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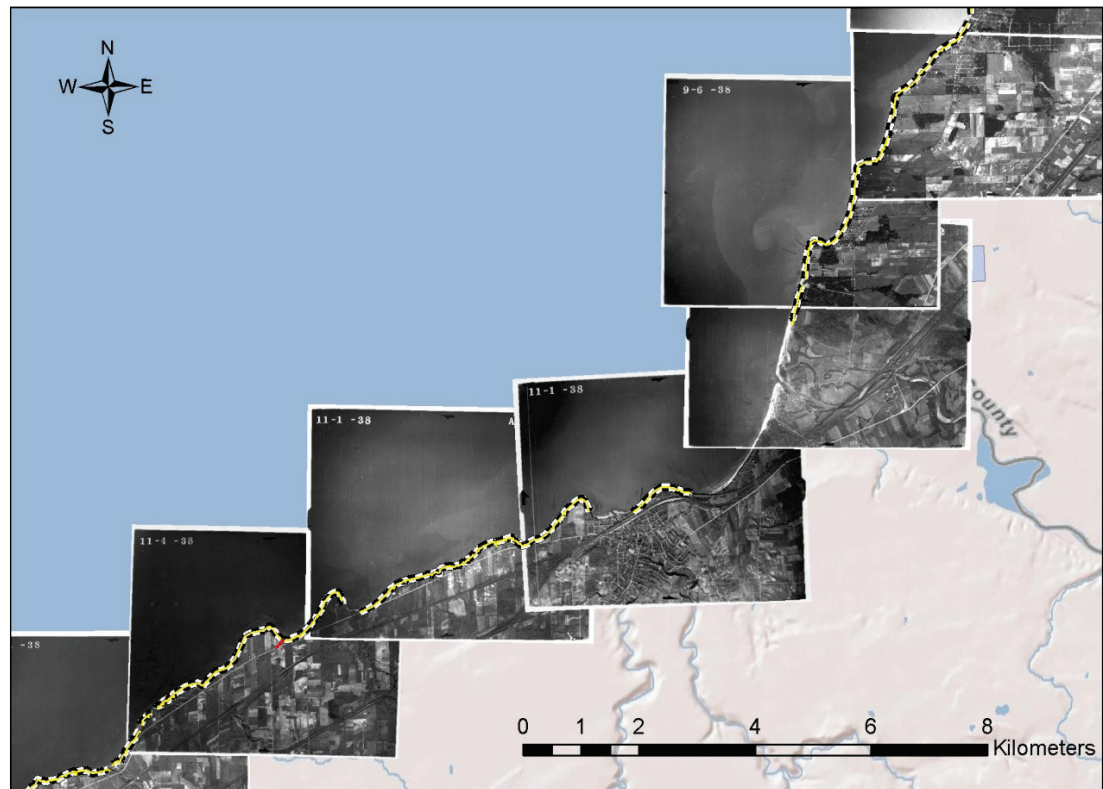
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Regional Sediment Management (RSM) Program

Historical Sediment Budget (1860s to Present) for the United States Shoreline of Lake Erie

Weston Cross, Andrew Morang, Ashley E. Frey,
Michael C. Mohr, Shanon Chader, and Craig M. Forgette

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Historical Sediment Budget (1860s to Present) for the United States Shoreline of Lake Erie

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Abstract

A sediment budget was developed for the U.S. shoreline of Lake Erie from Maumee Bay, OH, to Buffalo, NY, covering four time frames: (a) Pre-Armoring of the shoreline (1860s–1930s), (b) Mid-Century (mid-twentieth century, 1930s–1970s), (c) Recent era (1970s–2000s), and (d) Future expected conditions (2010+). Sources of data included historic U.S. Army Corps of Engineers Lake Survey charts, aerial photographs, and lidar survey data. The Ohio Department of Natural Resources provided historical recession lines for Ohio. The Pennsylvania Department of Conservation, Natural Resources, and the U.S. Geological Survey supplied historical bluff lines for Pennsylvania.

Analysis of harbor sedimentation and sediment bypassing provides verification of the volume of sediment calculated from bluff recession measurements. These volumes were consistent with harbor sedimentation or sediment bypassing measurements at most points along the shoreline, with the exception of underpredicting sediment volumes at Fairport Harbor, OH.

Most reaches show a decrease in bluff-supplied sediment over time. The decrease is a result of greater bluff armoring during the twentieth century, particularly after the 1970s. For New York and eastern Pennsylvania, the future projected sediment supply from bluffs is similar or slightly less than from the recent era. But in Ohio, the future supply is projected to decrease in most areas because of the almost complete armoring of the Ohio shore.

For the predicted future conditions, total eroded bluff volume will range from 15,000 cubic meters per year in Erie County, NY, to 200,000 cubic meters per year in Ashtabula County, OH.

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Preface

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE), Washington, D.C. under the USACE Regional Sediment Management (RSM) Program; Project 454632, “Lake Erie Regional Sediment Management Study” Project. The HQUSACE RSM Program Manager was Linda S. Lillycrop, CEERD-HN-C. Jeffrey A. McKee was the HQUSACE Navigation Business Line Manager overseeing the RSM Program.

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The Commander of ERDC was COL Bryan S. Green, and the Director was Dr. Jeffery P. Holland.

Unit Conversion Factors

| Multiply | By | To Obtain |
|----------------------|------------------------|----------------------|
| cubic meters | 1.308 | cubic yards |
| cubic yards | 0.765 | cubic meters |
| feet | 0.3048 | meters |
| meters | 3.281 | feet |
| meters | 5.396×10^{-4} | miles (nautical) |
| meters | 6.214×10^{-4} | miles (U.S. statute) |
| miles (nautical) | 1852 | meters |
| miles (U.S. statute) | 1609.34 | meters |
| square meters | 3.861×10^{-7} | square miles |
| square miles | 2.59×10^6 | square meters |

Metric units are used in this report except for historical dredging volumes, which are shown in cubic yards, as per common use in dredging records and contractual documents in the United States. Dredging volumes, even when converted to metric, have been reported in the same number of significant digits shown in the original source data. Volumes in the computed sediment budget have been rounded to the nearest 100 cubic meters (m³).

1 Introduction

Background

The U.S. Army Corps of Engineers (USACE) District, Buffalo (hereafter, the Buffalo District), has recently been implementing principles of Regional Sediment Management (RSM) into projects and studies along the southern Lake Erie shoreline. Historically, sediment studies were isolated to individual projects along a limited stretch of shoreline. It is now recognized that sediment management must be addressed on a regional basis because engineering activities or construction that influences sediment processes in one location can have unforeseen consequences tens or hundreds of kilometers (km) away. Managing sediment to benefit a region will reduce costs, allow use of natural processes to solve engineering problems, and improve recreation resources and natural habitat.

Geology and sediment sources¹

General

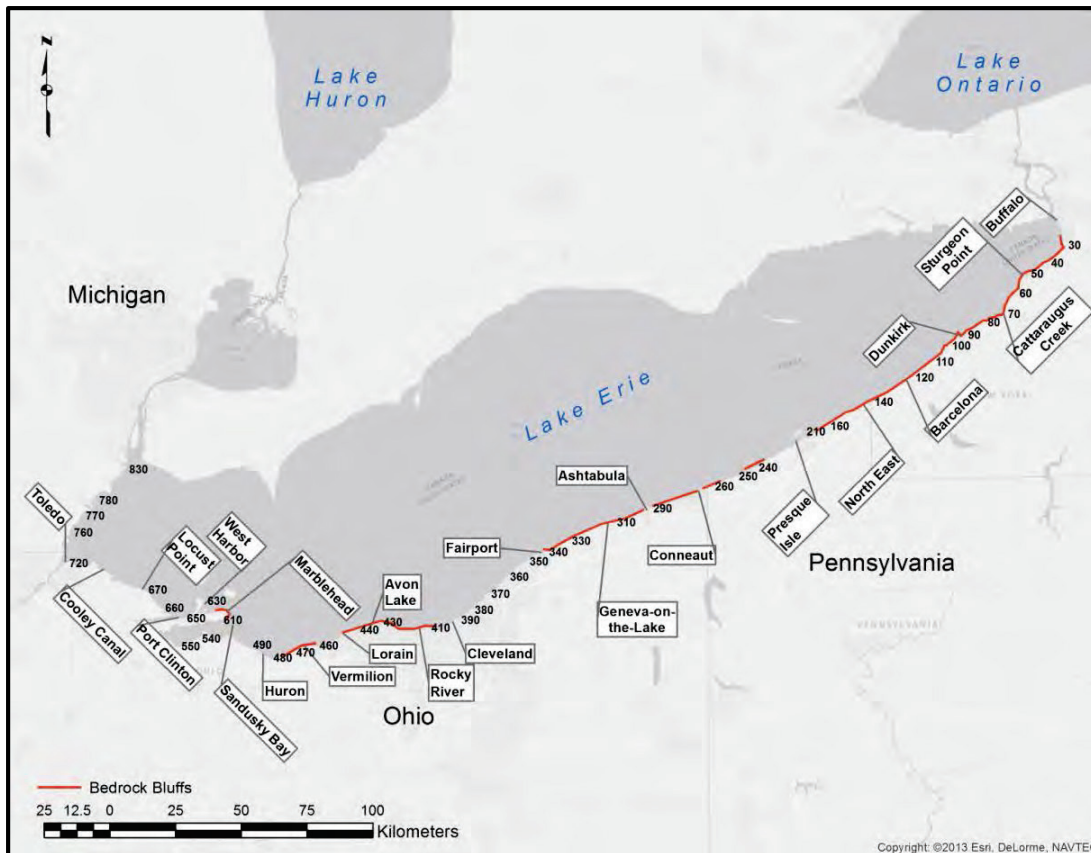
The study area covers the U.S. shoreline of Lake Erie between Maumee Bay, OH, and Buffalo, NY. From Toledo in Lucas County, OH, the shore continues southeast past Sandusky Bay to Huron, OH. East of Huron, the shoreline orientation turns to northeast and continues through Ohio, Pennsylvania, and New York to the city of Buffalo in Erie County, NY, at the northeast end of the lake (Figure 1).

In low-relief areas of western Lake Erie, modern sediments of variable thickness overlie Pleistocene glacial drift (Fuller 1996; Ohio Department of Natural Resources 2007). Beaches are composed of sand, gravel, and shell hash. Some of the beaches are mainland attached whereas others are barriers that enclose marshes. Rock fragments from upland sources are delivered via streams and from erosion of onshore and nearshore deposits. The shell content of beaches increased after the 1987 invasion of the zebra mussel and the more recent invasion of the quagga mussel. In some places, shells compose almost 100% of the beach sediment. Organic material is also often found on beaches. This is exhumed from wetland deposits that are exposed on the lakebed as barrier beaches recede. Dredging of the

¹ Adapted from Morang and Melton (2001) and Morang et al. (2011).

major tributaries during the last century has significantly reduced the volume of sand and gravel provided from upland sources (Guy and Rockaway 2004). Jetty construction, bluff and shore armoring, and other factors discussed later also contributed to reduced sand supply. Sand spits like the Cedar Point Peninsula were once fed by a generous supply of littoral material, but most of these features are now vulnerable to wash-over and inundation and as a result, have been largely armored (Morang and Chader 2005).

Figure 1. Lake Erie study area. Solid line shows shale and limestone bedrock exposures along the lakeshore, in some areas, at the water line. Adapted from Holcombe et al. (2005). Numbers represent 1 km reaches used in this present study.



Most of the Pennsylvania and New York shore of Lake Erie consists of bluffs, usually less than 10 meters (m) high, composed of soft glacial deposits (primarily unconsolidated glacial till and glacio-lacustrine sediments) that overlie shale and siltstone bedrock (Figure 1 and Appendix A) (Geier and Calkin 1983). The elevation of the bedrock/till interface is a predominant factor in shaping and molding the morphology along this part of the lakeshore. Typically, where the interface is above the water level, the lake shoreline reaches to near-vertical bluffs that are devoid of beaches.

Occasional failures occur when large blocks of the bluffs collapse, but for the most part, these exposed bedrock sections resist erosion much more than till bluffs.

In contrast, where the bedrock interface is at or below the water level, the bluffs are composed of much more vulnerable unconsolidated glacial till at the base of which a sand/gravel beach may be present. These beaches are formed from both locally derived sediment and material moved alongshore as littoral drift. The fact that littoral sediment moves from west to east along the Pennsylvania shore over great distances was verified during a coastal processes study conducted at North East Marina, PA, in 2001 (Morang and Melton 2001). At the site, irregularly shaped rubber blocks with characteristic protrusions were lying in the surf zone and on the beach. The rubber came from a landfill at Erie that collapsed, dumping debris into the lake. Within a few years, the rubber blocks had moved east over 30 km.

Geier and Calkin (1983) concluded that the most important single control of erosion rates along unprotected stretches of the New York shore was the composition of the material in the bluffs and the height of the bedrock.

Areas where the bedrock extended 4 m or more above lake level had statistically lower erosion rates than the areas where till bluffs were accessible to storm waves.

Bedrock

In coastal Ohio, the bedrock consists of the Ohio Shale and is above lake level near Avon Lake, in Bay Village, and Lakewood (Stone et al.¹). East of Cleveland the glacially-eroded rock surface is approximately at present lake level and is overlain by the Ashtabula Till.

Along the Pennsylvania shore, exposed bedrock is part of the Devonian Age Canadaway Formation, locally known as the Northeast Shale (Taylor and Buyce 1994). The bluffs contain poorly differentiated sequences of inter-bedded shales, claystones, siltstones, and sandstones (Knuth 2001). Near the town of North East, the bedrock layers dip approximately 5° to

¹ Stone, B. D., R. R. Pavey, J. A. Fuller, and D. S. Foster. Unpublished report. Map of surficial surface materials in the Lake Erie coastal area, northeastern Ohio. U.S. Geological Survey Open-File Report. Denver, CO: U.S. Geological Survey Publications Warehouse.

the southwest and are fractured by irregular joints. Because of the joints, offshore exposures resemble a series of flat terraces with irregular edges. Similar terraces occur near Dunkirk, NY, and farther east (Figure 2).

Bedrock on the beach and in the shallow near-shore can be a source of cobbles and coarse gravel beach sediment. During storms or during ice movement, pieces of shale break off from the edges of the terraces. Joints within the flat units are enlarged over time as they fill with cobbles and boulders that serve as abrasive agents. Aprons of debris eroded from the jagged edges of the terraces are seen at the base of many of the steps. Some of these loose pieces move onto the beach, becoming part of the coarse cobble. Over time, the angular blocks are broken down into smaller and smaller pieces, eventually becoming sand sized. Examination of beach sand near North East Marina using a hand-held magnifier revealed that the sediment has been sorted alongshore. The brown fine-grain sand on the beach west of the marina's west wall was mostly well-rounded quartz with various dark minerals, but the sand at the mouth of Twentymile Creek approximately 1 km east of the marina was grey and much coarser, consisting of approximately 50% shale fragments (Morang and Melton 2001).

Knuth (2001) also documented this process of sediment being supplied from offshore terraces:

Since bedrock is exposed at or near mean water level for both the western and eastern reaches, erosion of the exposed layers by plucking and abrasion adds to the sedimentary load. Large shingles and flagstones make up a substantial portion of some beaches devoid of fine- to coarse-grained sands. As the shingles are reduced in size by milling, the silt and clay fractions are released and dispersed offshore. The smaller shingles are carried by the longshore transport system and make up a portion of the beaches downdrift.

A fundamental question is how long does shale remain on the beach as sand-size or greater fragments? Field tests with blocks of measured and marked shale or shale slakability tests in a geotechnical laboratory will be needed to provide answers.

Figure 2. Shale slabs offshore Dunkirk, NY. Jointing and patterns can be seen through the clear water. Photography 2008.



Till

Pleistocene glacial deposits overlie the Devonian shale and siltstone. These deposits include unconsolidated tills composed of cobble in a matrix of sand, silt, and clay overlain by lacustrine sands (Taylor and Buyce 1994). Often the lower portions of the till contain large stones from the local bedrock, up to 80% by volume (Geier and Calkin 1983). The upper till unit is sometimes thinly stratified and is characterized by stiff to very stiff cohesive clayey silt to silty clay, sometimes also containing traces of fine sand and gravel-shale fragments (Knuth 2001).

The till bluffs vary greatly in composition along the shore as well as within the stratigraphic section and are much more susceptible to wave erosion than the bedrock. Carter (1977) collected 10 till samples from along the Lake Erie shore between Silver Creek, NY, and Marblehead, OH. The coarse fraction of the till ranged from 8% to 40%. Carter (1977) settled on an average coarse fraction of 25%, concluding that this value may be high by approximately 5%.

Conneaut, OH, to Presque Isle, PA. Table 1 lists sand/gravel percentage summarized from various sources.

Table 1. Till composition, Conneaut, OH, to Presque Isle, PA.

| Location | Source | Measured Percent Sand/ Gravel | Sand/Gravel Percent Used for Sediment Budget | Applied to Reaches |
|------------------------------|--------------------------|-------------------------------|--|--------------------|
| Ohio-Pennsylvania border | D'Appalonia ¹ | 24.8 | 25 | 262-263 |
| Girard, PA | Table 4, Carter 1975 | 24 | | |
| PA recession control site 1 | Table 5, Knuth 2001 | 27.5 | 27 | 259-261 |
| PA recession control site 4 | Table 5, Knuth 2001 | 6.8 | 7 | 254-258 |
| PA recession control site 13 | Table 5, Knuth 2001 | 19.3 | 19 | 248-253 |
| PA recession control site 14 | Table 5, Knuth 2001 | 23 | 23 | 226-246 |

¹D'Appalonia Consulting Engineers, Inc. Unpublished report. Geotechnical investigations: Proposed Greenfield site. Pittsburgh, PA: United States Steel Corporation.

Erie to Buffalo. In 1985, the Buffalo District collected samples from the bluffs between Erie and North East, PA, and conducted geotechnical tests to determine the clastic (sand and gravel) content of the till bluffs. Values ranged from 11% to 74%. For samples collected by Geier and Calkin (1983) in New York, sand and gravel content ranged from 0% to 39%. An average of 25% was applied as the till factor through this reach.

Ohio and remainder of New York shoreline. Detailed sieve analysis is not available for the remainder of the shoreline within the study area.

For the purposes of this present study, a coarse fraction of 20% was assumed for areas lacking detailed till sampling data.

Given the high level of variability within the till units eroding into the lake, a detailed analysis measuring the coarse fraction at a higher resolution would provide a greater degree of certainty of the sediment values entering the lake.

Lacustrine layer

Some of the higher bluffs and a low area east of Van Buren Point, NY, are capped with a layer of lacustrine deposits. The unit consists of soft to very stiff finely interbedded clayey silt to silty clay with some silt partings and rare shale fragments (Knuth 2001). Because the soft material is so

vulnerable to waves, homeowners in Van Buren Bay built seawalls or gabions to protect their property. When exposed to waves, much of this material disperses into deeper water, forming sediment plumes (Figure 3).

Beach sand

Layers of beach sands up to 2 m thick overlie some of the higher bluffs in Pennsylvania. Sand blankets the shore-face off Cattaraugus Creek, NY, and near Evans Beach Park, NY, and narrow beaches follow the bluffs in restricted areas throughout the study area. For Pennsylvania beaches, Knuth (2001) reported that the sand/gravel proportion ranged from 90% to 99%. D'Appalonia¹ measured 96% at the Ohio-Pennsylvania border. This present study uses a value of 95% for the sediment budget calculations.

An unknown, and probably greatly variable, amount of sand may be lost offshore as a result of ice rafting. Barnes et al (1993) examined ice transport in Lake Michigan beaches in the early 1990s and concluded that in northern Illinois, quantities entrained may be similar to the amount of sediment supplied by bluff erosion. Conditions along Lake Erie's shore are different in that many bluff areas have bedrock exposure above the water line without a flanking beach. The bedrock will be more resistant to ice than sand beaches. Additionally, shallowness of the lake allows the ice to grow/melt more quickly, and the entire lake may become ice covered. The timing of ice formation and storms further complicate the potential for erosion and transport from the near-shore ice complex. In the sediment budget developed in this project, some cells required an offshore loss factor to balance. Ice rafting may be responsible for some of this offshore loss. This is a mechanism that needs a field study to quantify.

Cedar Point Peninsula

The shale/till bluffs end west of Huron, OH, near the Sawmill Creek Golf Course. From there the Cedar Point Peninsula extends west into the mouth of Sandusky Bay. This sand spit was formerly fed by littoral transport from the east. It was probably a stable or growing geomorphic feature before the mid-1800s when European settlement and industrialization caused profound disruptions to the coastal sediment regime. Construction and urbanization diminished sediment supply as a result of

¹ D'Appalonia Consulting Engineers, Inc. Unpublished report. Geotechnical investigations: Proposed Greenfield site. Pittsburgh, PA: United States Steel Corporation.

- armoring bluffs
- interrupting littoral sediment transport patterns by harbor jetty construction
- trapping sediment at harbor fillets
- depositing material dredged from river mouths into deep water or onto land.

Figure 3. Sediment plume rounding Van Buren Point, NY. The shore along the bay consists of till overlain by lacustrine deposits. Photography: 2004 Chautauqua County 24-inch (in.) Resolution Natural Color Orthoimagery from NYSGIS Clearinghouse.



Morang and Mohr (2007) and Morang et al. (2011) provide a more complete discussion of Lake Erie sediment losses and inputs. The Ohio Department of Natural Resources (ODNR), Office of Lake Survey, conducted many years of research on Ohio counties and lakefront geological processes (Benson 1978; Carter 1976; Carter and Guy 1980, 1983; Carter et al. 1986).

During the late-1800s, the only way to reach the Cedar Point amusement park was by steamboat. To increase business, a 10 km paved road known as Chausee opened in 1914. Originally a sand beach extended along the lake

side of the roadway. Because of steady erosion over the decades, much of the lake side of the roadway has been protected with a rock revetment, effectively fixing the position of the shoreline. The eastern portion of the roadbed along Sheldon Marsh Nature Preserve disappeared as a result of steady beach erosion during the twentieth century (Morang and Chader 2005).

Even if sediment were available, the Cedar Point peninsula is now fixed in position and could not grow to the west. The tip of the peninsula was first stabilized in 1844 when wood cribs were built to fill breaches that threatened the safety of the harbor (U.S. Army Corps of Engineers [USACE] 1941). In 1898, Congress authorized the jetties to be extended as far as necessary to maintain currents across the bar. A dike with several small spurs was built along the west side of the sand spit. The protective structures now consist of over 3 km of rubble-mound stone breakwaters, dikes, and jetties (USACE 2010).

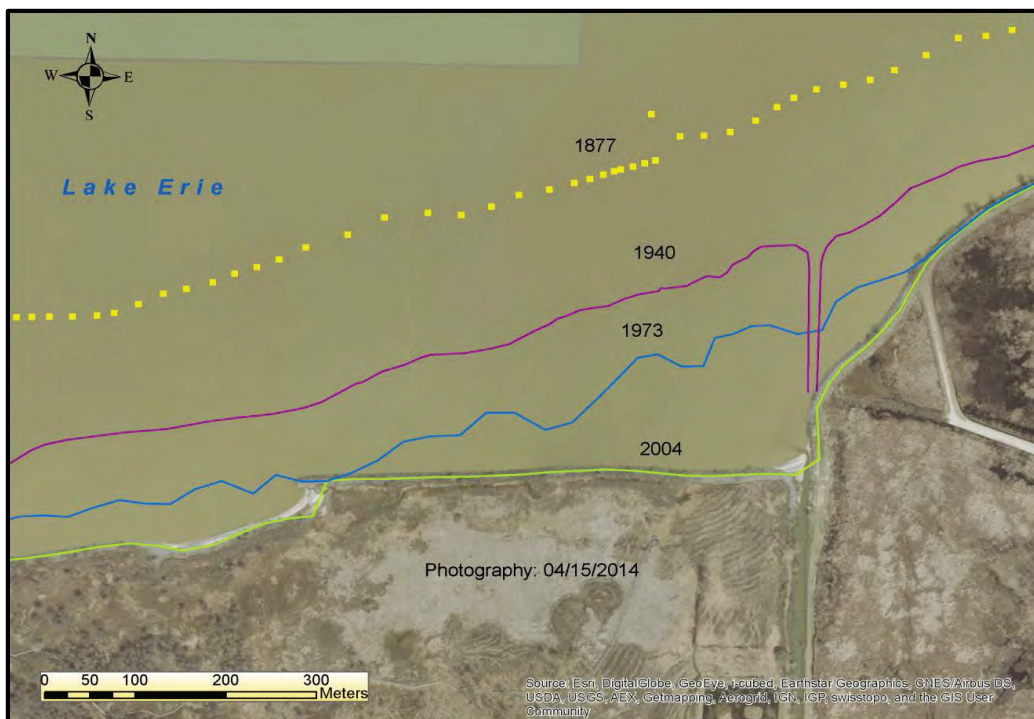
Marshy/lacustrine sediments, West Lake Erie

West of Catawba Island, the Ohio shore becomes low and marshy with occasional sand spits and limited beaches. Most of the terrain consists of Late Wisconsinan lake-wave deposits (ODNR 2007). In northwest Ohio, the relatively soft bedrock was repeatedly scoured by glacial ice flowing southwest from the Erie Basin, which destroyed most of the pre-existing drainage systems and allowed for deposition of thick layers of drift. The upper surface was smoothed away by wave action in the pro-glacial lakes that formed at the margin of the retreating Wisconsinan glaciers (the most recent major advance of the North American ice sheet complex). Thickness of the glacial drift ranges from 15 to 18 m, with less accumulation in Maumee Bay. The underlying bedrock consists of Ordovician fractured shale and Trenton limestone, from which oil is produced in the Toledo Field (ODNR 2007).

Because of the soft and highly erodible glacial drift and lacustrine deposits, the shoreline has suffered severe recession during the twentieth century.

Net littoral transport is to the west. As a response to the erosion, many kilometers of coastline have been armored with dikes and rock revetment (Figure 4).

Figure 4. Shoreline recession in Maumee Bay, OH. Much of the shore is now protected with a levee and rock revetment. Shoreline data from ODNR; photography 15 April 2014 from Esri.



Objective

There are three objectives of this study. First, this sediment budget and analysis of bluff line change and harbor sedimentation are expected to determine sediment movement along the lakeshore and improve planning of shoreline management. Second, the study will lead to better decision making for planning for maintenance dredging and harbor structure projects to reduce sedimentation in Federal channels. Third, the Buffalo District RSM program plans to use this study to provide information to initiate beneficial use of dredged material for ecosystem restoration projects along the Lake Erie shore.

In addition to the main objectives, an important element in implementing RSM along the Lake Erie shore is to develop a sediment budget for the purposes of

- gaining a better understanding of coastal processes in the area
- identifying effects of harbor structures on these processes
- identifying sources and pathways of sediment
- determining if sediment sources have changed over a century due to engineering activities and bluff armoring.

Approach

This report describes the development of a sediment budget for the Lake Erie coast between Maumee Bay, OH, and Buffalo, NY (Figure 1), prepared by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), and the Buffalo District. The sediment budget covered four time frames representing different stages in development along the lakeshore:

- Pre-Armoring of the shoreline (1860s–1930s)
- Mid-Century (mid-twentieth century, 1930s–1970s)
- Recent era (1970s–2000s)
- Future expected conditions (2010+).

Note that although development and shoreline armoring were occurring in the Pre-Armoring time frame, the majority of the lakeshore was in a natural state and is therefore treated as a baseline condition.

The study area did not include

- armored (artificial) lakefront at Buffalo, Erie, Cleveland, and Sandusky
- low shores within Sandusky Bay
- the Ohio islands
- sediment contributions between the Detroit River and Maumee Bay
- sediment contributions or transport west of Toledo.

The general approach to develop the sediment budget and conduct the analyses is described in the subsequent chapters of this report. In order to develop the sediment budget, shoreline and bluff line data were collected from a number of sources (Chapter 2). Data were organized and displayed in Esri ArcMap GIS software. Bluff lines and shorelines were traced in ArcGIS (Chapter 3). The Digital Shoreline Analysis System (DSAS) was used to calculate bluff line and shoreline change rates (Chapter 4). To determine the magnitude of sediment accumulation at each Federal harbor, bathymetric data were analyzed (Chapter 5). The sediment derived from bluffs and beaches was measured and used as input for the sediment budget (Chapter 8). Finally, the sediment budgets (pre-armoring, mid-century, recent era, and future expected conditions) were calculated based on the data and analyses (Chapter 8-11).

2 Data Sources

Existing shoreline/bluff line data

Ohio

The ODNR supplied shoreline/bluff line files generated by the Office of Lake Survey. These included an 1870s line (with earlier and later dates in some areas), along with 1973, 1990, and 2004 lines. The 1990 file was not needed for this present study, and the 2004 file was used as the contemporary condition (versus 2008–2009 in New York). Because a 1930s shoreline was not available for the Ohio shore, a 1937–1938 bluff line was drawn from historical aerial photography (described subsequently).

Pennsylvania

Pennsylvania Sea Grant supplied a 1991 bluff line and shoreline covering the entire Pennsylvania Lake Erie shore, and the U.S. Geological Survey (USGS) supplied 1938, 1998, and 2006 bluff lines (Hapke et al. 2009).

New York

Only limited historical bluff line data are available in digital vector form for New York. The National Oceanic and Atmospheric Administration's (NOAA) Shoreline Data Explorer lists a 2006–2007 shoreline. Based on comparisons with 2008 aerial photography, the 2006–2007 shoreline represents the water-land interface only and does not follow the bluff edge in bluff areas. Therefore, these data were not suitable for this study. No other digital shorelines or bluff lines were identified from any other source.

Historical USACE coastal charts are available from NOAA, Office of Coast Survey, Historical Map, and Chart Project. These files are raster images and must be geo-referenced for use with Geographic Information System (GIS) software. The geo-referencing process is described later in the report.

Aerial photography–contemporary

Ohio

Initially, this project used 2007 imagery from the Ohio Statewide Imagery Program (OSIP). Mosaics for entire counties can be downloaded as single files but the files are large and cover more land area than was needed in this project.

Midway through the project, it proved more efficient to use imagery accessed online from Esri Maps and Data. This Esri imagery consists of satellite data supplied by various commercial and government organizations and covers the entire United States. Ohio coverage was dated September 2009 and was full color with 0.3 m pixel resolution.

Pennsylvania

The Pennsylvania Spatial Data Access (PASDA) is the Commonwealth's official public access geospatial information clearinghouse (<http://www.pasda.psu.edu/>). Individual aerial frames from Erie County can be selected from an online imagery navigator tool. The photography used in this present study was dated 1 March 2006.

New York

The state of New York distributes digital aerial photography from its New York State Geographic Information Systems (NYSGIS) Clearinghouse. To trace recent bluff lines, this study used 1-foot (ft) resolution natural color imagery from April 2008. The aerial photography can be downloaded from the following web pages:

- Chautauqua County: <http://www.nysgis.state.ny.us/gateway/mg/2008/chautauqua/>
- Erie County: <http://www.nysgis.state.ny.us/gateway/mg/2008/erie/>.

Table 2 lists the coordinate system and other details about the 2008 photographs.

Table 2. Lake Erie orthophotography used as a basemap.

| County, State | Date | Resolution | Format | Coordinate system |
|-------------------|-------------|------------|-----------|--|
| Erie, NY | April 2008 | 12 in. | JPEG 2000 | State Plane NY West, NAD 83 |
| Chautauqua, NY | April 2008 | 12 in. | JPEG 2000 | State Plane NY West, NAD 83 |
| Erie, PA | 1 Mar 2006 | 12 in. | MrSid | State Plane PA North, NAD 83 |
| All Ohio counties | Spring 2006 | 12 in. | MrSid | State Plane, OH North, NAD 83 HARN (U.S.feet) |
| | Sep 2009 | 0.3 m | Online | Served online from Esri Maps and Data |

Notes:

1. NAD = North American Datum
2. For future analysis, online data served dynamically via Esri Maps and Data is more convenient than downloading aerial photographs. This also reduces file storage requirements.

Aerial photography–historical

Ohio

For late-1930s coverage, ODNR scanned 12 × 18 in. paper prints from the department’s archives at 300 × 300 dots/in. (dpi) and saved them as TIFF files. Some of these frames were exposure- and contrast-enhanced with Photoshop Elements software to bring out subtle features.

Pennsylvania

Because 1938 digital bluff line data were already available, only a few frames needed to be downloaded and geo-referenced to plot the shoreline near Presque Isle and check the bluff interpretation near the Ohio border. The 1938 frames can be downloaded from Penn Pilot, an online library of historical aerial photography for the Commonwealth of Pennsylvania (<http://www.pennpilot.psu.edu/>).

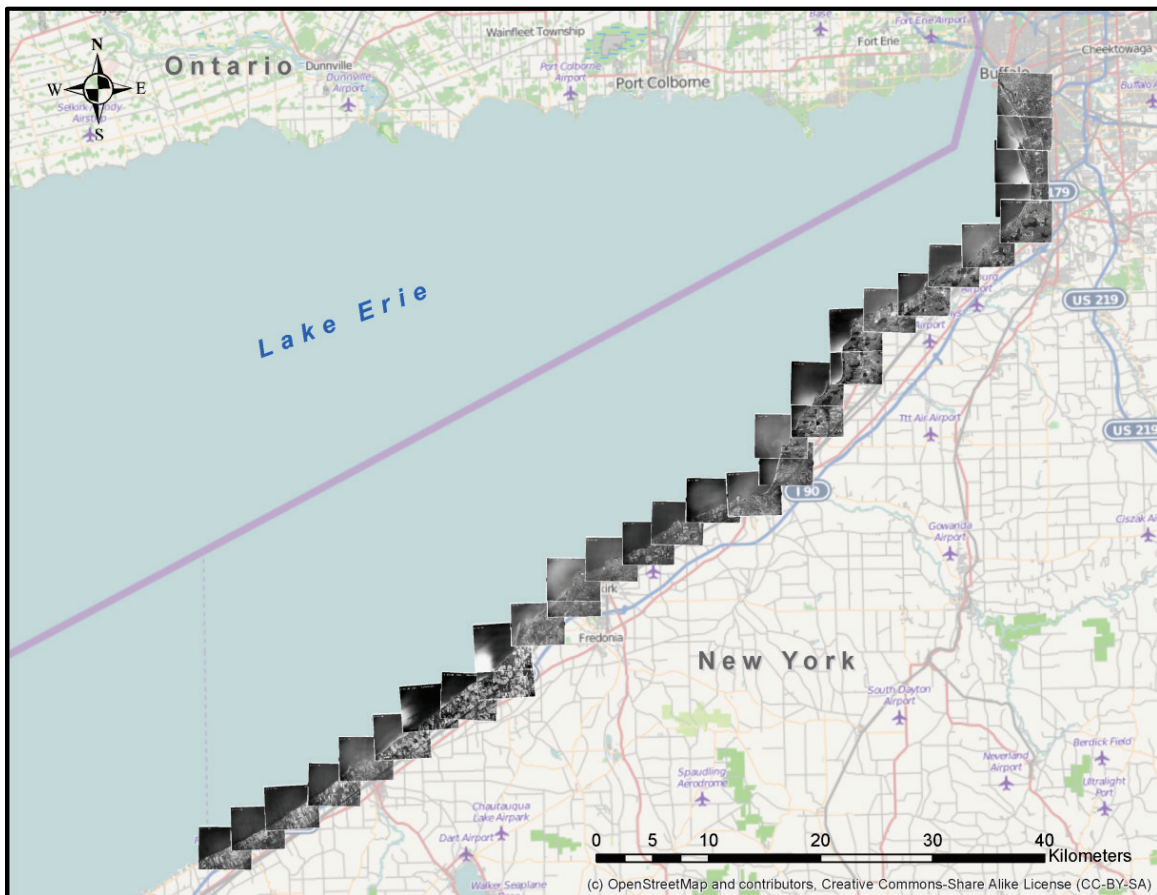
Pennsylvania Department of Conservation and Natural Resources (DCNR) supplied 1978 aerial photography in digital form. These were the same date and scale as the 1978s from New York and Ohio. The DCNR scanned the paper prints at 1,200 × 1,200 dpi and saved them as TIFF files.

New York

The ODNR supplied 1938 aerial photographs for New York State in the form of TIFF digital files (Figure 5). These were scanned from paper prints in the department’s archives. Resolution of these photographs was approximately

1 to 2 m. Many were slightly blurred, possibly as a result of transfer from nitrate film stock to safety film by the National Archives. The original source of these photographs was the U.S. Department of Agriculture (USDA), Agricultural Adjustment Administration. The contractor may have been Continental Aerasurveys, Inc. of New York, NY. The 1930s photography was conducted as part of a pioneering program to improve conservation practices and precisely measure the nation's agricultural lands (Monmonier 2002). These frames were geo-referenced, and the bluff lines traced as per the procedure described in Chapter 4 of this document.

Figure 5. 1938 aerial photography in New York State. Resolution approximately 1 to 2 m. Imagery supplied by ODNR as TIFF files scanned from paper prints.



June 1978 photographs were retrieved from archives at Buffalo District or from Pennsylvania DCNR. These were scanned at $1,200 \times 1,200$ dpi and saved as jpeg files. These were geo-referenced and saved in the GIS project. Resolution was approximately 15 centimeters (cm).

For the westernmost 10 km of New York, the 1978 photographs were missing. A set of faded 1974 frames was used instead. The optical quality

was not as good as the 1978 photographs but was the only alternative from the 1970s for this area. The 1974 files were color enhanced and sharpened in Adobe Photoshop Elements software version 8.

Topography

U.S. Army Corps of Engineers (USACE) coastal charts

As stated previously, 1870s shoreline/bluff lines for New York or Pennsylvania were not available from any Federal or state agency. To plot a bluff line for this time frame, it was first necessary to geo-reference and digitize historical charts published by the Corps of Engineers as part of the “Survey of Northern and Northwestern Lakes.” Buffalo District purchased copies of the 1870s charts from the National Archives and scanned them at 600 dpi to produce raster TIFF files.

Coast Charts Numbers 1, 2, and 3 were digitized for this project, extending from Buffalo to the Ohio-Pennsylvania border (Figure 6). Chart scale was 1:80,000. The charts farther west were not needed because ODNR supplied the Ohio 1870s bluff line.

Figure 6. Final transformation of 1870s Lake Survey Charts Numbers 1, 2, and 3 to UTM Zone 17 coordinate system. Background from Esri Maps and Data.



Contemporary lidar data

The USACE Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) collected topography and bathymetry data along the Lake Erie shore in 2006 using the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system. The NOAA Ocean Service, Coastal Services Center (CSC), distributes these data via an interactive web page. In terrain where tree cover obscured the bluff edge in the aerial photographs, the bare-earth-interpreted data with contour interval of 1 m helped delineate this boundary. This contoured topography was not necessary in pasture or cleared farmland, where the bare earth extended to the bluff edge and the edge was marked by a distinct shadow line.

Bathymetry

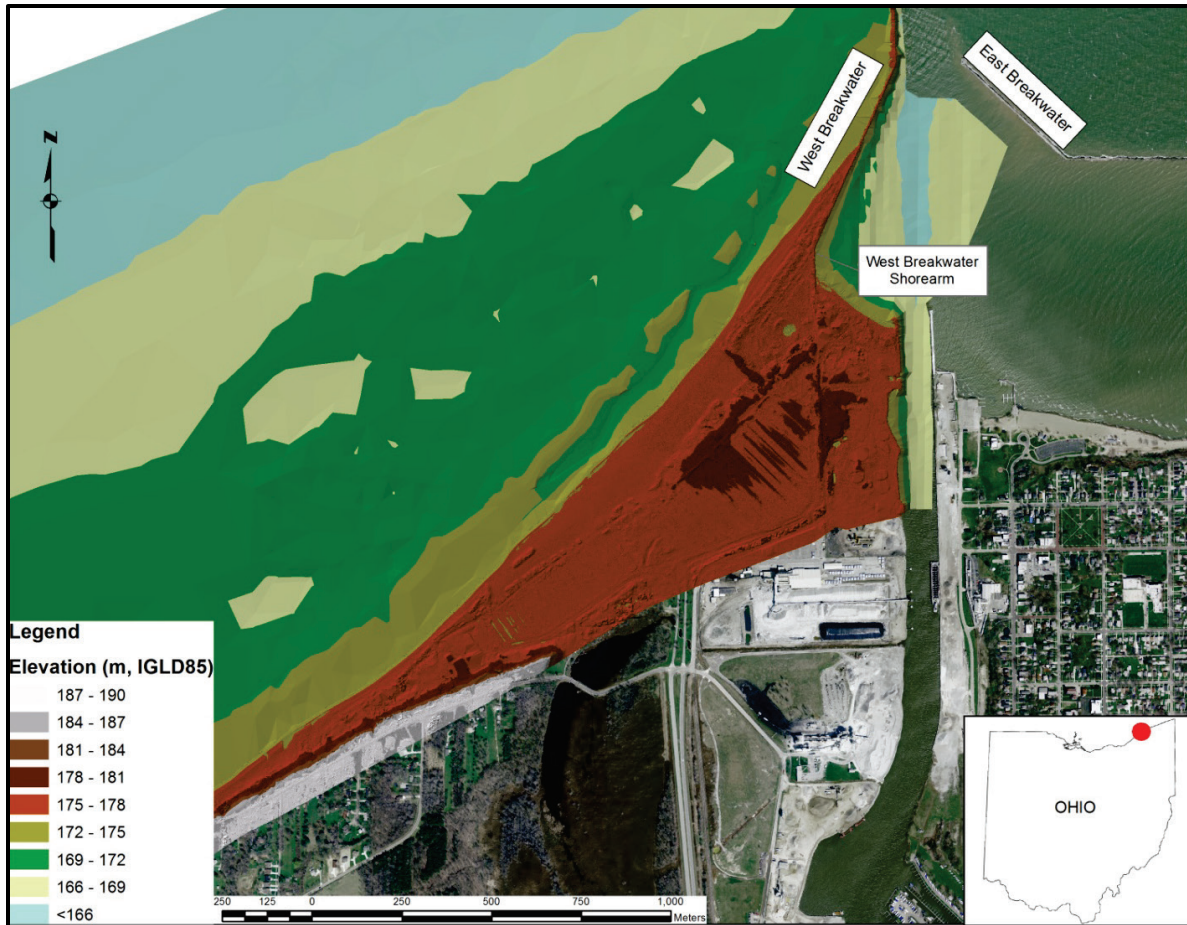
Contemporary lidar data

Lidar data acquired by JALBTCX were used to determine bathymetric conditions at Buffalo District harbors. Lidar was converted into a Triangulated Irregular Network (TIN) at each harbor and used as a modern basis for determining sedimentation (Figure 7). A TIN is a vector-based, three-dimensional (3D) representation of a surface, consisting of a set of irregularly distributed vertices (nodes) of a known elevation connected by a series of edges (break lines) to form a network of nonoverlapping triangles (Esri 2009).

USACE Buffalo District survey charts

Internal USACE survey charts were used extensively to fill data gaps in the lidar data and to determine historic bathymetry. Depending on availability, survey data were acquired digitally (either as an XYZ text file or as a scanned image of a chart) via microfiche or as an original paper chart (Figure 8). Survey charts dating as far back as 1866 were procured for this study. Any data not provided as an XYZ file was digitized and georeferenced as necessary.

Figure 7. 2006 TIN at Fairport Harbor, OH. The TIN combines lidar data with 2006 USACE survey data.



