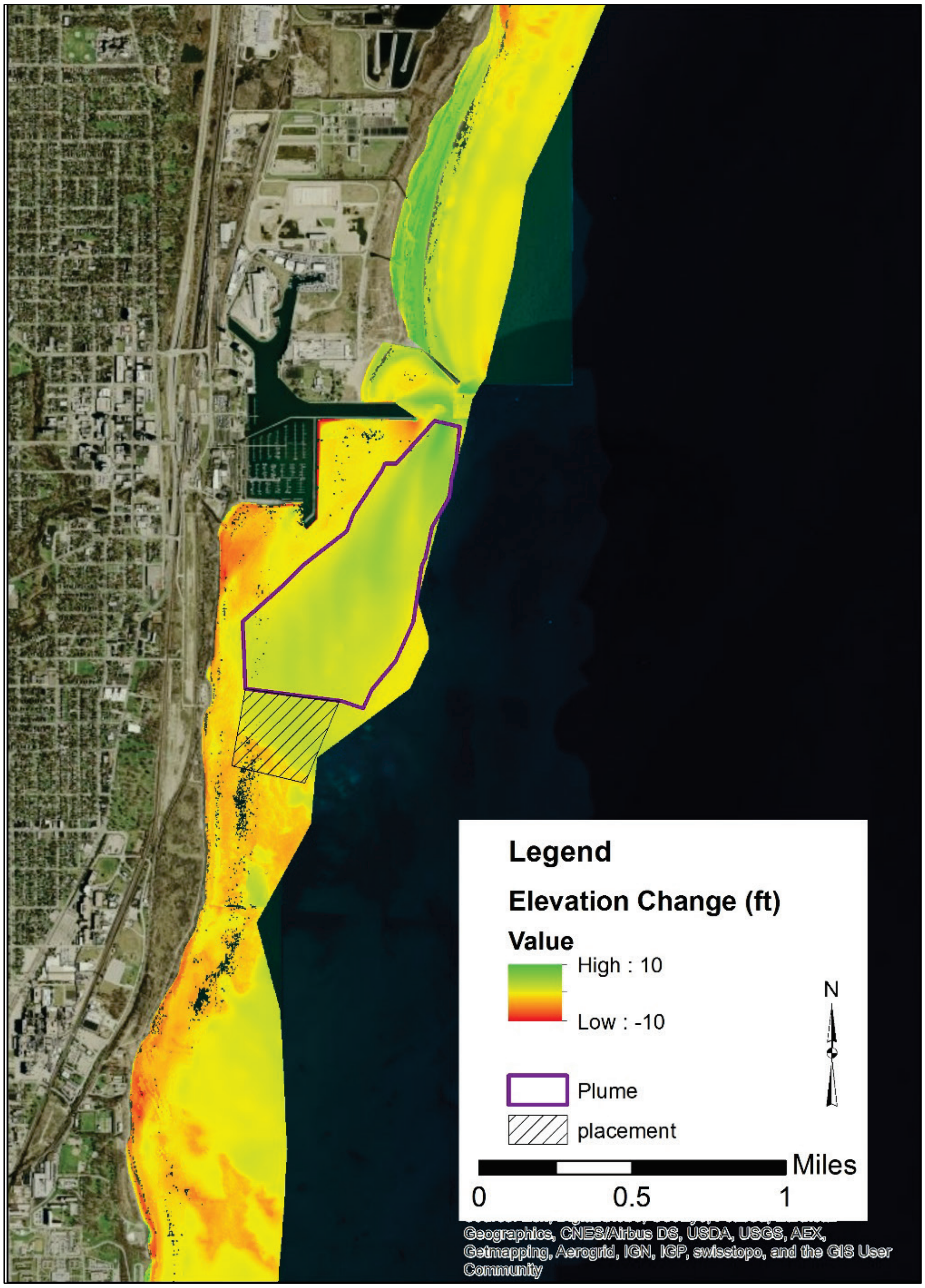
Waukegan is a deep-draft federal harbor, and the USACE is responsible for maintaining authorized navigation depths in the entrance channel. Federal participation in the harbor began in 1852 with construction of an offshore breakwater, but it was rapidly destroyed in storms. Construction of the north and south piers began in 1881 and over the years, were progressively lengthened and renovated (see Chrzastowski and Trask [1996a] for more historical details). Annual dredging increased as the fillet beach reached capacity and sand wrapped around the north breakwater and entered the navigation channel (Figure 15). This sediment budget uses the 1995-2013 average value of 43,800 yd^3/year (Table 5). Of this amount, 27,000 yd^3/year has been bypassed to the north to the IBSP while 16,800 yd^3/year has been placed south in shallow water off North Chicago.

Figure 15. Waukegan Harbor north breakwater, view looking east. Shallow lakebed on the north side of the pier is demonstrated by the bathers standing in shallow water left of the structure. Photograph 17 June 2014.

Cell 9, Waukegan to U.S. Naval Station Great Lakes north fillet

This cell extends from just south of Waukegan Harbor to the fillet north of U.S. Naval Station Great Lakes. Sand has been bypassing the mouth of Waukegan Harbor for several decades (Chrzastowski and Trask 1996a), and an accumulation of sand on the lake bed south of the harbor mouth was interpreted as this bypassing feature (Figure 16). The volume of the plume was measured as 27,300 yd^3/year, based on comparing the 1974/1975 acoustic surveys and the 2012 lidar with 1% of cells from the 2008 lidar dataset in the area of the plume that is delineated in Figure 16. The lakebed outside the plume area was glacial till. Therefore, as described earlier, only 5% of this volume contributed sand to the littoral system while the 95% fine material was lost. This 5% sand was measured as 600 yd^3/year. The amount mechanically bypassed from Waukegan harbor dredging was 16,800 yd^3/year and is represented in Figure 16 by the black hatched box.