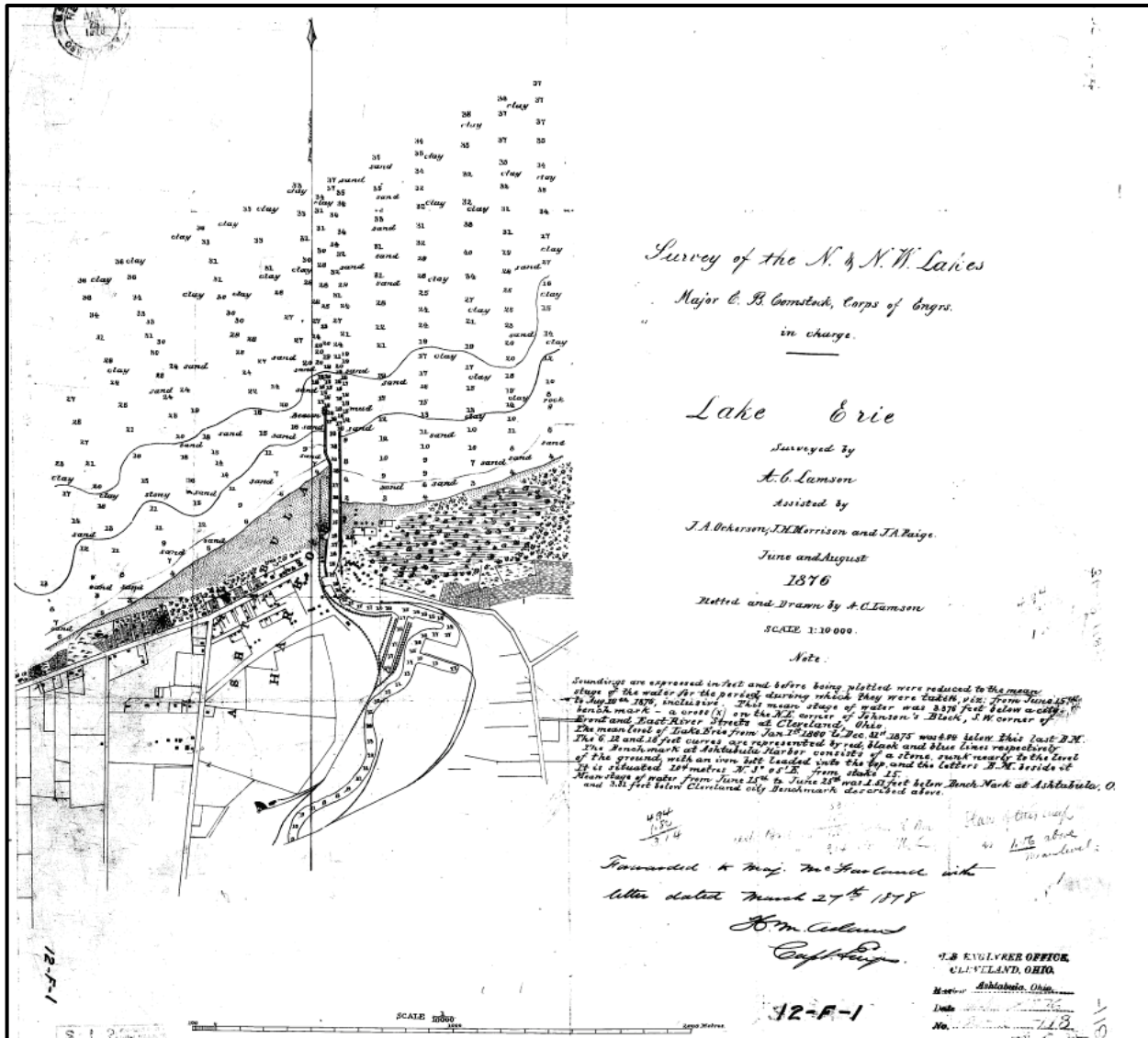
NOAA Great Lakes survey charts

Additional historical bathymetric data were acquired from the NOAA Lake Survey Charts. These charts were used as a secondary source, filling in gaps in the lidar and District surveys. Charts were downloaded as jpeg files, geo-referenced, and digitized.

Data display and software

All spatial and geographic data were organized and displayed in Esri ArcMap GIS software, versions 9.3.1 or 10.1. Data were projected in Universal Transverse Mercator (UTM) Zone 17N, North American Datum 1983 (NAD83), with units in meters. Lake Erie is in Zone 17N, and for multistate analysis, UTM allows data from multiple states to be displayed in the same projection.

Figure 8. 1876 USACE Survey Chart for Ashtabula, OH.



To visualize and develop the budget, the USACE Sediment Budget Analysis System for ArcMap (SBAS-A) software was applied (Dopsovic et al. 2002). SBAS allows modification to the budget as the study proceeds and more analysis is completed.

3 Bluff Line and Lacustrine Shoreline Mapping

Bluff line mapping 1870s—New York State

Chart geo-referencing

Because the 1870s T-sheets were raster image files, it was necessary to transform or geo-reference them onto a modern earth projection. The geo-referencing procedure required the following steps:

1. Import the T-sheet file into the ArcMap project.
2. Approximately fit the raster image to the study area.
3. Register known monuments marked on the chart to the correct latitude and longitude. For Chart No.1, the monuments were Tonawanda, West Base, Buffalo Plains, and Dunkirk Light. The locations in NAD83 coordinates were transcribed from National Geodetic Survey data sheets.
4. Identify man-made features on the raster file such as railroad bridges or street intersections that can also be clearly seen in the 2008 aerial photographs. Use the modern photograph to register the features on the 1880 chart. In some areas, it proved to be challenging to find common points because many roads have been relocated in the past 130 years and many farm fields have reverted to woodland or have been converted to suburbia.
5. Register one or two geographic coordinate positions on the upper regions of Charts Numbers 1, 2, and 3 to prevent the transformation from creating an unrealistic warped map image. The position of the latitude-longitude lines were not fully trusted to register the entire 1880 charts because charts of different vintages had lines scribed in slightly different positions. Nevertheless, using the geographic coordinates in the open water of the charts, even if in the wrong position by a few millimeters (mm), had minimal effect in the study area. The Ohio Geological Survey also did not use the latitude-longitude lines for their shoreline mapping¹.
6. Warp the raster file using the spline transformation. The spline transformation is a true rubber sheeting method and optimizes for local accuracy but not global accuracy. The spline transformation, with its emphasis on local accuracy, produced more realistic results in the vicinity

¹ Donald E. Guy, Jr., Ohio Geological Survey (retired), personal communication, 8 March 2010.

of the bluff and shoreline than the polynomial transformations. Table 3 provides the T-sheet geo-referencing with spline transformation.

Table 3. T-sheet geo-referencing with spline transformation.

| Lake Survey Chart | Date Published | Monuments | Links | Total RMS error |
|--|----------------|--|-------|-----------------|
| No. 1, Buffalo, NY, to Dunkirk, NY | 1880 | Tonawanda, West Base, Buffalo Plains, Dunkirk Lighthouse | 29 | 0.00002 |
| No. 2, Dunkirk, NY, to Vicinity of Erie, PA | 1878 | Dunkirk Lighthouse, VanBuren Point | 38 | 0.0064 |
| No. 3, Erie, PA to Conneaut, OH, and Long Point, Ontario | 1879 | Erie Lighthouse | 40 | 0.00003 |

Paper charts purchased from National Archives, scanned at Buffalo District at 600 dpi, and saved as TIFF files.

It is difficult to estimate geo-referencing error. The width of the line used to mark the shoreline, bluff line, or road-edge line is approximately 10 m on the 1870s charts. Main roads are drawn with width of approximately 25 m while the corresponding actual roads are only 10 m. The error of marking the position of the centerline on the modern aerial photographs was approximately 0.5 m but on the 1880 chart probably 2 to 3 m. Overall, an error of two pen widths or ± 20 m is reasonable for these data. As a comparison, Woods Hole Group and Aubrey Consulting (2004) estimated that line width error representing the shoreline for 1864/1944 maps from Saco Bay, ME, to be ± 12 m (± 40 ft).

Bluff line tracing and accuracy

Once Charts Nos. 1, 2, and 3 were transformed, the shoreline or bluff line was traced manually (on screen) at a scale of approximately 1:5,000.

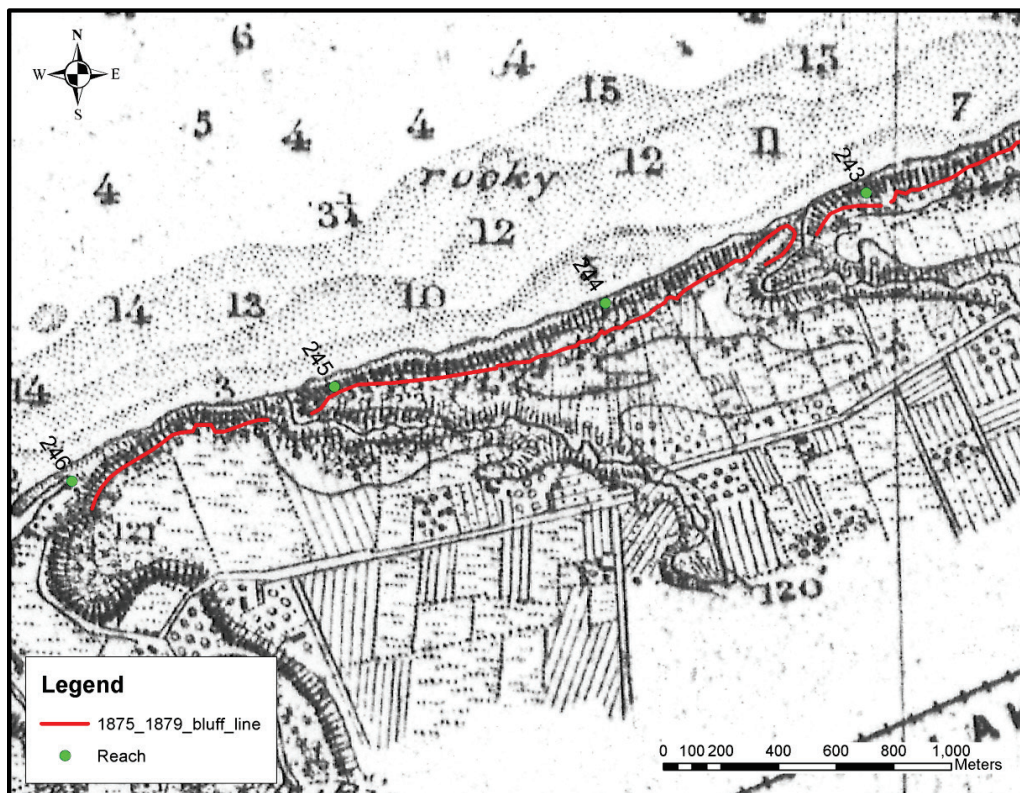
On Chart No.1, the draftsman drew the bluff line as a single distinct line. The width of a printed line was approximately 10 m, so the best possible accuracy here was ± 10 m.

On Chart No. 2, the position of the bluff top was shown as a fuzzy line with cross-hatching. The bluff edge was usually interpreted to be along the center of the cross-hatching after being aided by modern photographs and the 1938 bluff line.

On Chart No. 3, the cross-hatching was less distinct. It is unclear if the original topographers measured a separate shoreline and bluff line or just

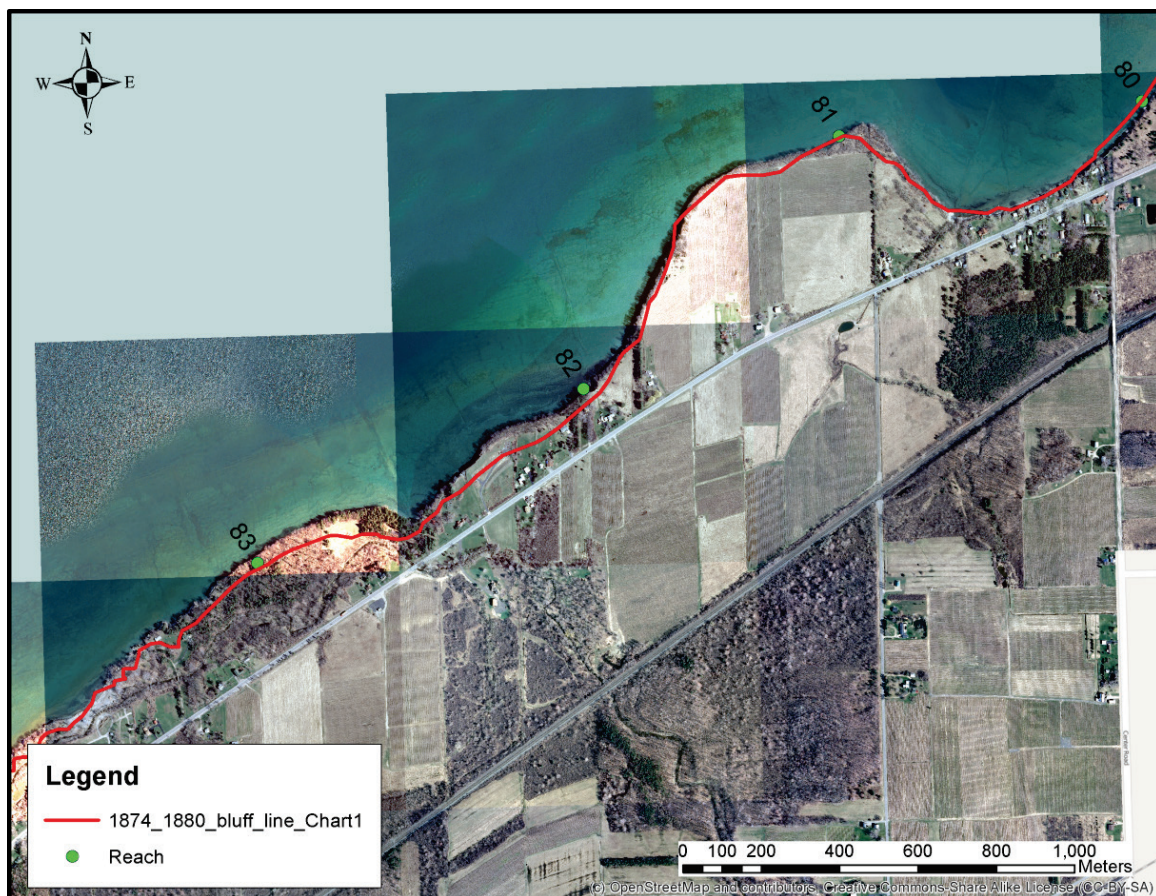
measured the shoreline and drew hatch-lines to show the existence of a sloping bluff. Along much of the shore between the New York state line and Erie, PA, the bluff line was interpreted to be approximately mid-way along this indistinct shore-bluff zone. Accuracy here realistically is ± 20 m. West of Presque Isle, the cross-hatching was wider, and the top of the bluff was interpreted closer to the landward (south) edge of the marks. Figure 9 is an example near Elk Creek in western Pennsylvania.

Figure 9. Example of bluff line interpretation in western Pennsylvania near Elk Creek, Lake Survey Chart No. 3, 1879 publication. Water depths change from feet near the shore to fathoms offshore.



The major source of error in this mapping effort is a result of topographic features that were incorrectly drawn on the 1870s charts. Some of the till headlands on these charts do not project into the lake as far as they do in the 2008 photography. No contemporary geological mechanism can create till bluffs. There was no obvious cause for this error related to tracing the shore or transforming the charts. As an example, Figure 10 shows the 1874 shoreline superimposed on the 2008 photographs just east of Dunkirk, NY. The 1874 bluff line between reaches 81 and 83 is erroneously south of the modern bluff.

Figure 10. 1874 bluff line east of Dunkirk, NY. In this example, the 1874–1880 line is erroneous because it should be lakeward of the bluff in the 2008 photographs.



Bluff line mapping–1930s and 1970s aerial photography

Photograph transformation

The procedure for transforming raster photographs was similar to the procedure used for the 1870s Lake Survey charts. It consisted of identifying common points between the historical photographs and the 2000s aerial photographs (2008 for New York, 2006 for Pennsylvania, 2009–2011 for Ohio). Reference points included sidewalk intersections, monuments, fountains, walkways, some major in-water features like breakwater stones, and some corners of prominent buildings such as schools.

Transformation accuracy was estimated to be ± 10 – 15 m for the 1938 photography and ± 10 m for the 1970s photography. In a similar study of historical aerial photography along the Southern California Bight, Orme et al. (2011) also estimated that accuracies associated with rectification fell within ± 10 m

root-mean-square (RMS). They noted that source errors include photograph distortion, scale, scanning issues, and rectification difficulties.

Bluff line tracing

The bluff edge was interpreted from geo-referenced aerial photographs (1938 for New York and Ohio; 1978 for New York and Pennsylvania). In some areas, 1 m contours based on topographic lidar surveys provided extra verification of the visual interpretation. Three degrees of ground cover were present:

1. Farm or lawn with grass mowed to the bluff edge: Here the interpretation was straightforward.
2. Intermittent tree coverage: The interpretation consisted of identifying the bluff edge at bare ground areas and drawing the line from one bare area to the next.
3. Complete tree coverage: The last sun-lit trees at the crest of the bluff were identified and the line drawn approximately through the middle of these trees. In some areas, subtle changes in gray tone or foliage type marked the bluff edge. Interpretation was aided with lidar-based contours.

Shoreline mapping--Ohio shore west of Catawba Island

West of the Marblehead Peninsula and Catawba Island, the coastal morphology changes to a low lacustrine muddy/sandy terrain. Therefore, for mapping shoreline change, a low shoreline had to be defined in contrast to the bluff edge used along the eastern portion of the lake.

When the Ohio Geological Survey mapped this area in the past, they developed a set of administrative rules to maintain a standard procedure. In all cases, they tried to find a geomorphic mark that represented a semi-permanent feature they could define as *shoreline*¹. The Ohio Geological survey did not adjust for lake level. They considered a geomorphic feature such as a wave-cut scarp, vegetated dune, or a tree line to be a more representative shoreline at the time a photograph was taken. For this present study, the following features were interpreted as a shoreline:

1. Prominent light/dark line where light represented a sand/mud beach while dark was a more permanent feature like vegetation.

¹ Donald Guy, ODNR, Division of Geological Survey (retired), personal communication, 11 July 2012.

2. Tree or vegetation line.
3. Prominent scarp.
4. Man-made feature like a revetment or harbor wall. These were much less common in 1938 compared to the 1970s and later.


Accuracy was estimated to be ± 10 m.

4 Bluff Line and Shoreline Change

Digital Shoreline Analysis System (DSAS)

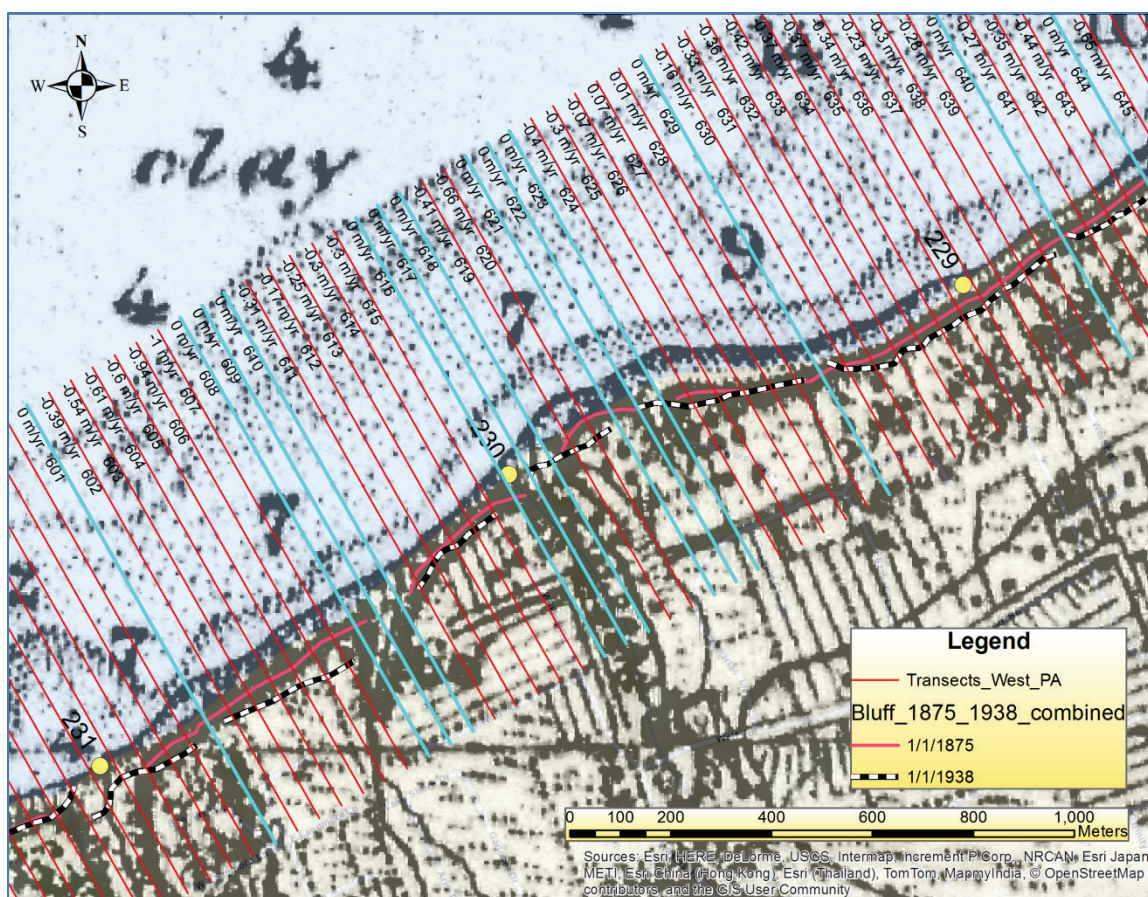
The USGS ArcGIS extension known as the Digital Shoreline Analysis System (DSAS), initially Version 3 and later Version 4, was used to calculate bluff line or shoreline change rates. USGS Open File Reports 2005-1304 and 2008-1278 describe the theory and procedures for DSAS (Thieler et al. 2005, 2009).

Calculating bluff recession statistics requires several steps:

1. Draw a baseline parallel to the shoreline.
2. Select a transect interval. In this present project, a 50 m interval provided 20 transects per 1 km reach. The DSAS program draws transects perpendicular from the baseline.
3. Select pairs of bluff edge shape-files (1878/1879–1938, 1938–1978, 1978–2006/2007).
4. Modify the attribute tables of each shape-file to include a date field with the numeric date in the form of <mm/dd/yyyy>.
5. Select input options for calculations (baseline, transect length, etc.).
6. Generate recession rate for each date pair with the Calculate Statistics button .
7. In the Source menu of the ArcMap project, open the table of rates generated by the calculation procedure. Export the table to an Excel spreadsheet.

Not all transects could be used for shoreline measurements. First, each transect must intersect bluff lines for two dates. Second, transects where the older shape-file was landward of the newer date were rejected. Because there is no contemporary mechanism that can recreate glacial till deposits, till bluffs can only remain stable or recede, and younger bluff lines must be at the same location or landward of older bluff lines. As described earlier, the 1870s maps showed erroneous bluff lines and shorelines in some areas. For these transects, the data were removed (i.e., would not be used in the calculation of average recession in the reach). The averaged recession rate for each 1 km reach was entered in the master calculation spreadsheet. An example of cross-shore transects calculated by DAS software is shown in Figure 11.

Figure 11. Example of cross-shore transects calculated by DSAS software near Reaches 229 and 230 in western Pennsylvania. Red lines show transects that intersect recession lines for 1875 and 1938. Non-intersection returns a result of 0.0 m/year change.



The End Point Rate (EPR) method was used to compute the recession rate (Theiler et al. 2009). Because the differences in recession for the three time segments were being evaluated, the DSAS software was not used to evaluate an overall recession (1870s–2000s) via linear regression or weighted linear regression. This latter method is appropriate to an environment where the study requires one number to categorize shoreline advance or recession over the entire study period.

Ohio bluff lines and shorelines

The ODNR developed cross-shore transects at approximately 30 m intervals (100 ft originally) from which they computed historic shoreline retreat. The original mapping was conducted optically from 1848, 1870s, and later coast charts or T-sheets with transects drawn on Mylar transparencies. These transects were designed to provide a legal basis for various Ohio management uses and in many areas, included calculations

made across harbor fillets and other low terrain. Therefore, for this present project, the ODNR transects were not used; instead, new baselines were drawn, and DSAS was used to compute recession statistics.

5 Sediment Accumulation at Harbors Based on Historic Bathymetric Data

Bathymetric data were acquired at Buffalo District harbors to determine the magnitude of sediment accumulation since the construction of the harbors. Sediment changes have been computed at the following locations.

1. Port Clinton Harbor, OH
2. West Harbor, OH
3. Huron Harbor, OH
4. Fairport, OH
5. Lorain, OH
6. Geneva-on-the-Lake, OH
7. Ashtabula, OH
8. Conneaut, OH
9. Barcelona, NY
10. Dunkirk, NY
11. Cattaraugus Creek, NY

Sediment accumulation within and adjacent to each harbor was computed using a combination of lidar data acquired in 2006 and 2011; aerial images from 1938, 1974, 2006, and 2007; a series of Buffalo District historic drawings ranging from 1866 to 2006; and historic navigation charts retrieved from NOAA (<http://historicalcharts.noaa.gov/>). All elevations were converted to the IGLD85 vertical datum based on the work of Gardner (1875), Lippincott (1985), and USACE (1940). This involved converting data from NAVD88, IGLD55, USLS 1935, NGVD29, USLS 1903, Mean Level of Lake Erie (1860–1875) (Toledo-Conneaut), Mean Lake Level of Lake Erie (1860–1875) (Erie-Buffalo), and Mean Lake Level of Lake Erie (1844–1857).

As the 2006 lidar data were reported in elevation NAVD88, datum conversions were made during this present study for each harbor using NOAA's VDATUM vertical datum transformation software (<http://vdatum.noaa.gov/>). Because elevations were reported on historic charts as soundings from the respective datum, the soundings were imported into ArcGIS and then subtracted from the appropriate converted water datum as listed in Table 4.

Table 4. Base elevations used for datum conversion (based on work by Gardner [1875], Lippincott [1985], and USACE [1940]).

| Datum | LWD IGLD85 (m) |
|---|--------------------------|
| Mean Lake Level, 1844–1857 | 174.19 |
| Mean Lake Level, 1860–1875, Toledo-Conneaut | 174.09 |
| Mean Lake Level, 1860–1875, Erie-Buffalo | 174.12 |
| U.S. Lake Service Low Water Datum of 1903 | 173.58 |
| U.S. Lake Survey, 1935 | 173.5 |
| International Great Lakes Datum, 1955 | 173.5 |
| North American Vertical Datum, 1988 | Varied based on location |

Base bathymetric conditions were determined from the USACE Survey Charts. The charts cover conditions from deep water up to the shoreline and were pulled from preconstruction surveys where available; otherwise, the earliest available survey was used. These data were digitized into ArcGIS and used to create a triangulated irregular TIN. All TIN creation was accomplished with Esri's ArcGIS 3D Analyst software.

Additional TINs were created for the years 1938, 1974, and 2006 to measure sediment deposition/erosion patterns due to the construction of harbor structures (piers and breakwaters). Where harbor structures had been constructed that were likely to cause significant changes to longshore transport (e.g., a shorearm constructed at Ashtabula Harbor, OH, in 1922), an additional TIN was created representing conditions at the time of construction. This allowed for determination of sedimentation rates pre- and post-construction.

Outside of the Federal channels, high-resolution bathymetric data were not available at most harbors for the 1860s, 1930s, and 1970s time frames. These areas, especially on the updrift side of the harbor, were often the sites of the greatest sedimentation. To facilitate TIN creation for these areas, a method of shoreline regression was performed at the largest harbors, utilizing the historic shoreline positioning and the contemporary lidar data. For this process, it was assumed that the basic cross-shore profile at a harbor had remained consistent over time but had shifted in space lakeward as sedimentation occurred. Using historic aerial imagery, the position of the shoreline at previous time-steps (1970s, 1930s, and 1860s) was digitized and normalized to a consistent water level based on the local foreshore slope and water levels at the time of the image (Tides and Currents 2015). A series of transects spaced 50 m apart was set up

over the modern TIN, and an XYZ value was determined at 1 m spacing along these transects (Figure 12). The XY location of each point was then shifted backwards along the transect by an amount equal to the shoreline change, giving a shifted XYZ position. This position was adjusted where necessary based upon the location of the bedrock bluff and the basal elevation of the bedrock underlying the fillet, where known or inferred. These computations were carried out using a program running in Microsoft Excel software. Finally, historic NOAA charts were used to confirm and fill in data.

Figure 12. Shorelines (normalized to LWD +2 ft) and transects at Fairport Harbor, OH.

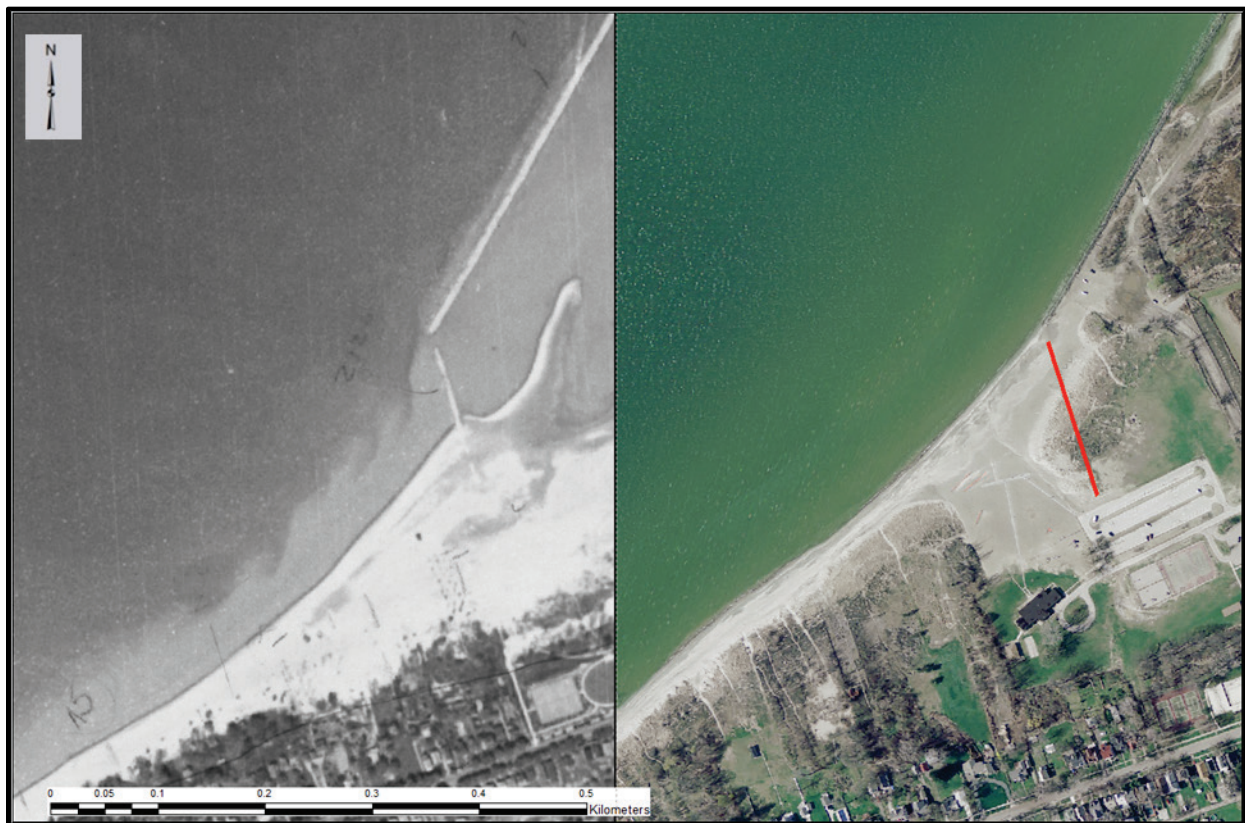


Once the TIN surfaces were created, the ArcGIS TIN Difference tool was utilized to determine volumetric changes between successive time periods. TIN Difference functions in the vector domain by creating a third temporary TIN from the height difference between nodes and breaklines of the two input surfaces. Zero contours in this difference TIN are added as break lines, and triangles are classified as either above, below, or equal to a value of 0.0. The tool then groups contiguous triangles, summing their volumes and writing these volumetric contributions to a polygon feature

class. This polygon feature class thus contains areas where the second (older) TIN is above the first (counted as volume loss), below the first (counted as volume gain), or is coincident with the first (no change). Summing the losses and the gains gives a net volume change between the two surfaces (Esri 2010).

Where necessary, the breakwaters were modeled into 3D surfaces, and the volume of each structure was determined. Determining the breakwater volume was necessary where the breakwater had been partially or fully buried in sediment (Figure 13). These volumes were subtracted from the total volume computations resulting from the TIN difference analysis to ensure that the computed volumes were for sediment deposition only.

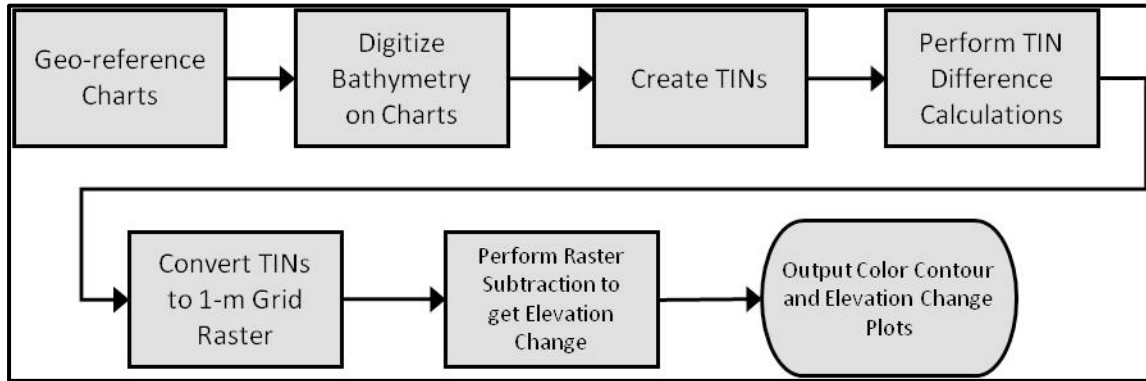
Figure 13. Ashtabula, OH, 1938–2006. Red line in modern image represents location of the now-buried Shorearm Breakwater (constructed 1924).



The TIN Difference tool was run between each of the time periods, giving a complete picture of sediment change patterns at each harbor. By dividing the volumetric change by the total area of analysis, an average elevation change across the project area was determined. Additionally, for visualization purposes, each TIN was converted into a raster image

consisting of 1 m pixels. The older raster was then subtracted from the newer raster, resulting in an elevation change map throughout the project area. Figure 14 shows a simplified flowchart of the computation process.

Figure 14. Simplified computation process.



6 Sediment Budget

Sediment budget littoral cells

A sediment budget is a tallying of sediment gains and losses, or sources and sinks, within a specified control volume (cell) or series of connecting cells over a given time frame. 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. Rosati (2005) provides a more complete description of sediment budget methodology.

The basic sediment budget equation can be expressed as

$$Q_{source} - Q_{sink} - \Delta V + P - R = Residual \quad (1)$$

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 amount of material placed in the cell

R = the amount of material removed from the cell

Residual = the degree to which the cell is balanced.

For a balanced cell, the residual is zero. For a region consisting of many contiguous cells, the budgets for individual cells must balance to achieve a balanced budget for the entire regional system.

Sediment gains and losses that may apply to a Lake Erie budget cell are summarized in Table 5. Aeolian transport now is a lesser factor in the Lakes than along many ocean beaches, although before 1800s development, southern Lake Michigan had extensive dunes.

Table 5. Sediment gains and losses for budget calculation.

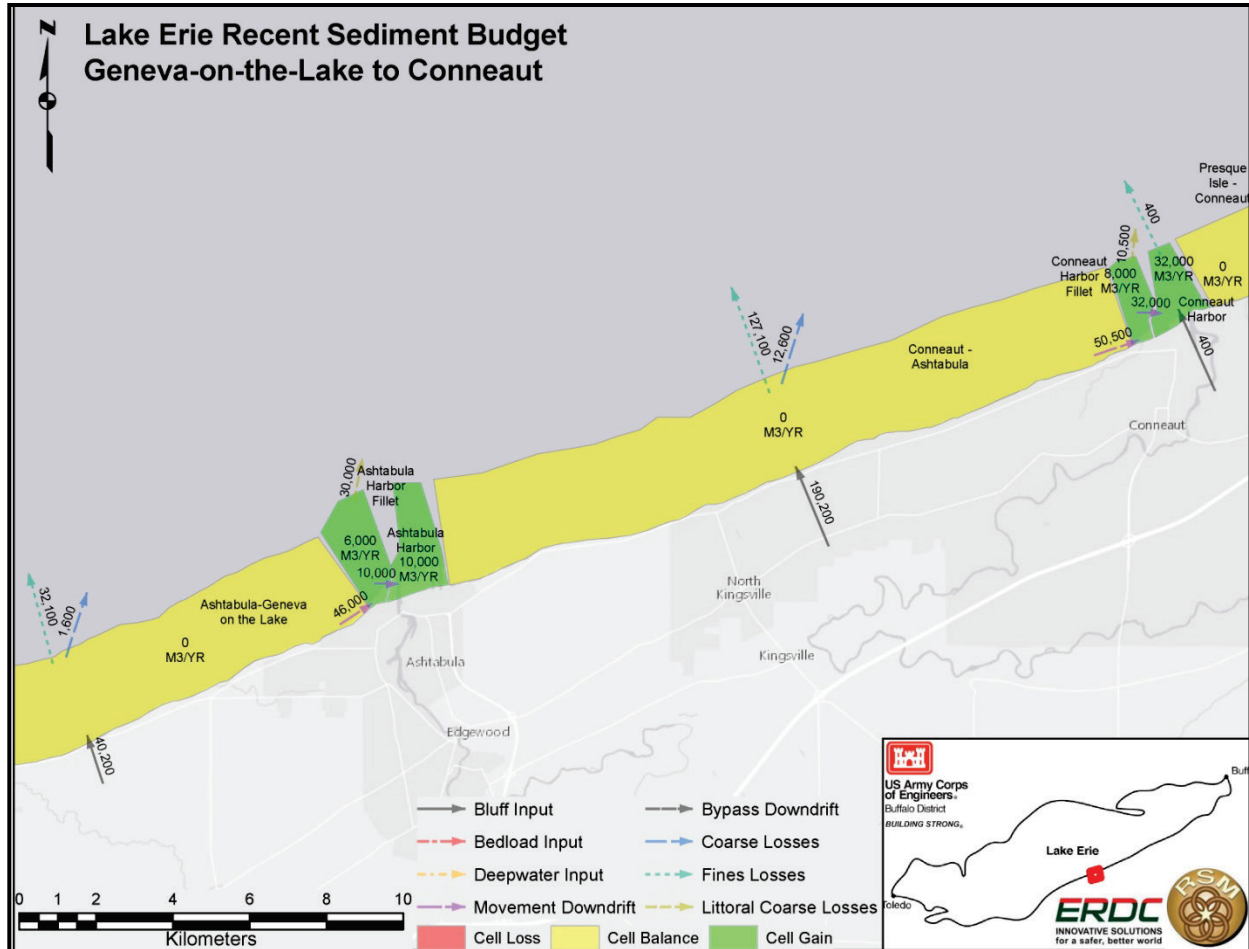
| Gains | Losses |
|----------------------------------|---|
| Longshore transport into cell | Longshore transport out of cell |
| Riverine supply | Offshore transport (to deep water) |
| Bluff erosion | Aeolian transport inland or out to lake |
| Aeolian transport onto the beach | Transport into dredged navigation channels |
| Onshore transport | Beach mining or other anthropogenic causes (unknown volumes historically) |
| Beach nourishment | |
| Dumping of debris | |

For this present study, the primary flux into the system is bluff erosion (ΔV) and includes both the fine (silt and clay) fraction as well as coarse (sand and gravel). Loss of fine grain sediment offshore is a flux out of the cell (shown as arrows pointing out into the lake). Owing to the shorter fetch over which waves can build, shoreline processes are dominated by the higher amplitude, shorter wavelength erosive storm waves. Based on this hydrodynamic setting, the present study assumes an additional loss of 20% of the coarse sediment contribution from the bluff to deep water. This value comes from the sediment budget developed for the Presque Isle Beach Nourishment Project in Erie, PA, in USACE (1984). Artificial sediment movement out of the cell, such as the bypassing at North East Marina, is shown as a flux out of the cell representing a positive number for the term R . Artificial placement, such as at the cell east of North East Marina, is entered as a positive number for the term P .

For most of the Lake Erie shore, cell boundaries are defined by harbor structures, which have functioned as littoral barriers since the early to mid-1800s. Updrift of the largest of these harbors, a substantial fillet has accumulated since construction. For clarity, additional cells are defined to delineate this accumulation (Figure 15). Additional cells were created at known nodal points in the general transport direction as identified by ODNR (2007) (Figure 16).

If a substantial fillet has accumulated on the updrift side of a harbor structure, the modern extent of the fillet defines another cell (for example, the cells just east of the Ashtabula and Conneaut Harbors in Figure 15).

Figure 15. Example of sediment budget between Geneva-on-the-Lake and Conneaut, OH. Littoral cells represent a geomorphic unit of bluff, beach (if existent), and nearshore. Arrows represent fluxes into and out of each cell. Cell symbology is determined by the net change in littoral cell volume. The full SBAS outputs are provided in Appendix B.



Each littoral cell represents a geomorphic unit that includes bluff, beach, and the shallow nearshore zone (representing the active zone, or approximately less than 10 m water depth). The dimension alongshore represents the linear extent of the cell, but the shore-perpendicular width does not represent a specific value or dimension. The depth of the nearshore zone is unspecified, and cells have been drawn with exaggerated cross-shore dimension for display purposes. Table 6 lists the littoral cells needed to represent the southern Lake Erie littoral system.

Figure 16. Sand transport map of Ohio (ODNR 2007).

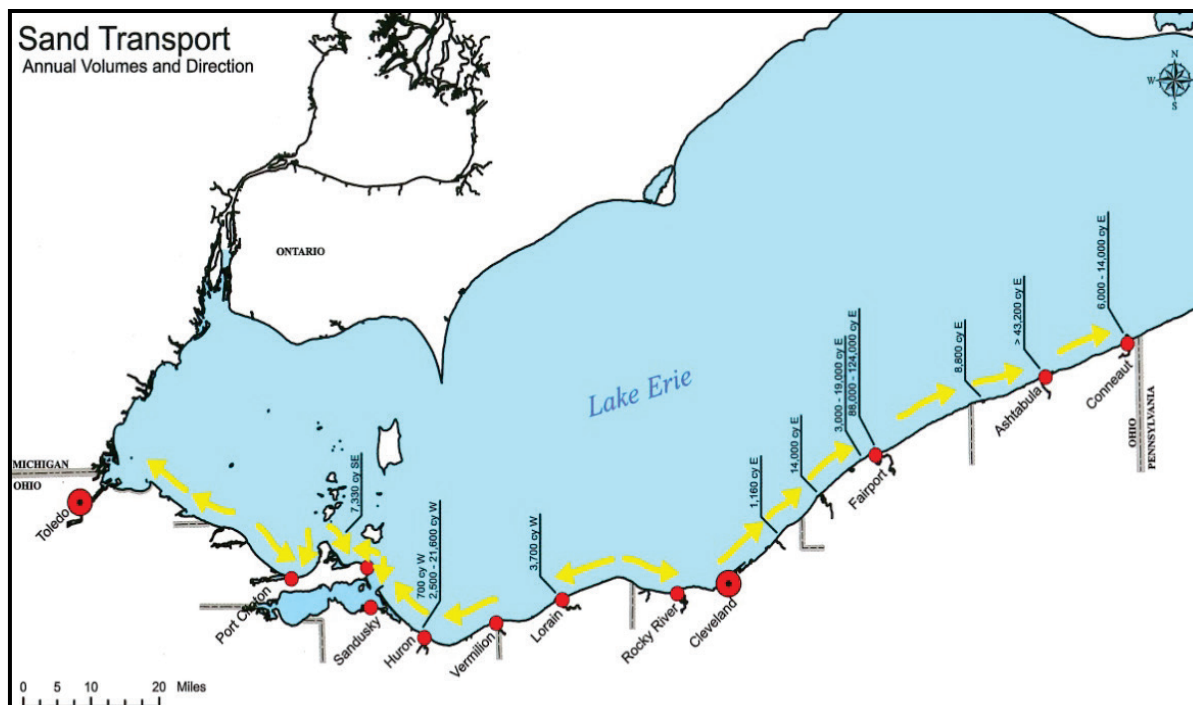


Table 6. Lake Erie littoral cells (listed west to east).

| Cell # | Cell Name | Cell # | Cell Name |
|--------|---|--------|---|
| 1 | Toledo-Cooley Canal | 19 | Lorain Harbor West |
| 2 | Cooley Canal Harbor | 20 | Lorain Harbor East |
| 3 | Cooley Canal-Locust Point Nodal Point | 21 | Lorain-Domonkas Library |
| 4 | Locust Point Nodal Point-Port Clinton | 22 | Domonkas Library |
| 5 | Port Clinton Harbor | 23 | Domonkas Library-Avon Lake |
| 6 | Port Clinton-Catawba Island Nodal Point | 24 | Avon Lake |
| 7 | Catawba Island Nodal Point-West Harbor | 25 | Avon Lake-Avon Lake Nodal Point |
| 8 | White City Park | 26 | Avon Lake Nodal Point-Rocky River |
| 9 | West Harbor-Marblehead Nodal Point | 27 | Rocky River Harbor |
| 10 | Marblehead Nodal Point-Sandusky | 28 | Rocky River-Cleveland |
| 11 | Sandusky-Huron | 29 | Cleveland Harbor Fillet |
| 12 | Huron Harbor | 30 | Cleveland Harbor |
| 13 | Huron-Vermilion | 31 | Cleveland-White City Park |
| 14 | Vermilion Harbor | 32 | White City Park |
| 15 | Vermilion Harbor Fillet | 33 | White City Park-Cleveland Lakefront St Park |
| 16 | Vermilion-Beaver Park Marina | 34 | Cleveland Lakefront St Park |
| 17 | Beaver Park Marina | 35 | Cleveland Lkft St Park-Eastlake PP |
| 18 | Beaver Park Marina-Lorain | 36 | Eastlake Power Plant Fillet |

| Cell # | Cell Name | Cell # | Cell Name |
|--------|------------------------------------|--------|---|
| 37 | East Lake Power Plant | 60 | Shades Beach-Crittenden Point |
| 38 | Eastlake Power Plant-Mentor Harbor | 61 | Crittenden Point-North East Marina |
| 39 | Mentor Harbor Fillet | 62 | North East Marina Fillet |
| 40 | Mentor Harbor-Fairport | 63 | North East Marina |
| 41 | Fairport Harbor Fillet | 64 | North East Marina-Twenty Mile Creek Point |
| 42 | Fairport Harbor | 65 | Twenty Mile Creek Point-Barcelona |
| 43 | Fairport-North Perry | 66 | Barcelona Fillet |
| 44 | North Perry Marina | 67 | Barcelona Harbor |
| 45 | North Perry-Geneva-on-the-Lake | 68 | Barcelona-Van Buren Point |
| 46 | Geneva-on-the-Lake Fillet | 69 | Van Buren Point-Dunkirk |
| 47 | Geneva-on-the-Lake | 70 | Dunkirk Outer Basin |
| 48 | Geneva-on-the-Lake-Ashtabula | 71 | Dunkirk Harbor |
| 49 | Ashtabula Harbor Fillet | 72 | Dunkirk-Fletcher Point |
| 50 | Ashtabula Harbor | 73 | Fletcher Point-Silver Creek |
| 51 | Ashtabula-Conneaut | 74 | Silver Creek |
| 52 | Conneaut Harbor Fillet | 75 | Cattaraugus Fillet |
| 53 | Conneaut Harbor | 76 | Cattaraugus |
| 54 | Conneaut-Presque Isle | 77 | Cattaraugus Scour |
| 55 | Presque Isle | 78 | Cattaraugus Shoal |
| 56 | Gull Point | 79 | Cattaraugus-Sturgeon Point |
| 57 | Erie East Fillet | 80 | Sturgeon Point Fillet |
| 58 | Erie-Shades Beach | 81 | Sturgeon Point |
| 59 | Shades Beach | 82 | Sturgeon Point-Buffalo |

7 Sediment Budget Littoral Fluxes

Flux lines are vector-based representations of sediment movement within SBAS. They must begin or end within a littoral cell, and the direction they are drawn indicates the positive direction of sediment movement. Fluxes that begin in a cell and end outside of any other cells are net sinks from the system, while the reverse shows net gains into the system.

Bluff recession is the primary source of material input into the system. Secondary sources are beach nourishment (at Presque Isle State Park) and riverine bed load. The largest source of riverine sediment within the study area is Cattaraugus Creek, where a flux of 2,700 m³/year (3,500 yd³/year) is modeled, based on USACE (1976). Additional sources of riverine load are likely, but definitive coarse fraction quantities are not available. Bluff recession is annotated within the sediment budget by an arrow directed from onshore into each littoral cell. The bluff recession input volume represents both the coarse and fine fraction of material resulting from erosion. Of this, the fine fraction is presumed to be lost from the system to deep water, represented by the arrow running approximately perpendicular to the cell into deep water. Additionally, 20% of the coarse fraction is assumed lost to deep water beyond the depth of effective sediment transport as a result of short-period storm waves. This volume is represented by an arrow running obliquely from the cells into deep water.

Two additional sediment sinks from the system are modeled. At harbors with a well-developed fillet (Conneaut, Fairport, and Ashtabula, OH), the sediment is moved along the fillet by wave action and eventually diverted into deep water at the lakeward end of the coastal structures. Along the eastern Pennsylvania/New York coast, a series of headlands extend out into the lake. At these headlands, some littoral material is carried around the headland and continues in the system while the remainder is lost to deep water (Figure 3). At each of these headlands, a percentage of material is removed from the system (Table 7). These losses were determined based on the geometry of each of the headlands, and additional study is necessary to refine and verify these values. An example of the sediment budget visualization is shown in Figure 15.

Table 7. Littoral cell sediment losses at headlands (in percent).

| | |
|-------------------------|----|
| Sturgeon Point | 25 |
| Silver Creek | 10 |
| Fletcher Point | 10 |
| Point Gratiot (Dunkirk) | 50 |
| Van Buren Point | 50 |
| Barcelona | 50 |
| Twentymile Creek | 25 |
| Crittendon Point | 50 |

8 Measurement of Sediment Derived from Bluffs and Beaches

Determination of stratigraphy of bluffs

Ohio

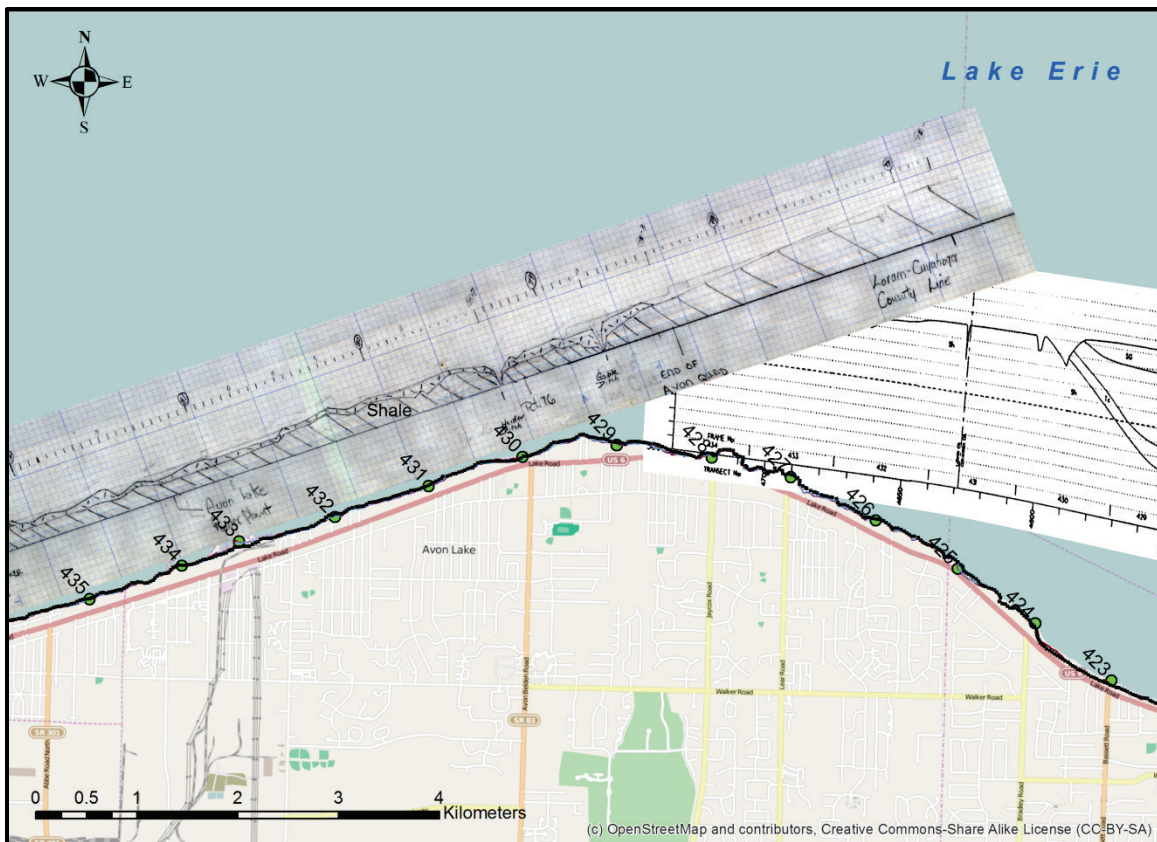
ODNR supplied cross sections of coastal stratigraphy. Some of the cross sections had been published (Pavey et al. 1995; Stone et al. 1995, 1996), while others were unpublished hand-drawn diagrams on cross-section paper. Appendix A reproduces cross sections from Stone et al.¹, covering the Ohio shore from Avon Point to the Pennsylvania border. The cross sections were marked with transect numbers, but these transect numbers are not the same as the contemporary Ohio cross-shore transects, and it was not possible to establish locations using these numbers. Instead, the individual sections were fitted into their appropriate location along the shore within ArcMap, using rivers and prominent geographic features as the boundaries (Figure 17).

Eastern Ohio presented a challenge to determining stratigraphy and recession. From approximately Port Clinton through Toledo, there is little to no bedrock bluff exposed. The sediments in this area consist primarily of highly erodible lacustrine silts and clays deposited by old glacial lakes (ODNR 2007), interspersed with occasional lenses of beach sand.

The shoreline bluff height and composition were generated through a combination of JALBTCX bare earth processed lidar and U.S. Department of Agriculture (USDA) Soil Survey Data (Natural Resources Conservation Service, Soil Survey Geographic (SSURGO) Database), (<http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>). These surveys contain a wide range of soil attributes, including a typical profile and parent material. The soil data are downloadable by county and consists of a polygon shape-file associated with a document containing the relevant symbols and descriptions.

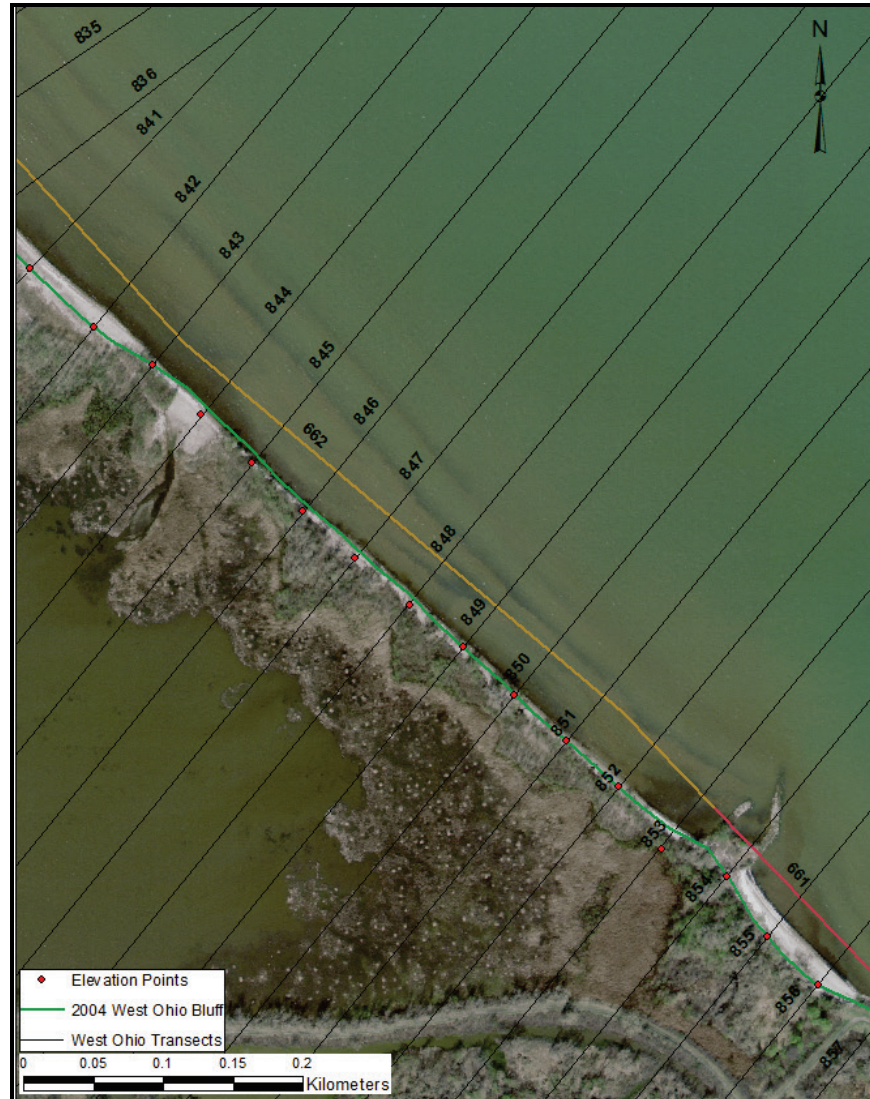
¹ Stone, B. D., R. R. Pavey, J. A. Fuller, and D. S. Foster. Unpublished report. Map of surficial surface materials in the Lake Erie coastal area, northeastern Ohio. U.S. Geological Survey Open-File Report. Denver, CO: U.S. Geological Survey Publications Warehouse.

Figure 17. Example of Ohio bluff stratigraphy cross section fitted to the correct location along the coast, based on towns, creeks, and topographic features.



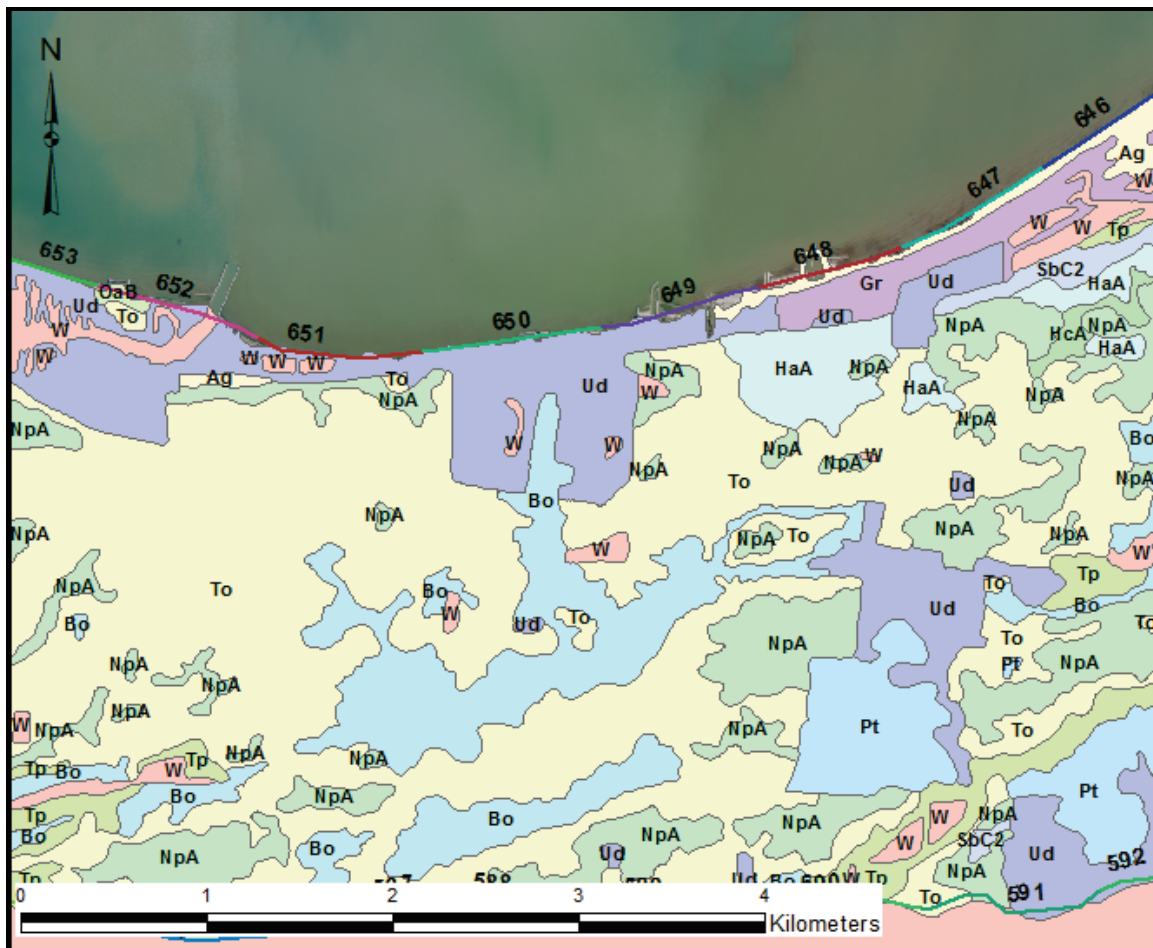
To determine the bluff or recession line feature elevation, the Intersect tool in ArcMap was run to provide a map of the intersection of the most modern bluff line with each of the transects generated by DSAS. These intersection points were then joined to the 1 km reaches to write the appropriate reach for each point to the attribute table. These points were manually adjusted or removed where necessary to a surface that approximately represented the bluff elevation for that transect. Once the points were positioned properly, elevation data were written to the points from the bare earth lidar data using the Add Surface Information tool. Transects within each 1 km reach were then averaged to give an average elevation over the reach. A section of the West Ohio low shoreline is displayed in Figure 18, with transects, the 2004 recession line, and the elevation points representing the bluff elevation superimposed.

Figure 18. West Ohio low shoreline with the associated reach number. Black lines represent shore-normal transects; orange and red lines represent 1 km reaches and reach number; green line represents the 2004 recession line position; and the red points are the adjusted points used to determine recession line elevation.



To define the soil classification, the soil polygon shape-files (Figure 19) for each of the two West Ohio counties were brought into ArcMap, and the dominant soil classification for each 1 km reach was determined. Each 1 km reach was classified either as glacio-lacustrine, till or beach sand, or limestone and was combined with the elevation data to give a bluff height, recession rate, and percentage of coarse material provided to the littoral system.

Figure 19. USDA Soil Classification polygons with 1 km reaches. Each polygon has a 2- to 4-digit classification code indicating the dominant soil type.



Pennsylvania

No stratigraphic cross sections were available for the Pennsylvania shore. Therefore, the stratigraphy has been based on reports by Knuth (2001) and Carter (1977), aerial photography, and personal observations.

In a report prepared for the Great Lakes Commission on the Pennsylvania shore, Kunth (2001) calculated the amount of sediment supplied from bluff erosion in 14 segments using stratigraphy, sediment characteristics, and late twentieth century recession rates. The recession values were calculated at the State of Pennsylvania's recession control points, located at approximately 1 km intervals along the coast, and covered the period 1982–1998. These control points are not at the same locations as the 1 km reaches used in this present study.

Table 8 compares sediment input calculated by Knuth (2001) and Carter (1977) with the results of this present study for the 1874–1938 period.

Table 8. Comparison of bluff sediment volumes along the Pennsylvania shore.

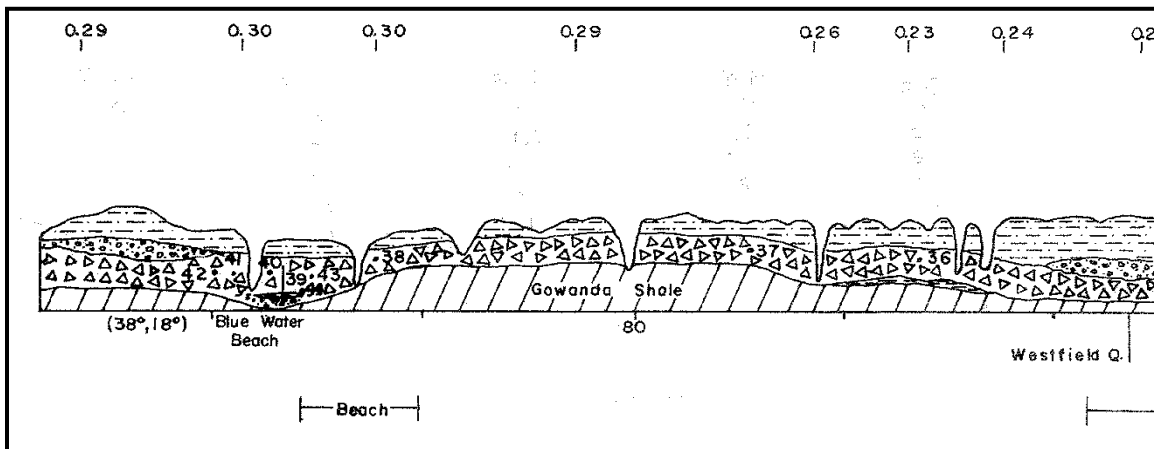
| | Knuth (2001) Table 6 1982–1988 | Carter (1977) 1870s–1970s | This Present Study, 1874–1938 |
|------------------------------------|-----------------------------------|------------------------------|----------------------------------|
| Conneaut to Presque Isle | | | |
| Sand/gravel (m ³ /year) | 58,640 | 29,600 | 38,280 |
| Silt/clay (m ³ /year) | 148,650 | | 181,075 |
| Erie to PA/NY border | | | |
| Sand/gravel (m ³ /year) | 26,510 | 58,860 | 75,075 |
| Silt/clay (m ³ /year) | 85,410 | | 219,620 |

From Erie, PA, to the Pennsylvania/New York border, this present study calculated almost four times the volume of coarse sediment that Knuth (2001) reported. The main reason for the increase is the recession rate for the 1874–1938 period used in this study was two to four times the rate Knuth used in his calculations.

New York

Geier and Calkin (1983) published a detailed bluff stratigraphy for the New York coast, which is reproduced in Appendix A. This stratigraphy was plotted on 35 × 42 in. paper, and the location of each 1 km reach along the shoreline was determined using creeks and other prominent geomorphic features (Figure 20). In ArcMap, distances were measured with the measurement tool. Then the same distances were scaled on the paper plot using a Gerber Variable Scale.

Figure 20. Example of Geier and Calkin (1983) stratigraphy plot.



Computation of bluff volumes

The procedure to calculate bluff sediment supply included the following steps:

1. Reaches of 1 km in length developed by Stewart (1999) as a recession rate database for Buffalo District serve as the framework for calculating recession data in this study. These reaches are available in digital form with node locations in latitude-longitude coordinates (NAD83).
2. Using the USACE Corpscon software, convert nodes to UTM Zone 17 coordinates.
3. Import the table into Esri ArcMap software and plot the reach points.
4. Using the Buffer tool in ArcMap, create a 1 km buffer around each reach point.
5. Using the Dissolve tool in ArcMap, remove overlap from cells.
6. From aerial imagery, coarsely trace the approximate bluff/recession line of the lake.
7. Using the Overlay and Split tools, match the traced recession line with the 1 km reaches and split the shoreline into individual reaches. From this, measure an effective length exposed to erosion.
8. Based on the various sources of geomorphic data cited, measure the thickness of strata at each location: shale, till, lacustrine/silt, sand, and limestone.
9. Enter the strata thickness measurements into an Excel data table.
10. Enter a sediment factor representing the proportion of the bluff material that becomes littoral sediment. These factors were approximations and could be refined in the future based on laboratory or field tests of bluff materials.
 - a. Shale: Varies from 0.3 to 0.5
 - b. Till: Varies
 - i. 0.2 (Toledo-Conneaut)
 - ii. Variable depending on measurements from Knuth (2001) (Conneaut-Presque Isle)
 - iii. 0.25 (Presque Isle-Buffalo)
 - c. Lacustrine silts and clays: 0.1
 - d. Sand and gravel: 0.95
 - e. Limestone: 0.0

11. Overlay transects computed by DSAS with the 1 km reach lines to determine in which 1 km reach each transect falls.
12. For each 1 km reach, average the recession rate from the appropriate transects.
13. To determine predicted future sediment volumes, draw polylines representing areas where the shoreline has been armored. This is determined from high-resolution aerial imagery and oblique imagery acquired by the USACE (<http://greatlakes.usace.army.mil/>). These data are exportable as a .csv file, which is then pulled into ArcMap and set up with hyperlinking to ease overlay and viewing of imagery. Overlay the hardened shoreline polylines with the cross-shore transects. For each transect that intersects a hardened shoreline, set the future recession rate to zero.
14. Estimate the contribution of each strata for each reach using the Volume Contribution Formula, Equation 2:

$$\text{Sed-vol} = \text{Strata_ht} \times \text{Factor} \times \text{Recession_rate} \times \text{Effective_reach_length} \quad (2)$$

15. Overlay the 1 km transects with the littoral cells to determine sediment inputs to each cell. Where a 1 km reach falls into two or more littoral cells, determine the percentage of the reach that falls within each and apply the appropriate ratio of material to each cell.
16. Sum up the littoral volumes for each littoral cell.

Patsch and Griggs (2006) described a similar procedure to calculate sediment volumes supplied by bluffs along the Pacific coast of California. As they pointed out, bluff calculations have a high degree of uncertainty because of the high spatial variability of sediment content and episodic nature of cliff or bluff failure.

The predicted Future sediment budget is based on the bluff recession rates from the Recent time frame, but volumes are adjusted to reflect the lengths of shoreline that are now armored (these are treated as zero sediment input). It also incorporates bypassing at harbors based on dredging data.

Computed sediment volumes

Tables 9 and 10 list the sediment volumes per reach of the Lake Erie shoreline for Pre-Armoring and Mid-Century time frames and Recent and Future time frames, respectively.

Table 9. Bluff recession volumes for the Pre-Armoring (1860s to 1930s) and Mid-Century (1930s to 1970s) time frames (all units in cubic meters/year).

| Reach | Pre-Armoring Total Bluff Volume | Pre-Armoring Total Coarse Volume | Pre-Armoring Total Fine Volume | Pre-Armoring Coarse Loss to deep | Pre-Armoring Coarse Continue to Littoral System | Mid-Century Total Bluff Volume | Mid-Century Coarse Bluff Volume | Mid-Century Fine Bluff Volume | Mid-Century Coarse Loss to deep | Mid-Century Coarse Continue to Littoral System |
|---|---------------------------------|----------------------------------|--------------------------------|----------------------------------|---|--------------------------------|---------------------------------|-------------------------------|---------------------------------|--|
| Toledo-Cooley Canal | 68900 | 6900 | 62000 | 1400 | 5500 | 58800 | 5900 | 52900 | 1200 | 4700 |
| Cooley Canal Harbor | 1600 | 100 | 1500 | 100 | 0 | 3500 | 400 | 3100 | 100 | 300 |
| Cooley Canal-Locust Point Nodal Point | 39900 | 4000 | 35900 | 800 | 3200 | 25600 | 2500 | 23100 | 500 | 2000 |
| Locust Point Nodal Point-Port Clinton | 33100 | 3300 | 29800 | 700 | 2600 | 19600 | 2000 | 17600 | 400 | 1600 |
| Port Clinton Harbor | 0 | 0 | 0 | 0 | 0 | 3200 | 300 | 2900 | 100 | 200 |
| Port Clinton-Catawba Island Nodal Point | 5400 | 800 | 4600 | 200 | 600 | 17100 | 2100 | 15000 | 400 | 1700 |
| Catawba Island Nodal Point-West Harbor | 1100 | 100 | 1000 | 0 | 100 | 2100 | 400 | 1700 | 100 | 300 |
| West Harbor-Marblehead Nodal Point | 5400 | 500 | 4900 | 100 | 400 | 7900 | 900 | 7000 | 200 | 700 |
| Marblehead Nodal Point-Sandusky | 2100 | 200 | 1900 | 0 | 200 | 2700 | 400 | 2300 | 100 | 300 |
| Sandusky-Huron | 7000 | 3500 | 3500 | 700 | 2800 | 11300 | 10300 | 1000 | 2100 | 8200 |
| Huron Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Huron-Vermilion | 41600 | 6600 | 35000 | 1300 | 5300 | 30400 | 5400 | 25000 | 1100 | 4300 |
| Vermilion Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Vermilion Harbor Fillet | 1000 | 300 | 700 | 100 | 200 | 600 | 100 | 500 | 0 | 100 |
| Vermilion-Beaver Park Marina | 22700 | 4600 | 18100 | 900 | 3700 | 10000 | 2700 | 7300 | 600 | 2100 |
| Beaver Park Marina | 4600 | 500 | 4100 | 100 | 400 | 2200 | 300 | 1900 | 100 | 200 |
| Beaver Park Marina-Lorain | 22600 | 4400 | 18200 | 900 | 3500 | 4900 | 1000 | 3900 | 200 | 800 |
| Lorain Harbor West | 500 | 100 | 400 | 0 | 100 | 100 | 0 | 100 | 0 | 0 |

| Reach | Pre-Armoring Total Bluff Volume | Pre-Armoring Total Coarse Volume | Pre-Armoring Total Fine Volume | Pre-Armoring Coarse Loss to deep | Pre-Armoring Coarse Continue to Littoral System | Mid-Century Total Bluff Volume | Mid-Century Coarse Bluff Volume | Mid-Century Fine Bluff Volume | Mid-Century Coarse Loss to deep | Mid-Century Coarse Continue to Littoral System |
|---|---------------------------------|----------------------------------|--------------------------------|----------------------------------|---|--------------------------------|---------------------------------|-------------------------------|---------------------------------|--|
| Lorain Harbor East | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Lorain-Domonkas Library | 11300 | 2300 | 9000 | 400 | 1900 | 5000 | 1000 | 4000 | 200 | 800 |
| Domonkas Library | 500 | 100 | 400 | 0 | 100 | 100 | 0 | 100 | 0 | 0 |
| Domonkas Library-Avon Lake | 5200 | 1100 | 4100 | 200 | 900 | 1700 | 400 | 1300 | 100 | 300 |
| Avon Lake | 2000 | 500 | 1500 | 100 | 400 | 200 | 0 | 200 | 0 | 0 |
| Avon Lake-Avon Lake Nodal Point | 3300 | 900 | 2400 | 200 | 700 | 1700 | 500 | 1200 | 100 | 400 |
| Avon Lake Nodal Point-Rocky River | 50400 | 17400 | 33000 | 3500 | 13900 | 18200 | 5900 | 12300 | 1200 | 4700 |
| Rocky River Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Rocky River-Cleveland | 33100 | 9700 | 23400 | 2000 | 7700 | 17400 | 5100 | 12300 | 1000 | 4100 |
| Cleveland Harbor Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cleveland Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cleveland-White City Park | 15500 | 5700 | 9800 | 1100 | 4600 | 11000 | 4500 | 6500 | 900 | 3600 |
| White City Park | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| White City Park-Cleveland Lakefront St Park | 1300 | 300 | 1000 | 100 | 200 | 1400 | 300 | 1100 | 100 | 200 |
| Cleveland Lakefront. St Park | 1100 | 200 | 900 | 0 | 200 | 600 | 100 | 500 | 0 | 100 |
| Cleveland Lakefront St Park-Eastlake PP | 58100 | 11600 | 46500 | 2300 | 9300 | 41000 | 8300 | 32700 | 1700 | 6600 |
| Eastlake Power Plant Fillet | 7100 | 1600 | 5500 | 300 | 1300 | 2600 | 600 | 2000 | 100 | 500 |
| Eastlake Power Plant | 2100 | 400 | 1700 | 100 | 300 | 500 | 100 | 400 | 0 | 100 |
| Eastlake Power Plant-Mentor Harbor | 53700 | 14200 | 39500 | 2800 | 11400 | 30500 | 8500 | 22000 | 1700 | 6800 |
| Mentor Harbor Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Reach | Pre-Armoring Total Bluff Volume | Pre-Armoring Total Coarse Volume | Pre-Armoring Total Fine Volume | Pre-Armoring Coarse Loss to deep | Pre-Armoring Coarse Continue to Littoral System | Mid-Century Total Bluff Volume | Mid-Century Coarse Bluff Volume | Mid-Century Fine Bluff Volume | Mid-Century Coarse Loss to deep | Mid-Century Coarse Continue to Littoral System |
|------------------------------------|---------------------------------|----------------------------------|--------------------------------|----------------------------------|---|--------------------------------|---------------------------------|-------------------------------|---------------------------------|--|
| Mentor Harbor-Fairport | 28500 | 6000 | 22500 | 1200 | 4800 | 55200 | 11500 | 43700 | 2300 | 9200 |
| Fairport Harbor Fillet | 500 | 100 | 400 | 0 | 100 | 0 | 0 | 0 | 0 | 0 |
| Fairport Harbor | 8600 | 1700 | 6900 | 300 | 1400 | 1300 | 300 | 1000 | 100 | 200 |
| Fairport-North Perry | 124200 | 33600 | 90600 | 6700 | 26900 | 172300 | 50300 | 122000 | 10100 | 40200 |
| North Perry Marina | 2300 | 900 | 1400 | 200 | 700 | 2800 | 1100 | 1700 | 200 | 900 |
| North Perry-Geneva-on-the-Lake | 24300 | 12900 | 11400 | 2600 | 10300 | 9200 | 5000 | 4200 | 1000 | 4000 |
| Geneva-on-the-Lake Fillet | 600 | 100 | 500 | 0 | 100 | 900 | 200 | 700 | 0 | 200 |
| Geneva-on-the-Lake | 200 | 100 | 100 | 0 | 100 | 300 | 100 | 200 | 0 | 100 |
| Geneva-on-the-Lake-Ashtabula | 66300 | 13400 | 52900 | 2700 | 10700 | 42500 | 8600 | 33900 | 1700 | 6900 |
| Ashtabula Harbor Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ashtabula Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ashtabula-Conneaut | 140300 | 42400 | 97900 | 8500 | 33900 | 97200 | 31900 | 65300 | 6400 | 25500 |
| Conneaut Harbor Fillet | 400 | 100 | 300 | 0 | 100 | 300 | 100 | 200 | 0 | 100 |
| Conneaut Harbor | 1700 | 300 | 1400 | 100 | 200 | 200 | 0 | 200 | 0 | 0 |
| Conneaut-Presque Isle | 228900 | 47800 | 181100 | 9600 | 38200 | 261800 | 52400 | 209400 | 10500 | 41900 |
| Presque Isle | 0 | 0 | 0 | 0 | 0 | 198200 | 198200 | 0 | 39600 | 158600 |
| Erie East Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Erie-Shades Beach | 51300 | 13800 | 37500 | 2800 | 11000 | 31100 | 8400 | 22700 | 1700 | 6700 |
| Shades Beach | 1500 | 400 | 1100 | 100 | 300 | 1500 | 400 | 1100 | 100 | 300 |
| Shades Beach-Crittenden Point | 162000 | 40800 | 121200 | 8100 | 32700 | 125700 | 31700 | 94000 | 6300 | 25400 |
| Crittenden Point-North East Marina | 69600 | 17500 | 52100 | 3500 | 14000 | 80700 | 20200 | 60500 | 4000 | 16200 |
| North East Marina Fillet | 900 | 200 | 700 | 0 | 200 | 900 | 200 | 700 | 0 | 200 |

| Reach | Pre-Armoring Total Bluff Volume | Pre-Armoring Total Coarse Volume | Pre-Armoring Total Fine Volume | Pre-Armoring Coarse Loss to deep | Pre-Armoring Coarse Continue to Littoral System | Mid-Century Total Bluff Volume | Mid-Century Coarse Bluff Volume | Mid-Century Fine Bluff Volume | Mid-Century Coarse Loss to deep | Mid-Century Coarse Continue to Littoral System |
|---|---------------------------------|----------------------------------|--------------------------------|----------------------------------|---|--------------------------------|---------------------------------|-------------------------------|---------------------------------|--|
| North East Marina | 700 | 200 | 500 | 0 | 200 | 700 | 200 | 500 | 100 | 100 |
| North East Marina-Twenty mile Creek Point | 3800 | 900 | 2900 | 200 | 700 | 3200 | 800 | 2400 | 200 | 600 |
| Twenty mile Creek Point-Barcelona | 84200 | 20800 | 63400 | 4100 | 16700 | 20800 | 5100 | 15700 | 1000 | 4100 |
| Barcelona Fillet | 0 | 0 | 0 | 0 | 0 | 400 | 100 | 300 | 0 | 100 |
| Barcelona Harbor | 700 | 200 | 500 | 100 | 100 | 100 | 0 | 100 | 0 | 0 |
| Barcelona-Van Buren Point | 116400 | 31600 | 84800 | 6300 | 25300 | 33300 | 8600 | 24700 | 1700 | 6900 |
| Van Buren Point-Dunkirk | 4400 | 1100 | 3300 | 200 | 900 | 2800 | 600 | 2200 | 100 | 500 |
| Dunkirk Outer Basin | 500 | 100 | 400 | 0 | 100 | 400 | 100 | 300 | 0 | 100 |
| Dunkirk Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dunkirk-Fletcher Point | 20500 | 6000 | 14500 | 1200 | 4800 | 7700 | 2300 | 5400 | 500 | 1800 |
| Fletcher Point-Silver Creek | 20000 | 5800 | 14200 | 1100 | 4700 | 3400 | 1000 | 2400 | 200 | 800 |
| Silver Creek | 6700 | 2000 | 4700 | 400 | 1600 | 1000 | 300 | 700 | 100 | 200 |
| Cattaraugus Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cattaraugus | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cattaraugus Sturgeon Point | 45800 | 29700 | 16100 | 6000 | 23700 | 10500 | 6000 | 4500 | 1200 | 4800 |
| Sturgeon Point Fillet | 800 | 300 | 500 | 0 | 300 | 300 | 100 | 200 | 0 | 100 |
| Sturgeon Point | 2800 | 1000 | 1800 | 200 | 800 | 1000 | 400 | 600 | 100 | 300 |
| Sturgeon Point-Buffalo | 60100 | 17400 | 42700 | 3500 | 13900 | 26000 | 7600 | 18400 | 1500 | 6100 |

Table 10. Bluff recession volumes for the Recent (1970s to 2000s) and Future time frames (all units in cubic meters/year).

| Reach | Recent Total Bluff Volume | Recent Coarse Bluff Volume | Recent Fine Bluff Volume | Recent Coarse Loss to deep | Recent Coarse Continue to Littoral System | Future Total Bluff Volume | Future Coarse Bluff Volume | Future Fine Bluff Volume | Future Coarse Loss to deep | Future Coarse Continue to Littoral System |
|---|---------------------------|----------------------------|--------------------------|----------------------------|---|---------------------------|----------------------------|--------------------------|----------------------------|---|
| Toledo-Cooley Canal | 12500 | 1300 | 11200 | 300 | 1000 | 1800 | 200 | 1600 | 0 | 200 |
| Cooley Canal Harbor | 300 | 0 | 300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cooley Canal-Locust Point Nodal Point | 17800 | 1800 | 16000 | 400 | 1400 | 5200 | 500 | 4700 | 100 | 400 |
| Locust Point Nodal Point-Port Clinton | 8400 | 800 | 7600 | 100 | 700 | 7100 | 700 | 6400 | 100 | 600 |
| Port Clinton Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Port Clinton-Catawba Island Nodal Point | 3200 | 300 | 2900 | 100 | 200 | 2000 | 100 | 1900 | 0 | 100 |
| Catawba Island Nodal Point-West Harbor | 1200 | 200 | 1000 | 0 | 200 | 200 | 0 | 200 | 0 | 0 |
| West Harbor-Marblehead Nodal Point | 3800 | 600 | 3200 | 100 | 500 | 2000 | 400 | 1600 | 100 | 300 |
| Marblehead Nodal Point-Sandusky | 400 | 0 | 400 | 0 | 0 | 100 | 0 | 100 | 0 | 0 |
| Sandusky-Huron | 14300 | 13500 | 800 | 2700 | 10800 | 14200 | 13500 | 700 | 2700 | 10800 |
| Huron Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Huron-Vermilion | 19200 | 3200 | 16000 | 600 | 2600 | 11800 | 2000 | 9800 | 400 | 1600 |
| Vermilion Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Vermilion Harbor Fillet | 400 | 100 | 300 | 0 | 100 | 400 | 100 | 300 | 0 | 100 |
| Vermilion-Beaver Park Marina | 10100 | 2700 | 7400 | 500 | 2200 | 3900 | 1000 | 2900 | 200 | 800 |
| Beaver Park Marina | 800 | 100 | 700 | 0 | 100 | 800 | 100 | 700 | 0 | 100 |
| Beaver Park Marina-Lorain | 1100 | 200 | 900 | 0 | 200 | 800 | 200 | 600 | 100 | 100 |
| Lorain Harbor West | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Lorain Harbor East | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