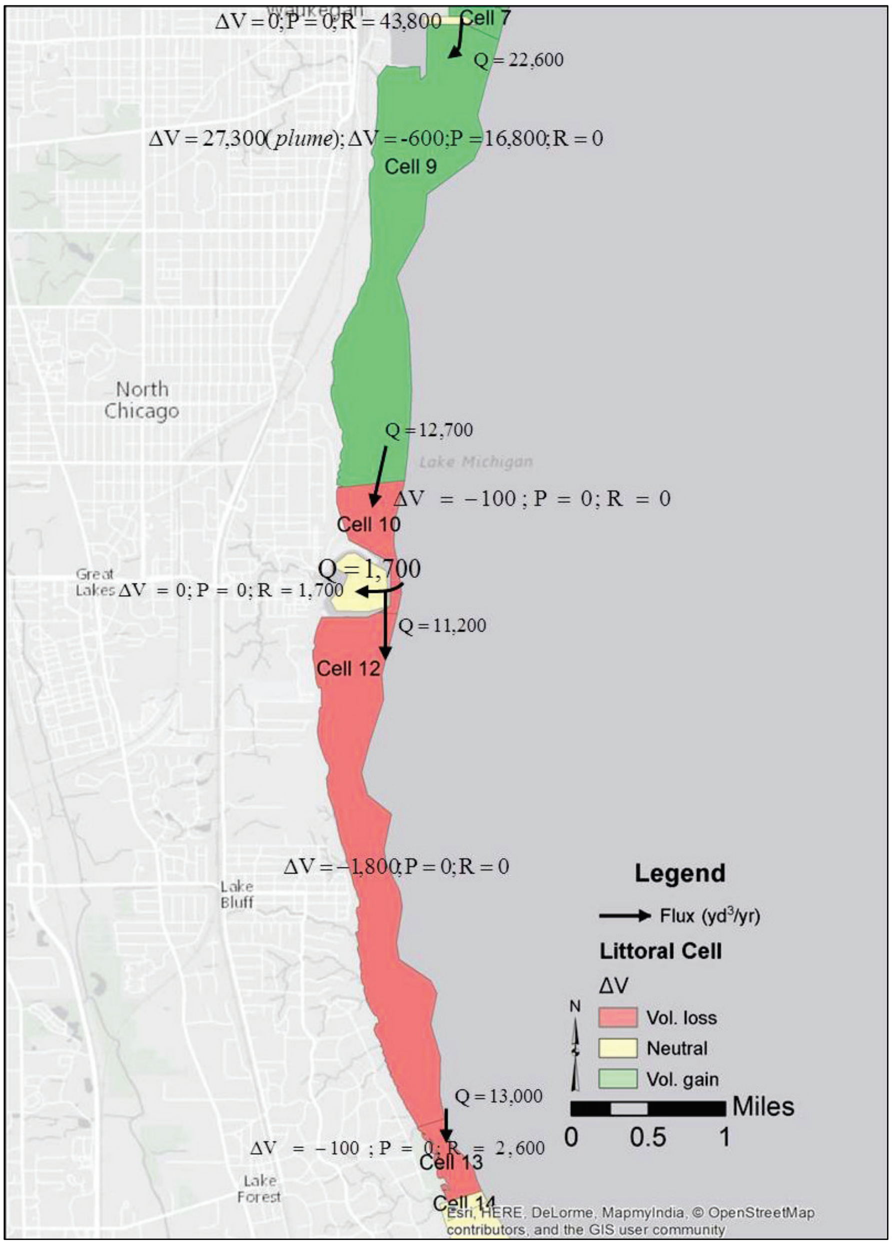
Figure 16. Elevation changes 1974/1975 - 2012 on the lakebed south of Waukegan harbor. The green plume extending south from the harbor mouth represents sand bypassing (outlined in purple). The placement site for material dredged from Waukegan Harbor is represented by the black hatched box south of the sand bypassing plume.



Cell 10, U.S. Naval Station Great Lakes fillet

The fillet at U.S. Naval Station Great Lakes has been filled to capacity since the 1970s or 1980s (Chrzastowski and Trask 1996a). Therefore, ΔV is extremely small at -100 yd^3/year as calculated using the 2012 lidar dataset with 3% of the values from the 2008 lidar dataset compared with the 1976 contours. Also, the assumption of 5% sand being available to the littoral system was included for this cell. Sand that enters the cell from the north either enters the harbor (1,700 yd^3/year) or bypasses to the south 12,800 yd^3/year (Figure 17).

Figure 17. North Illinois sediment budget, central section, from Waukegan to Fort Sheridan. All units in yd^3/year; ΔV = net change in volume within the cell; R = amount of material removed from the cell, usually by dredging; P = amount of material placed in the cell. Background map from ESRI Maps and Data.



Cell 11, U.S. Naval Station Great Lakes Harbor

U.S. Naval Station Great Lakes is the U.S. Navy's only boot camp for recruits. The site covers 193 acres and includes numerous historical buildings erected between 1905 and 1911. Originally, the harbor consisted of two piers or groins built in 1910 that enclosed the mouth of Pettibone Creek (Figure 18). Sailors trained in the enclosed anchorage. The present outer breakwaters (Figure 19) were built in 1923. Sand rapidly accumulated in the fillet to the north and entered the harbor, and the enclosed harbor south of the north jetty is partly emergent.

Figure 18. Painting of U.S. Naval Station Great Lakes, circa pre-1923 (photographed from display prepared by Illinois Work Projects Administration, War Services). The present outer jetties are not shown in this painting. The north breakwater now extends out from the shore at approximately the power station.

Figure 19. U.S. Naval Station Great Lakes, oblique view from Google Earth showing approximately the same view as Figure 18. Photograph June 2015. The bluffs are vegetated and not obvious in this photograph.

No documents pertaining to previous dredging have been located, but the authors were told that the outer harbor had not been dredged since the 1970s (Harvey Pokorny, Environmental Project Manager, NAVFAC MIDLANT, personal communication, 11 March 2015). The entrance channel and select areas were dredged in 2009-2011, with the material barged to Indiana for beneficial use including roadway construction (North Wind 2011a,b,c). For the sediment budget, the time interval is assumed to be 40 years, and R = 1,700 yd^3/year. Q was assumed to be this same amount because aerial photographs over time show that the exposed shoals and marsh within the northern part of the harbor have not appreciably changed for two or three decades. The harbor does not appear to be a major sediment sink now.

In 2010, 31,600 yd^3 of fine grained material was removed from the mouth of Pettibone Creek. This was disposed on land and has not been included in the sediment budget calculations.

Cell 12, U.S. Naval Station Great Lakes to Forest Park

Sand in this cell south of the mouth of the U.S. Naval Station was computed using the 2008 lidar dataset since 77% of the pixels in the cell were null for the 2012 lidar dataset. The computed value is -1,800 yd^3/year when using the assumption to include 5% as littorally available sand. Historically, this stretch of coast received minor input from bluff recession. The flux (Q) out of this cell to the south is calculated as 13,000 yd^3/year.

Cell 13, Forest Park Beach

Forest Park Beach, in the City of Lake Forest, is protected with three stone shore-parallel breakwaters and a fourth section to the south with south-facing arm that encloses a boat ramp. The breakwaters were designed to contain crescent-shaped recreation beaches, which curve out to the breakwaters, forming tombolos (Figure 20). Chrzastowski and Trask (1996b) intensively surveyed the four-cell breakwater system between 1991 and 1995. A sand deficit was caused by the development of a sand bridge around the breakwater system, but there was no evidence of adverse impacts to downdrift properties. Annual sand removal is 2,600 yd^3 (Table 7). This is placed to the south. A negligible amount of volumetric change was calculated for this cell (-100 yd^3/year), and therefore the flux to the south is 10,500 yd^3/year.

Figure 20. Forest Park Beach, City of Lake Forest. The shore-parallel breakwaters protect crescent-shaped beaches. Photograph 17 June 2014.

Cell 14, Forest Park to Winnetka water plant

This long cell extends from Lake Forest to the water plant at Winnetka (Figure 21). The bluffs along this cell have been armored, and a comparison with ISGS bluff edge data and 2012 lidar indicates essentially no bluff retreat in recent decades (Figure 4). Therefore, sediment input from the bluff was treated as zero. The beaches along this shore have been sand-limited for decades, and groins built decades ago attest to the attempt by homeowners to preserve the limited amount of sand that did exists (Figure 22). A fillet beach has accumulated north of the pier at the Winnetka water plant. Historical shoreline data were not available at this site, but an examination of photographs on Google Earth Pro showed minor shoreline changes between 2002 and 2015. Placement from the Forest Park boat ramp is 2,600 yd^3/year, and flux to the south is 13,100 yd^3/year.

Figure 21. North Illinois sediment budget, southern section. All units in yd^3/year; ΔV = net change in volume within the cell; R = amount of material removed from the cell, usually by dredging; P = amount of material placed in the cell. Background map from ESRI Maps and Data.

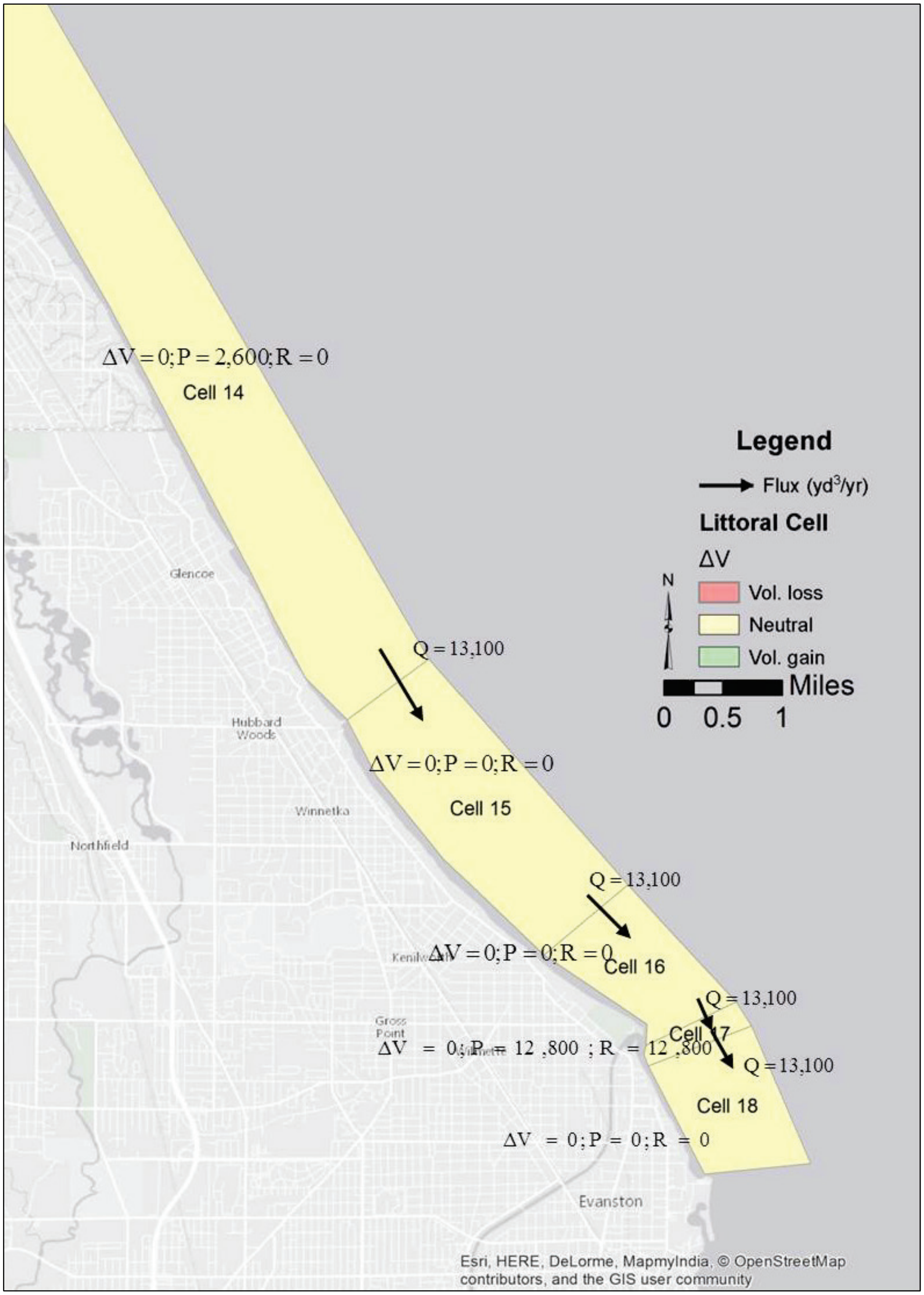


Figure 22. Shore protection at base of Harbor Street, Village of Glencoe, view looking south, November 1945 (photograph from the archives of the Beach Erosion Board, USACE).

Cell 15, Winnetka water plant to Gillson Park

This section of coast has minimal sand on the upper shoreface. The entire reach is armored, with a variety of structures. Based on aerial photographs, some groins are partly sand-filled while other sections have stone riprap directly at the water's edge. ΔV, P, and R are zero in this cell. The flux was computed based on dredging at Wilmette and equals 13,100 yd^3/year.

Cell 16, Gillson Park

This cell covers Gillson Park. The park, which is operated by the Wilmette Park District, offers 60 acres of lakefront property, with swimming and other recreation facilities. The southern end of the beach is anchored by a stone groin approximately 400 ft north of the pier that marks the entrance to Wilmette Harbor (Figure 22).

Shoreline data were not available for the beach, and Google Earth Pro historical photographs did not show a long-term pattern of beach change. Therefore, ΔV is assumed to be zero, and flux into this cell is equal to flux out (13,100 yd^3/year).

Cell 17, Wilmette Harbor and beach

Wilmette Harbor, which serves recreational boats, is located at the end of the North Shore Channel. The channel, dug between 1907 and 1910, provides flushing to the north branch of the Chicago River. The U.S. Coast Guard has a station in Wilmette Harbor.

Average annual dredging at the harbor for the period 1998-2015 was 12,800 yd^3. This value is consistent with historical volumes. Shabica et al. (2004; citing a personal communication from the former Wilmette Harbor Master, Mr. William Z. Wente) listed longshore transport to be from 10,000 to 15,000 yd^3/year based on late 20th century dredge records.