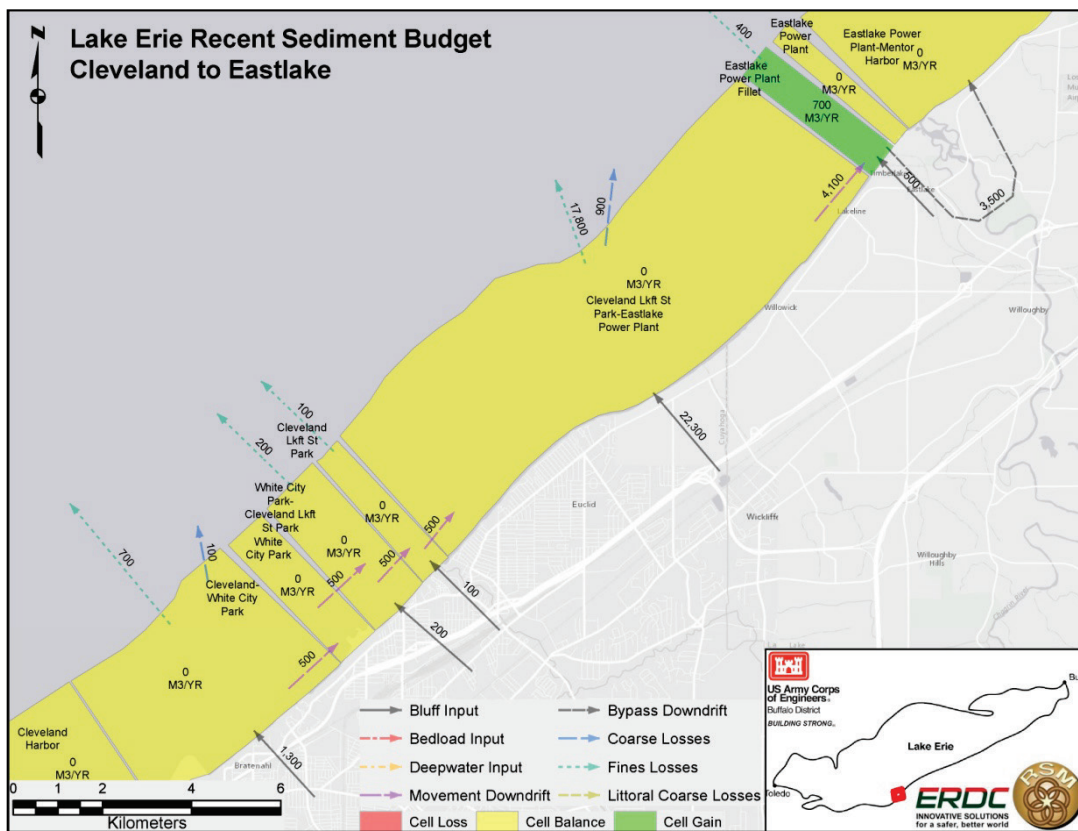
| Reach | Recent Total Bluff Volume | Recent Coarse Bluff Volume | Recent Fine Bluff Volume | Recent Coarse Loss to deep | Recent Coarse Continue to Littoral System | Future Total Bluff Volume | Future Coarse Bluff Volume | Future Fine Bluff Volume | Future Coarse Loss to deep | Future Coarse Continue to Littoral System |
|---|---------------------------|----------------------------|--------------------------|----------------------------|---|---------------------------|----------------------------|--------------------------|----------------------------|---|
| Lorain-Domonkas Library | 1300 | 300 | 1000 | 100 | 200 | 500 | 100 | 400 | 0 | 100 |
| Domonkas Library | 100 | 0 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Domonkas Library-Avon Lake | 2200 | 500 | 1700 | 100 | 400 | 900 | 200 | 700 | 0 | 200 |
| Avon Lake | 300 | 100 | 200 | 0 | 100 | 0 | 0 | 0 | 0 | 0 |
| Avon Lake-Avon Lake Nodal Point | 1100 | 300 | 800 | 100 | 200 | 300 | 100 | 200 | 0 | 100 |
| Avon Lake Nodal Point-Rocky River | 14200 | 4600 | 9600 | 900 | 3700 | 8100 | 2500 | 5600 | 500 | 2000 |
| Rocky River Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Rocky River-Cleveland | 9000 | 2600 | 6400 | 500 | 2100 | 7500 | 2200 | 5300 | 400 | 1800 |
| Cleveland Harbor Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cleveland Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cleveland-White City Park | 1300 | 600 | 700 | 100 | 500 | 300 | 100 | 200 | 0 | 100 |
| White City Park | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| White City Park-Cleveland Lakefront St Park | 200 | 0 | 200 | 0 | 0 | 100 | 0 | 100 | 0 | 0 |
| Cleveland Lakefront St Park | 100 | 0 | 100 | 0 | 0 | 100 | 0 | 100 | 0 | 0 |
| Cleveland Lakefront St Park-Eastlake PP | 22300 | 4500 | 17800 | 900 | 3600 | 9800 | 2000 | 7800 | 400 | 1600 |
| Eastlake Power Plant Fillet | 500 | 100 | 400 | 0 | 100 | 500 | 100 | 400 | 0 | 100 |
| Eastlake Power Plant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Eastlake Power Plant-Mentor Harbor | 30300 | 7700 | 22600 | 1600 | 6100 | 18900 | 4800 | 14100 | 1000 | 3800 |
| Mentor Harbor Fillet | 1900 | 1800 | 100 | 400 | 1400 | 1800 | 1700 | 100 | 400 | 1300 |
| Mentor Harbor-Fairport | 12300 | 2800 | 9500 | 600 | 2200 | 10600 | 2500 | 8100 | 500 | 2000 |
| Fairport Harbor Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Reach | Recent Total Bluff Volume | Recent Coarse Bluff Volume | Recent Fine Bluff Volume | Recent Coarse Loss to deep | Recent Coarse Continue to Littoral System | Future Total Bluff Volume | Future Coarse Bluff Volume | Future Fine Bluff Volume | Future Coarse Loss to deep | Future Coarse Continue to Littoral System |
|---|---------------------------|----------------------------|--------------------------|----------------------------|---|---------------------------|----------------------------|--------------------------|----------------------------|---|
| Fairport Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fairport-North Perry | 155700 | 43500 | 112200 | 8700 | 34800 | 115000 | 33300 | 81700 | 6700 | 26600 |
| North Perry Marina | 1000 | 400 | 600 | 100 | 300 | 500 | 200 | 300 | 0 | 200 |
| North Perry-Geneva-on-the-Lake | 20600 | 12100 | 8500 | 2400 | 9700 | 16200 | 9900 | 6300 | 2000 | 7900 |
| Geneva-on-the-Lake Fillet | 900 | 200 | 700 | 100 | 100 | 300 | 100 | 200 | 0 | 100 |
| Geneva-on-the-Lake | 300 | 100 | 200 | 0 | 100 | 100 | 0 | 100 | 0 | 0 |
| Geneva-on-the-Lake-Ashtabula | 40200 | 8100 | 32100 | 1600 | 6500 | 26200 | 5200 | 21000 | 1000 | 4200 |
| Ashtabula Harbor Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ashtabula Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ashtabula-Conneaut | 190200 | 63100 | 127100 | 12600 | 50500 | 158500 | 50500 | 108000 | 10100 | 40400 |
| Conneaut Harbor Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Conneaut Harbor | 400 | 0 | 400 | 0 | 0 | 400 | 0 | 400 | 0 | 0 |
| Conneaut-Presque Isle | 171300 | 37900 | 133400 | 7600 | 30300 | 159600 | 35700 | 123900 | 7100 | 28600 |
| Presque Isle | 26600 | 26600 | 0 | 4000 | 22600 | 26600 | 26600 | 0 | 4000 | 22600 |
| Erie East Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Erie-Shades Beach | 31000 | 8300 | 22700 | 1700 | 6600 | 29600 | 7900 | 21700 | 1600 | 6300 |
| Shades Beach | 1500 | 400 | 1100 | 100 | 300 | 1300 | 300 | 1000 | 0 | 300 |
| Shades Beach-Crittenden Point | 98900 | 24900 | 74000 | 5000 | 19900 | 97000 | 24500 | 72500 | 4900 | 19600 |
| Crittenden Point-North East Marina | 59200 | 14900 | 44300 | 3000 | 11900 | 47600 | 11900 | 35700 | 2400 | 9500 |
| North East Marina Fillet | 700 | 200 | 500 | 0 | 200 | 400 | 100 | 300 | 0 | 100 |
| North East Marina | 500 | 100 | 400 | 0 | 100 | 300 | 100 | 200 | 0 | 100 |
| North East Marina-Twenty mile Creek Point | 2400 | 600 | 1800 | 100 | 500 | 600 | 200 | 400 | 0 | 200 |

| Reach | Recent Total Bluff Volume | Recent Coarse Bluff Volume | Recent Fine Bluff Volume | Recent Coarse Loss to deep | Recent Coarse Continue to Littoral System | Future Total Bluff Volume | Future Coarse Bluff Volume | Future Fine Bluff Volume | Future Coarse Loss to deep | Future Coarse Continue to Littoral System |
|----------------------------------|---------------------------|----------------------------|--------------------------|----------------------------|---|---------------------------|----------------------------|--------------------------|----------------------------|---|
| Twentymile Creek Point-Barcelona | 20500 | 5000 | 15500 | 1000 | 4000 | 17300 | 4300 | 13000 | 900 | 3400 |
| Barcelona Fillet | 100 | 0 | 100 | 0 | 0 | 100 | 0 | 100 | 0 | 0 |
| Barcelona Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Barcelona-Van Buren Point | 33500 | 9100 | 24400 | 1800 | 7300 | 31900 | 8700 | 23200 | 1700 | 7000 |
| Van Buren Point-Dunkirk | 1400 | 300 | 1100 | 100 | 200 | 900 | 200 | 700 | 100 | 100 |
| Dunkirk Outer Basin | 200 | 0 | 200 | 0 | 0 | 200 | 0 | 200 | 0 | 0 |
| Dunkirk Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dunkirk-Fletcher Point | 15000 | 4400 | 10600 | 900 | 3500 | 14700 | 4300 | 10400 | 900 | 3400 |
| Fletcher Point-Silver Creek | 4300 | 1300 | 3000 | 300 | 1000 | 3700 | 1100 | 2600 | 200 | 900 |
| Silver Creek | 1000 | 300 | 700 | 100 | 200 | 1000 | 300 | 700 | 100 | 200 |
| Cattaraugus Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cattaraugus | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cattaraugus Sturgeon Point | 7500 | 3800 | 3700 | 700 | 3100 | 6500 | 3300 | 3200 | 700 | 2600 |
| Sturgeon Point Fillet | 100 | 0 | 100 | 0 | 0 | 100 | 0 | 100 | 0 | 0 |
| Sturgeon Point | 300 | 100 | 200 | 0 | 100 | 300 | 100 | 200 | 0 | 100 |
| Sturgeon Point-Buffalo | 12300 | 3500 | 8800 | 700 | 2800 | 8100 | 2400 | 5700 | 500 | 1900 |

The bluff recession data displayed in Table 9 and Table 10 were brought into SBAS to determine total Longshore Sediment Transport (LST). Based on flux directions, the coarse fraction of the bluff material was summed as necessary to determine the magnitude of each flux. The LST quantities were also compared with the computed harbor sedimentation rates to refine the positioning and magnitude of sediment flux. Figure 21 presents an example of the completed sediment budget from Cleveland to Fairport Harbor, OH. The entire sediment budget for Lake Erie is presented in Appendix B.

Figure 21. Completed sediment budget, Cleveland to Eastlake, during the Recent time frame.



The net littoral volumes are listed in Table 11 and Table 12 for Pre-Armoring and Mid-Century time frames, and Recent and Future time frames, respectively. “Net Coarse Volume In” represents the sum of any coarse fraction from updrift, from bluff erosion, and from bed load into a littoral cell. “Coarse Loss at end of Cell” represents any material lost to deep water at the end of a littoral cell. The “Net Coarse Volume to Downdrift” represents the quantity of material transported into the downdrift littoral cell. The “Net Volume Retained” represents the ΔV term in Equation 1.

Table 11. Net littoral cell volumes for the Pre-Armoring (1860s to 1930s) and Mid-Century (1930s to 1970s) time frames (all units in cubic meters/year).

| Reach | Pre-Armoring | | | | Mid-Century | | | |
|---|----------------------|----------------------------|--------------------------------|---------------------|---------------|----------------------------|--------------------------------|---------------------|
| | Net Coarse Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained |
| Toledo-Cooley Canal | 8800 | 0 | 8800 | 0 | 7000 | 0 | 7000 | 0 |
| Cooley Canal Harbor | 3300 | 0 | 3300 | 0 | 2300 | 0 | 2300 | 0 |
| Cooley Canal-Locust Point Nodal Point | 3200 | 0 | 3200 | 0 | 2000 | 0 | 2000 | 0 |
| Locust Point Nodal Point-Port Clinton | 2700 | 0 | 2700 | 0 | 1600 | 0 | 1600 | 0 |
| Port Clinton Harbor | 3200 | 600 | 0 | 2600 | 3500 | 700 | 0 | 2800 |
| Port Clinton-Catawba Island Nodal Point | 600 | 0 | 600 | 0 | 1700 | 0 | 1700 | 0 |
| Catawba Island Nodal Point-West Harbor | 100 | 0 | 100 | 0 | 300 | 0 | 300 | 0 |
| West Harbor | 500 | 0 | 0 | 500 | 1000 | 0 | 0 | 1000 |
| West Harbor-Marblehead Nodal Point | 400 | 0 | 400 | 0 | 700 | 0 | 700 | 0 |
| Marblehead Nodal Point-Sandusky | 200 | 0 | 200 | 0 | 300 | 0 | 0 | 300 |
| Sandusky-Huron | 4100 | 4100 | 0 | 0 | 8200 | 8200 | 0 | 0 |
| Huron Harbor | 5000 | 1300 | 1300 | 2500 | 4000 | 0 | 0 | 4000 |
| Huron-Vermilion | 5300 | 0 | 5300 | 0 | 4300 | 0 | 4300 | 0 |
| Vermilion Harbor | 1200 | 0 | 0 | 1200 | 1000 | 0 | 0 | 1000 |
| Vermilion Harbor Fillet | 1700 | 0 | 900 | 800 | 1200 | 0 | 700 | 500 |
| Vermilion-Beaver Park Marina | 3700 | 0 | 3700 | 0 | 2100 | 0 | 2100 | 0 |
| Beaver Park Marina | 2600 | 0 | 2600 | 0 | 1200 | 0 | 1400 | -200 |
| Beaver Park Marina-Lorain | 6100 | 0 | 6100 | 0 | 2200 | 0 | 2200 | 0 |
| Lorain Harbor West | 6200 | 0 | 0 | 6200 | 2200 | 0 | 0 | 2200 |
| Lorain Harbor East | 4000 | 0 | 0 | 4000 | 1100 | 0 | 0 | 1100 |
| Lorain - Domonkas Library | 4000 | 0 | 4000 | 0 | 1100 | 0 | 1100 | 0 |
| Domonkas Library | 2100 | 0 | 2100 | 0 | 300 | 0 | 300 | 0 |

| Reach | Pre-Armoring | | | | Mid-Century | | | |
|---|----------------------|----------------------------|--------------------------------|---------------------|---------------|----------------------------|--------------------------------|---------------------|
| | Net Coarse Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained |
| Domonkas Library-Avon Lake | 2000 | 0 | 2000 | 0 | 300 | 0 | 300 | 0 |
| Avon Lake | 1100 | 0 | 1100 | 0 | 400 | 0 | 0 | 400 |
| Avon Lake - Avon Lake Nodal Point | 700 | 0 | 700 | 0 | 400 | 0 | 400 | 0 |
| Avon Lake Nodal Point - Rocky River | 13900 | 0 | 13900 | 0 | 4700 | 0 | 4700 | 0 |
| Rocky River Harbor | 13900 | 4600 | 9300 | 0 | 4700 | 0 | 0 | 4700 |
| Rocky River-Cleveland | 17000 | 0 | 17000 | 0 | 4100 | 0 | 4100 | 0 |
| Cleveland Harbor Fillet | 17000 | 0 | 0 | 17000 | 4100 | 2100 | 0 | 2000 |
| Cleveland Harbor | 17000 | 8500 | 0 | 8500 | 0 | 0 | 0 | 0 |
| Cleveland-White City Park | 4600 | 0 | 4600 | 0 | 3600 | 0 | 3600 | 0 |
| White City Park | 4600 | 0 | 4600 | 0 | 3600 | 0 | 2600 | 1000 |
| White City Park-Cleveland Lakefront St Park | 4800 | 0 | 4800 | 0 | 2800 | 0 | 2800 | 0 |
| Cleveland Lkft St Park | 5000 | 0 | 5000 | 0 | 2900 | 0 | 1900 | 1000 |
| Cleveland Lkft St Park-Eastlake PP | 14300 | 0 | 14300 | 0 | 8500 | 0 | 8500 | 0 |
| Eastlake Power Plant Fillet | 15600 | 0 | 15600 | 0 | 9000 | 0 | 8000 | 1000 |
| Eastlake Power Plant | 15900 | 0 | 15900 | 0 | 100 | 0 | 100 | 0 |
| Eastlake Power Plant-Mentor Harbor | 27300 | 0 | 27300 | 0 | 14900 | 0 | 14900 | 0 |
| Mentor Harbor Fillet | 27300 | 0 | 27300 | 0 | 14900 | 0 | 13900 | 1000 |
| Mentor Harbor-Fairport | 32100 | 0 | 32100 | 0 | 23100 | 0 | 23100 | 0 |
| Fairport Harbor Fillet | 32200 | 0 | 3600 | 28600 | 23100 | 0 | 4800 | 18300 |
| Fairport Harbor | 5000 | 0 | 0 | 5000 | 5000 | 0 | 0 | 5000 |
| Fairport-North Perry | 26900 | 0 | 26900 | 0 | 40200 | 0 | 40200 | 0 |
| North Perry Marina | 27600 | 0 | 27600 | 0 | 41100 | 0 | 41100 | 0 |
| North Perry-Geneva-on-the-Lake | 37900 | 0 | 37900 | 0 | 45100 | 0 | 45100 | 0 |

| Reach | Pre-Armoring | | | | Mid-Century | | | |
|---|----------------------|----------------------------|--------------------------------|---------------------|---------------|----------------------------|--------------------------------|---------------------|
| | Net Coarse Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained |
| Geneva-on-the-Lake Fillet | 38000 | 0 | 38000 | 0 | 45300 | 0 | 45300 | 0 |
| Geneva-on-the-Lake | 38100 | 0 | 38100 | 0 | 45400 | 0 | 45400 | 0 |
| Geneva-on-the-Lake-Ashtabula | 48800 | 0 | 48800 | 0 | 52300 | 0 | 52300 | 0 |
| Ashtabula Harbor Fillet | 48800 | 6400 | 34400 | 8000 | 52300 | 24300 | 10000 | 18000 |
| Ashtabula Harbor | 34300 | 6500 | 6500 | 21400 | 10000 | 0 | 0 | 10000 |
| Ashtabula-Conneaut | 40400 | 0 | 40400 | 0 | 25500 | 0 | 25500 | 0 |
| Conneaut Harbor Fillet | 40500 | 10200 | 30300 | 0 | 25600 | 0 | 15600 | 10000 |
| Conneaut Harbor | 30500 | 10300 | 10200 | 10000 | 15600 | 0 | 0 | 15600 |
| Conneaut-Presque Isle | 48500 | 0 | 48500 | 0 | 41900 | 0 | 41900 | 0 |
| Presque Isle | 48500 | 48500 | 0 | 0 | 200500 | 0 | 221000 | -20500 |
| Gull Point | 0 | 0 | 0 | 0 | 221000 | 156100 | 0 | 64900 |
| Erie East Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Erie - Shades Beach | 11000 | 0 | 11000 | 0 | 6700 | 0 | 6700 | 0 |
| Shades Beach | 11300 | 0 | 11300 | 0 | 7000 | 0 | 7000 | 0 |
| Shades Beach-Crittenden Point | 44000 | 22000 | 22000 | 0 | 32300 | 16200 | 16200 | 0 |
| Crittenden Point-North East Marina | 36000 | 0 | 36000 | 0 | 32400 | 0 | 32400 | 0 |
| North East Marina Fillet | 36200 | 0 | 36200 | 0 | 32500 | 0 | 32500 | 0 |
| North East Marina | 36300 | 0 | 36300 | 0 | 32700 | 0 | 32700 | 0 |
| North East Marina-Twenty mile Creek Point | 37100 | 18500 | 18500 | 0 | 33300 | 16700 | 16600 | 0 |
| Twenty mile Creek Point-Barcelona | 35200 | 0 | 35200 | 0 | 20700 | 0 | 20700 | 0 |
| Barcelona Fillet | 35200 | 17600 | 17600 | 0 | 20800 | 10400 | 5200 | 5200 |
| Barcelona Harbor | 17700 | 0 | 17700 | 0 | 5200 | 0 | 5300 | -100 |
| Barcelona-Van Buren Point | 43000 | 21500 | 21500 | 0 | 12200 | 6100 | 6100 | 0 |

| Reach | Pre-Armoring | | | | Mid-Century | | | |
|-----------------------------|----------------------|----------------------------|--------------------------------|---------------------|---------------|----------------------------|--------------------------------|---------------------|
| | Net Coarse Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained |
| Van Buren Point-Dunkirk | 22400 | 11200 | 11200 | 0 | 6600 | 3300 | 3300 | 0 |
| Dunkirk Outer Basin | 11300 | 8500 | 1300 | 1500 | 3400 | 2500 | 1400 | -500 |
| Dunkirk Harbor | 1300 | 0 | 0 | 1300 | 5400 | 0 | 0 | 5400 |
| Dunkirk-Fletcher Point | 4800 | 500 | 4300 | 0 | 1800 | 200 | 1600 | 0 |
| Fletcher Point-Silver Creek | 9000 | 900 | 8100 | 0 | 2400 | 200 | 2200 | 0 |
| Silver Creek | 9700 | 0 | 9700 | 0 | 2400 | 0 | 2400 | 0 |
| Cattaraugus Fillet | 9700 | 0 | 9700 | 0 | 2400 | 0 | 2400 | 0 |
| Cattaraugus | 12400 | 0 | 12400 | 0 | 5100 | 0 | 5100 | 0 |
| Cattaraugus Shoal | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Cattaraugus Scour | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Cattaraugus Sturgeon Point | 36100 | 0 | 36100 | 0 | 9900 | 0 | 9900 | 0 |
| Sturgeon Point Fillet | 36400 | 9100 | 27300 | 0 | 10000 | 2500 | 7500 | 0 |
| Sturgeon Point | 28100 | 0 | 28100 | 0 | 7800 | 0 | 7800 | 0 |
| Sturgeon Point-Buffalo | 42000 | 0 | 42000 | 0 | 13900 | 0 | 13900 | 0 |

Table 12. Net littoral cell volumes for the Recent (1970s to 2000s) and Future time frames (all units in cubic meters/year).

| Reach | Recent | | | | Future | | | |
|---|---------------|----------------------------|--------------------------------|---------------------|---------------|----------------------------|--------------------------------|---------------------|
| | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained |
| Toledo-Cooley Canal | 1000 | 0 | 1000 | 0 | 200 | 0 | 200 | 0 |
| Cooley Canal Harbor | 1400 | 0 | 0 | 1400 | 400 | 0 | 0 | 400 |
| Cooley Canal-Locust Point Nodal Point | 1400 | 0 | 1400 | 0 | 400 | 0 | 400 | 0 |
| Locust Point Nodal Point-Port Clinton | 700 | 0 | 700 | 0 | 600 | 0 | 600 | 0 |
| Port Clinton Harbor | 900 | 1,200 | 0 | -300 | 700 | 1,200 | 0 | -500 |
| Port Clinton-Catawba Island Nodal Point | 200 | 0 | 200 | 0 | 100 | 0 | 100 | 0 |
| Catawba Island Nodal Point-West Harbor | 200 | 0 | 200 | 0 | 0 | 0 | 0 | 0 |
| West Harbor | 600 | 0 | 0 | 600 | 300 | 0 | 0 | 300 |
| West Harbor-Marblehead Nodal Point | 500 | 0 | 500 | 0 | 300 | 0 | 300 | 0 |
| Marblehead Nodal Point-Sandusky | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sandusky-Huron | 10800 | 10800 | 0 | 0 | 10800 | 10800 | 0 | 0 |
| Huron Harbor | 2300 | 0 | 0 | 2300 | 1400 | 0 | 0 | 1400 |
| Huron-Vermilion | 2600 | 0 | 2600 | 0 | 1600 | 0 | 1600 | 0 |
| Vermilion Harbor | 800 | 0 | 0 | 800 | 500 | 0 | 0 | 500 |
| Vermilion Harbor Fillet | 900 | 0 | 500 | 400 | 700 | 0 | 300 | 400 |
| Vermilion-Beaver Park Marina | 2200 | 0 | 2200 | 0 | 800 | 0 | 800 | 0 |
| Beaver Park Marina | 1500 | 500 | 500 | 1000 | 300 | 100 | 100 | 100 |
| Beaver Park Marina-Lorain | 700 | 0 | 700 | 0 | 200 | 0 | 200 | 0 |
| Lorain Harbor West | 700 | 0 | 0 | 700 | 200 | 0 | 0 | 200 |
| Lorain Harbor East | 600 | 0 | 0 | 600 | 100 | 0 | 0 | 100 |
| Lorain - Domonkas Library | 600 | 0 | 600 | 0 | 100 | 0 | 100 | 0 |
| Domonkas Library | 400 | 0 | 400 | 0 | 200 | 0 | 0 | 200 |

| Reach | Recent | | | | Future | | | |
|---|---------------|----------------------------|--------------------------------|---------------------|---------------|----------------------------|--------------------------------|---------------------|
| | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained |
| Domonkas Library-Avon Lake | 400 | 0 | 400 | 0 | 200 | 0 | 200 | 0 |
| Avon Lake | 300 | 0 | 0 | 300 | 100 | 0 | 0 | 100 |
| Avon Lake - Avon Lake Nodal Point | 300 | 0 | 300 | 0 | 100 | 0 | 100 | 0 |
| Avon Lake Nodal Point - Rocky River | 3700 | 0 | 3700 | 0 | 2000 | 0 | 2000 | 0 |
| Rocky River Harbor | 3600 | 0 | 0 | 3600 | 2000 | 0 | 0 | 2000 |
| Rocky River-Cleveland | 2100 | 0 | 2100 | 0 | 1800 | 0 | 1800 | 0 |
| Cleveland Harbor Fillet | 2100 | 1100 | 0 | 1100 | 1800 | 900 | 0 | 900 |
| Cleveland Harbor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cleveland-White City Park | 500 | 0 | 500 | 0 | 100 | 0 | 100 | 0 |
| White City Park | 500 | 0 | 500 | 0 | 100 | 0 | 100 | 0 |
| White City Park-Cleveland Lkft St Park | 500 | 0 | 500 | 0 | 100 | 0 | 100 | 0 |
| Cleveland Lakefront St Park | 500 | 0 | 500 | 0 | 200 | 0 | 200 | 0 |
| Cleveland Lakefront St Park-Eastlake PP | 4100 | 0 | 4100 | 0 | 1800 | 0 | 1800 | 0 |
| Eastlake Power Plant Fillet | 4300 | 0 | 3500 | 700 | 1900 | 0 | 1400 | 500 |
| Eastlake Power Plant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Eastlake Power Plant-Mentor Harbor | 9600 | 0 | 9600 | 0 | 5200 | 0 | 5200 | 0 |
| Mentor Harbor Fillet | 11000 | 0 | 10300 | 700 | 6500 | 0 | 6000 | 500 |
| Mentor Harbor-Fairport | 12500 | 0 | 12500 | 0 | 8000 | 0 | 8000 | 0 |
| Fairport Harbor Fillet | 12500 | 0 | 4600 | 7900 | 8000 | 0 | 4600 | 3400 |
| Fairport Harbor | 4600 | 0 | 0 | 4600 | 4600 | 0 | 0 | 4600 |
| Fairport-North Perry | 34800 | 0 | 34800 | 0 | 26600 | 0 | 26600 | 0 |
| North Perry Marina | 35100 | 0 | 35100 | 0 | 26800 | 0 | 26800 | 0 |
| North Perry-Geneva-on-the-Lake | 44800 | 0 | 44800 | 0 | 34700 | 0 | 34700 | 0 |

| Reach | Recent | | | | Future | | | |
|---|---------------|----------------------------|--------------------------------|---------------------|---------------|----------------------------|--------------------------------|---------------------|
| | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained |
| Geneva-on-the-Lake Fillet | 44900 | 0 | 39900 | 5000 | 34800 | 8700 | 21100 | 5000 |
| Geneva-on-the-Lake | 40000 | 0 | 39500 | 500 | 21100 | 0 | 20600 | 500 |
| Geneva-on-the-Lake-Ashtabula | 46000 | 0 | 46000 | 0 | 24800 | 0 | 24800 | 0 |
| Ashtabula Harbor Fillet | 46000 | 30000 | 10000 | 6000 | 24800 | 12300 | 7500 | 5000 |
| Ashtabula Harbor | 10000 | 0 | 0 | 10000 | 7500 | 0 | 0 | 7500 |
| Ashtabula-Conneaut | 50500 | 0 | 50500 | 0 | 40400 | 0 | 40400 | 0 |
| Conneaut Harbor Fillet | 50500 | 10500 | 32000 | 8000 | 40400 | 10400 | 25000 | 5000 |
| Conneaut Harbor | 32000 | 0 | 0 | 32000 | 25000 | 0 | 0 | 25000 |
| Conneaut-Presque Isle | 30300 | 0 | 30300 | 0 | 28600 | 0 | 28600 | 0 |
| Presque Isle | 52900 | 0 | 52900 | 0 | 51200 | 0 | 51200 | 0 |
| Gull Point | 52900 | 39000 | 0 | 13900 | 51200 | 39000 | 0 | 12200 |
| Erie East Fillet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Erie-Shades Beach | 6600 | 0 | 6600 | 0 | 6300 | 0 | 6300 | 0 |
| Shades Beach | 6900 | 0 | 6900 | 0 | 6600 | 0 | 5000 | 1700 |
| Shades Beach-Crittenden Point | 26900 | 13400 | 13400 | 0 | 24500 | 12300 | 12300 | 0 |
| Crittenden Point-North East Marina | 25300 | 0 | 25300 | 0 | 21800 | 0 | 21800 | 0 |
| North East Marina Fillet | 25500 | 0 | 12400 | 13100 | 21900 | 0 | 12400 | 9500 |
| North East Marina | 100 | 0 | 0 | 100 | 100 | 0 | 0 | 100 |
| North East Marina-Twenty mile Creek Point | 12900 | 6400 | 6500 | 0 | 12600 | 6300 | 6300 | 0 |
| Twenty mile Creek Point-Barcelona | 10500 | 0 | 10500 | 0 | 9700 | 0 | 9700 | 0 |
| Barcelona Fillet | 10500 | 5400 | 1600 | 3500 | 9700 | 5900 | 800 | 3000 |
| Barcelona Harbor | 1600 | 0 | -800 | 2400 | 800 | 0 | -400 | 1200 |
| Barcelona-Van Buren Point | 6500 | 3200 | 3300 | 0 | 6500 | 3300 | 3300 | 0 |

| Reach | Recent | | | | Future | | | |
|-----------------------------|---------------|----------------------------|--------------------------------|---------------------|---------------|----------------------------|--------------------------------|---------------------|
| | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained | Net Volume In | Coarse Loss at End of Cell | Net Coarse Volume to Downdrift | Net Volume Retained |
| Van Buren Point-Dunkirk | 3500 | 1700 | 1700 | 0 | 3400 | 1700 | 1700 | 0 |
| Dunkirk Outer Basin | 1800 | 1400 | 1400 | -1000 | 1800 | 1300 | 1400 | -1000 |
| Dunkirk Harbor | 3400 | 0 | 0 | 3400 | 3400 | 0 | 0 | 3400 |
| Dunkirk-Fletcher Point | 3500 | 300 | 3200 | 0 | 3400 | 300 | 3100 | 0 |
| Fletcher Point-Silver Creek | 4200 | 400 | 3800 | 0 | 4000 | 400 | 3600 | 0 |
| Silver Creek | 4000 | 0 | 4000 | 0 | 3800 | 0 | 3800 | 0 |
| Cattaraugus Fillet | 4000 | 0 | 900 | 3100 | 3800 | 0 | 1900 | 1900 |
| Cattaraugus | 3500 | 0 | 3500 | 0 | 4600 | 0 | 4600 | 0 |
| Cattaraugus Shoal | 0 | 4400 | 13100 | -17500 | 0 | 900 | 2600 | -3500 |
| Cattaraugus Scour | 17700 | 2000 | 9700 | 6000 | 8000 | 1500 | 4500 | 2000 |
| Cattaraugus Sturgeon Point | 12700 | 0 | 12700 | 0 | 7100 | 0 | 7100 | 0 |
| Sturgeon Point Fillet | 12700 | 0 | 12700 | 0 | 7100 | 0 | 7100 | 0 |
| Sturgeon Point | 5200 | 0 | 5200 | 0 | 2200 | 0 | 2200 | 0 |
| Sturgeon Point-Buffalo | 15600 | 0 | 15600 | 0 | 9100 | 0 | 9100 | 0 |

9 Harbor Comparisons

Computing changes in sediment volume at harbor structures provides a means to confirm the computed bluff erosion volumes. Sediment volume change computations have been completed at 12 of the Buffalo District Harbors (Section 5). The historic sediment budget developed for Presque Isle as part of the 1980 Phase II General Design Memorandum (USACE 1984) was used for comparison as well. Appendix C contains a complete set of figures for the harbors analyzed in this present study.

Port Clinton Harbor

Port Clinton Harbor structures consist of East (375 m long) and West (205 m long) Piers. Construction began in 1872, and the earliest data used for sediment computation date to 1881.

To model the budget at Port Clinton Harbor, only a harbor cell was used (cell 5). The harbor has been relatively stable over the years, accreting slowly over much of the time since construction. The cell at Port Clinton is modeled to have sediment coming in from both the east and the west, with some sediments accumulating within the cell while most is lost offshore.

The harbor analysis at Port Clinton Harbor indicated a depositional rate of 400 m³/year at the harbor in the Pre-Armoring time frame (200 m³/year both east and west of the harbor). Due to the limited data available to model Port Clinton Harbor, the harbor analysis rates likely underpredict sediment changes in the Pre-Armoring and Mid-Century time frames. The bluff analysis during the Pre-Armoring time frame indicates 3,200 m³/year moving into Port Clinton. The cell was modeled with a loss of 1,200 m³/year to offshore, leaving a total accretion rate of 2,000 m³/year.

In the Mid-Century time frame, the harbor analysis measured an accretion rate of 1,200 m³/year (600 m³/year both east and west of the harbor). As with the Pre-Armoring time frame, limited data restrict the coverage of the harbor analysis, underpredicting sediment gains. The bluff analysis measured a total of 3,500 m³/year of sediment moving into the Port Clinton cell. The cell was modeled with a loss of 1,200 m³/year to offshore, leaving a total accretion rate of 2,300 m³/year.

In the Recent time frame, the harbor analysis measured net erosion at a rate of 1,500 m³/year at Port Clinton. The erosion rate was measured as -1,100 m³/year east of the harbor and -400 m³/year west of the harbor. Due to shoreline hardening, sediment inputs into the cell decreased dramatically to a total of 900 m³/year. A loss of 1,200 m³/year is estimated to deep water, leaving a net erosion rate of -300 m³/year.

In the Future time frame, the incoming sediment load will decrease to 700 m³/year with a continued loss of 1,200 m³/year to offshore, resulting in a net erosion rate of -500 m³/year.

Table 13 gives predicted and measured sediment flux values at Port Clinton Harbor.

Table 13. Predicted and measured volumetric change at Port Clinton Harbor (all units in cubic meters/year).

| | Pre-Armoring | | Mid-Century | | Recent | | Future |
|-------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|
| | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs |
| East | | 200 | | 600 | | -1,100 | |
| West | | 200 | | 600 | | -400 | |
| Total | 2,000 | 400 | 2,300 | 1,200 | -300 | -1,500 | -500 |
| | Total Difference | 2,200 | Total Difference | 1,100 | Total Difference | 1,200 | 1,000 |
| | | 550% | | 92% | | -80% | -67% |

The SBAS cells for Port Clinton from the Pre-Armoring through the Future time frames are presented in Figures 22 through 25.

Figure 22. Port Clinton Harbor Pre-Armoring sediment budget.

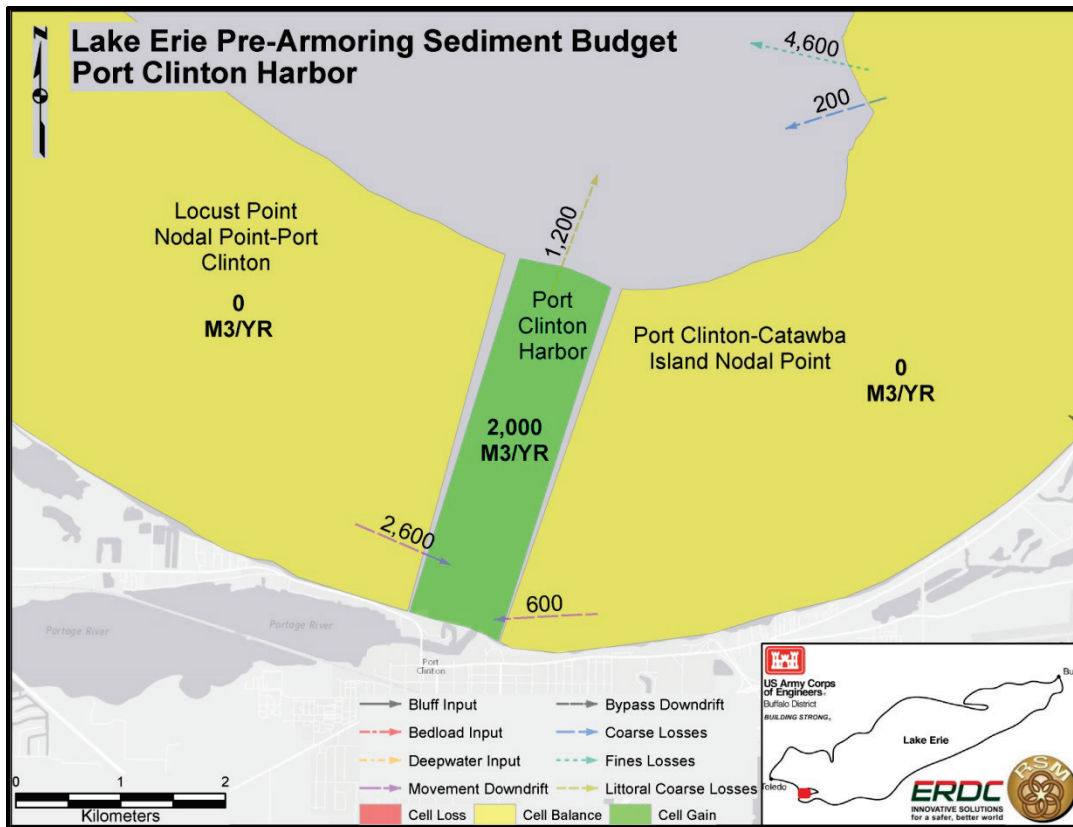


Figure 23. Port Clinton Harbor Mid-Century sediment budget.

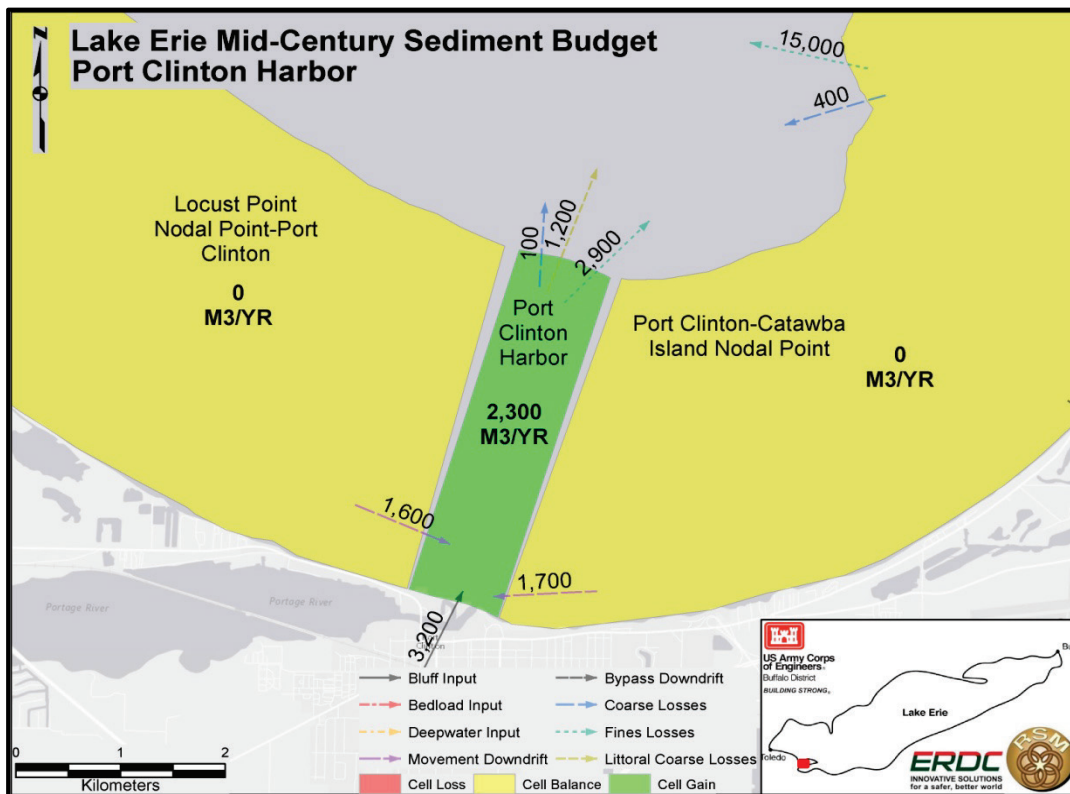


Figure 24. Port Clinton Harbor Recent sediment budget.

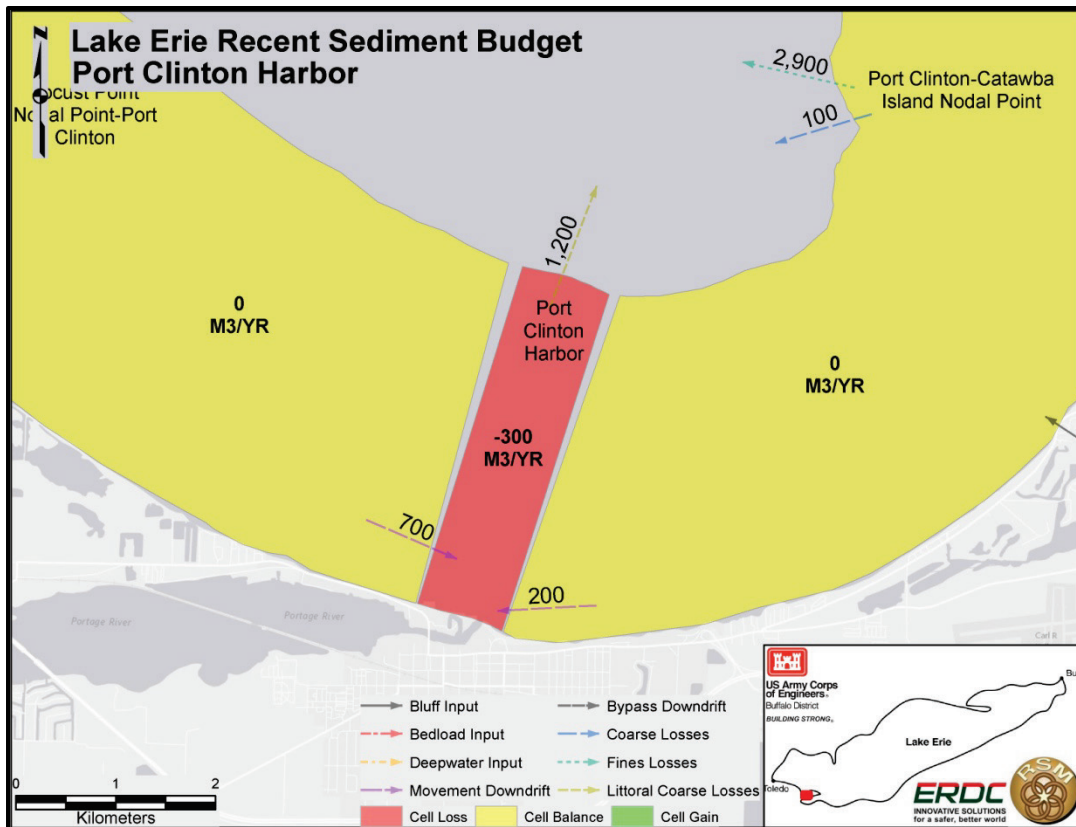
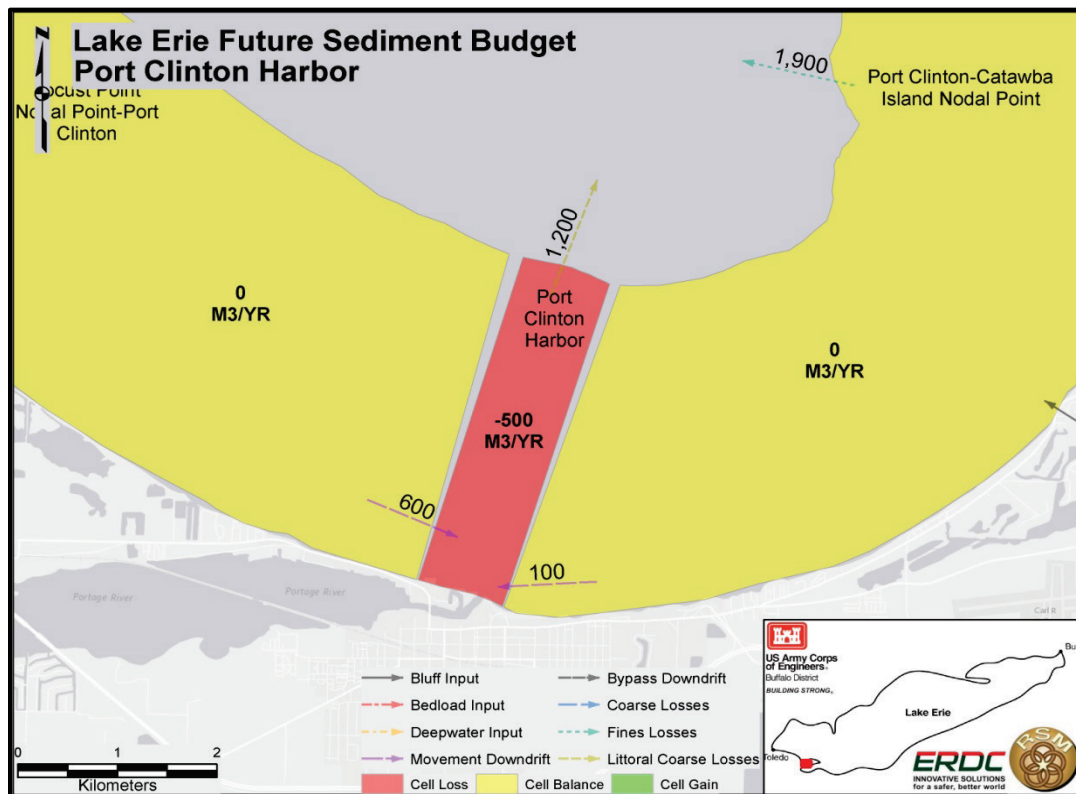


Figure 25. Port Clinton Harbor Future sediment budget.