Sand dredged from Wilmette Harbor is placed offshore of the beach south of the harbor. The barges release the sand in water depths of 8-10 ft (Sabine Herber, Wilmette Harbor Association, personal communication, 12 August 2015). A curved groin near the end of Linden Avenue anchors this narrow beach. The groin was built between 1999 and 2002. Google Earth Pro photographs show that the groin was almost filled in 2002, but a minor fillet at the south side emerged and disappeared over time.

Google Earth photographs show multiple sand bars, indicating active sediment transport. With northeast winds, a sand bar forms across the mouth of the harbor, while southeast winds push sand into the harbor. In the past, approximately 10% of the annual dredging was placed off Gillson Beach, but now all is moved to the south. Depending on winds and water levels, some of the sand moves onto the beach while the rest moves south in littoral transport (Sabine Herber, Wilmette Harbor Association, personal communication, 12 August 2015). The volume is assumed equal to the annual dredging, but the total longshore transport may be greater.

Cell 18, Wilmette Harbor to Northwestern University

This cell is outside of the sediment budget study area. It has been included because it receives sand from Cell 17. Much of the shore is armored without beach, but a small beach exists at the Evanston Water Treatment Plant.

8 Conclusions

Chrzastowski and Trask (1996a) computed a North Illinois sediment budget for the period 1974-1995. This study continues this earlier analysis to cover the 1990s to 2017. This sediment budget also provides a tool for decision-makers along the North Illinois Shore to evaluate littoral processes and make sand management decisions within a regional context. Many of the sediment budget cells developed by Chrzastowski and Trask (1996a) have been retained, but some have been divided into smaller cells for more detailed information. For example, the IBSP has been divided into two cells, the northern one covering the zone of major nearshore erosion, and the southern cell with approximately neutral volume change (Figure 8).

Longshore sediment transport along the north Illinois shore is predominately from north to south. The volume in the system varies greatly. At the Wisconsin-Illinois border, sand input was assumed to be 16,000 yd^3/year based on monitoring work by Chrzastowski (2003). Along the IBSP, the transport rate is approximately 190,000 yd^3/year primarily sourced from beach and lakebed erosion despite nearly annual placement of dredged material from the maintenance of Waukegan Harbor, North Point Marina and inland sources.

At the Waukegan Electric Generating Station, 52,000 yd^3/year are removed from the cooling water canal and placed on land. The sand pile now contains approximately 620,000 yd^3 (Figure 11 and Figure 12). South of the station, approximately 44,200 yd^3/year has accumulated in cell 6 north of the fillet beach while 5,100 yd^3/year has accumulated north of the Waukegan north jetty in the fillet beach (Figure 14). The fillet may have reached capacity, resulting in an increasing amount of sand rounding the north jetty and entering the navigation approach channel.

Some sand has historically bypassed Waukegan and accumulated on the lakebed. Comparison of mid-1970s acoustic and 2012 lidar bathymetry show the lakebed accumulation volume to be approximately 27,300 yd^3/year in the plume (Figure 17). Considering beach growth at the Waukegan fillet, navigation channel dredging, and lakebed accumulation south of Waukegan, littoral transport has reduced to only 11,200 yd^3/year at U.S. Naval Station Great Lakes.

The fillet at U.S. Naval Station Great Lakes has been at capacity for several decades (Chrzastowski and Trask 1996a). Less than 2,000 yd^3/year enter the harbor, based on recent dredging conducted by the U.S. Navy.

Along Lake Bluff, minor retreat of the bluff has supplied limited amount of sand to the littoral budget. Farther south, the bluffs are more fully armored and protected and therefore do not supply sand to the beaches. There may be minor fine grain material coming down ravines and streams, but these volumes are unknown.

Between Forest Park Beach and Wilmette, longshore transport is only approximately 13,100 yd^3/year (Figure 21).

The best available data were used for the computations in this sediment budget. However, some fluxes had to be inferred (i.e., from dredging records) and some were not considered (e.g., aeolian transport, offshore flux). Evaluating inter-annual variability in littoral sediment flux rates was beyond the scope of this study but should be included in refinement of this budget as this is important information for developing regional sand management strategies. Detailed field studies that build out from this sediment budget are needed to validate the flux rates used in this sediment budget as well as generate reasonable estimates for fluxes not included in this study. These studies will help to refine the estimates of littoral transport in this report.

An uncertainty analysis has not been conducted. Removal and placement values are the most reliable data used in this study because they are computed from barge, truck haul, or dredge volumes. Volumes based on bathymetry are less reliable because of uncertainty in the 1970s surveys and the fact that those surveys did not extend as far offshore as the contemporary lidar surveys.

Several topics will require further examination as a result of this study. The sediment input into Illinois from Wisconsin should be measured and then used to update the estimates of littoral transport put forth in this budget. Ultimately, a regional sediment budget for the west shore of Lake Michigan needs to include sediment supply and movement along both the Wisconsin and Illinois shores. The growth of the fillet beach at Waukegan could be re-examined to determine if it has reached capacity and is now promoting sand bypassing Annual beach profile surveys could be used to evaluate if the total sand volume in the fillet is changing or has stabilized, implying that new sand moving in from the north bypasses the beach and continues south into the Waukegan navigation channel. The littoral transport at Wilmette has been inferred based on the dredging history at the harbor; however, the piers open to the southeast, and it is likely that some sand bypasses the harbor mouth and moves south. Sand mass captured in the 2016 Google Earth aerial photographs suggest active sand bypassing; therefore, it is possible that the total sand in littoral transport is greater than the dredge volume of 12,800 yd^3/year. The beaches south of Wilmette Harbor and at the Evanston Water Treatment Plant could be profiled regularly to determine how much sand bypasses Wilmette.

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Appendix A: Data Used for Computing 1970s-2017 Sediment Budget

Table A-1 tabulates the data used in this study to compute the 1970s-2017 sediment budget. The nomenclature is the same used in the USACE SBAS software (used to plot the fluxes and cell volumes in the figures in the body of this report). The SBAS project files will be available for future users, but Table A-1 contains the same data.

Table A-1. Sediment Budget, north Illinois.

Nomenclature
Units: yd^3/year
Source 1 = bluffs, river influx, wind
Sink 1 = wind-blown loss or other
Source or sink 2 = offshore
Source or sink 3 = other (inlet, channel, trap, harbor)
LST1 = right (N) side of cell viewed from offshore
LST2 = left (S) side of cell viewed from offshore
Yellow = coastal cell
Purple = harbor cell

Cell (North-South)	Variable	Budget 1990s-2017	Notes, source
Cell WI-1	Qsource1		
Kenosha to WI border	Qsink1		
(placeholder - no data examined for this region)	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1		
	Qsink-LST1		

	Qsource-LST2		
	Qsink-LST2	16,000	South to Cell 1
	Placement		
	Removal		
	DeltaV		
	Residual	-16,000	

Cell 1	Qsource1		
North Point Marina, built 1987-88	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	16,000	From north
	Qsink-LST1		
	Qsource-LST2		
	Qsink-LST2	20,400	To Cell 2
	Placement	9,400	Sand imported to form feeder beach, Chrzastowski et al. (1996, p. 17).
	Removal	9,600	Annual dredge from David Suthard, 8/21/14
	Removal	0	
	DeltaV	-4,600	Compare 1976-2012 bathy
	Residual	0	

Cell 2	Qsource1		
IL Beach State Park N	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	20,400	From north, Cell 1
	Qsink-LST1		

	Qsource-LST2		
	Qsink-LST2	188,300	To Cell 3
	Placement	9,600	Bypassed from North Point Marina
	Placement	27,000	Backpassed from Waukegan
	Removal		
	DeltaV	-131,300	Compare 1976-2012 bathy
	Residual	0	

Cell 3	Qsource1		
IBSP S unit to Waukegan Electric Generating Station	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3	52,000	To canal, Cell 4
	Qsource-LST1	188,300	From Cell 2
	Qsink-LST1		
	Qsource-LST2	0	
	Qsink-LST2	167,700	To Canal, Cell 4
	Placement		
	Placement	0	Assume no placement from canal dredging
	Removal		
	DeltaV	20,600	Compare 1976-2012 bathy
	Residual	0	

Cell 4	Qsource1		
Waukegan Electric Generating Station	Qsink1		
	Qsource2	52,000	Dredged from canal 1995-2014 (Fred Veenbaas, 2/5/15)
	Qsink2		
	Qsource3	0	
	Qsink3		
	Qsource-LST1		

	Qsink-LST1		
	Qsource-LST2		
	Qsink-LST2		
	Placement		
	Removal	52,000	All placed on sand pile
	DeltaV	0	
	Residual	0	

Cell 5	Qsource1		
Sand pile Waukegan Electric Generating Station (on land)	Qsink1	11,000	Assume wind loss. Needed to balance cell.
	Qsource2		
	Qsink2	10,000	Assume compaction during drying
	Qsource3		
	Qsink3		
	Qsource-LST1		
	Qsink-LST1		
	Qsource-LST2		
	Qsink-LST2		
	Placement	52,000	Annual placement from canal; Fredrick Veenbaas (NRG Energy) (847) 662-6201 or Fredrick.veenbaas@NRGenergy.com
	Removal	0	
	DeltaV	31,000	620,000/20 years
	Residual	0	

Cell 6	Qsource1		
Waukegan Elec. Generating Station to Waukegan Harbor beach fillet	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	115,700	From Cell 5

	Qsink-LST1		
	Qsource-LST2		
	Qsink-LST2	71,500	To Cell 7
	Placement		
	Removal		
	DeltaV	44,200	Compare 1976-2012 bathy
	Residual	0	

Cell 7	Qsource1		
Waukegan Harbor Beach Fillet to Waukegan N. Jetty	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	71,500	From Cell 6
	Qsink-LST1		
	Qsource-LST2		
	Qsink-LST2	66,400	To Cell 8
	Placement		
	Removal		
	DeltaV	5,100	Compare 1976-2012 bathy
	Residual	0	

Cell 8	Qsource1		
Waukegan Harbor	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	66,400	Bypass and dredging total
	Qsink-LST1		

	Qsource-LST2		
	Qsink-LST2	22,600	To sand tongue S of jetties
	Placement		
	Removal	43,800	LRC spreadsheet 1995-2013
	DeltaV	0	
	Residual	0	

Cell 9	Qsource1		
Waukegan to N. Chicago	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	22,600	
	Qsink-LST1		
	Qsource-LST2		
	Qsink-LST2	12,200	To Cell 10
	Placement	16,800	From Waukegan dredging
	Removal		
	DeltaV	27,300	Based on 1975-2012 lakebed volume change sand
	Residual	0	

Cell 10	Qsource1		
Great Lakes, N. fillet	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3	1,700	Based on dredging in harbor
	Qsource-LST1	12,200	From Cell 9
	Qsink-LST1		

	Qsource-LST2		
	Qsink-LST2	12,800	To Cell 11
	Placement		
	Removal		
	DeltaV	-100	Reached capacity (Chrzastowski and Trask [1996], p. 73)
	Residual	0	

Cell 11	Qsource1		
Great Lakes Naval Station Harbor	Qsink1		
	Qsource2	1,700	Minor input from open coast
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1		
	Qsink-LST1		
	Qsource-LST2		
	Qsink-LST2		
	Placement		
	Removal	1,700	2009-2011 Closure Reports NAVFAC, based on 40-year interval
	DeltaV	0	Assume no more accumulation in harbor
	Residual	0	

Cell 12	Qsource1		
Great Lakes to Lake Forest	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	11,200	Assume bypass from N. fillet Cells_11
	Qsink-LST1		

	Qsource-LST2		
	Qsink-LST2	13,000	To Cell 13
	Placement		
	Removal		
	DeltaV	-1,800	Based on 5% sand and 1976-2012 lakebed volume change
	Residual	0	

Cell 13	Qsource1	0	Bluff armored (Chrz. and Trask [1996], p. 73)
Lake Forest (Forest Park Beach)	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	13,000	From Cell 12
	Qsink-LST1		
	Qsource-LST2		
	Qsink-LST2	10,500	To Cell 14
	Placement		
	Removal	2,600	From boat ramp (Mr. Rich Paulson, City of Lake Forest, 2/11/15)
	DeltaV	-100	No significant areas loss/gain
	Residual	0	

Cell 14	Qsource1	0	Negligible retreat (compare lidar to ISGS)
Lake Forest to Winnetka Power Plant, 4,600 ft long	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	10,500	
	Qsink-LST1		

	Qsource-LST2		
	Qsink-LST2	13,100	To Cell 15
	Placement	2,600	From Lake Forest Park boat ramp (Mr. Rich Paulson, City of Lake Forest, 2/11/15)
	Removal		
	DeltaV	0	
	Residual	0	

Cell 15	Qsource1	0	Bluff armored (Chrzastowski and Trask [1996], p. 73)
Winnetka Power Plant to Langdon Park	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	13,100	
	Qsink-LST1		
	Qsource-LST2		
	Qsink-LST2	13,100	To Gillson Park
	Placement		
	Removal		
	DeltaV		
	Residual	0	

Cell 16	Qsource1	0	Bluff armored (Chrzastowski and Trask [1996], p. 73)
Gillson Park	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	13,100	Assume equal to dredge volume
	Qsink-LST1		