West Harbor

West Harbor structures consist of 410 m long North and South breakwaters. Construction of structures began in 1981, and the earliest data used for sediment computation date to 1958. The Mid-Century time frame is considered the pre-construction period.

To model the budget at West Harbor, only a harbor cell was used (cell 8). Prior to construction, minor erosion was dominant east of the harbor and minor deposition was occurring to the west.

There were no harbor data available to measure conditions at the harbor in the Pre-Armoring time frame. The bluff analysis measured a total of 500 m³/year depositing at West Harbor.

The harbor analysis of the pre-construction conditions (Mid-Century time frame) at West Harbor indicated a depositional rate of 500 m³/year west of West Harbor and an erosion rate of 100 m³/year to the east, producing a net rate of change of 400 m³/year. The bluff analysis measured a total of 1,000 m³/year of sediment depositing at West Harbor. In the Recent time frame, the harbor analysis measured an accretion rate of 900 m³/year at West Harbor (800 m³/year west of the harbor and 100 m³/year to the east). The bluff analysis measured a total of 700 m³/year of sediment moving through the littoral system.

In the Future time frame, the incoming sediment load is predicted to decrease to 300 m³/year.

Table 14 gives predicted and measured sediment flux values at West Harbor.

Table 14. Predicted and measured volumetric change at West Harbor (all units in cubic meters/year).

| | Mid-Century | | Recent | | Future |
|-------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|
| | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs |
| East | | -100 | | 100 | |
| West | | 500 | | 800 | |
| Total | 1,000 | 400 | 700 | 900 | 300 |
| | Total Difference | 600 | Total Difference | -200 | -600 |
| | | 150% | | -22% | -67% |

The SBAS cells for West Harbor from the Mid-Century through the Future time frames are presented in Figures 26 through 28.

Figure 26. West Harbor Mid-Century sediment budget.

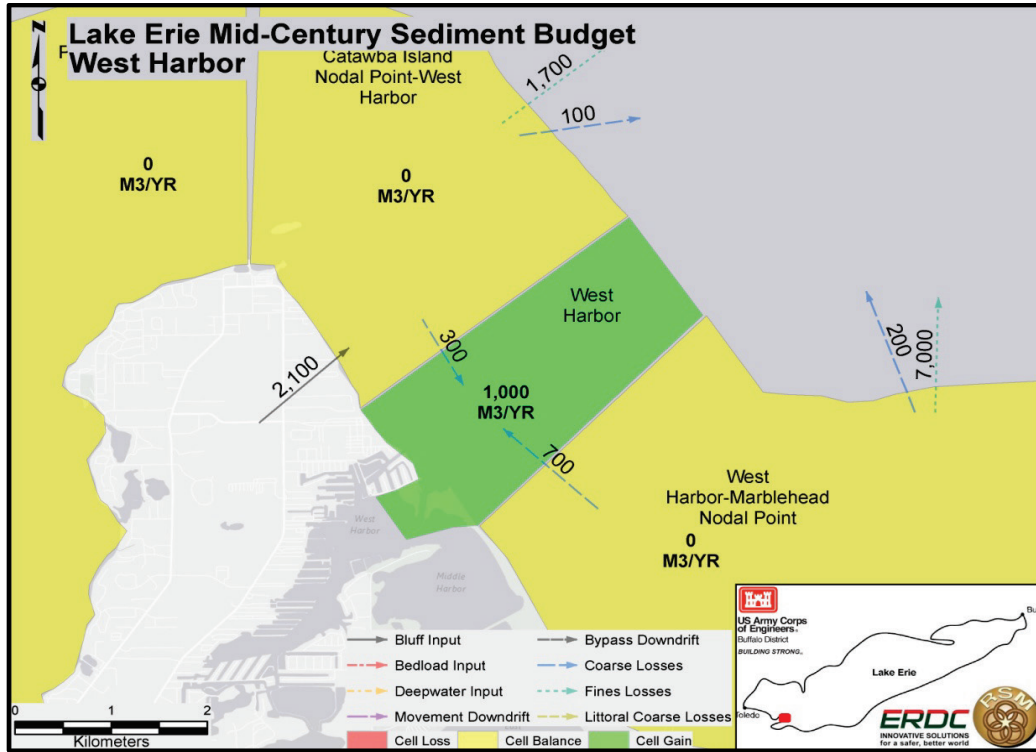


Figure 27. West Harbor Recent sediment budget.

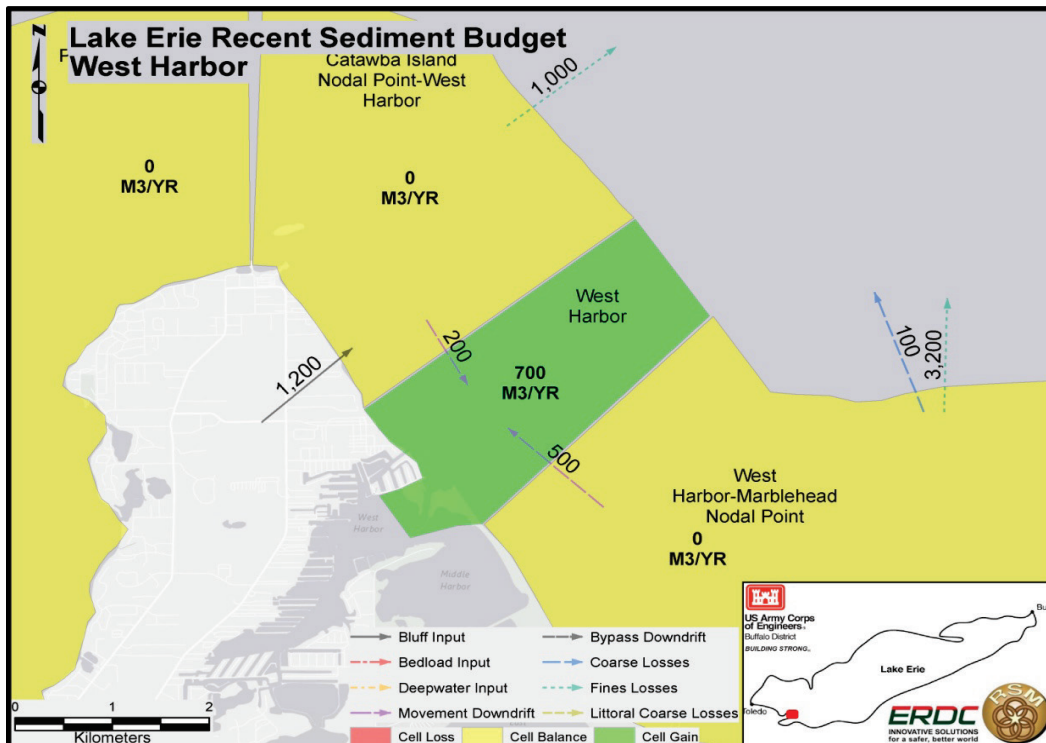
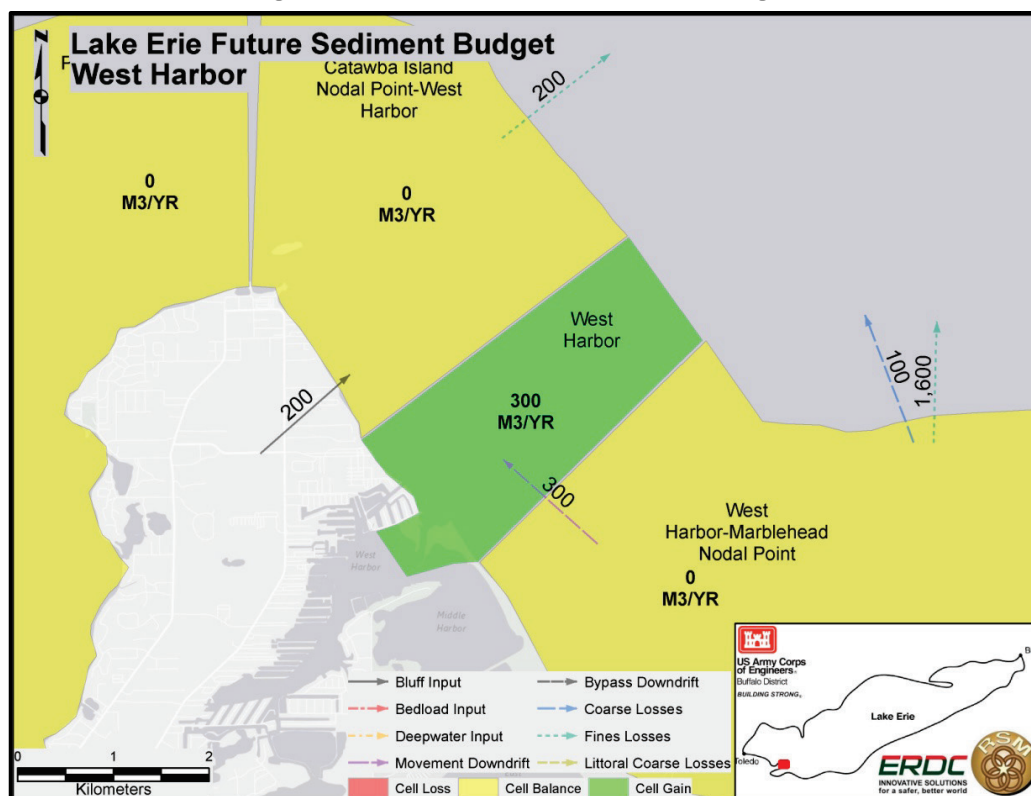


Figure 28. West Harbor Future sediment budget.



Huron Harbor

Huron Harbor structures consist of East (440 m long) and West (1075 m long) Breakwaters and a Confined Disposal Facility (CDF) operated by the Buffalo District. Construction of structures began in 1827 with installation of the East and West Piers. The east jetty was added in 1909, and the CDF was completed in 1974. The earliest data used for sediment computation date to 1877.

To model the budget at Huron Harbor, only a harbor cell was used (cell 12). Sediment movement in this area follows a predominantly east-to-west direction. With construction of the piers, erosion became the dominant process to the west of Huron Harbor, and the harbor change analysis measured an erosion rate of $-1,900 \text{ m}^3/\text{year}$. The region to the east of the harbor remained relatively stable, with a measured change of $-100 \text{ m}^3/\text{year}$. As the piers at Huron were constructed during this time frame, erosion to the west of the harbor was dominant while transport across the harbor decreased dramatically. The bluff analysis resulted in an input measurement of $5,000 \text{ m}^3/\text{year}$ into Huron Harbor. It is estimated that $1,300 \text{ m}^3/\text{year}$ was lost from Huron Harbor to the down-drift cell and

1,300 m³/year was lost to offshore during the Pre-Armoring time frame. This results in a net change at Huron Harbor of 2,500 m³/year. The difference between the estimated volumes from the bluff analysis and the measured volume change at the harbor during the Pre-Armoring time frame is likely a function of increased dredging activity at the harbor.

In the Mid-Century time frame, the harbor analysis measured an accretion rate of 4,600 m³/year (1,300 m³/year to the west of the harbor and 3,300 m³/year to the east). By this time frame, the erosion to the west of the harbor had stabilized, resulting in accretion due to short-term reversals in the LST direction. The east jetty was also constructed during this time frame, leading to deposition within the east basin and to the east of the harbor. The bluff analysis measured a total of 4,000 m³/year of sediment accreting in the Huron Harbor cell coming from the east.

In the Recent time frame, the harbor analysis measured an accretion rate of 4,600 m³/year (2,100 m³/year to the west of the harbor and 2,500 m³/year to the east). Shoreline hardening caused the volume of material measured from the bluffs coming into the eastern section of Huron Harbor to decrease to 2,300 m³/year. During this time frame, the CDF at Huron Harbor was completed, further protecting the western section of the harbor from erosion.

In the Future time frame, the incoming sediment load will decrease to 1,400 m³/year from the east due to shoreline hardening.

Table 15 gives predicted and measured sediment flux values at Huron Harbor.

Table 15. Predicted and measured volumetric change at Huron Harbor (all units in cubic meters/year).

| | Pre-Armoring | | Mid-Century | | Recent | | Future |
|-------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|
| | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs |
| East | | -100 | | 3,300 | | -200 | |
| West | | -1,900 | | 1,300 | | 2,100 | |
| Total | 2,500 | -2,000 | 4,000 | 4,600 | 2,300 | 1,900 | |
| | Total Difference | 4,500 | Total Difference | -600 | Total Difference | -400 | 1,400 |
| | | -225% | | -13% | | 21% | -26% |

The SBAS cells for Huron from the Pre-Armoring through the Future time frames are presented in Figures 29 through 32.

Figure 29. Huron Harbor Pre-Armoring sediment budget.

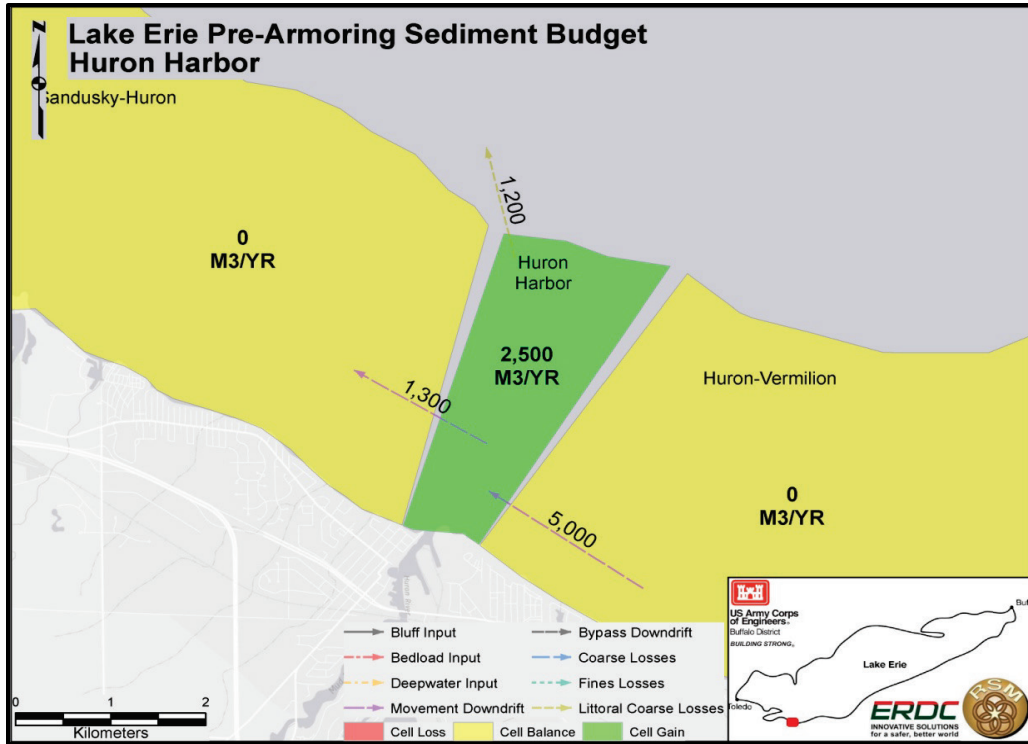


Figure 30. Huron Harbor Mid-Century sediment budget.

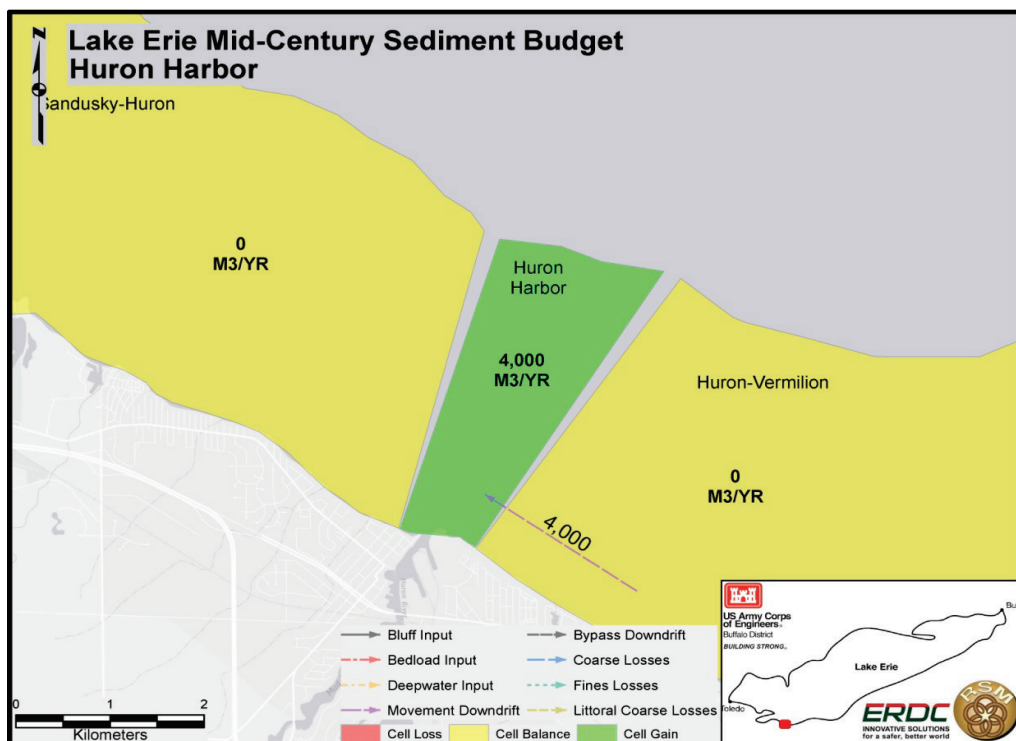


Figure 31. Huron Harbor Recent sediment budget.

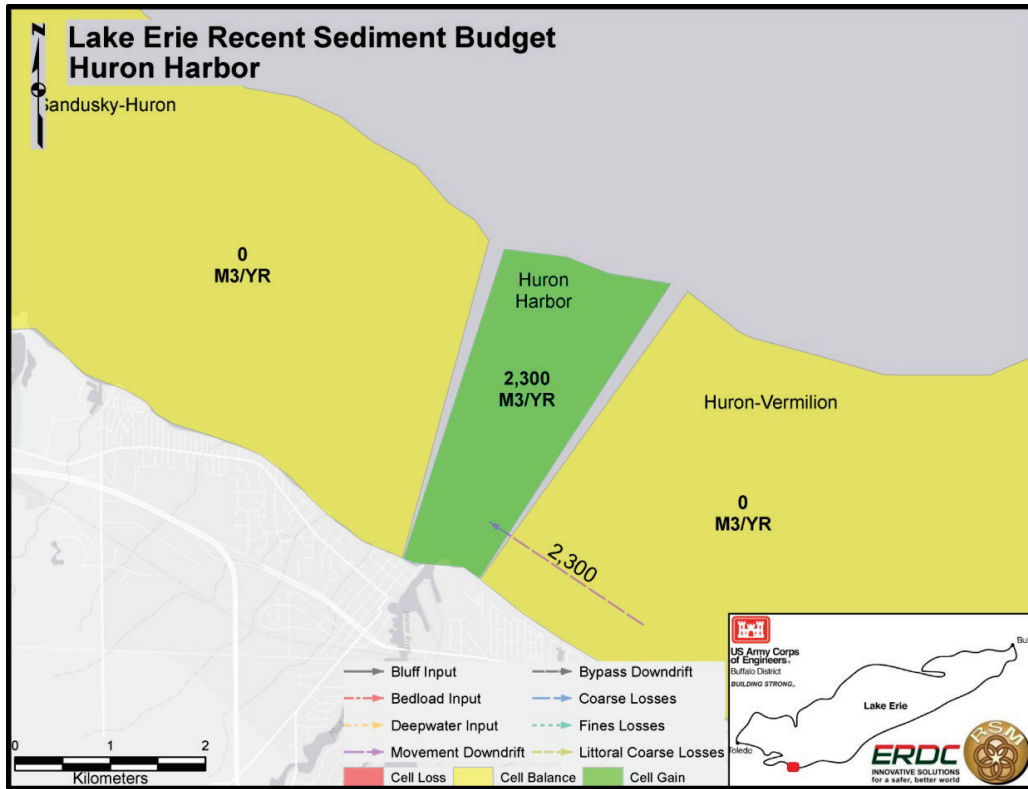
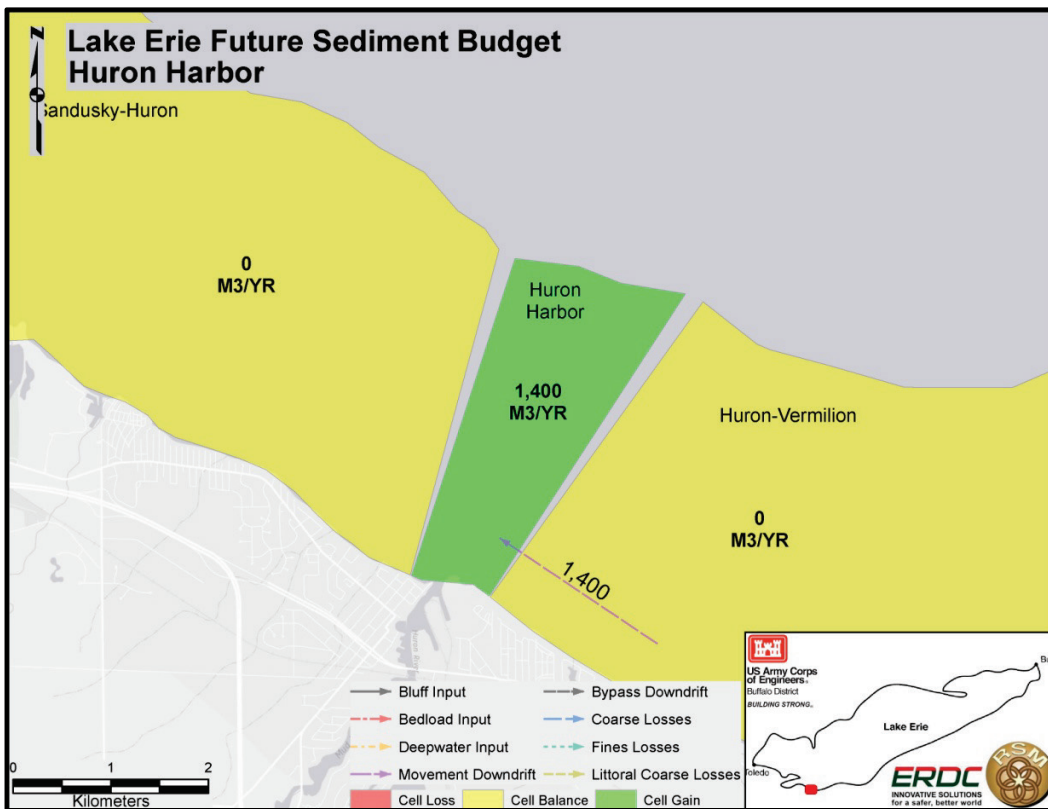


Figure 32. Huron Harbor Future sediment budget.



Vermilion Harbor, Beaver Park Marina, and Lorain Harbor, OH

Historically, the dominant direction of LST in this reach has been modeled from east to west, going from the Avon Lake Nodal Point east of Lorain and continuing west to Huron Harbor and farther to the west along the Cedar Point Peninsula. Analysis of aerial imagery, sedimentation rates at the harbors, and littoral volumes contributed to the system from bluff erosion has raised questions as to the dominant direction of LST.

A review of historical imagery indicates that the shoreline at Vermilion has been remarkably stable for both the Mid-Century and Recent time frames. Beaver Park Marina has been relatively stable on the east side while the west side underwent erosion in the Mid-Century time frame before accreting after construction of additional jetty in the Recent time frame. At Lorain, sediment accretes the east and west sides of the harbor.

Historic shorelines are overlain on the 2006 ortho-imagery for Vermilion Harbor, Beaver Park Marina, and Loraine Harbor in Figure 33, Figure 34, and Figure 35, respectively. Volumetric changes at Vermilion and Lorain Harbors are listed in Table 16, and bluff erosion volumes are listed in Table 17.

Table 16. Volumetric change rates at Lorain and Vermilion Harbors, OH (all units in cubic meters/year).

| Harbor-Region | Timeframe | | |
|----------------|--------------|-------------|--------|
| | Pre-Armoring | Mid-Century | Recent |
| Lorain-East | 2,600 | 6,000 | -200 |
| Lorain-West | 6,800 | 6,600 | 4,300 |
| Vermilion-East | 600 | 400 | 900 |
| Vermilion-West | 900 | 900 | 300 |

Table 17. LST Volumes from bluff erosion (all units in cubic meters/year).

| Littoral Cell | Coarse Contribution to Littoral System | | | |
|-------------------------------|--|-------------|--------|--------|
| | Pre-Armoring | Mid-Century | Recent | Future |
| To Lorain from East | 4,000 | 1,100 | 600 | 100 |
| Lorain-Beaver Park Marina, OH | 3,400 | 800 | 200 | 100 |
| Beaver Park Marina, OH | 400 | 200 | 100 | 100 |
| Beaver Park Marina-Vermilion | 3,700 | 2,200 | 2,200 | 800 |
| Vermilion Harbor Fillet | 200 | 100 | 100 | 100 |
| Total | 7,700 | 3,300 | 2,600 | 1,100 |

Figure 33. Historic shorelines and accretion rates at Vermilion Harbor, OH (inset map shows position along shoreline between Vermilion and Lorain, OH).



Figure 34. Historic shorelines at Beaver Park Marina, OH (inset map shows position along shoreline between Vermillion and Lorain, OH).

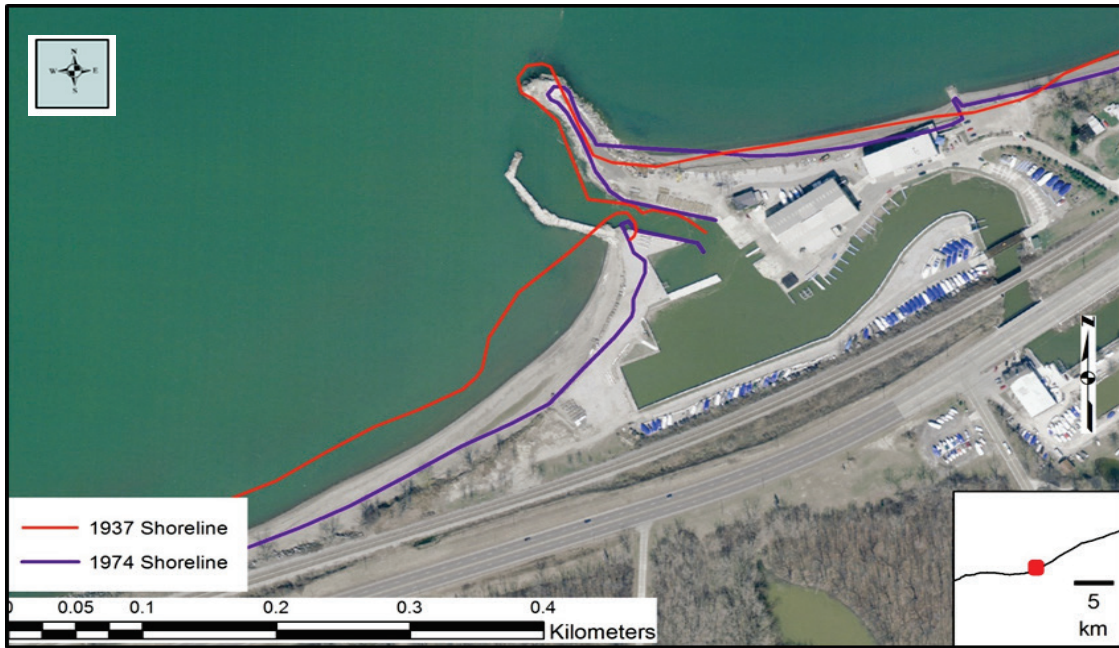
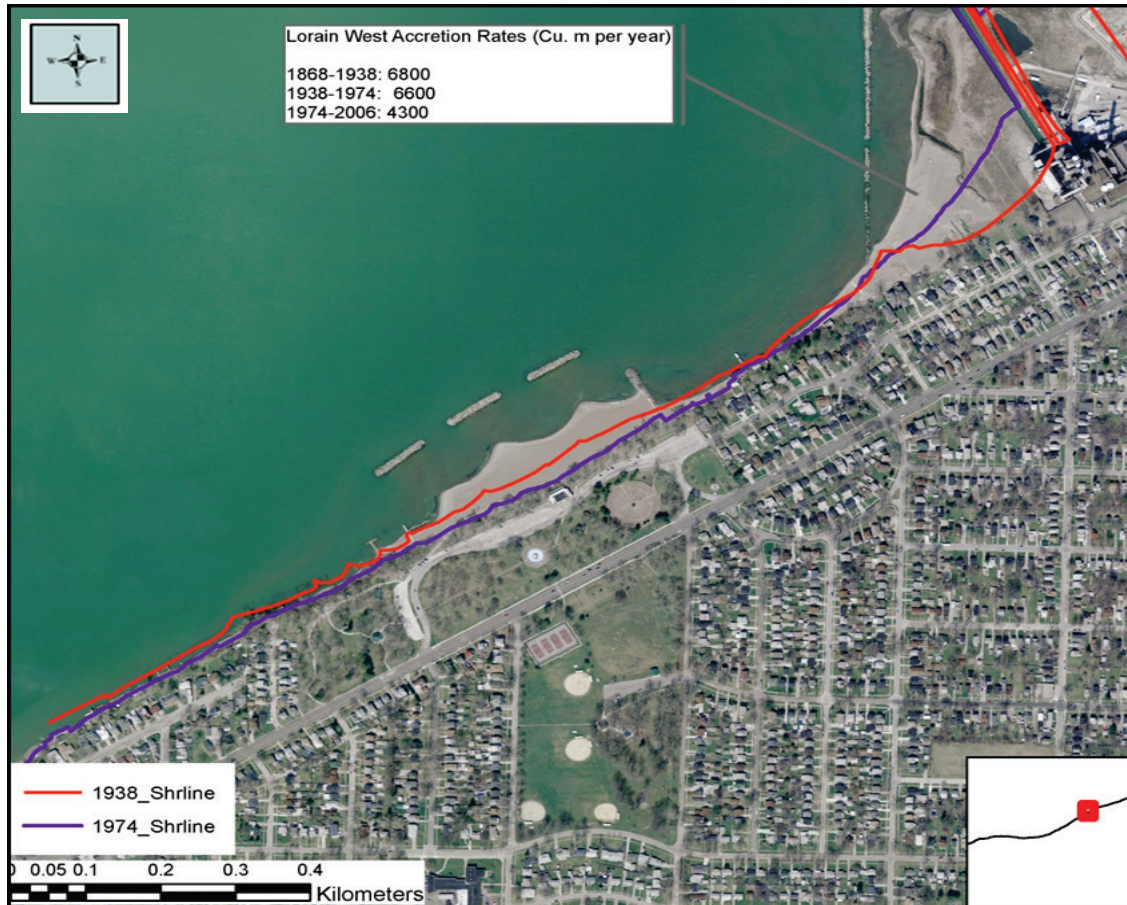


Figure 35. Historic shorelines and accretion rates at the west side of Lorain Harbor, OH (inset map shows position along shoreline between Vermillion and Lorain).



Vermilion Harbor

Vermilion Harbor structures consist of East (140 m long) and West (405 m long) Piers and a Detached Breakwater (263 m long). Construction of structures began in 1837, and the earliest data used for sediment computation date to 1874.

The uncertainty in dominant LST direction complicates budget modeling at Vermilion Harbor. Here, two cells were used: a harbor cell and a fillet cell (cells 14 and 15, respectively). The west side of Vermilion Harbor has remained very stable throughout all three time frames. The harbor analysis measured volumetric change rates in the harbor cell of Vermilion Harbor of 900, 900, and 300 m³/year for the Pre-Armoring, Mid-Century, and Recent time frames, respectively.

A substantial pocket beach or fillet leads up to the East Pier at Vermilion, but this beach has not increased substantially in volume during the period over which modeling occurred. The harbor analysis measured volumetric change rates in the fillet cell of Vermilion Harbor of 600, 400, and 900 m³/year for the Pre-Armoring, Mid-Century, and Recent time frames, respectively.

Beaver Park Marina

Beaver Park Marina structures consist of east (180 m long) and west (160 m long) jetties. The east jetty has been in place at least since 1937 while the west jetty was built sometime between 1974 and 2006. A volumetric computation was not carried out at Beaver Park Marina due to a lack of bathymetric data, but visual observation shows that the shoreline along the west jetty was eroding up to the construction of the jetty and has been accreting since while the shoreline along the east jetty has been stable since the Mid-Century time frame. The lack of change along the east jetty as well as the accretion west of the harbor since construction of the west jetty indicates that LST is predominantly west to east.

Lorain Harbor

Lorain Harbor structures consist of East and West piers (East, 615 m long; West, 990 m long), and Outer (665 m long) Breakwaters, and East (708 m long) and West (229 m long) Shorearm Breakwaters. Construction began in 1828, but the earliest data available for sediment computation date to 1865.

Short-term reversals to the LST direction occur in this area, but the magnitude of these reversals has not been quantified. Because of this, determination of sediment fluxes at Lorain Harbor is challenging. To model the budget at Lorain, two cells were used: a west cell and an east cell (cells 19 and 20, respectively).

The west basin has undergone accretion in all three time frames, demonstrating the presence of a west-to-east component of LST along this stretch of shoreline. The measured accretion rate in the west cell has decreased moderately over the course of the three time frames, from 6,800 m³/year in the Pre-Armoring time frame, to 6,600 m³/year in the Mid-Century time frame, to 4,300 m³/year in the Recent time frame. Due to structure construction and creation of a deep-water navigation channel, it is unlikely that sediment was transported across the harbor from the east to the west side.

The east cell underwent accretion for the Pre-Armoring and Mid-Century time frames but had a net loss of material in the Recent time frame. Computation of sediment accumulation in the Recent time frame was impeded by the construction of a confined disposal facility (CDF) and Small Boat Harbor, thus shifting the areas from which volume change was measured. The recent lidar acquisition at Lorain Harbor failed to capture bathymetric data, further limiting data analysis. The harbor analysis measured volumetric change rates in the east cell of Lorain Harbor at 2,600 m³/year, 6,000 m³/year, and -200 m³/year for the Pre-Armoring, Mid-Century, and Recent time frames, respectively. LST from the east for the three time frames was measured to be 4,000 m³/year, 1,100 m³/year, and 600 m³/year, respectively.

Discussion and modeling

To model this reach within SBAS, the LST direction on the east side of Lorain was assumed to be east to west, depositing sediment into the Lorain Harbor east cell. Between Lorain Harbor and Beaver Park Marina, the LST was assumed to be west to east, depositing sediment in the Lorain Harbor west cell. Between Beaver Park Marina and Lorain, the dominant direction of sediment movement is not clear, so sediment transport was modeled to be bidirectional, with some sediment depositing at Vermilion and some at Beaver Park Marina. At Beaver Park Marina prior to the construction of the west jetty, it was assumed that sediment was transported around the marina from west into the Lorain-Beaver Park Marina cell, eventually being deposited in the Lorain Harbor west cell.

After the jetty was constructed, sediment from the Beaver Park Marina-Vermilion Cell was trapped at the marina. Additionally, there is a small component of LST that is west to east, trapping material just to the west of Vermilion Harbor

Other assumptions

1. At Beaver Park Marina after the construction of the west jetty, one-third of LST is trapped in the fillet, one-third of LST is lost offshore, and the final-third of LST continues to Lorain Harbor.
2. Outputs from the Beaver Park Marina-Vermilion Cell
 - a. Pre-Armoring: 1,500 m³/year LST to the west, remainder to the east
 - b. Mid-Century: 1,100 m³/year LST to the west, remainder to the east
 - c. Recent: 800 m³/year LST to the west, remainder to the east
 - d. Future: 600 m³/year LST to the west, remainder to the east
3. Vermilion Harbor transport
 - a. Pre-Armoring: 900 m³/year LST from Vermilion Harbor fillet cell, 300 m³/year LST from the Vermilion-Huron cell
 - b. Mid-Century: 700 m³/year LST from Vermilion Harbor fillet cell, 300 m³/year LST from the Vermilion-Huron cell
 - c. Recent: 500 m³/year LST from Vermilion Harbor fillet cell, 300 m³/year LST from the Vermilion-Huron cell
 - d. Future: 300 m³/year LST from Vermilion Harbor fillet cell, 200 m³/year LST from the Vermilion-Huron cell

Tables 18 and 19 give the predicted and measured sediment flux values at Vermilion and Lorain Harbors, respectively.

Table 18. Predicted and measured volumetric change at Vermilion Harbor (all units in cubic meters/year).

| | Pre-Armoring | | Mid-Century | | Recent | | Future |
|-------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|
| | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs |
| East | 800 | 600 | 500 | 400 | 400 | 900 | 400 |
| West | 1,200 | 900 | 1,000 | 900 | 800 | 300 | 500 |
| Total | 2,000 | 1,500 | 1,500 | 1,300 | 1,200 | 1,200 | 900 |
| | Total Difference | 500 | Total Difference | 200 | Total Difference | 0 | -300 |
| | | 33% | | 15% | | 0 | -25% |

Table 19. Predicted and measured volumetric change at Lorain Harbor (all units in cubic meters/year).

| | Pre-Armoring | | Mid-Century | | Recent | | Future |
|------------------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|
| | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs |
| East | 4,000 | 2,600 | 1,100 | 6,000 | 600 | -200 | 100 |
| West | 6,200 | 6,800 | 2,200 | 6,600 | 700 | 4,300 | 200 |
| Total | 10,200 | 9,400 | 3,300 | 12,600 | 1,300 | 4,100 | 300 |
| Total Difference | | 800 | | -9,300 | | -2,800 | |
| | | 31% | | -155% | | -68% | |

The SBAS cells for Vermilion Harbor, Beaver Creek Marina, and Lorain Harbor from the Pre-Armoring through the Future time frames are presented in Figures 36 through 47.

Figure 36. Vermilion Harbor Pre-Armoring sediment budget.

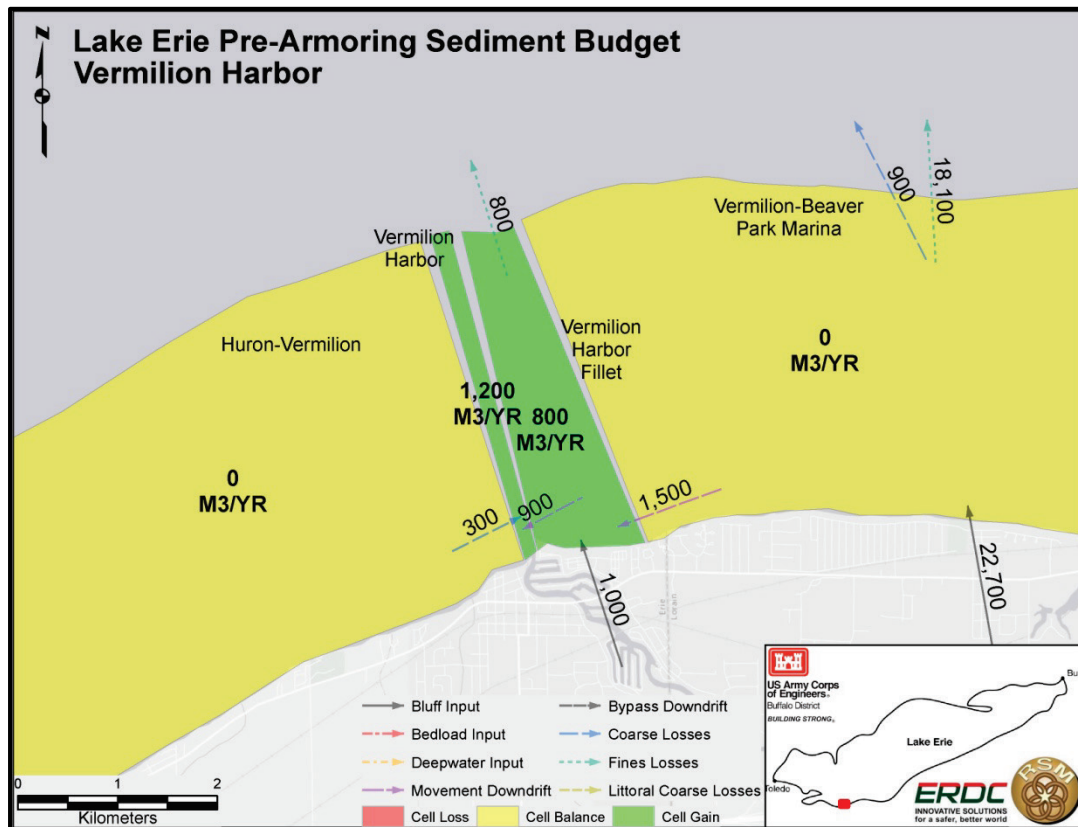


Figure 37. Vermilion Harbor Mid-Century sediment budget.

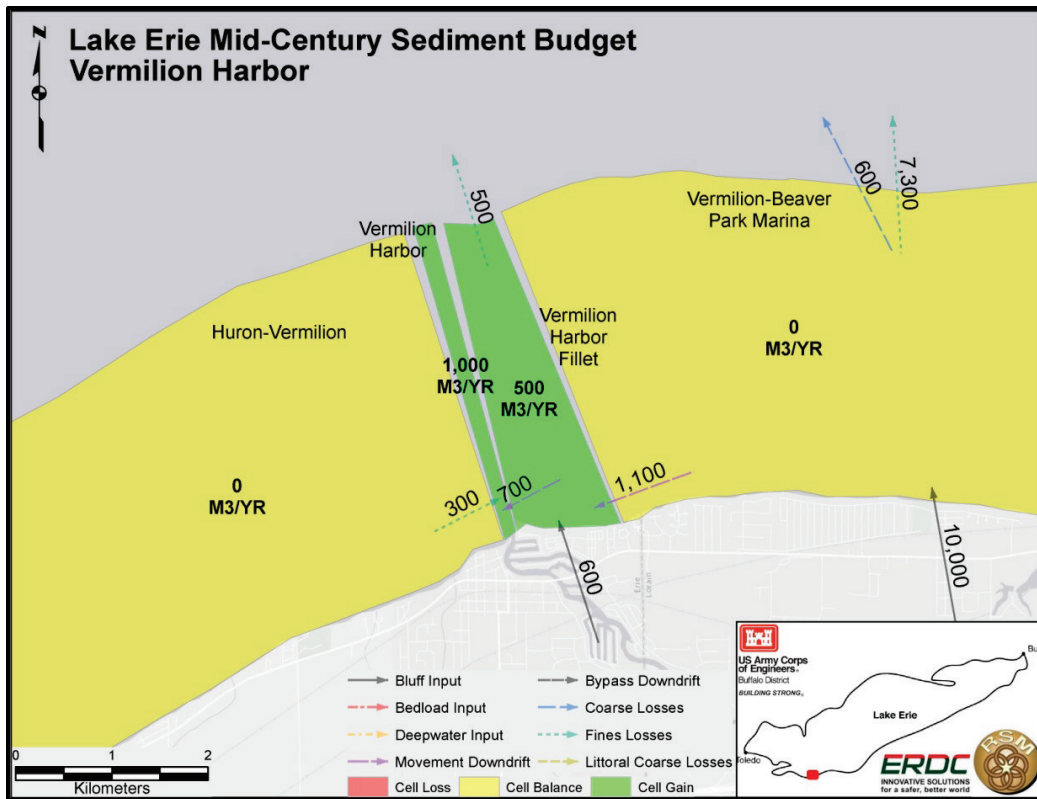


Figure 38. Vermilion Harbor Recent sediment budget.