	Qsource-LST2		
	Qsink-LST2	13,100	
	Placement		
	Removal		
	DeltaV		
	Residual	0	

Cell 17	Qsource1		
Wilmette Harbor and S. beach	Qsink1		
	Qsource2		
	Qsink2		
	Qsource3		
	Qsink3		
	Qsource-LST1	13,100	
	Qsink-LST1		
	Qsource-LST2		
	Qsink-LST2	13,100	Assume all moves south
	Placement	12,800	Placement offshore of beach to south
	Removal	12,800	1998-2015, Sabine Herber, Executive Director, Wilmette Harbor Association
	DeltaV		
	Residual	0	

Cell 18	Qsource1		No data
Wilmette S. beach to Northwestern University	Qsink1		No data
	Qsource2		No data
	Qsink2		No data
	Qsource3		No data
	Qsink3		No data
	Qsource-LST1	13,100	
	Qsink-LST1		No data

	Qsource-LST2		No data
	Qsink-LST2	13,100	
	Placement		No data
	Removal		No data
	DeltaV		No data
	Residual	13,000	

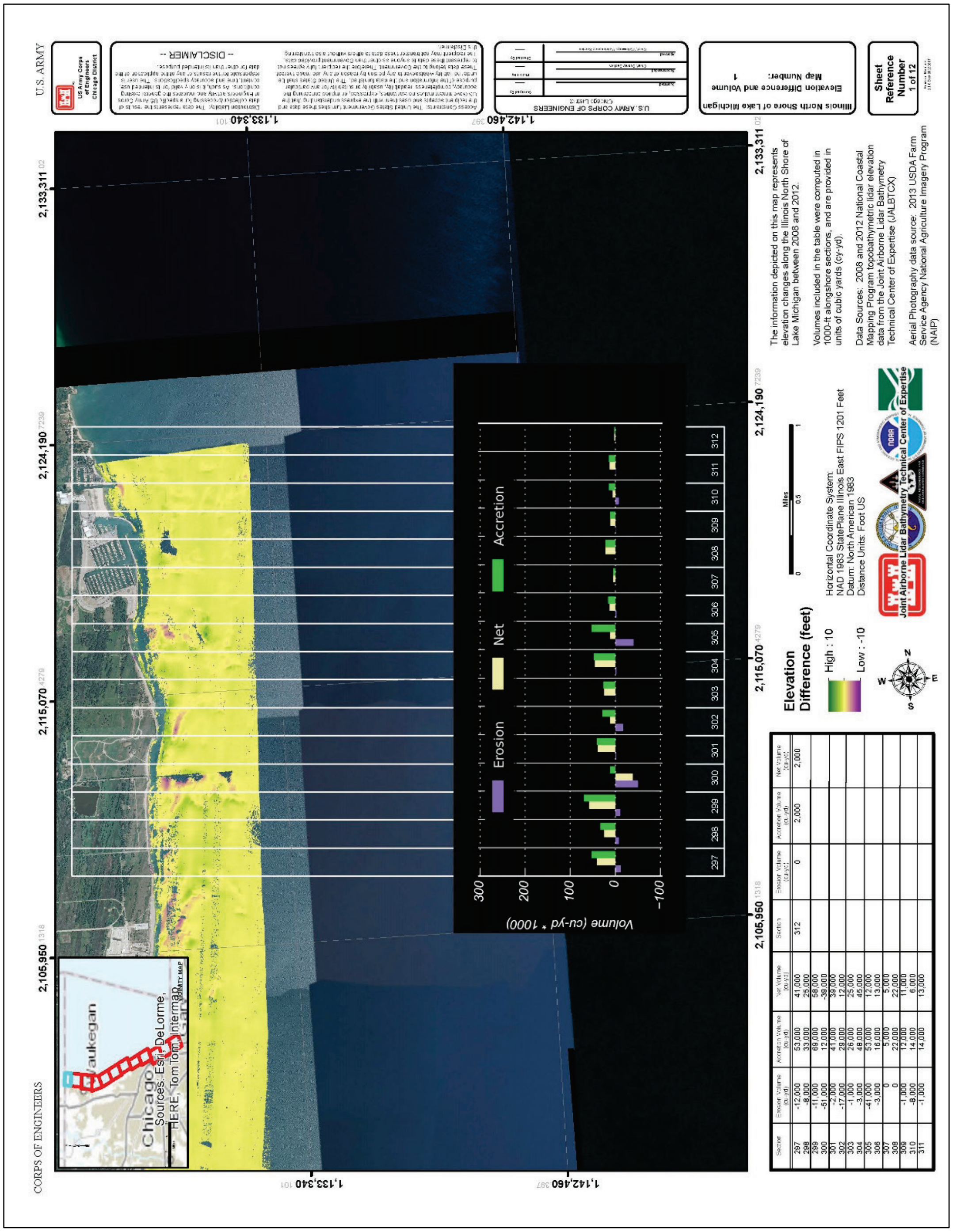
Appendix B: Elevation and Volume Change for Northern Illinois Coastline, 2008-2012

The USACE NCMP surveyed the northern Illinois coastline during the summers of 2008 and 2012. The standard NCMP 1 m grid products were used for the analysis since the grids are generated to ensure cells are snapped and offsets in the cell placement are removed. Both lidar datasets were projected in feet, NAVD88, and horizontal datum of NAD83 Illinois State Plane east zone, FIPS 1201.

An initial elevation difference comparison of the two datasets showed some unrealistic accumulation in the offshore area near Waukegan Harbor. Profiles were extracted from both datasets at a 1,000 ft spacing to determine the mean offset between the profiles. The majority of the profiles had a mean offset of 0.3 ft whereas in the 5-mile stretch near Waukegan Harbor the mean offset was 0.8 ft. To remove the bias as a result of this mean offset, the 2008 bathymetric data in the 5-mile stretch near Waukegan Harbor were shifted by 0.8 ft.

The 2012 and 2008 lidar datasets were differenced to determine elevation change. Bins that were spaced at 1,000 ft were generated to calculate the volume change. The volume change was determined by summing the cells for erosion, accretion, and net volume change. The results from the elevation and volume change comparison are provided in Figure B-1 through Figure B-4. Each map shows the elevation change comparison between the 2012 and 2008 datasets with areas of accretion displayed as green and areas of erosion displayed as purple. The bar chart provides the volume in cubic yards within each of the bins. The table at the bottom of the map provides the numeric value for the respective bin for erosion, accretion, and net volume change.

Figure B-1. Elevation and volume change for box 1 of northern Illinois coastline.