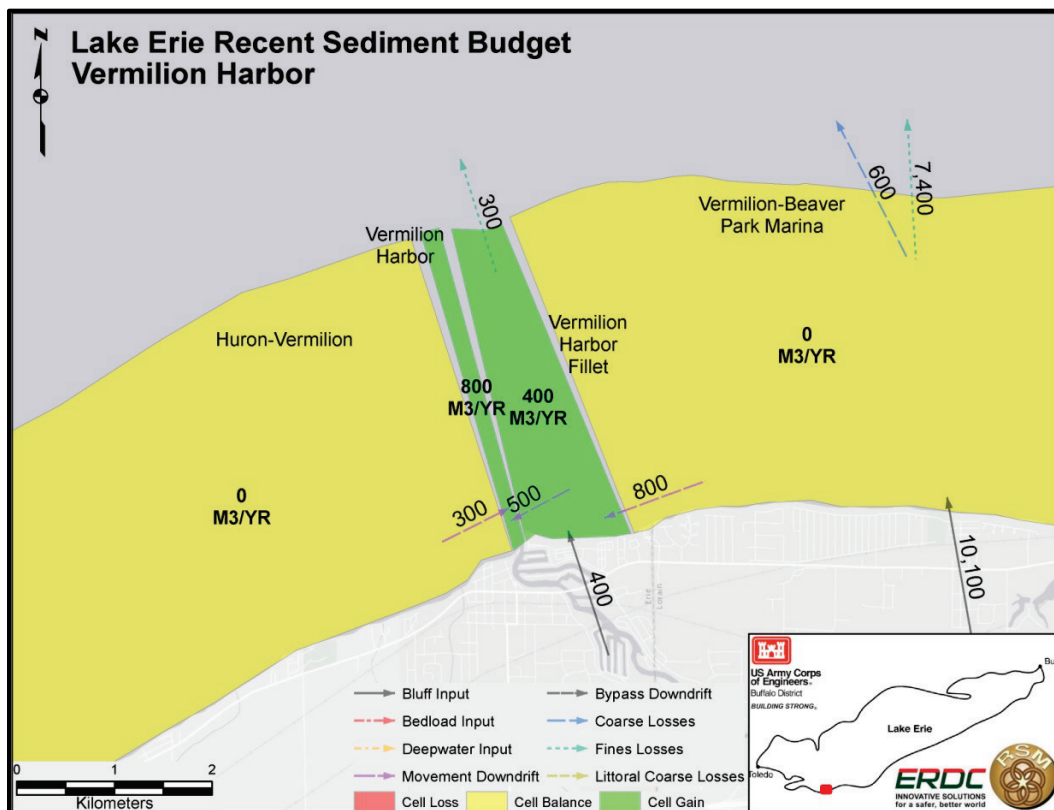


Figure 39. Vermilion Harbor Future sediment budget.

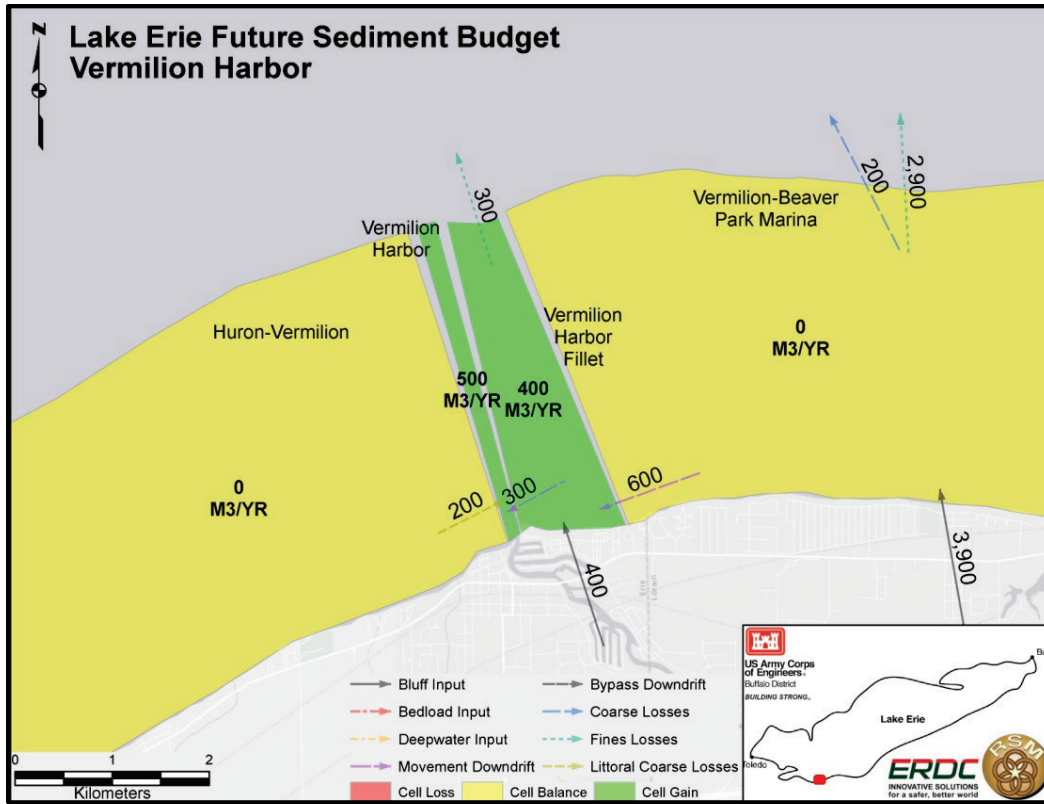


Figure 40. Beaver Park Marina Pre-Armoring sediment budget.

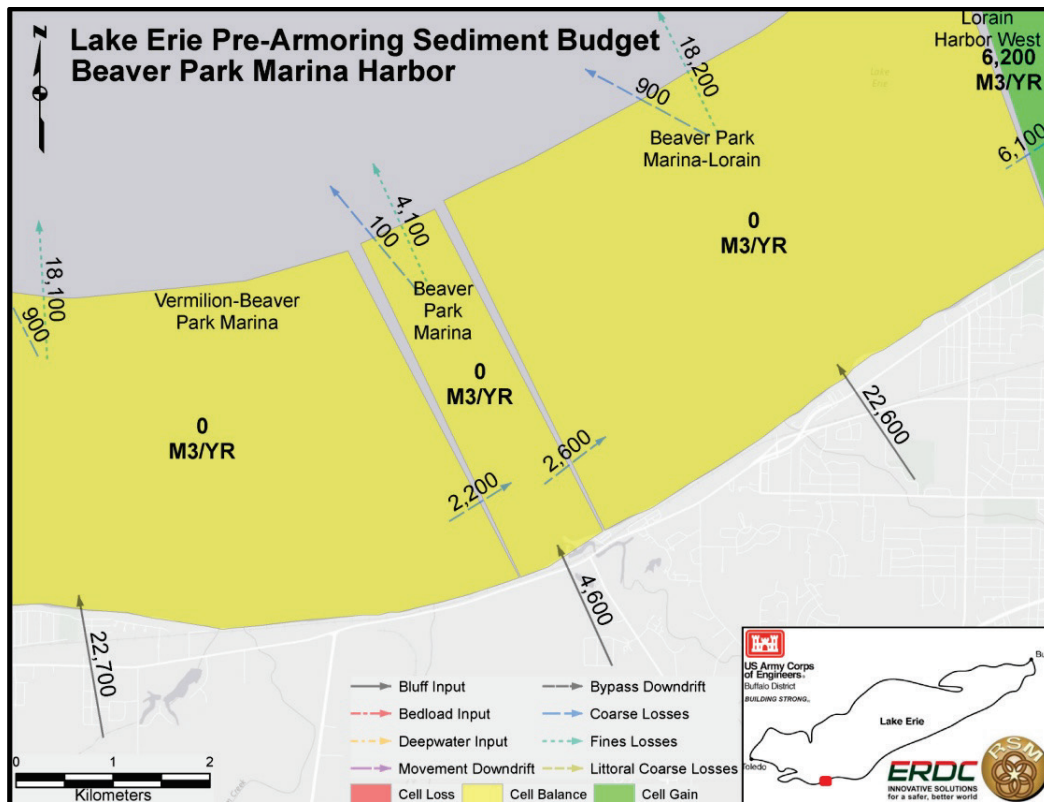


Figure 41. Beaver Park Marina Mid-Century sediment budget.

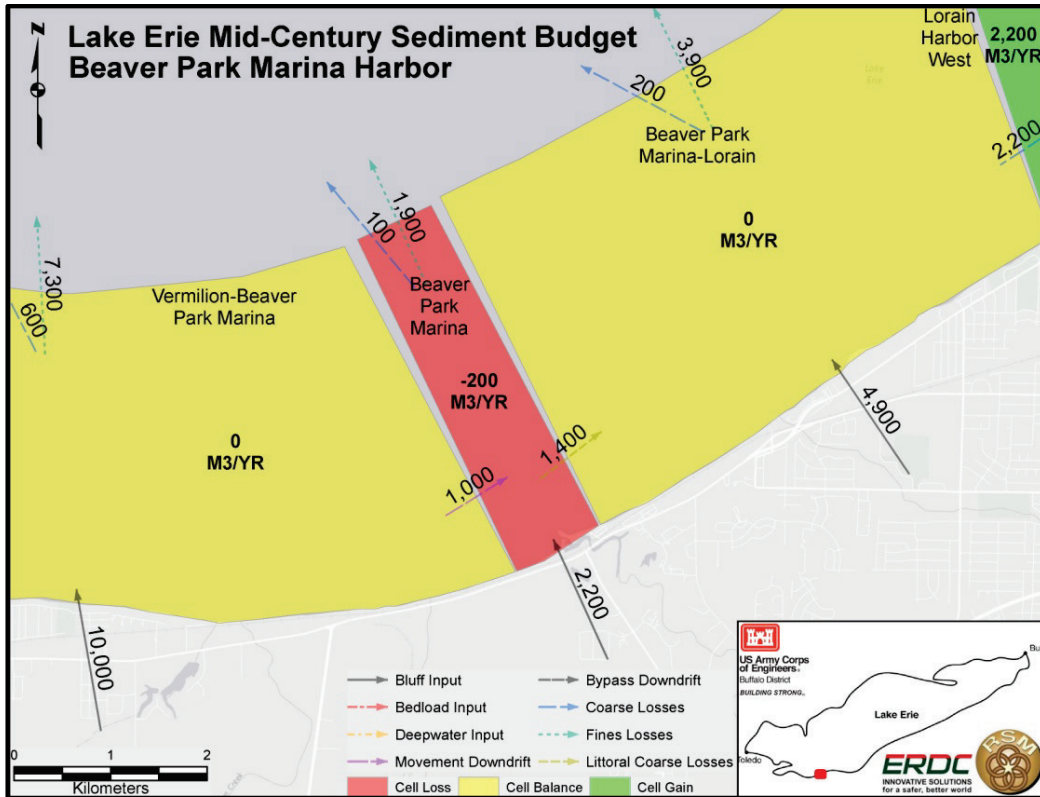


Figure 42. Beaver Park Marina Recent sediment budget.

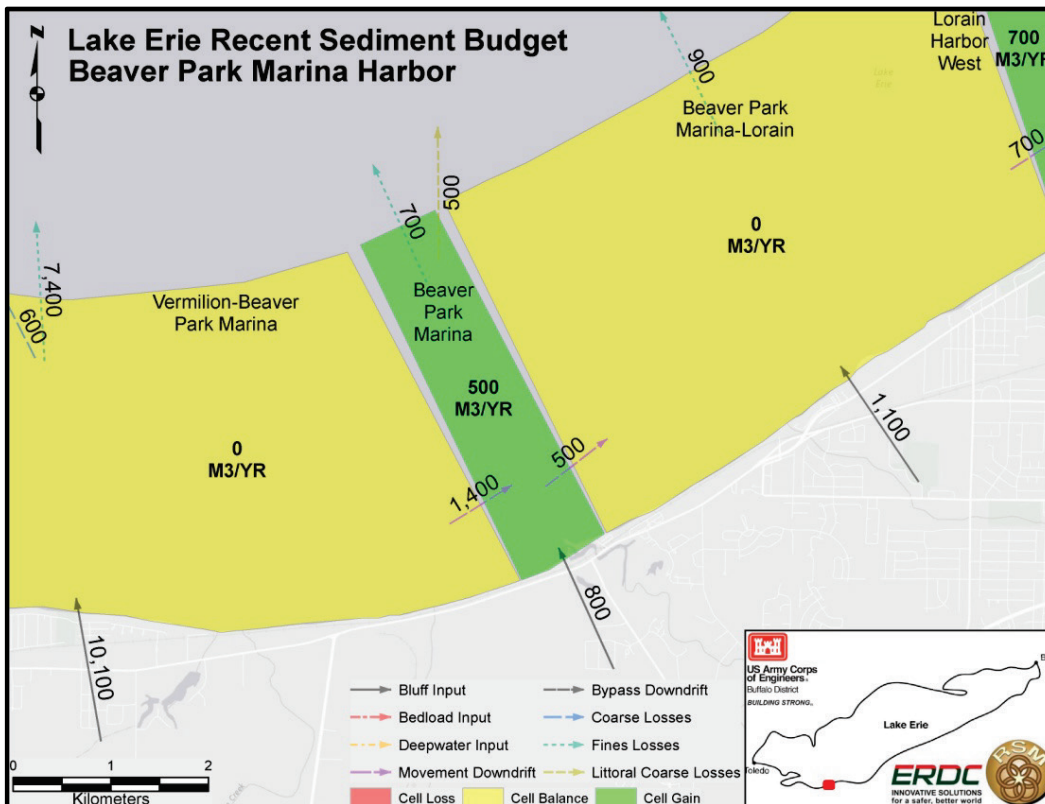


Figure 43. Beaver Park Marina Future sediment budget.

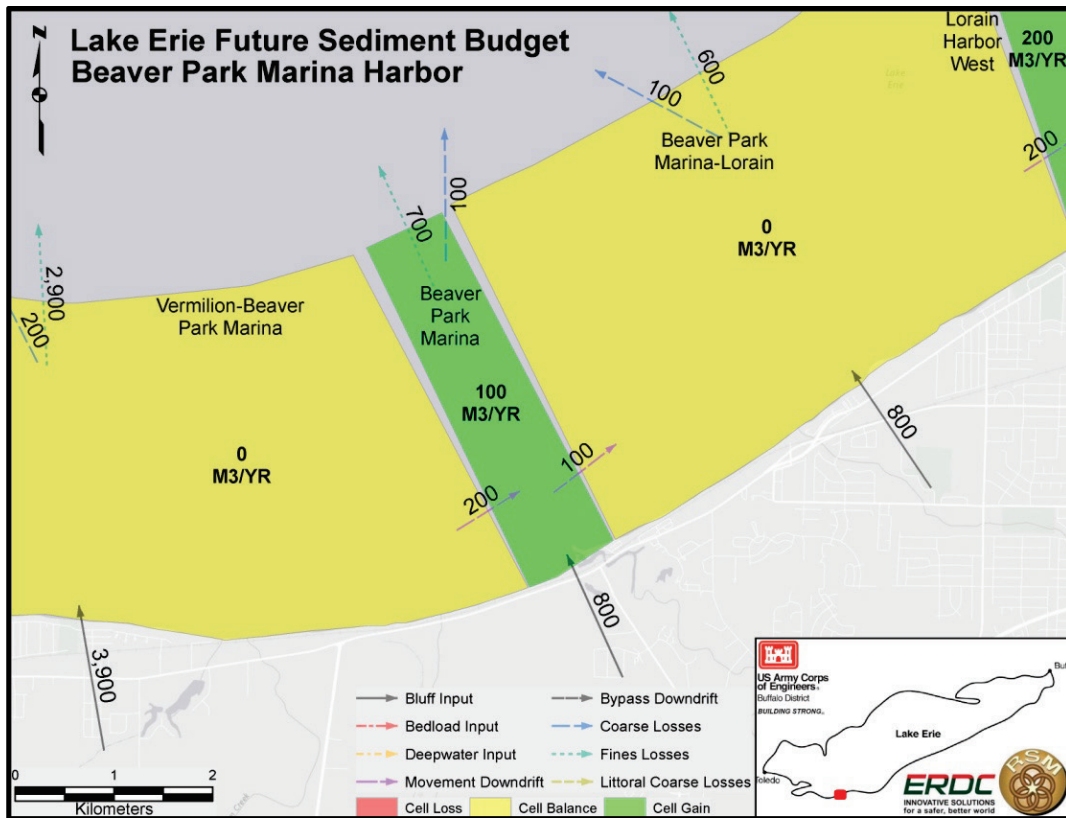


Figure 44. Lorain Harbor Pre-Armoring sediment budget.

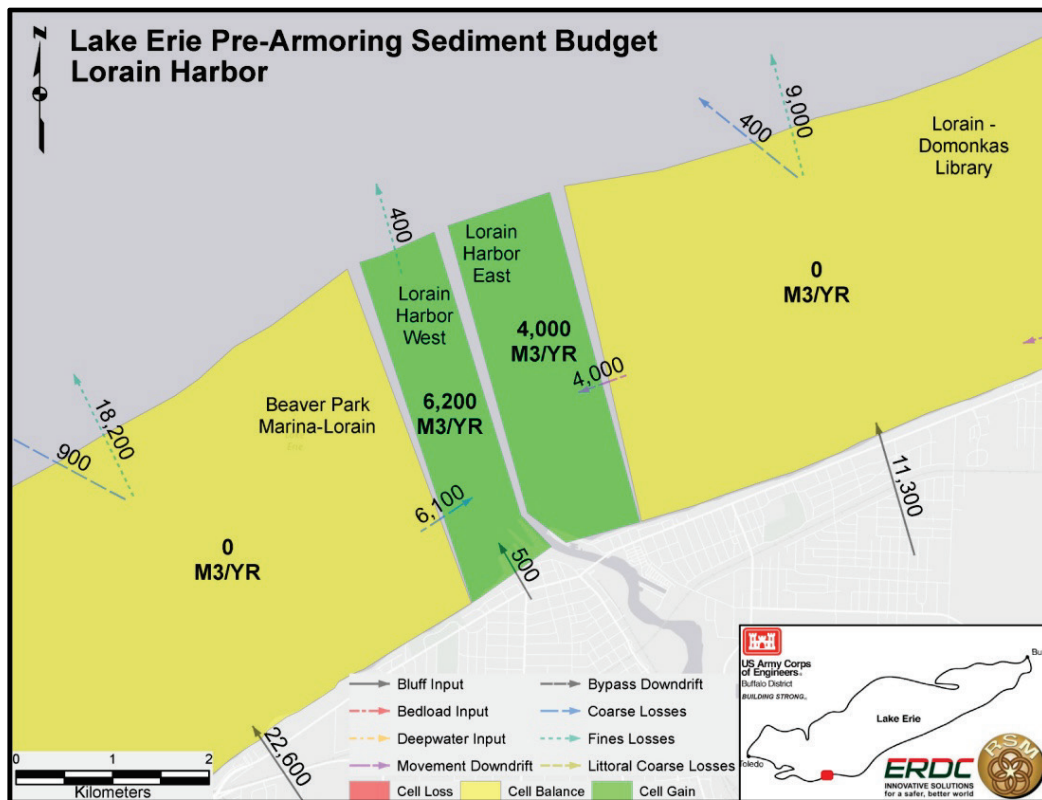


Figure 45. Lorain Harbor Mid-Century sediment budget.

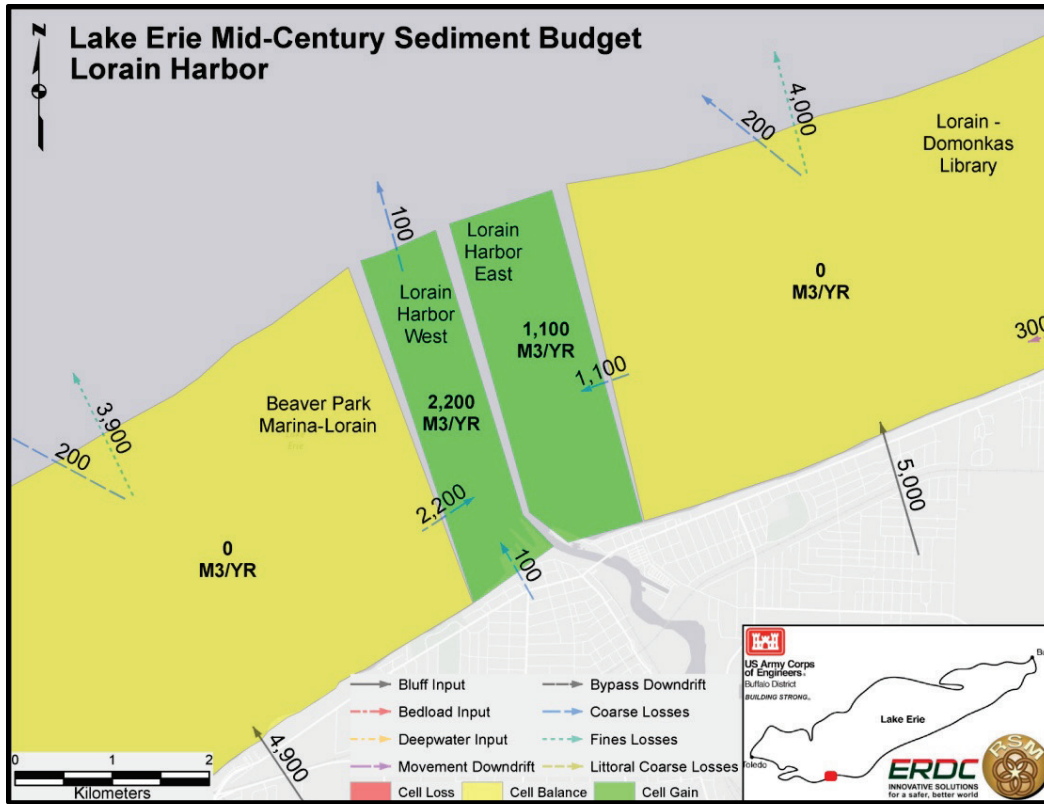


Figure 46. Lorain Harbor Recent sediment budget.

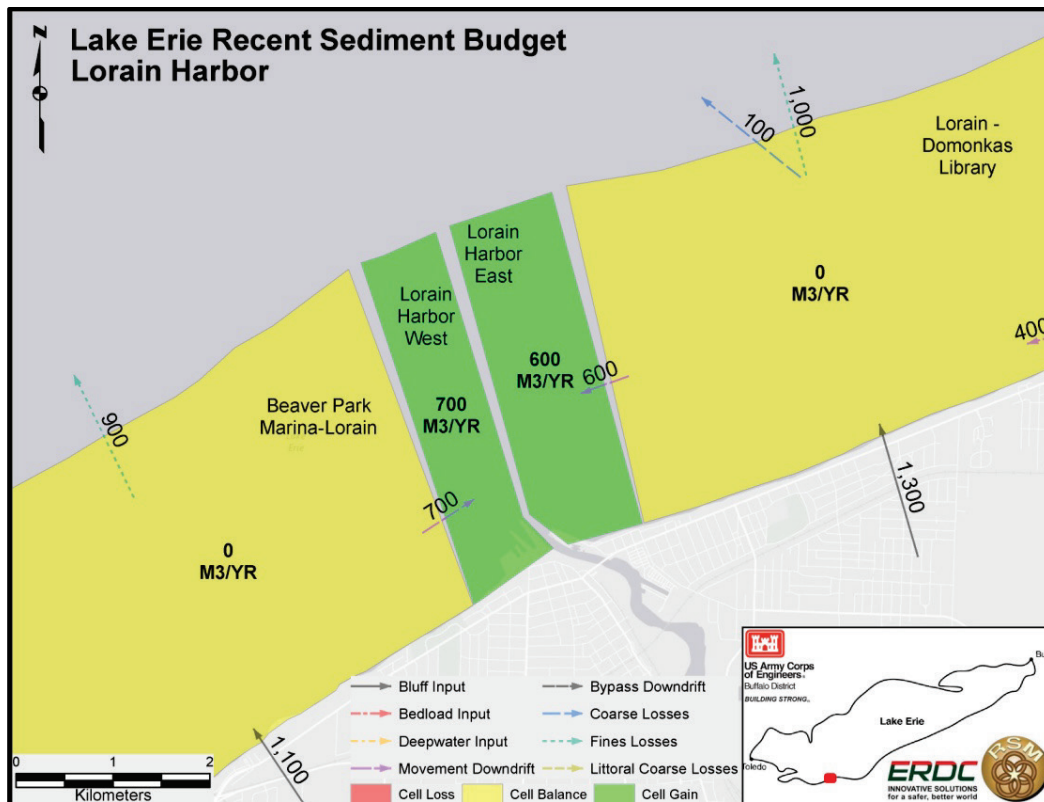
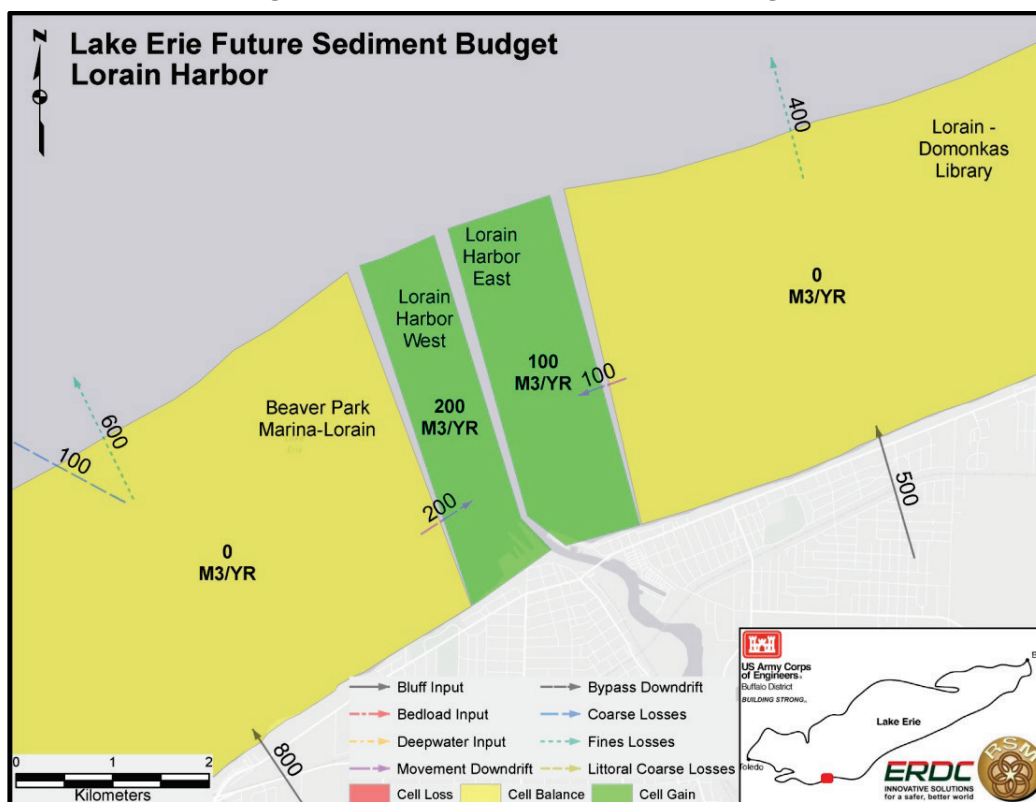


Figure 47. Lorain Harbor Future sediment budget.



Fairport Harbor, OH

Fairport Harbor structures consist of East and West Piers, and East (2,057 m long) and West (1,182 m long) Breakwaters. Construction of structures began in 1827. The earliest data used for sediment computation date to 1878.

To model the budget at Fairport, two cells were used: a fillet cell and a harbor cell (cells 41 and 42, respectively). The harbor cell has been accreting at an increasing rate since the construction of the piers, and the fillet sediments began accreting rapidly with the completion of the connection of the West Breakwater to shore in 1908. As the fillet began to fill, sediment began to pass over and through the shore-arm into the harbor. The littoral material entering Fairport Harbor from bluff recession was consistently less than measured sediment accumulation based on historic bathymetric data.

The harbor analysis at Fairport Harbor indicated a depositional rate of 55,900 m³/year within the harbor in the Pre-Armoring time frame while sediment deposited at a rate of 5,000 m³/year in the fillet. The bluff

analysis measured a total of 33,600 m³/year of sediment moving into Fairport; of this, 5,000 m³/year is modeled to have deposited within the harbor, and 28,600 m³/year is modeled to have deposited within the fillet.

In the Mid-Century time frame, the harbor analysis measured an accretion rate of 90,000 m³/year (85,000 m³/year in the fillet and 5,000 m³/year in the harbor). The bluff analysis measured a total of 23,300 m³/year of sediment moving through the littoral system. Of this, 18,300 m³/year was modeled to deposit in the fillet while 5,000 m³/year was modeled to deposit in the harbor.

In the Recent time frame, the harbor analysis measured an accretion rate of 13,700 m³/year (9,100 m³/year in the fillet and 4,600 m³/year in the harbor). The bluff analysis measured a total of 12,500 m³/year of sediment moving through the system. Of this, 7,900 m³/year was modeled to deposit within the fillet, and 4,600 m³/year was modeled to deposit in the harbor.

In the Future time frame, the incoming sediment load will decrease to 8,000 m³/year, with a deposition rate of 4,600 m³/year in the fillet and 3,400 m³/year in the harbor.

Table 20 gives predicted and measured sediment flux values at Fairport Harbor.

Table 20. Predicted and measured volumetric change at Fairport Harbor (all units in cubic meters/year).

| | Pre-Armoring | | Mid-Century | | Recent | | Future |
|--------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|
| | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs |
| Fillet | 28,600 | 55,900 | 18,300 | 85,000 | 7,900 | 9,100 | 3,400 |
| Harbor | 5,000 | 5,000 | 5,000 | 5,000 | 4,600 | 4,600 | 4,600 |
| Total | 33,600 | 60,900 | 23,300 | 90,000 | 12,500 | 13,700 | 8,000 |
| | Total Difference | -27,300 | Total Difference | -66,700 | Total Difference | -1,200 | -5,700 |
| | | -45% | | -74% | | -9% | -42% |

The SBAS cells for Fairport from the Pre-Armoring through the Future time frames are presented in Figures 48 through 51.

Figure 48. Fairport Harbor Pre-Armoring sediment budget.

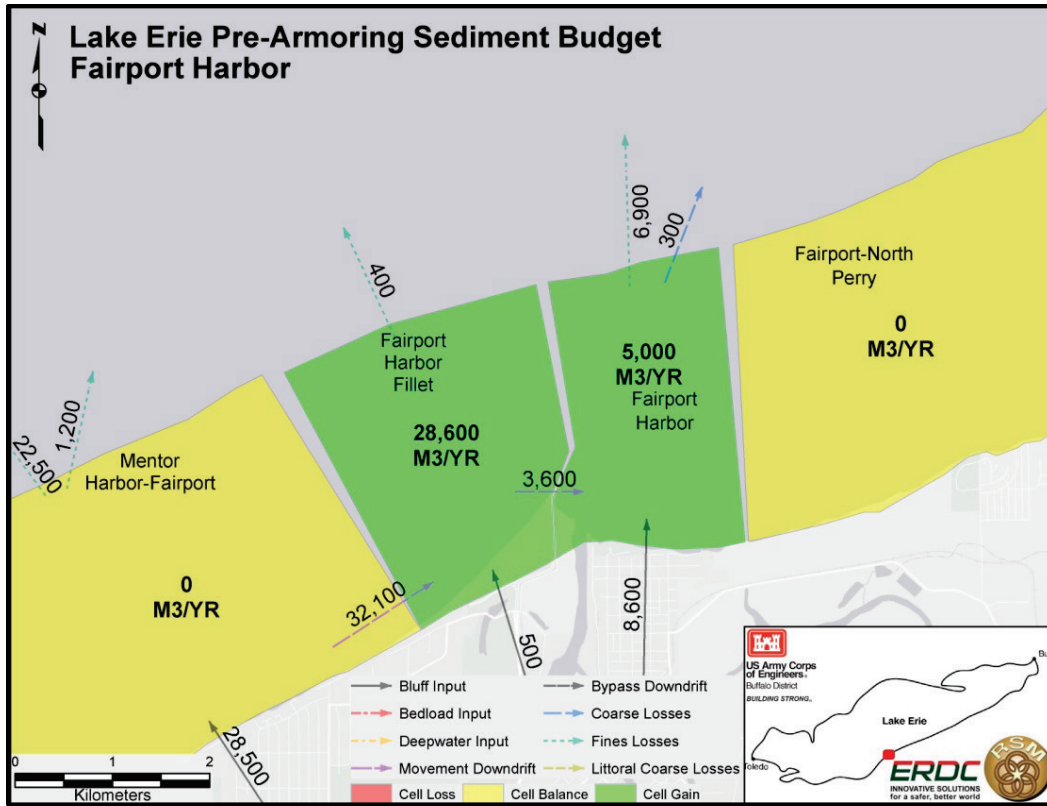


Figure 49. Fairport Harbor Mid-Century sediment budget.

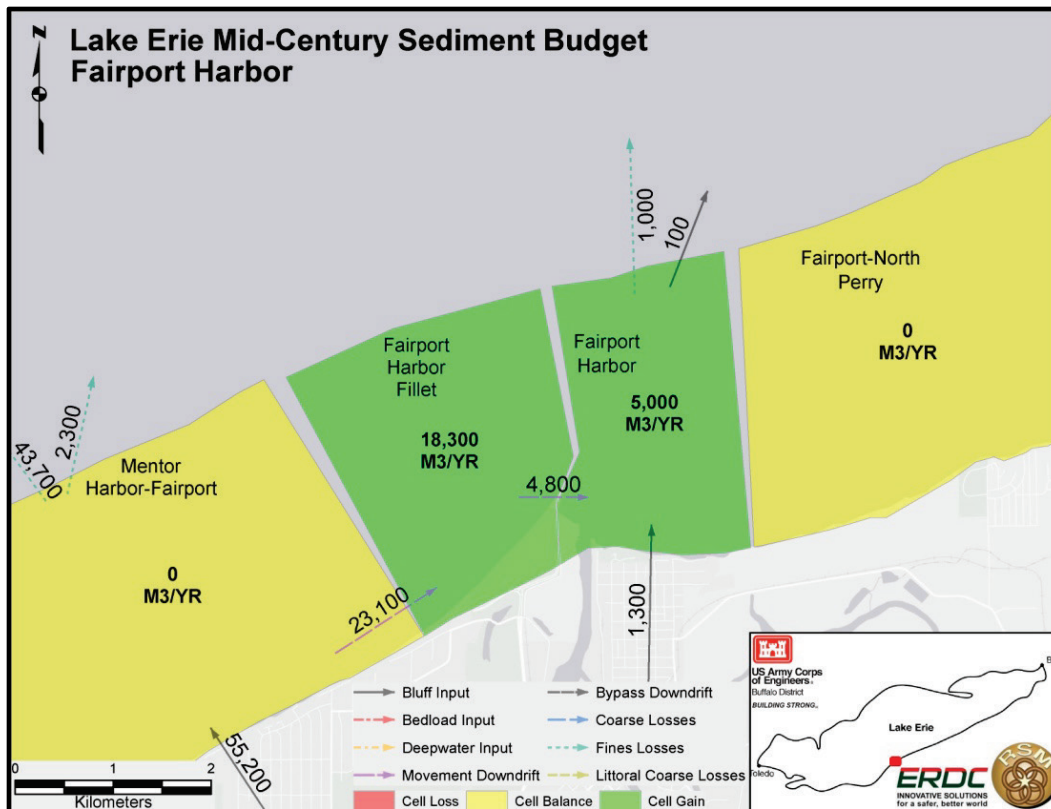


Figure 50. Fairport Harbor Recent sediment budget.

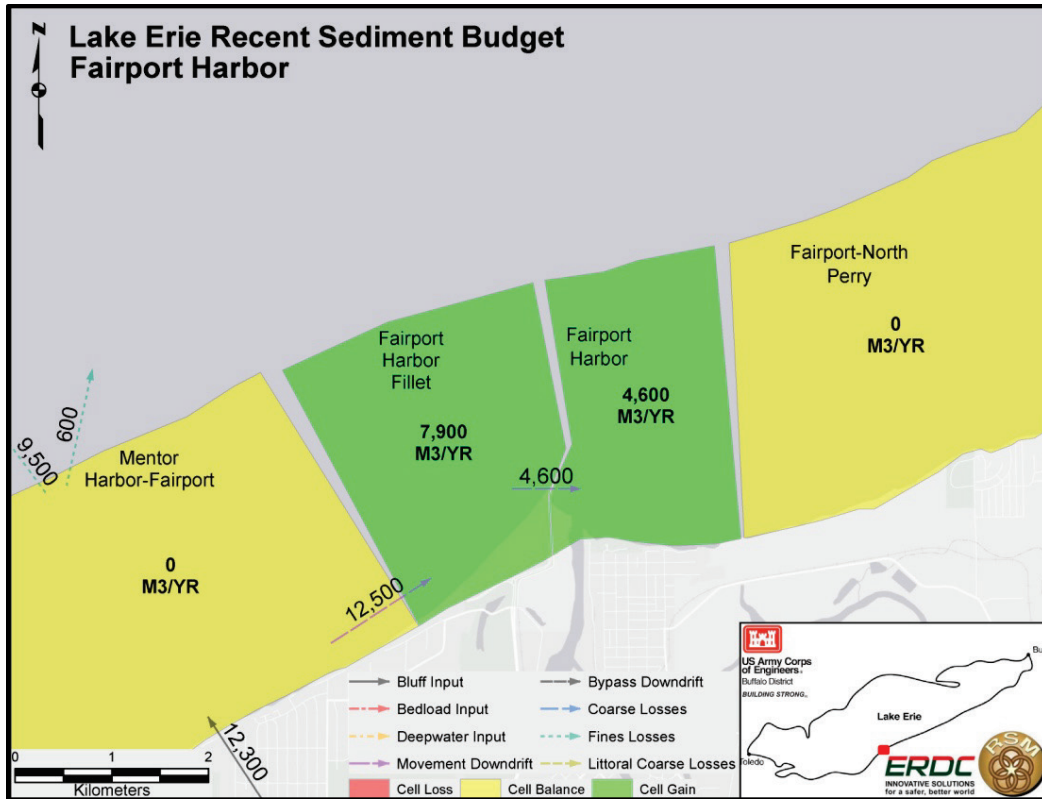
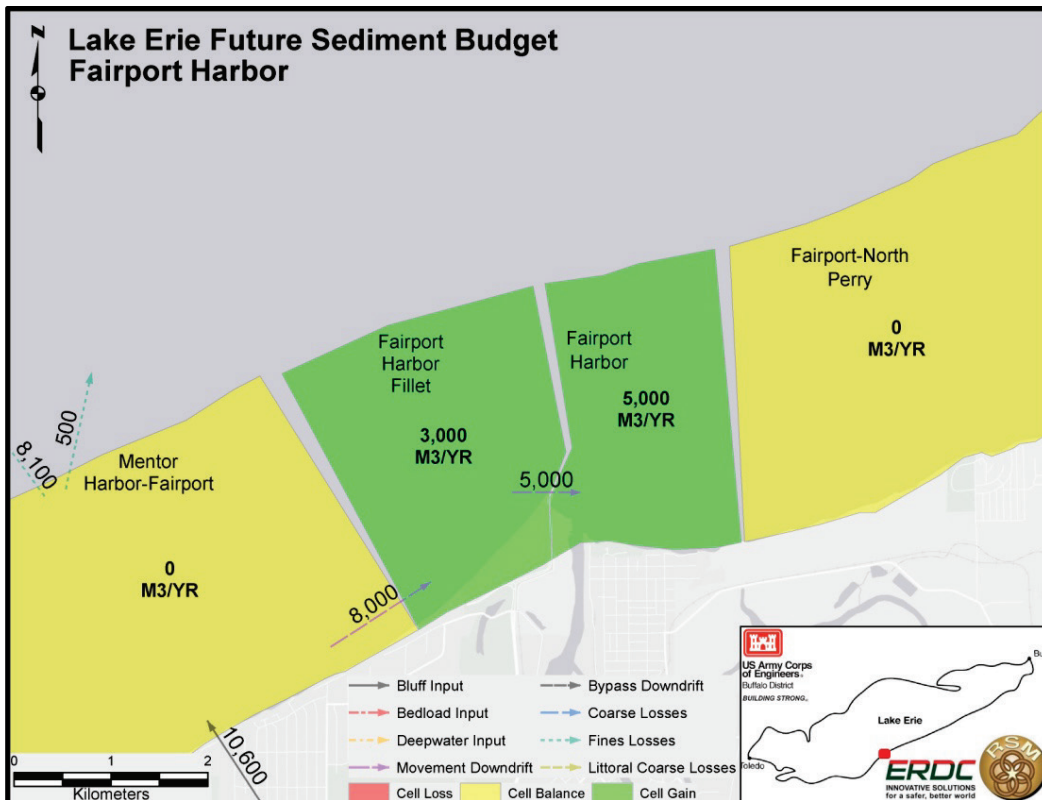


Figure 51. Fairport Harbor Future sediment budget.



Geneva-on-the-Lake Harbor, OH

Geneva-on-the-Lake Harbor structures consist of shore-attached east and west breakwaters (aggregated length 505 m). Breakwater construction was completed between 1986 to 1987. To model the budget at Geneva-on-the-Lake Harbor, two cells were used: a fillet cell and a harbor cell (cells 37 and 36, respectively). Preconstruction drawings contained bathymetric data, but the 2007 lidar flight failed to capture data below the waterline due to turbidity, so sediment accumulation could only be computed for the above-water portion of the fillet.

The Pre-Armoring and Mid-Century time frames predate the construction of the harbor, so the fillet and harbor cells did not trap any sediment. Since completion of the harbor, an average of 2,550 m³/year has accumulated in the fillet at Geneva-on-the-Lake. As this only measured the accumulation above the waterline, 5,000 m³/year of accretion was modeled in the fillet at Geneva-on-the-Lake Harbor, with an additional 500 m³/year depositing in the harbor cell.

USACE (1982) predicted a total flux of 25,500 m³/year of sediment moving through the littoral system at Geneva-on-the-Lake Harbor. This sediment budget reflects the longshore transport in the Mid-Century time frame. Because of changing shore conditions, the longshore transport rate in the Pre-Armoring time frame was assumed to be 20% greater than the Mid-Century amount.

Table 21 presents the sediment flux at Geneva-on-the-Lake Harbor from erosion of the bluffs between the harbor and Fairport Harbor, OH, and the values presented by USACE (1982) as Phase II GDM.

Table 21. Predicted and measured volumetric change at Geneva-on-the-Lake Harbor (all units in cubic meters/year).

| Pre-Armoring | | Mid-century | | Recent | | Future |
|---------------------------------|--------------|---------------------------------|--------------|---------------------------------|--------------|---------------------------------|
| Calculated Sediment from Bluffs | Phase II GDM | Calculated Sediment from Bluffs | Phase II GDM | Calculated Sediment from Bluffs | Phase II GDM | Calculated Sediment from Bluffs |
| 37,900 | 30,600 | 45,100 | 25,500 | 44,800 | 25,500 | 34,700 |
| Total Difference | 7,300 | Total Difference | 19,600 | Total Difference | 19,300 | 9,200 |
| | 24% | | 77% | | 76% | 36% |

The SBAS cells for Geneva-on-the-Lake Harbor from the Recent and Future time frames are presented in Figures 52 and 53, respectively.

Figure 52. Geneva-on-the-Lake Harbor Recent sediment budget.