Section	Erosion Volume (cu-yd)	Accretion Volume (cu-yd)	Net Volume (cu-yd)	Section	Erosion Volume (cu-yd)	Accretion Volume (cu-yd)	Net Volume (cu-yd)
297	-12,000	53,000	41,000	312	0	2,000	2,000
298	-8,000	33,000	25,000				
299	-11,000	69,000	58,000				
300	-51,000	12,000	-39,000				
301	-2,000	41,000	39,000				
302	-17,000	29,000	12,000				
303	-1,000	26,000	25,000				
304	-3,000	48,000	45,000				
305	-41,000	53,000	12,000				
306	-3,000	16,000	13,000				
307	0	5,000	5,000				
308	0	22,000	22,000				
309	-1,000	12,000	11,000				
310	-8,000	14,000	6,000				
311	-1,000	14,000	13,000				

Figure B-2. Elevation and volume change for box 2 of northern Illinois coastline.

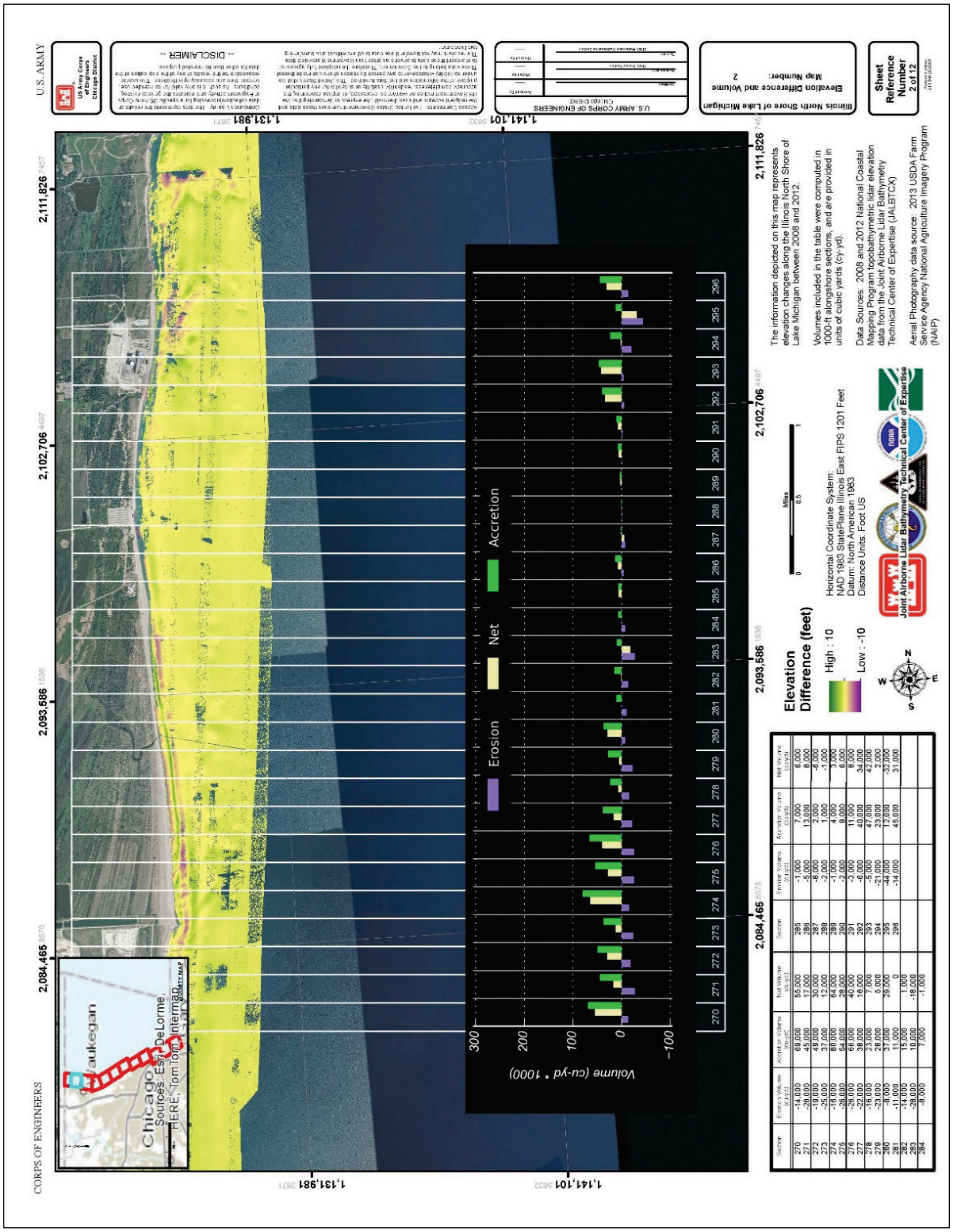


Figure B-3. Elevation and volume change for box 3 of northern Illinois coastline.

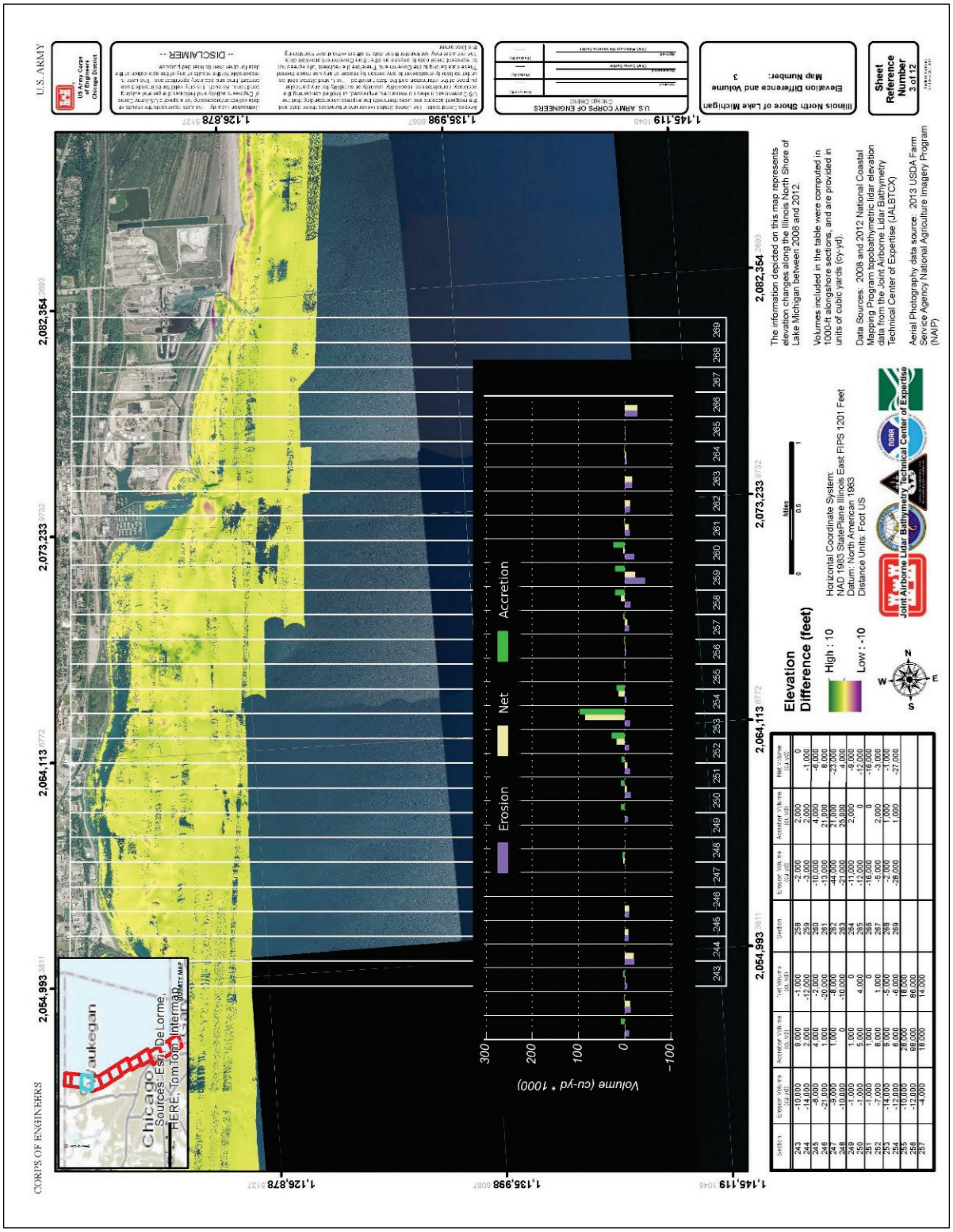
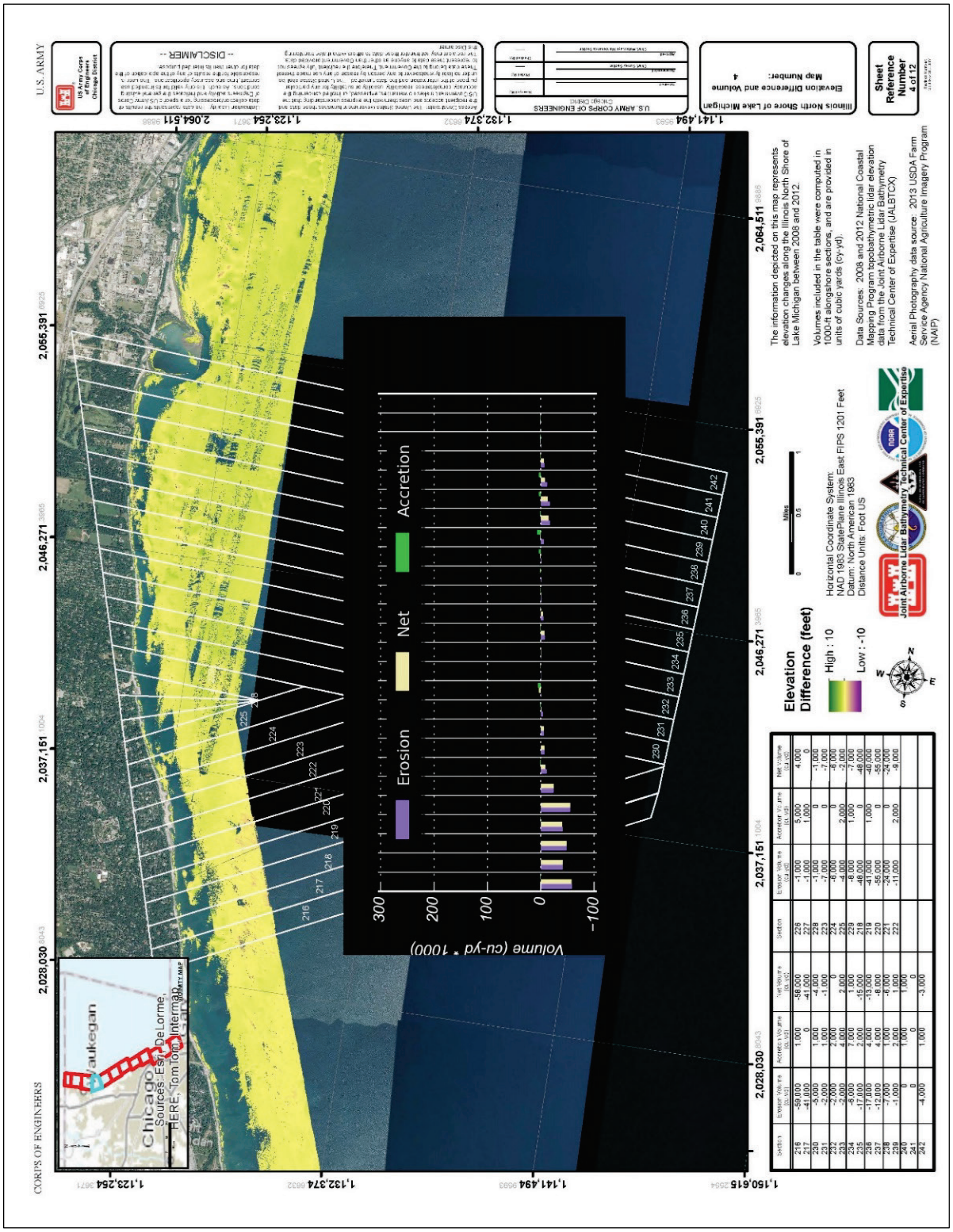


Figure B-4. Elevation and volume change for box 4 of northern Illinois coastline.



Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
miles (U.S. statute)	1,609.347	meters
tons (2,000 pounds mass)	907.1847	kilograms

REPORT DOCUMENTATION PAGE

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6. AUTHOR(S) Andrew Morang, Lauren M. Dunkin, David F. Bucaro, John A. Wethington, Michael J. Chrzastowski, and Ethan J. Theuerkauf		**5d. PROJECT NUMBER**
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14. ABSTRACT

A sediment budget for the North Illinois Shore was developed to evaluate littoral processes and provide a regional sand management decision support tool. This study time frame covers the 1990s to 2017. The North Shore of Illinois is a highly dynamic and diverse coastline with littoral processes complicated by coastal infrastructure, commercial harbors, and uncoordinated shoreline management. Longshore sediment transport along the North Illinois Shore is predominately from north to south, and the volume in the system varies greatly. The best available data were used for the computations in this sediment budget. However, some fluxes had to be inferred (i.e., from dredging records), and some were not considered (i.e., aeolian transport, offshore flux).

15. SUBJECT TERMS

Coast changes, Littoral drift, Michigan, Lake, Coast (Ill.), Michigan, Lake, Coast (Wis.), Sedimentation and deposition, Sediment control, Sediment transport, Shorelines

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