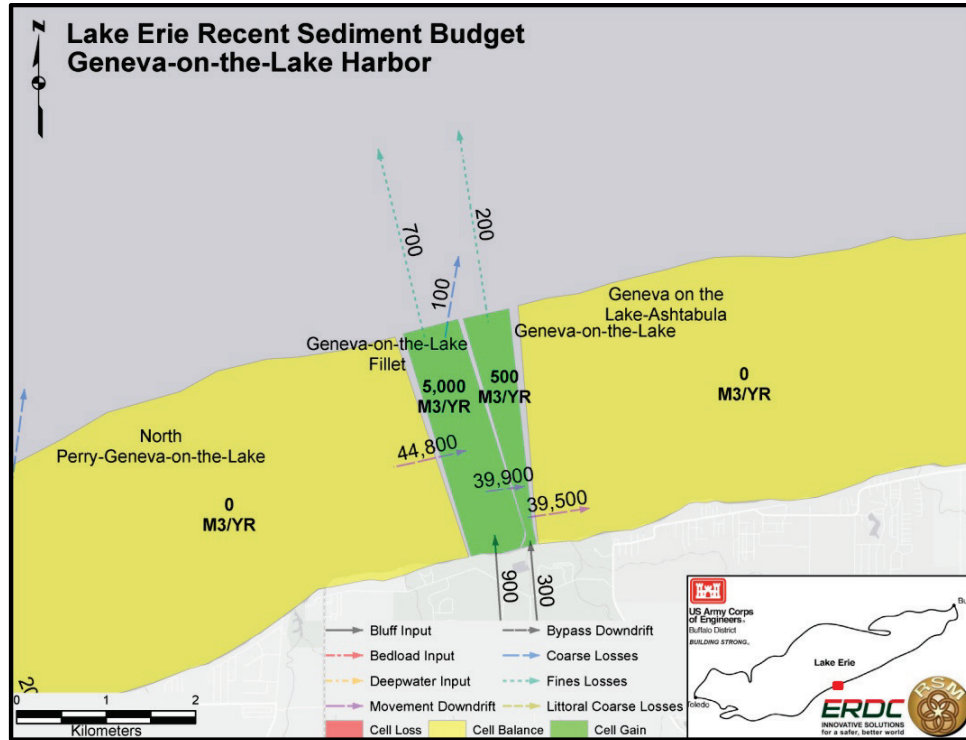
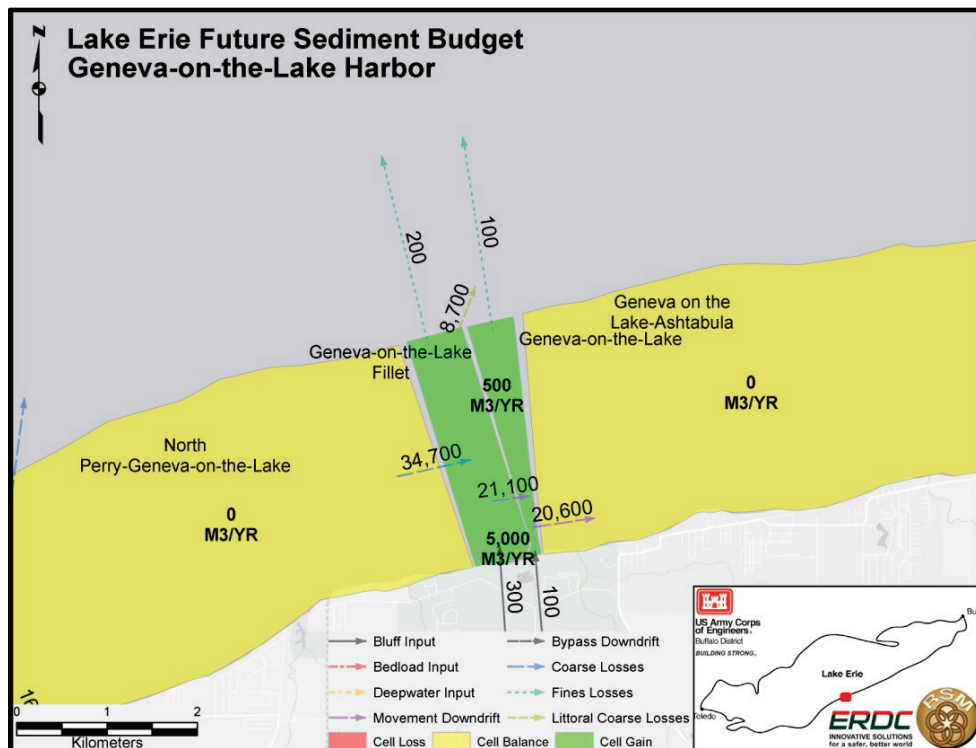


Figure 53. Geneva-on-the-Lake Harbor Future sediment budget.



Ashtabula Harbor, OH

Ashtabula Harbor structures consist of East and West piers; detached East (1,325 m long), West (2,405 m long), and Inner (425 m long) Breakwaters; and a West Shore-arm Breakwater (175 m long). Construction of structures began in 1826, and the earliest data used for sediment computation date to 1876.

To model the budget at Ashtabula Harbor, two cells were used: a fillet cell and a harbor cell (Cells 49 and 50, respectively). The harbor cell has been accreting at an increasing rate since the construction of the piers, and the fillet sediments began accreting rapidly with the completion of the West Shore-arm Breakwater in 1922. As the fillet began to fill, sediment began to pass over and through the shore-arm into the harbor. Presently, a well-developed fillet exists that has fully engulfed the shore-arm (Figure 13). This is directing a substantial amount of material along the West Breakwater and into deep water.

The harbor analysis at Ashtabula Harbor indicated a depositional rate of 21,400 m³/year within the harbor in the Pre-Armoring time frame while sediment deposited at a rate of 5,400 m³/year in the fillet. The bluff analysis measured a total of 48,800 m³/year of sediment moving into Ashtabula Harbor, of which 21,400 m³/year is modeled to have deposited within the harbor, 8,000 m³/year to have deposited within the fillet, 12,900 m³/year to have been lost offshore, and 6,500 m³/year continuing downdrift into the Ashtabula-Conneaut Littoral Cell.

In the Mid-Century time frame, the harbor analysis measured an accretion rate of 23,600 m³/year: 14,900 m³/year in the fillet and 8,700 m³/year in the harbor. The bluff analysis measured a total of 52,300 m³/year of sediment moving through the littoral system. Of this, 18,000 m³/year was modeled to deposit in the fillet while 10,000 m³/year was modeled to deposit in the harbor. As the fillet grew, an increasing amount of sediment was redirected along the West Breakwater into deep water and thereby lost from the system, representing the additional 24,300 m³/year of littoral material.

In the Recent time frame, the harbor analysis measured an accretion rate of 14,700 m³/year: 5,100 m³/year in the fillet and 9,600 m³/year in the harbor. The bluff analysis measured a total of 46,000 m³/year of sediment moving through the system. Of this, 6,000 m³/year was modeled to

deposit within the fillet, and 10,000 m³/year was modeled to deposit in the harbor with the remaining 30,000 m³/year lost from the system into deep water.

For the Future time frame, the incoming sediment load decreases to 24,800 m³/year. As the fillet and harbor have filled in, the accretion rate was modeled to decrease to 5,000 and 7,500 m³/year, respectively. The additional 12,300 m³/year was modeled to be lost offshore.

Table 22 gives predicted and measured sediment flux values at Ashtabula Harbor.

Table 22. Predicted and measured volumetric change at Ashtabula Harbor (all units in cubic meters/year).

| | Pre-Armoring | | Mid-Century | | Recent | | Future |
|--------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|
| | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs |
| Fillet | 8,000 | 5,400 | 18,000 | 14,900 | 6,000 | 5,100 | 5,000 |
| Harbor | 21,400 | 21,400 | 10,000 | 8,700 | 10,000 | 9,600 | 7,500 |
| Total | 29,400 | 26,800 | 28,000 | 23,600 | 16,000 | 14,700 | 12,500 |
| | Total Difference | 2,600 | Total Difference | 4,400 | Total Difference | 1,300 | -2,200 |
| | | 10% | | 19% | | 9% | -15% |

The SBAS cells for Ashtabula Harbor from the Pre-Armoring through the Future time frames are presented in Figures 54 through 57.

Figure 54. Ashtabula Harbor Pre-Armoring sediment budget.

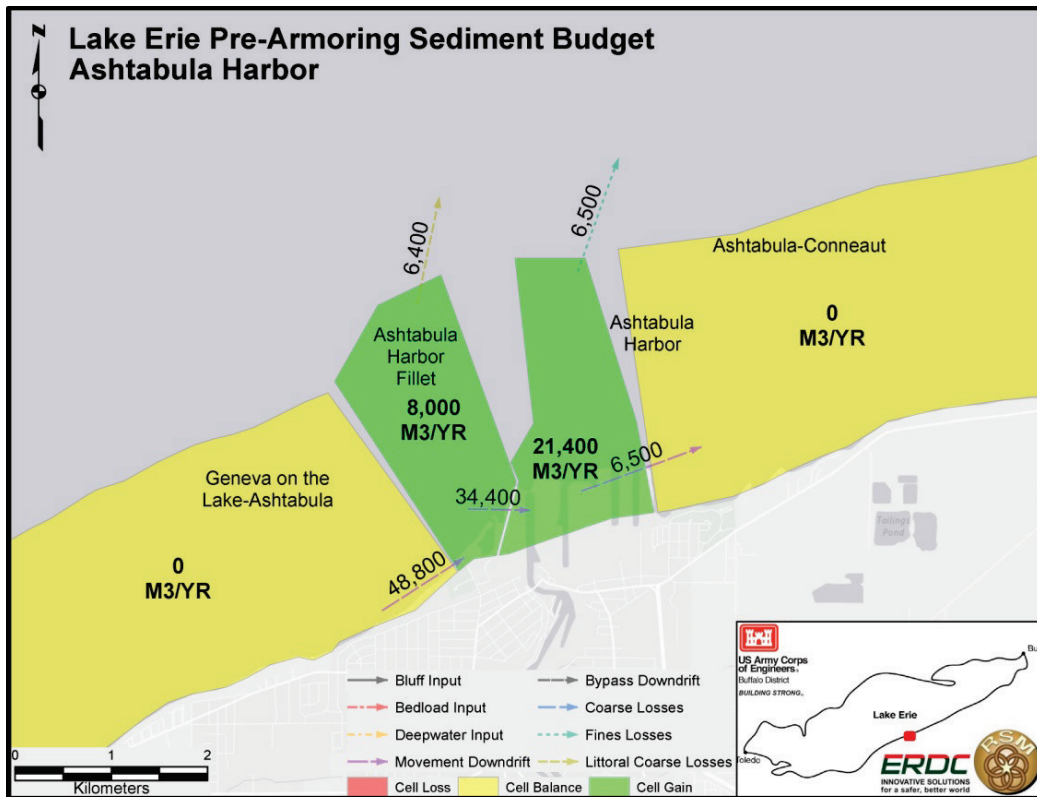


Figure 55. Ashtabula Harbor Mid-Century sediment budget.

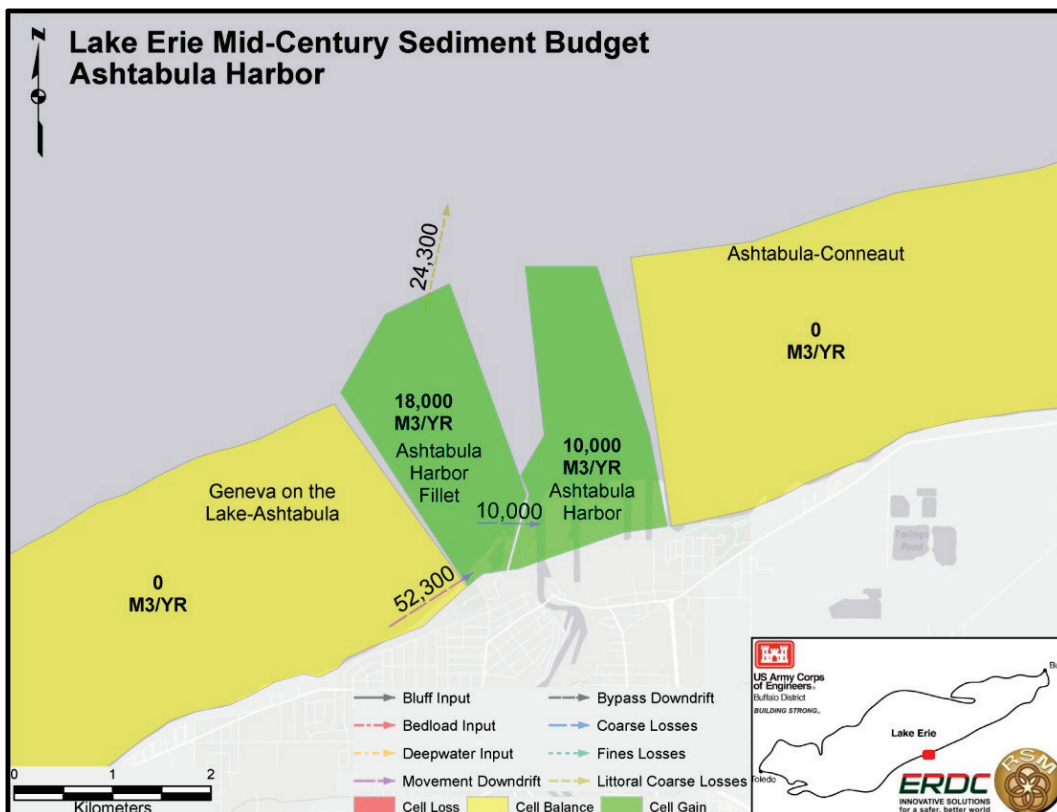


Figure 56. Ashtabula Harbor Recent sediment budget.

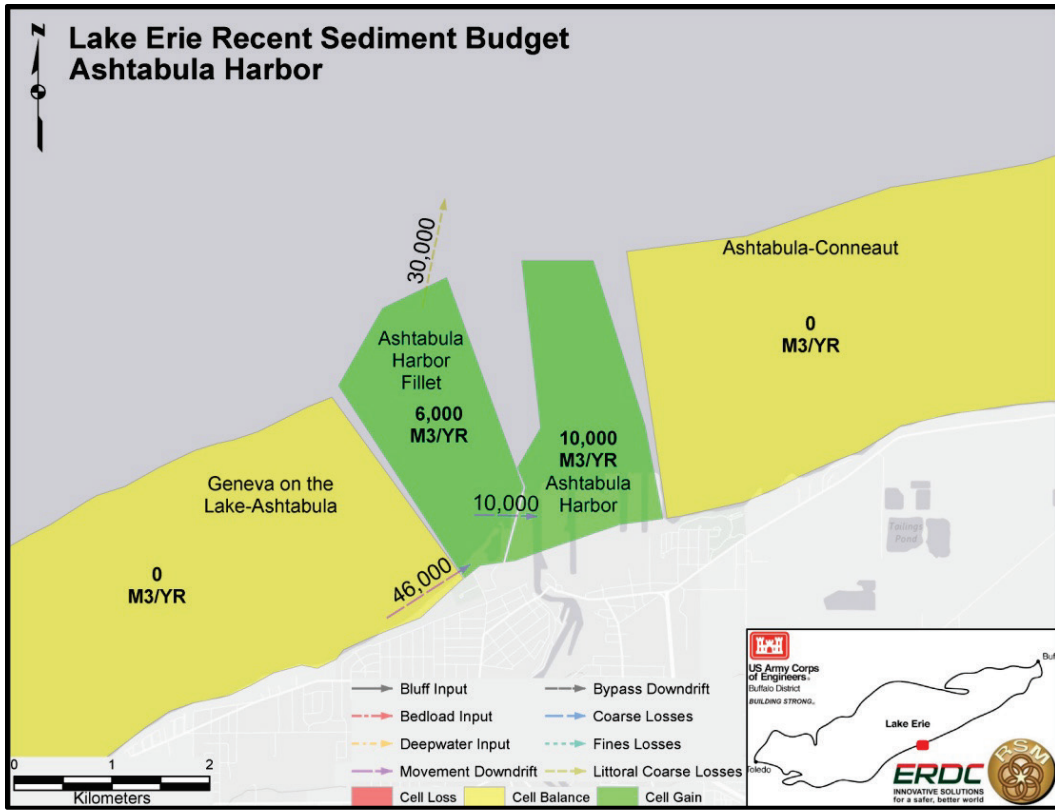
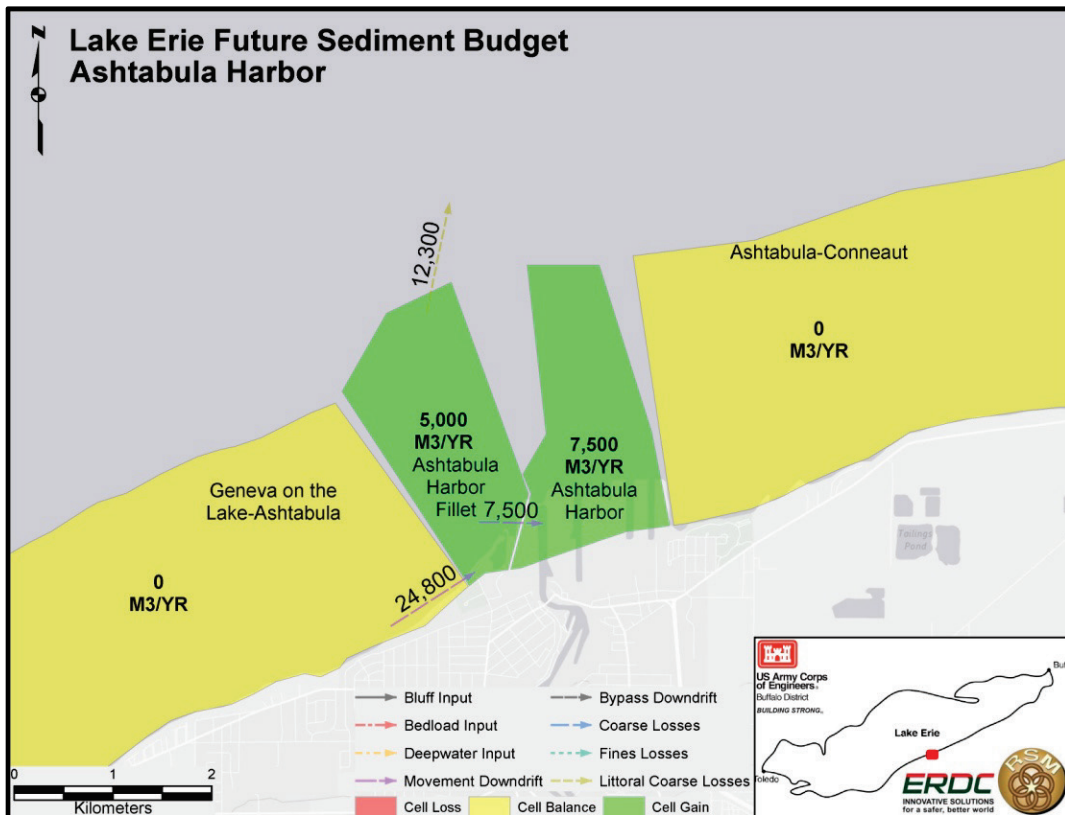


Figure 57. Ashtabula Harbor Future sediment budget.



Conneaut Harbor, OH

Conneaut Harbor structures consist of East and West Piers, detached East (1,120 m long) and West (1,810 m long) breakwaters, and East (360 m long) and West (510 m long) Shore-arm Breakwaters. Construction of structures began in 1829 and the earliest data used for sediment computation are from 1866.

To model the budget at Conneaut Harbor, two cells were used: a fillet and harbor (cells 52 and 53, respectively). The harbor cell has been accreting at an increasing rate since construction of the piers, and the fillet sediments began accreting rapidly with the completion of the West Shore-arm Breakwater in 1934. As the fillet filled, sediment began to pass over and through the shore-arm into the harbor. Presently, a well-developed fillet exists that is directing a substantial amount of material along the West Breakwater and into deep water.

The harbor analysis at Conneaut Harbor indicated a depositional rate of 7,000 m³/year within the harbor in the Pre-Armoring time frame while the fillet remained balanced. The actual harbor depositional rate is likely higher than what was measured due to the spatial limitations of the 1866 bathymetric data. The bluff analysis measured a total of 40,800 m³/year of sediment moving into Conneaut Harbor; of this, 10,000 m³/year is modeled to have deposited within the harbor, 20,400 m³/year lost offshore, and 10,300 m³/year continued into the down-drift littoral cell.

In the Mid-Century time frame, the harbor analysis measured an accretion rate of 21,900 m³/year (9,300 m³/year in the fillet and 12,600 m³/year in the harbor). The rate at the harbor is likely lower than the actual harbor sedimentation rate due to dredging. Historical dredging quantities were computed, but the data do not differentiate between dredging location, whether dredging was for maintenance purposes or expansion of the Federal harbor, or sediment type. Thus, the quantity does not give an estimate as to how much longshore drift material was removed. The bluff analysis measured a total of 25,600 m³/year of sediment moving through the littoral system. Of this, 10,000 m³/year was modeled to deposit in the fillet while 15,600 m³/year was modeled to deposit in the harbor. No sediment moves beyond the harbor from Conneaut Harbor into the downdrift cell for this time frame.

In the Recent time frame, the harbor analysis measured an accretion rate of 36,600 m³/year (5,700 m³/year in the fillet and 30,900 in the harbor). The harbor accretion rate increased dramatically as a result of the filling of the fillet, which allowed increased sediment to pass over and around the shore-arm breakwater. In addition, a reduction of the footprint of Federal dredging at the harbor created a sediment sink. The bluff analysis measured a total of 50,500 m³/year of sediment moving through the system. Of this, 8,000 m³/year was modeled to deposit within the fillet, and 32,000 m³/year was modeled to deposit in the harbor. As the fillet grew, an increased amount of sediment was redirected along the west breakwater into deep water where it was lost from the system. The remaining 10,500 m³/year of sediment in the littoral system is modeled in this way. No sediment moves beyond the harbor from Conneaut Harbor into the downdrift cell for this time frame.

In the Future time frame, the incoming sediment load decreases to 40,400 m³/year. As the fillet and harbor have filled in, the accretion rate was modeled to decrease to 5,000 and 25,000 m³/year, respectively. The additional 10,400 m³/year was modeled to be lost offshore.

Table 23 gives predicted and measured sediment flux values at Conneaut Harbor.

Table 23. Predicted and measured volumetric change at Conneaut Harbor (all units in cubic meters/year).

| | Pre-Armoring | | Mid-Century | | Recent | | Future |
|--------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|
| | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs |
| Fillet | 0 | 0 | 10,000 | 9,300 | 8,000 | 5,700 | 5,000 |
| Harbor | 10,000 | 7,000 | 15,600 | 12,600 | 32,000 | 30,900 | 25,000 |
| Total | 10,000 | 7,000 | 25,600 | 21,900 | 40,000 | 36,600 | 30,000 |
| | Total Difference | 3,000 | Total Difference | 3,700 | Total Difference | 3,400 | -6,600 |
| | | 43% | | 17% | | 9% | -18% |

The SBAS cells for Conneaut Harbor from the Pre-Armoring through the Future time frames are presented in Figures 58 through 61.

Figure 58. Conneaut Harbor Pre-Armoring sediment budget.

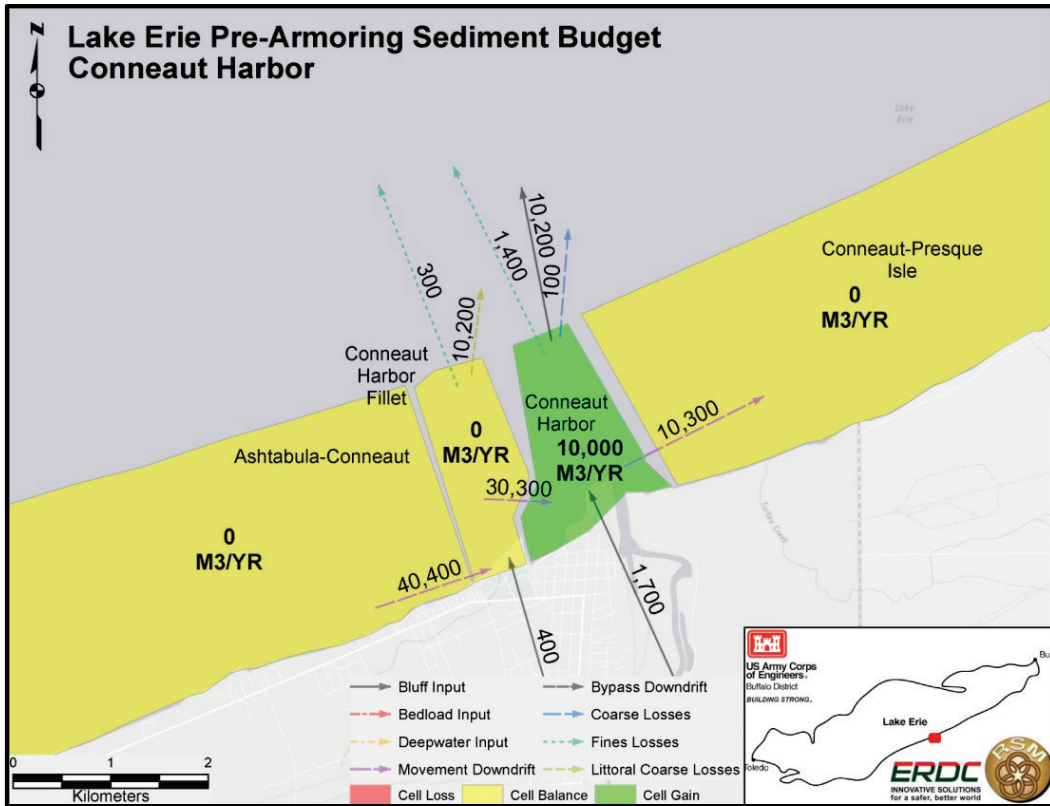


Figure 59. Conneaut Harbor Mid-Century sediment budget.

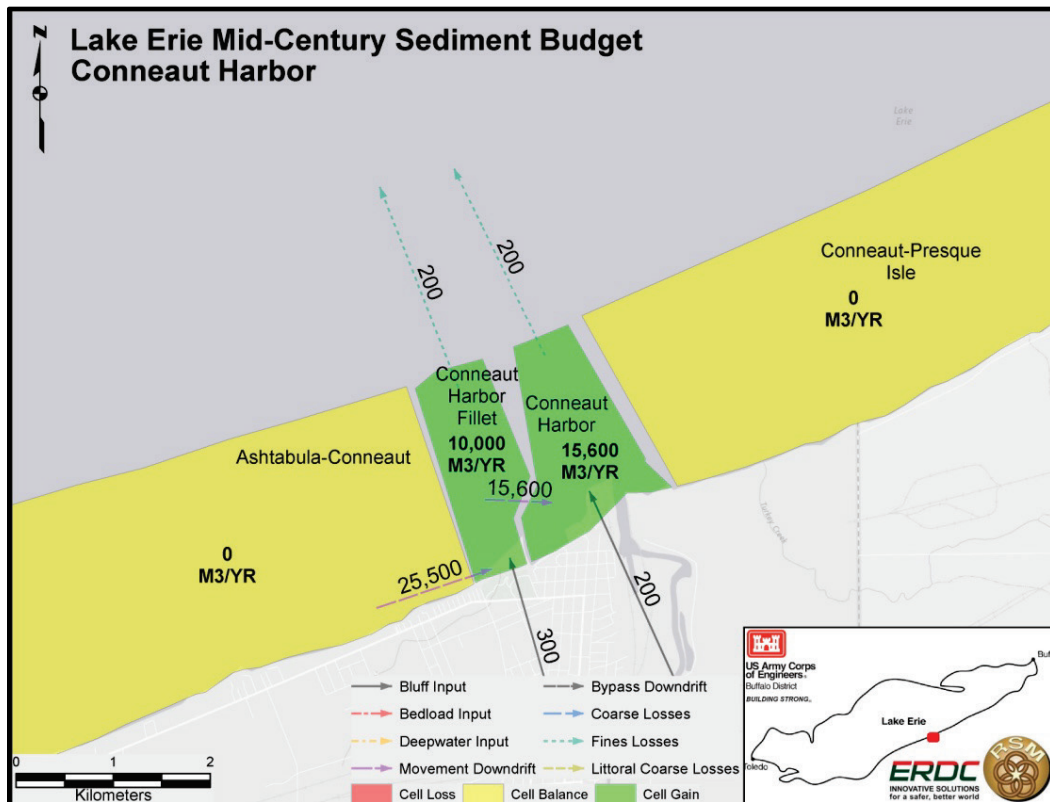


Figure 60. Conneaut Harbor Recent sediment budget.

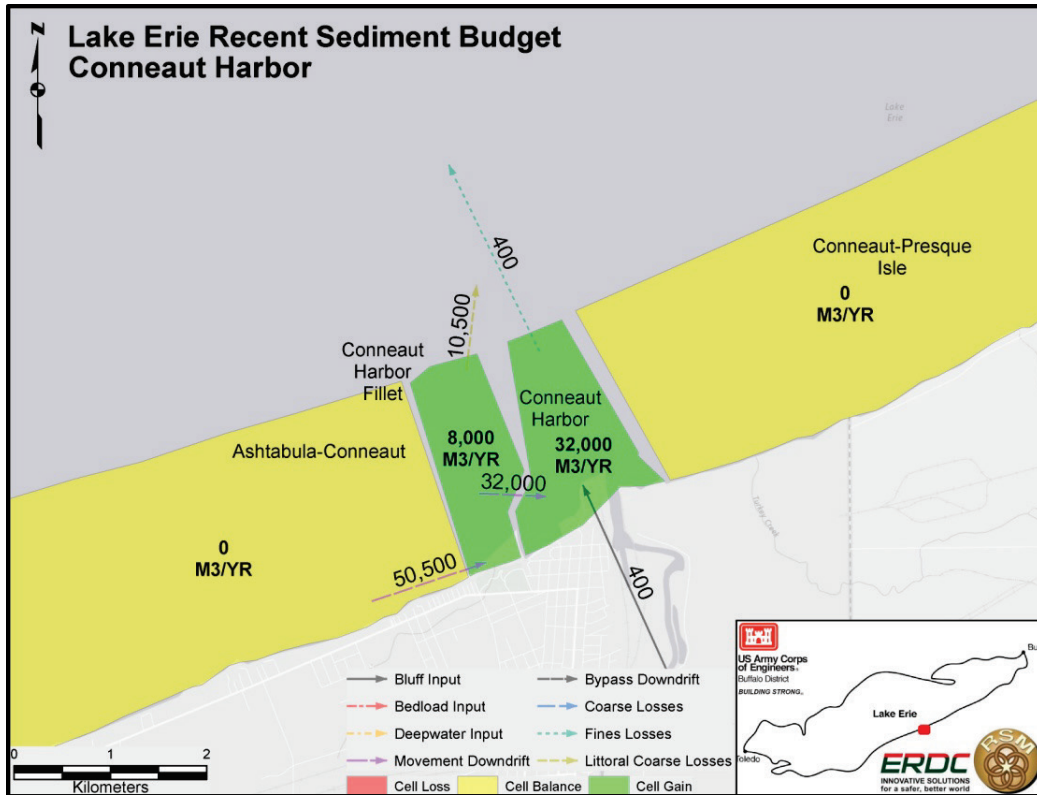
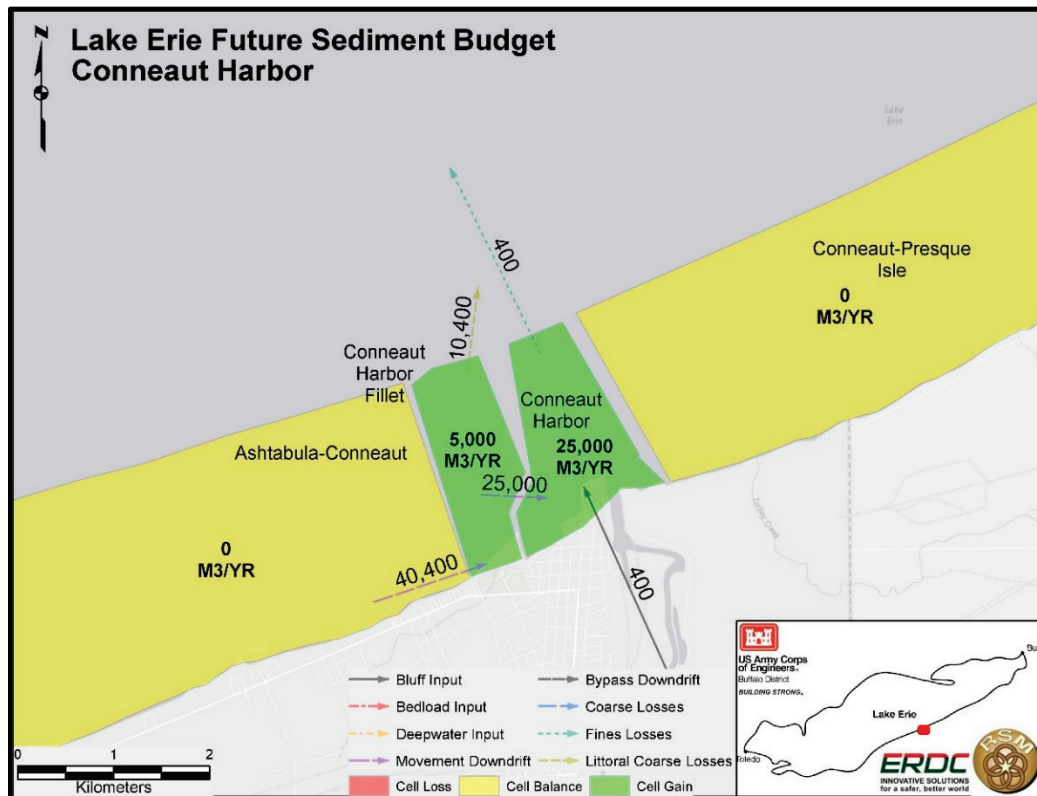


Figure 61. Conneaut Harbor Future sediment budget.



Presque Isle, PA

Presque Isle Peninsula is a natural sand spit extending into Lake Erie near Erie, PA. The spit encloses Erie Harbor and has undergone nourishment annually since 1960, with a history of erosion extending back 175 years. USACE (1984) developed sediment budgets representing the pre- and post-project conditions (Figures 62 and 63, respectively) as part of the segmented breakwater construction between October 1989 and November 1992. This sediment budget is used as the baseline comparison for the bluff erosion analysis.

Prior to completion of the breakwaters, beach nourishment at Presque Isle Peninsula averaged $\sim 198,200 \text{ m}^3/\text{year}$, with an additional $\sim 30,600 \text{ m}^3/\text{year}$ of sand supplied by longshore transport from the west. Of this, $39,700 \text{ m}^3/\text{year}$ was lost offshore, and $\sim 221,000 \text{ m}^3/\text{year}$ continued to the east as longshore transport. This left the peninsula with a predicted annual deficit of $\sim 31,900 \text{ m}^3/\text{year}$.

Figure 62. Presque Isle Peninsula pre-project sediment budget (USACE 1984).

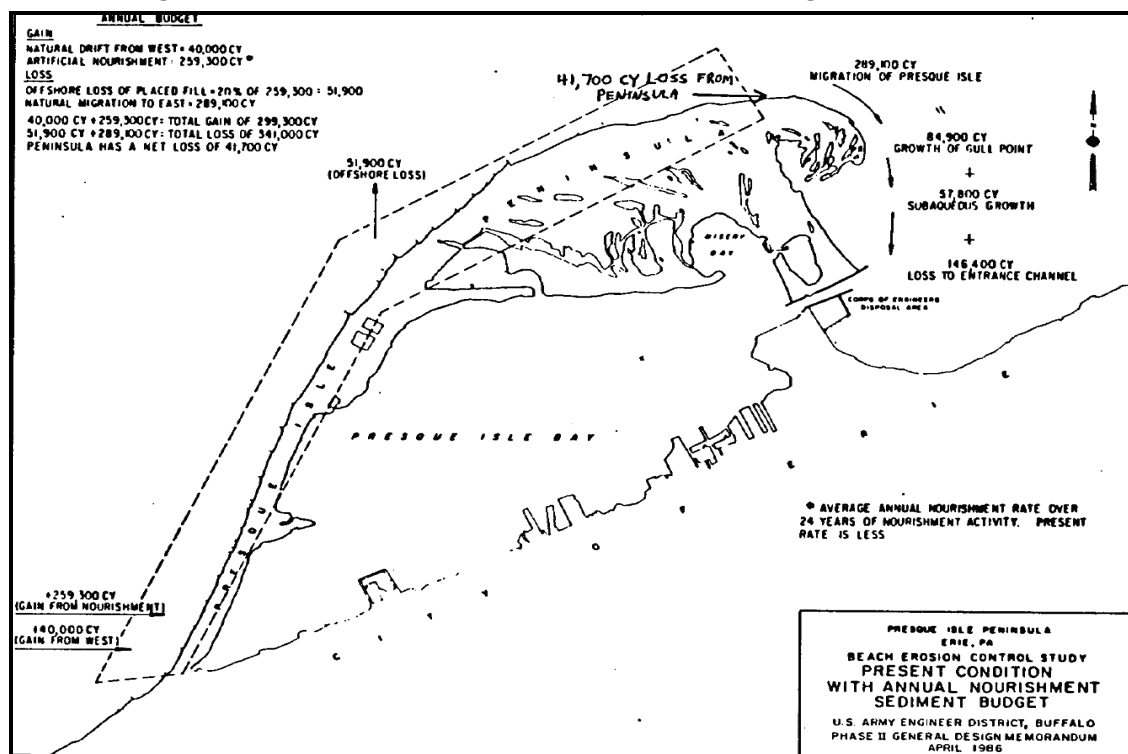
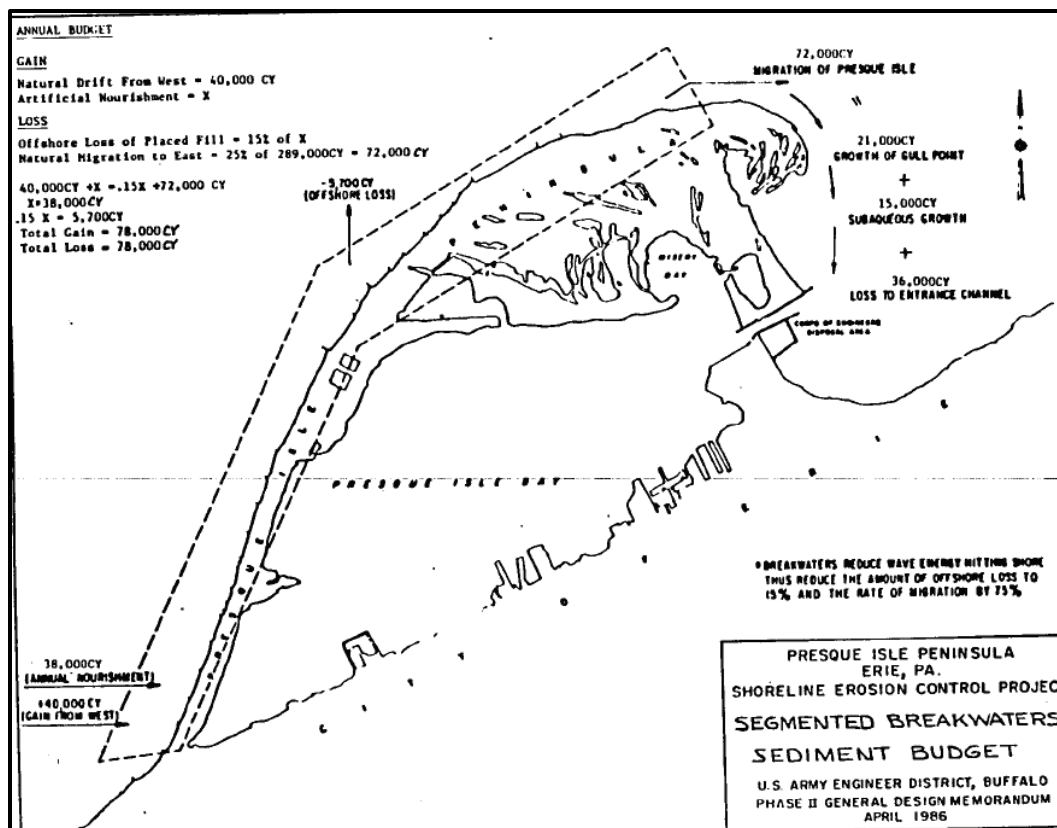


Figure 63. Presque Isle Peninsula post-project sediment budget (USACE 1984).



Post-project, the budget presented called for beach nourishment to decrease to $\sim 29,000 \text{ m}^3/\text{year}$ ($38,000 \text{ yd}^3/\text{year}$), with offshore losses decreasing to $\sim 4,400 \text{ m}^3/\text{year}$ ($5,700 \text{ yd}^3/\text{year}$) and longshore transport to the east decreasing to $\sim 55,100 \text{ m}^3/\text{year}$ ($72,000 \text{ yd}^3/\text{year}$). Actual placement since completion of the project has averaged $\sim 26,600 \text{ m}^3/\text{year}$ ($34,780 \text{ yd}^3/\text{year}$).

An important additional feature at Presque Isle Peninsula is Gull Point at the eastern end of the peninsula. Gull Point is the result of sand drifting to the east quicker than the resulting sand spit can be recurved by wave action. Gull Point did not undergo extensive growth until after the commencement of beach nourishment. Because of this, Presque Isle Peninsula was modeled in SBAS two separate ways. For the Pre-Armoring time frame, Presque Isle was modeled as a single littoral cell (cell 55) in equilibrium. For the Mid-Century, Recent, and Future time frames, a littoral cell for Gull Point was added (cell 56), and flux values were included representing nourishment, offshore loss, and longshore transport into Gull Point.

The sediment budgets presented in USACE (1984) reflect the longshore transport in the Mid-Century time frame. Because of changing shore conditions, the longshore transport rate in the Pre-Armoring time frame was assumed to be 20% greater than the Mid-Century amount. Table 24 presents the sediment flux at Presque Isle Peninsula from erosion of the bluffs between the peninsula and Conneaut, OH, and the values presented in USACE Buffalo (1984).

Table 24. Predicted and measured volumetric change at Presque Isle Peninsula (all units in cubic meters/year).

| Pre-Armoring | | Mid-century | | Recent | | Future |
|---------------------------------|--------------|---------------------------------|--------------|---------------------------------|--------------|---------------------------------|
| Calculated Sediment from Bluffs | Phase II GDM | Calculated Sediment from Bluffs | Phase II GDM | Calculated Sediment from Bluffs | Phase II GDM | Calculated Sediment from Bluffs |
| 48,500 | 36,700 | 41,900 | 30,600 | 30,300 | 30,600 | 28,600 |
| Total Difference | 11,800 | Total Difference | 11,300 | Total Difference | -300 | -2,000 |
| | 32% | | 37% | | -1% | -7% |

The SBAS cells for Presque Isle Peninsula from the Pre-Armoring through the Future time frames are presented in Figures 64 through 67.

Figure 64. Presque Isle Peninsula Pre-Armoring sediment budget.

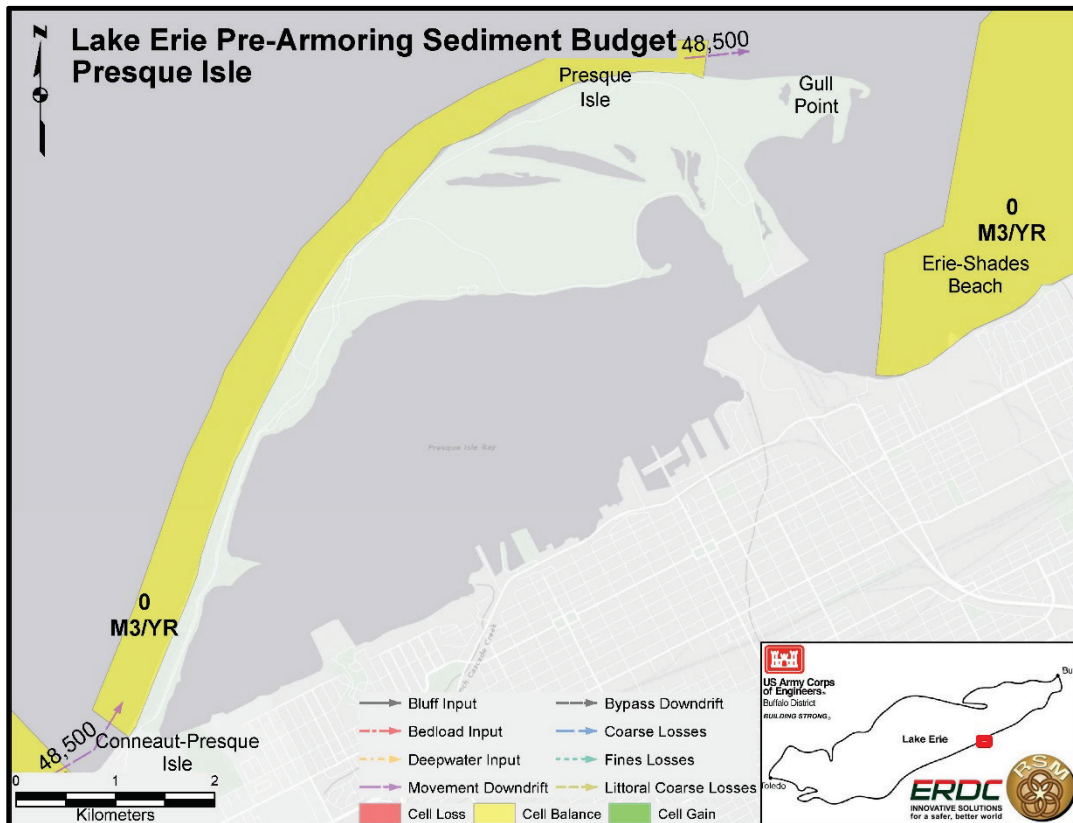


Figure 65. Presque Isle Mid-Century sediment budget.

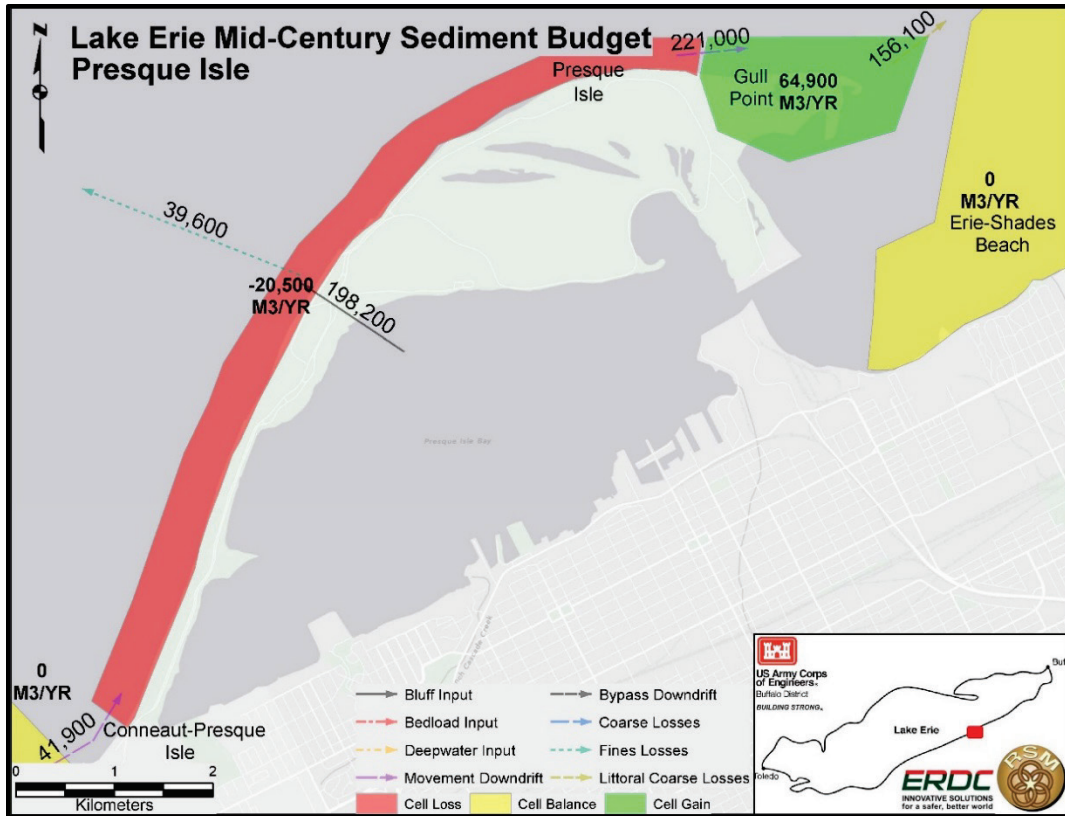


Figure 66. Presque Isle Recent sediment budget.

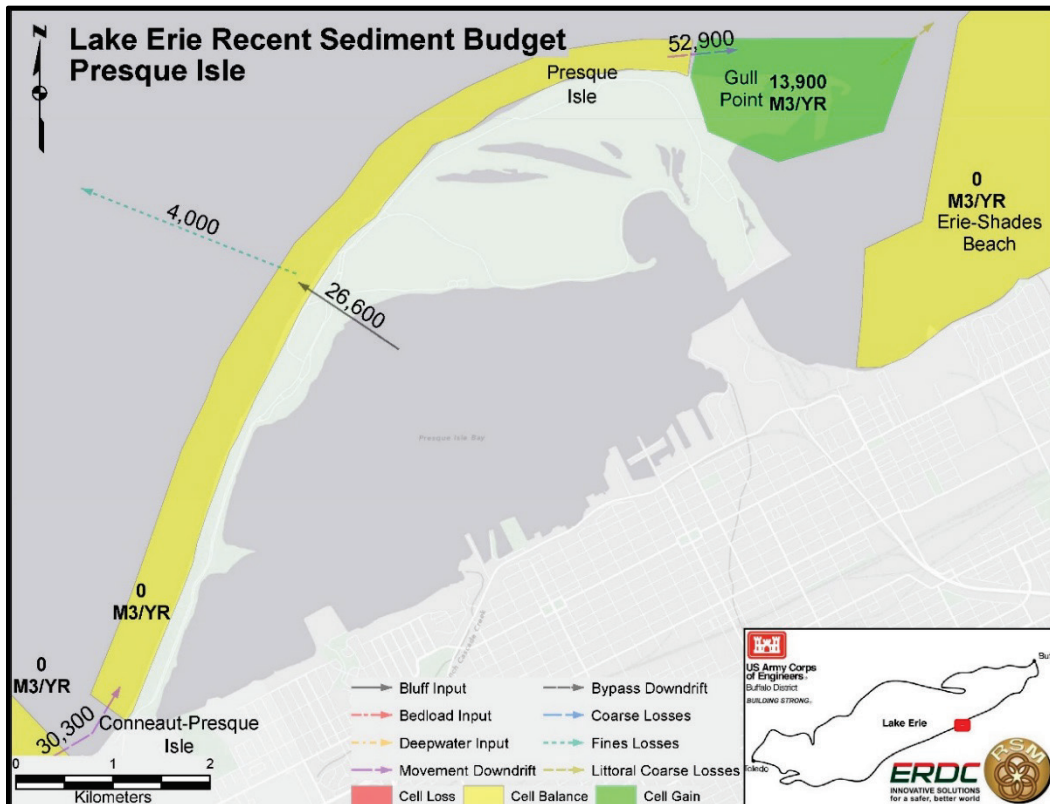
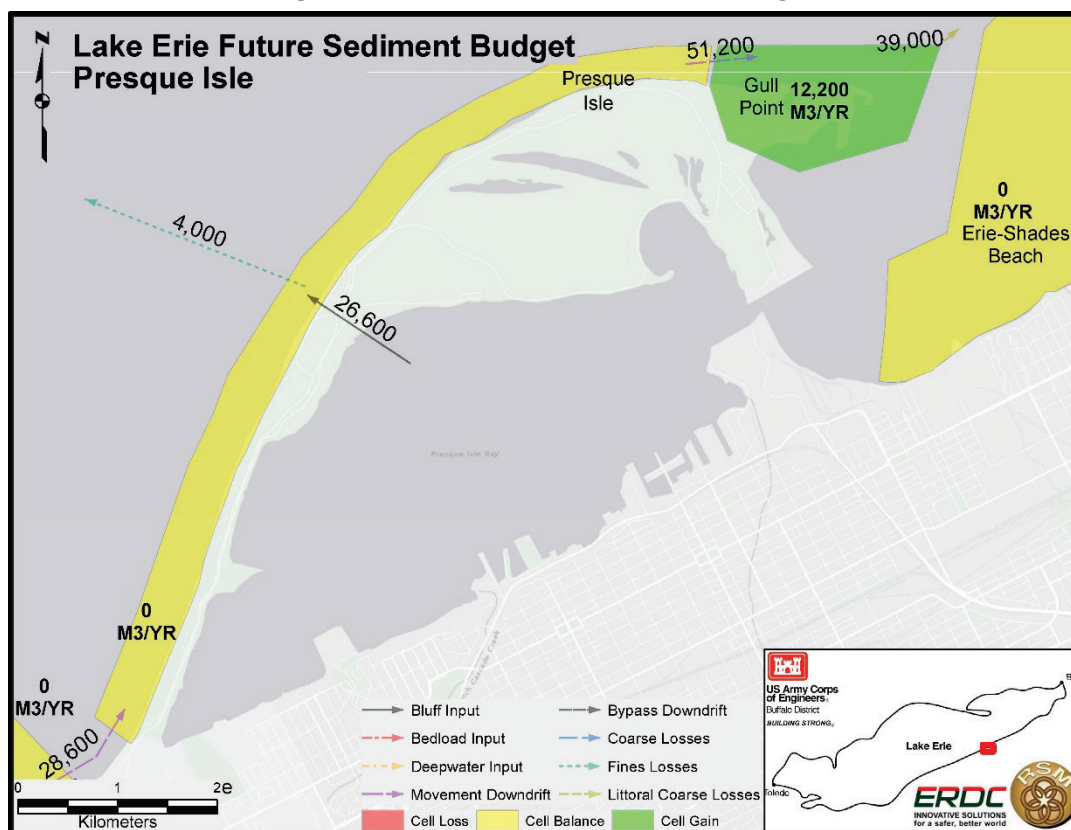


Figure 67. Presque Isle Future sediment budget.



Barcelona Harbor, NY

Barcelona Harbor structures consist of a shore-attached West Breakwater (240 m long) and a detached East Breakwater (210 m long). Breakwater construction was completed between 1958 and 1960, with modifications installed at a later date. The project was constructed at a natural headland that was redirecting sediment offshore prior to the project being built.

To model the budget at Barcelona Harbor, two cells were used: a fillet cell and a harbor cell (cells 66 and 67, respectively). It was assumed that 50% of littoral material was lost to deep water due to the headland prior to harbor development. During the Mid-Century time frame, the harbor analysis determined an accretion value approximately one-half the bluff erosion rate (5,200 m³/year of sediment accretion from bluff erosion vs. 2,500 m³/year measured in the fillet). This is likely due to the limited spatial extent of data available from the 1930s and 1970s. The harbor cell was also relatively balanced prior to construction of the harbor structures but has been steadily accreting since project completion. The majority of the material is transported over and around the West Breakwater;

however, because of the orientation of the harbor and the sedimentation within the harbor basin, this material is partially a result of sediment transported by storm events blowing out of the north-northeast.

Table 25 gives predicted and measured flux values at Barcelona Harbor.

Table 25. Predicted and measured volumetric change at Barcelona Harbor (all units in cubic meters/year).

| | Mid-Century | | Recent | | Future |
|--------|---------------------------------|--------------------------------------|---------------------------------|--------------------------------------|---------------------------------|
| | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs |
| Fillet | 5,200 | 2,500 | 3,500 | 3,100 | 3,000 |
| Harbor | -100 | -100 | 2,400 | 2,400 | 1,200 |
| Total | 5,100 | 2,400 | 5,900 | 5,500 | 4,200 |
| | Total Difference | 2,700 | Total Difference | 400 | -1,300 |
| | | 113% | | 7% | -24% |

The SBAS cells for Barcelona Harbor from the Pre-Armoring through the Future time frames are presented in Figures 68 through 71.

Figure 68. Barcelona Harbor Pre-Armoring sediment budget.

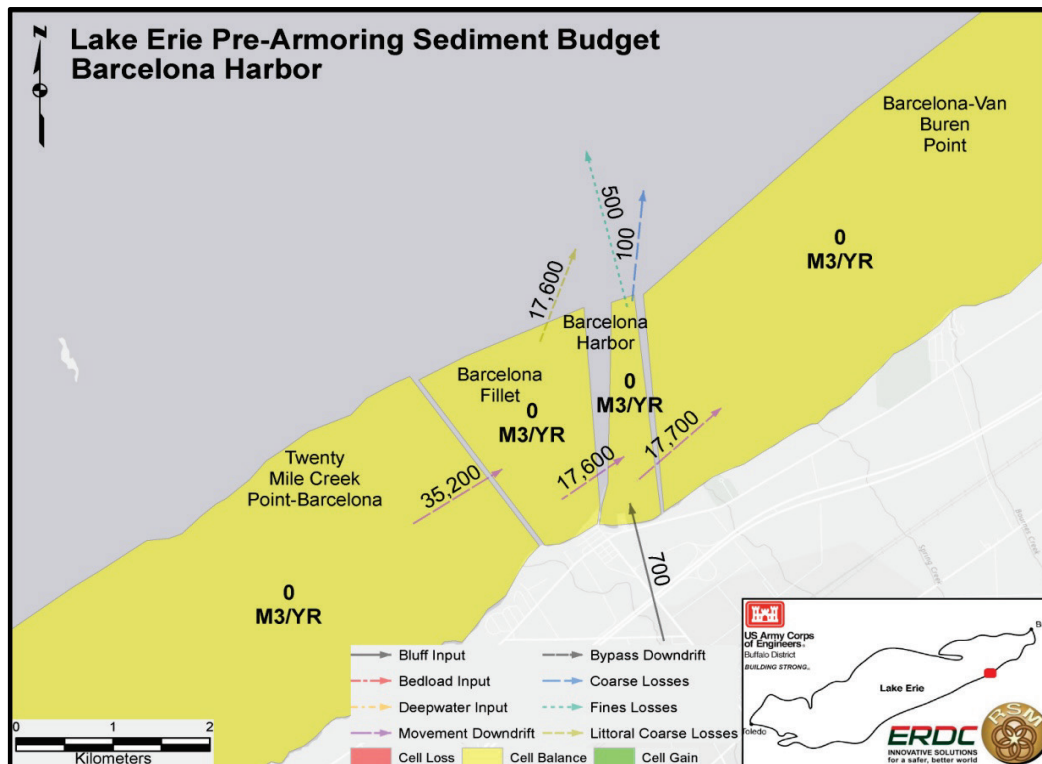


Figure 69. Barcelona Harbor Mid-Century sediment budget.

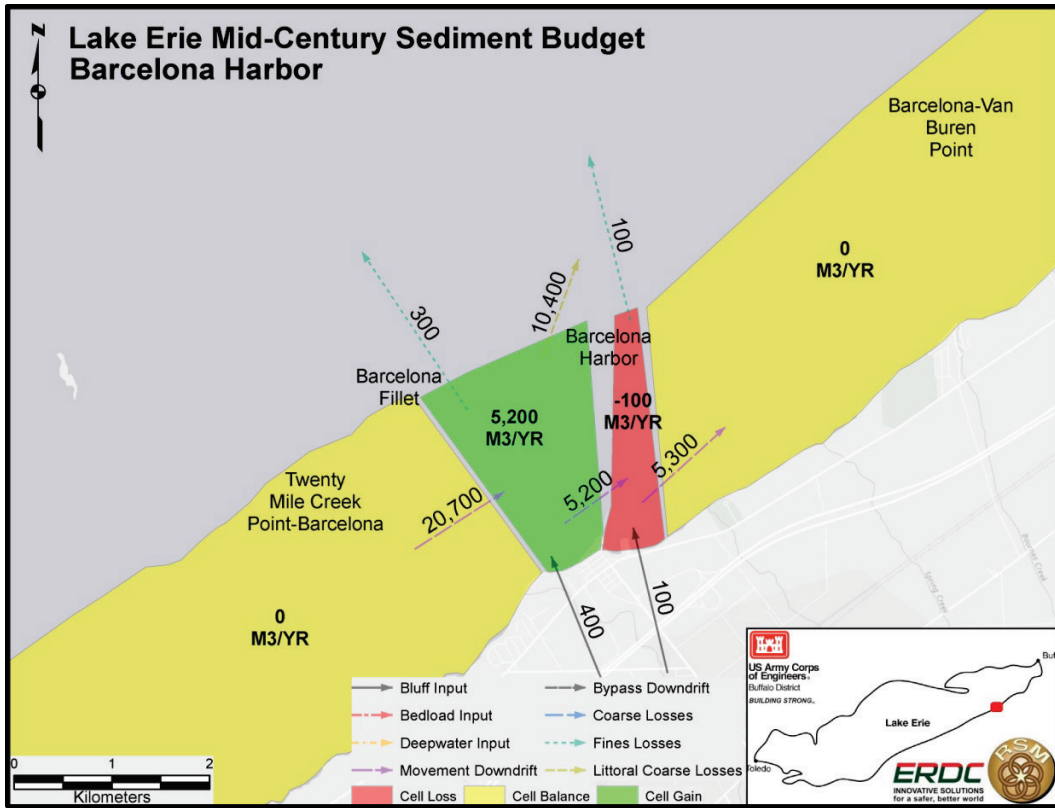


Figure 70. Barcelona Harbor Recent sediment budget.

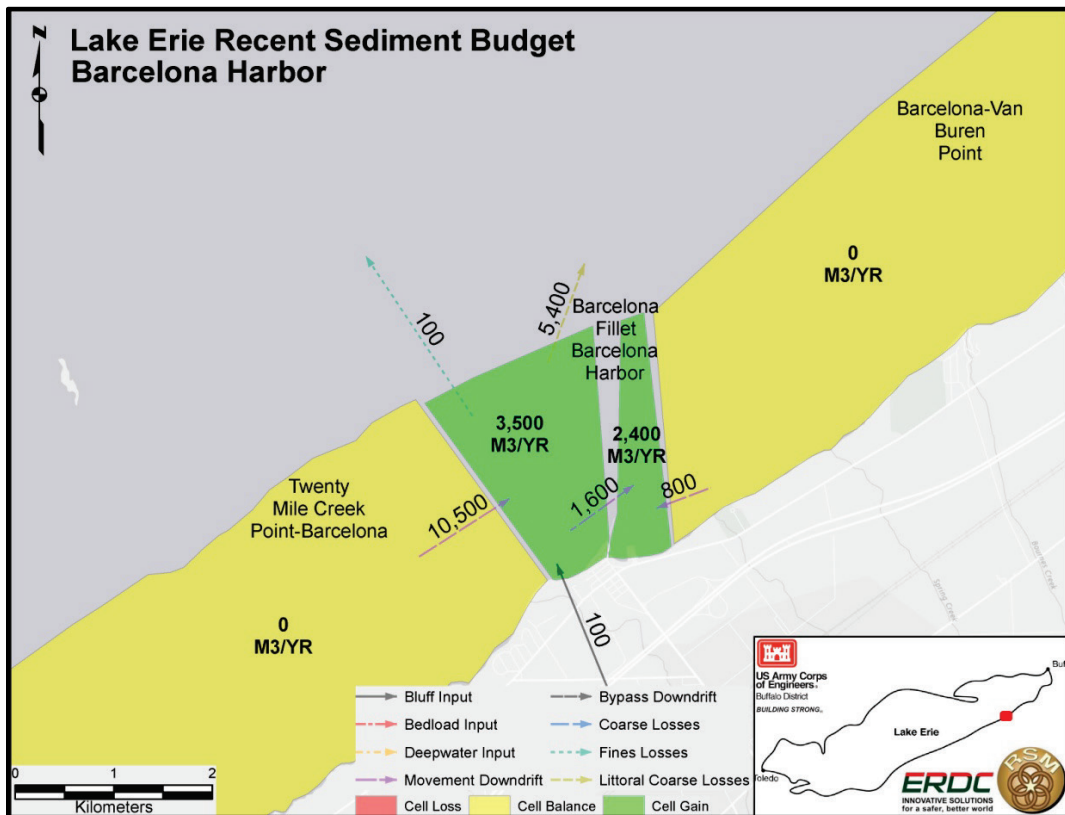
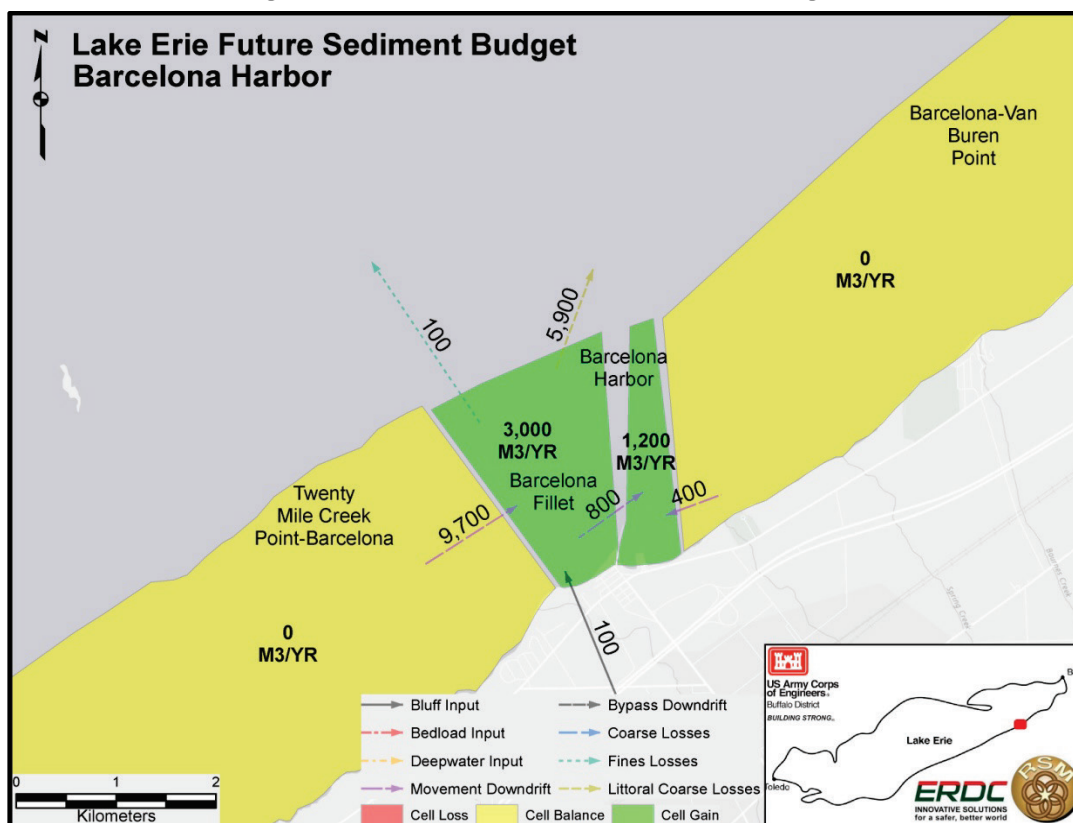


Figure 71. Barcelona Harbor Future sediment budget.



Dunkirk Harbor, NY

Dunkirk Harbor structures consist of a shore-attached West Pier (1,410 m long), a detached Outer Breakwater (860 m long), and two inner breakwaters (West, 365 m long; East, 445 m long). Breakwater construction began in 1827, and the earliest data used for sediment computation date to 1870.

To model the budget at Dunkirk Harbor, two cells were used: an outer basin cell and a harbor cell (cells 70 and 71, respectively). The outer harbor cell has been steadily eroding since the 1930s while sedimentation in the harbor increased rapidly in the Mid-Century time frame and continues in the Recent time frame at a slower rate. Because of the orientation of the harbor and the sedimentation within the harbor basin, fluxes of 4,000 m³/year for the Mid-Century time frame and 2,000 m³/year for the Recent and Future time frames have been added with orientation from the northeast, representing material brought in by storm events blowing out of the north-northeast. The heaviest accretion in the Mid-Century time frame took place in the east basin of the harbor, supporting the addition of this flux.

Table 26 gives predicted and measured sediment flux at Dunkirk Harbor.

Table 26. Predicted and measured volumetric change at Dunkirk Harbor (all units in cubic meters/year).

| | Pre-Armoring | | Mid-Century | | Recent | | Future |
|------------------|---------------------------------|--------------------------------------|--|--------------------------------------|--|--------------------------------------|--|
| | Calculated Sediment from Bluffs | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs ¹ | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs ² | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs ² |
| Outer Basin | 1,500 | 900 | -500 | -700 | -1,000 | -900 | -1,000 |
| East/West Basins | 1,300 | 1,800 | 5,400 | 8,700 | 3,400 | 3,300 | 3,400 |
| Total | 2,800 | 2,700 | 4,900 | 8,000 | 2,400 | 2,400 | 2,400 |
| | Total Difference | -100 | Total Difference | 3,100 | Total Difference | 0 | 0 |
| | | -4% | | 39% | | 0% | 0% |

¹ Includes a flux of 4,000 m³/year from the Northeast.

² Includes a flux of 2,000 m³/year from the Northeast.

The SBAS cells for Dunkirk Harbor from the Pre-Armoring through the Future time frames are presented in Figures 72 through 75.

Figure 72. Dunkirk Harbor Pre-Armoring sediment budget.

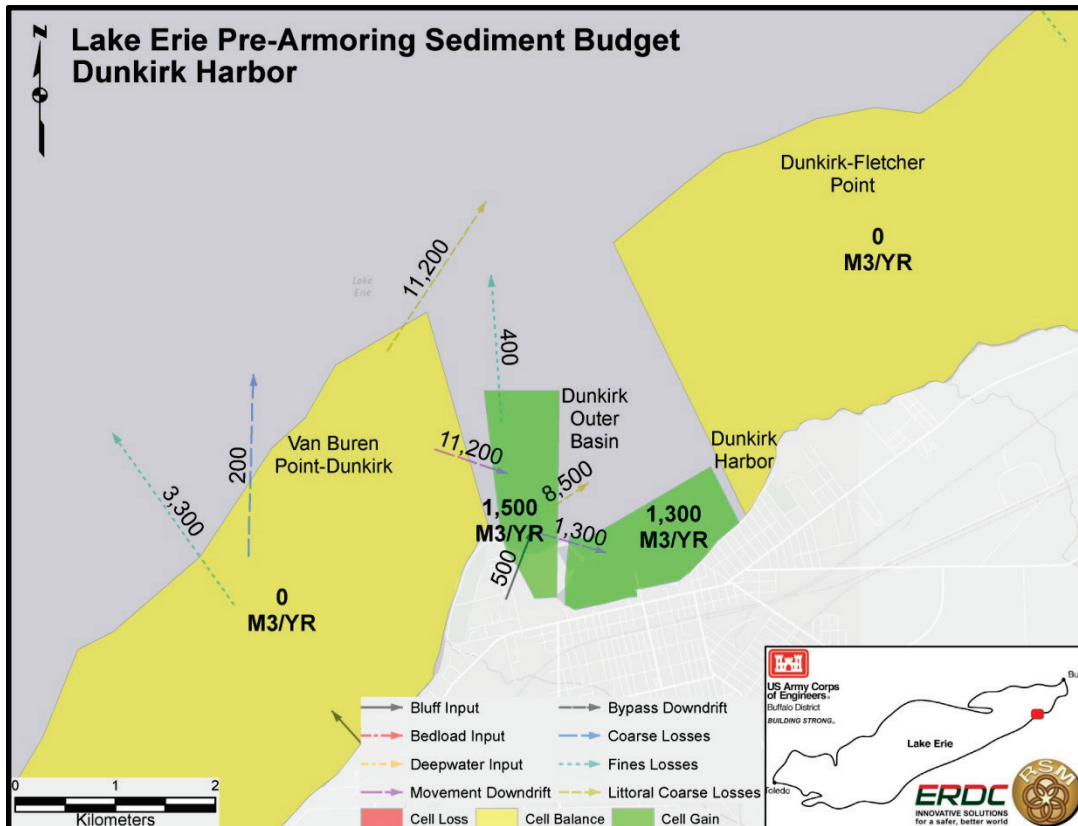


Figure 73. Dunkirk Harbor Mid-Century sediment budget.

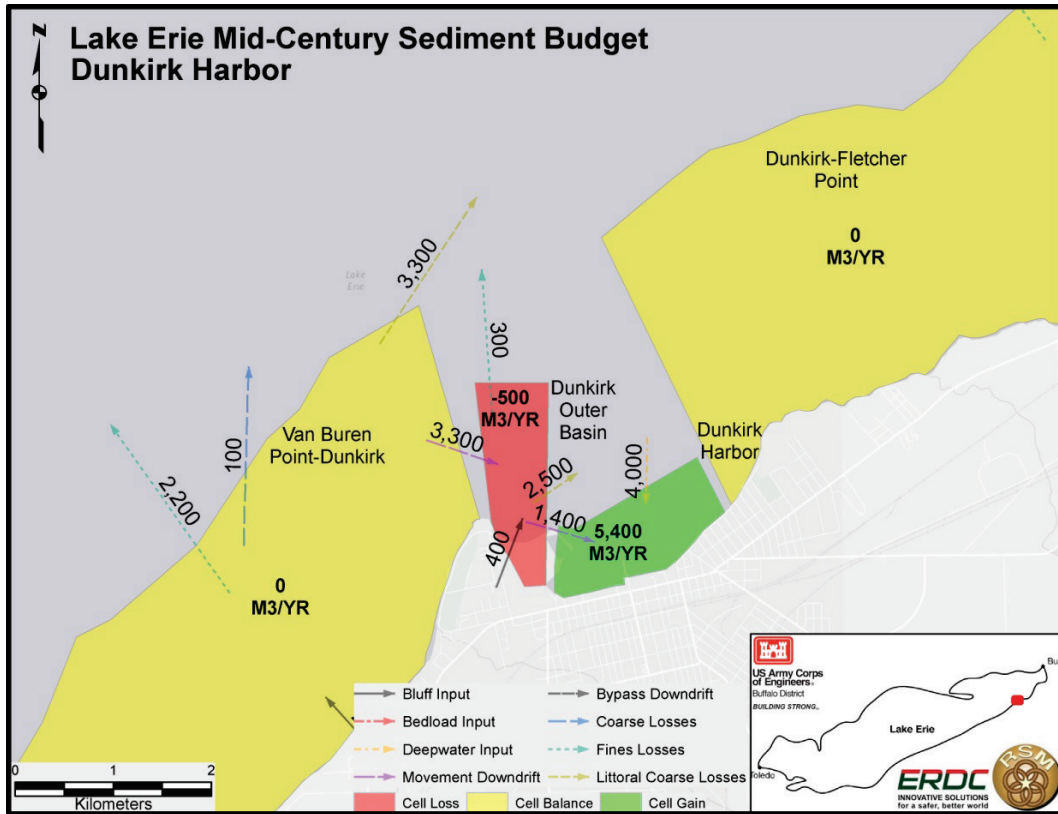


Figure 74. Dunkirk Harbor Recent sediment budget.

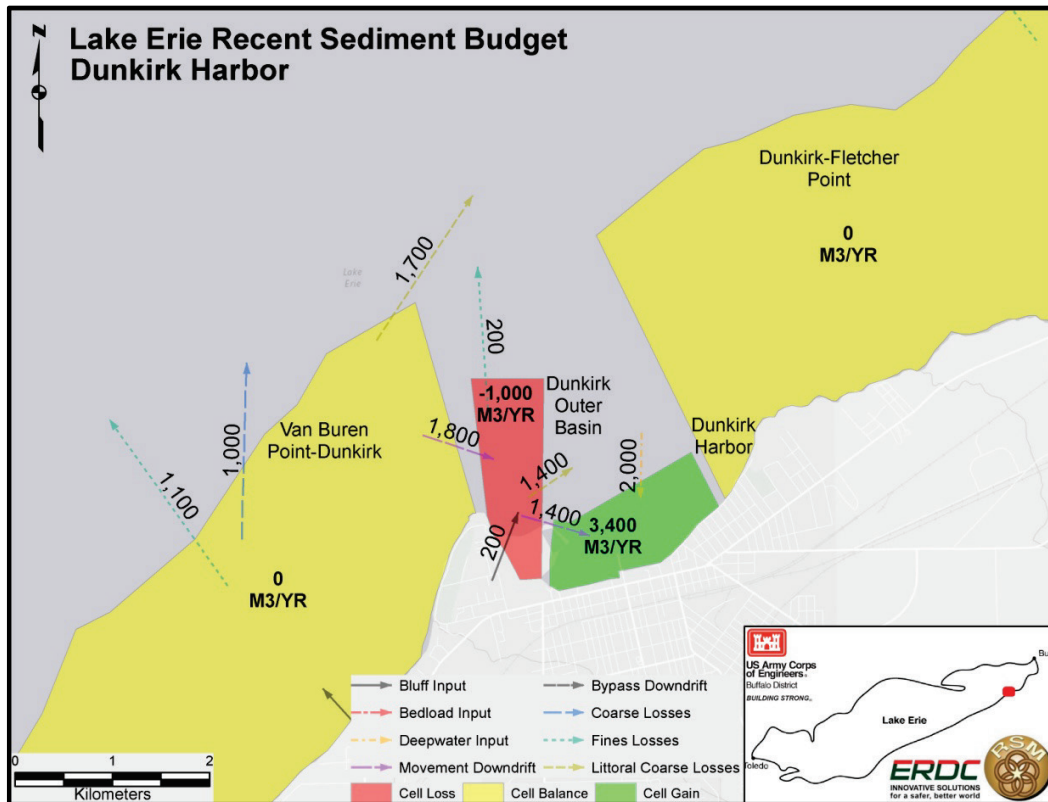
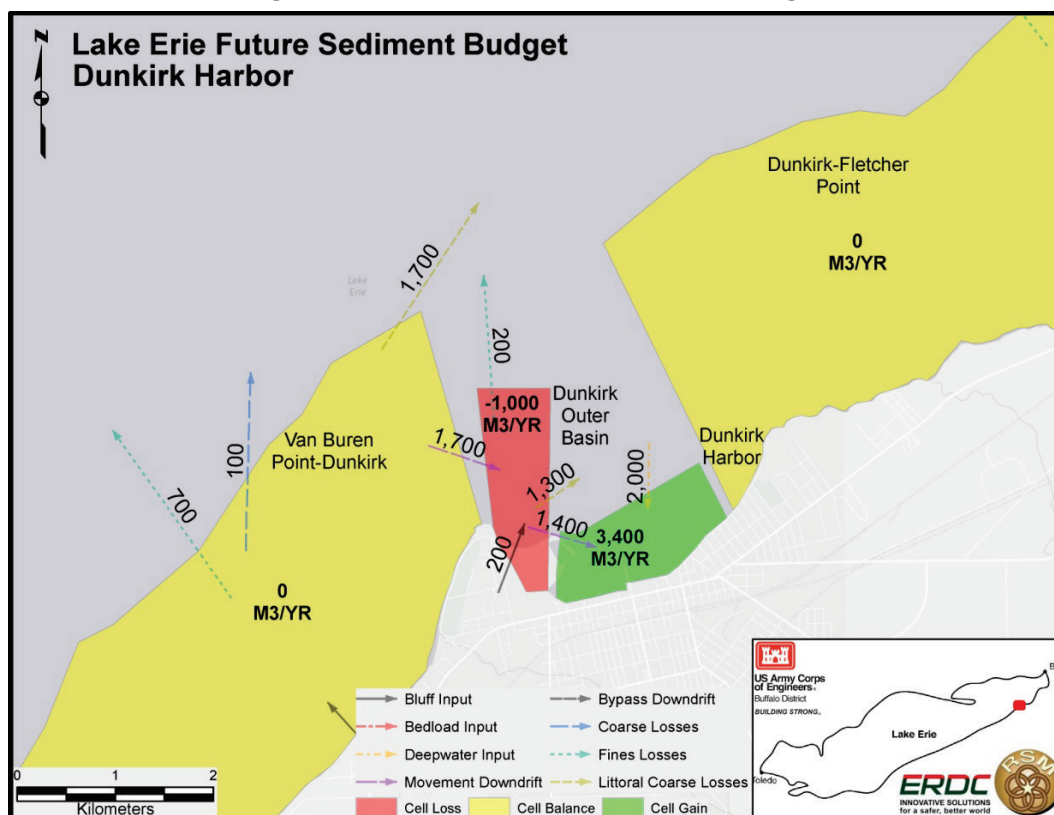


Figure 75. Dunkirk Harbor Future sediment budget.



Cattaraugus Creek Harbor, NY

Cattaraugus Creek Harbor structures consist of two arrowhead breakwaters (South, 565 m long; North, 180 m long) at the mouth of Cattaraugus Creek, completed in 1983. At Cattaraugus Creek Harbor, a bedload of 2,700 m³/year (~3,500 yd³) is added into the system (USACE 1976) from Cattaraugus Creek Harbor. Additionally, since completion of the project, an area of erosion has been identified off the southwestern edge of the South Breakwater. The likely cause is ice and wave scour of the original shoal at the outlet of the creek. The completion of the project shifted the locus of deposition to the north, causing the original shoal to erode.

To model the budget at Cattaraugus Creek Harbor, two separate sets of cells were used: pre-construction and post-construction. The pre-construction budget consists of two cells: a fillet cell updrift of the creek mouth and a harbor cell at the mouth of the creek (cells 75 and 76, respectively). The pocket beach updrift of Cattaraugus Creek Harbor had been stable prior to construction, so sediment passed through the fillet cell into the harbor cell. A flux of 2,700 m³/year is added to the harbor cell to represent bed load and is passed downdrift.

The Recent and Future budgets had two additional cells modeled at Cattaraugus Creek Harbor: a scour cell and a shoal cell (cells 77 and 78, respectively). An additional flux into the shoal cell of 1,000 m³/year is added in from erosion of the beach and near-shore down-drift of the harbor.

An average of 3,200 m³/year has accumulated on the beach immediately south (updrift) of Cattaraugus Creek Harbor, agreeing with the predicted longshore transport rate of 4,000 m³/year from the bluff analysis. The accretion rate in the fillet cell was modeled to be 3,200 m³/year, with 800 m³/year continuing downdrift. In the Future time frame, the accretion rate at the fillet is predicted to decrease to 1,000 m³/year, with 1,900 m³/year of LST continuing around, over, and through the South Breakwater, and 1000 m³/year lost from the system.

During the Recent time frame, an average of 17,700 m³/year has eroded at the location of the shoal. A new shoal has formed at the redirected mouth of Cattaraugus Creek Harbor, accreting at a rate of 7,400 m³/year. The nearshore zone downdrift has eroded at a rate of 1,000 m³/year, giving a net rate of change of 6,400 m³/year between the shoal and downdrift nearshore erosion.

The erosion of the historic shoal to the southwest of the existing mouth is a result of the redirection of flow by the harbor structures, providing a temporary source of littoral material. The 2011 lidar data show the bathymetry in this area moving towards an equilibrium cross-shore profile, indicating the shape of the original shoal has gotten closer to a stable state. Because of this, the quantity of littoral material coming from this scour is projected to decrease substantially in the Future to 3,500 m³/year in this scour cell (900 m³/year removed from the system offshore and 2,600 m³/year continuing into the shoal cell). As the date gets further from the construction of the project, this erosion rate will continue to decrease.

The accretion of the shoal cell in the Recent time frame is also a temporary condition. As the project matures, accretion rates in this cell will likely decrease as the project reaches equilibrium, resulting in an accretion rate of 2,000 m³/year. Total littoral transport downdrift is expected to decrease to 4,500 m³/year with an additional 1,500 m³/year lost to deep water.

Other assumptions:

1. A total of 25% of the eroded material from the scour is lost from the system while the remaining 75% continues into the harbor cell and downdrift to the northeast.
2. 2,000 m³/year of sediment is lost to deep water from the shoal in the Recent time frame, falling to 1,500 m³/year in the Future time frame.
3. 800 m³/year of material passes over and through the South Breakwater into the harbor cell in the Recent time frame, increasing to 1,900 m³/year in the Future time frame as a result of the fillet reaching equilibrium.

Table 27 gives predicted and measured sediment flux values at Cattaraugus Creek Harbor.

Table 27. Measured and predicted volumetric change at Cattaraugus Creek Harbor (all units in cubic meters/year).

| | Recent | | Future** |
|---------------|----------------------------------|--------------------------------------|----------------------------------|
| | Calculated Sediment from Bluffs* | Calculated Rate from Harbor Analysis | Calculated Sediment from Bluffs* |
| South | 3,100 | 3,200 | 1,900 |
| North (Shoal) | 6,000 | 6,400 | 2,000 |
| Total | 9,100 | 9,600 | 3,900 |
| | Total Difference | 500 | 5,700 |
| | | 5% | 59% |

* Includes sediment from the Cattaraugus Creek bedload and sediment eroded from shoal.

**Accretion rates are predicted to decrease to conditions closer to preproject as a result of the project reaching a new equilibrium.

The SBAS cells for Cattaraugus Creek Harbor from the Pre-Armoring through the Future time frames are presented in Figures 76 through 79.

Figure 76. Sediment budget for Cattaraugus Creek Harbor for Pre-Armoring period.

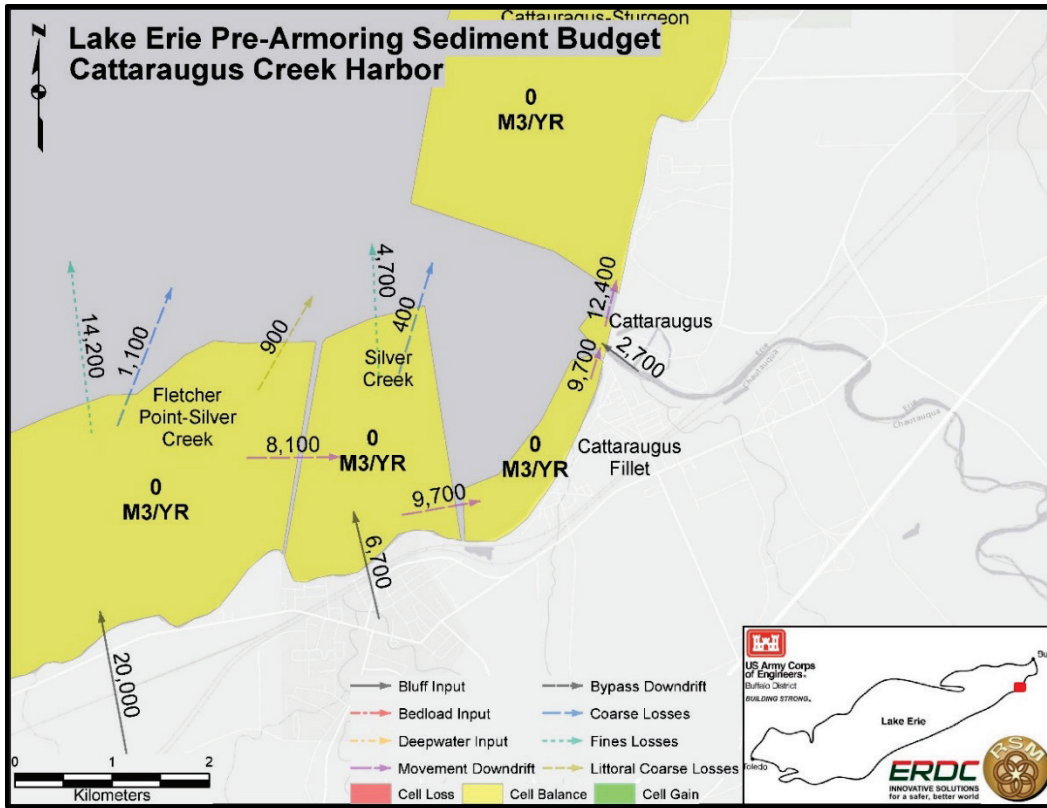


Figure 77. Sediment budget for Cattaraugus Creek Harbor for Mid-Century period.

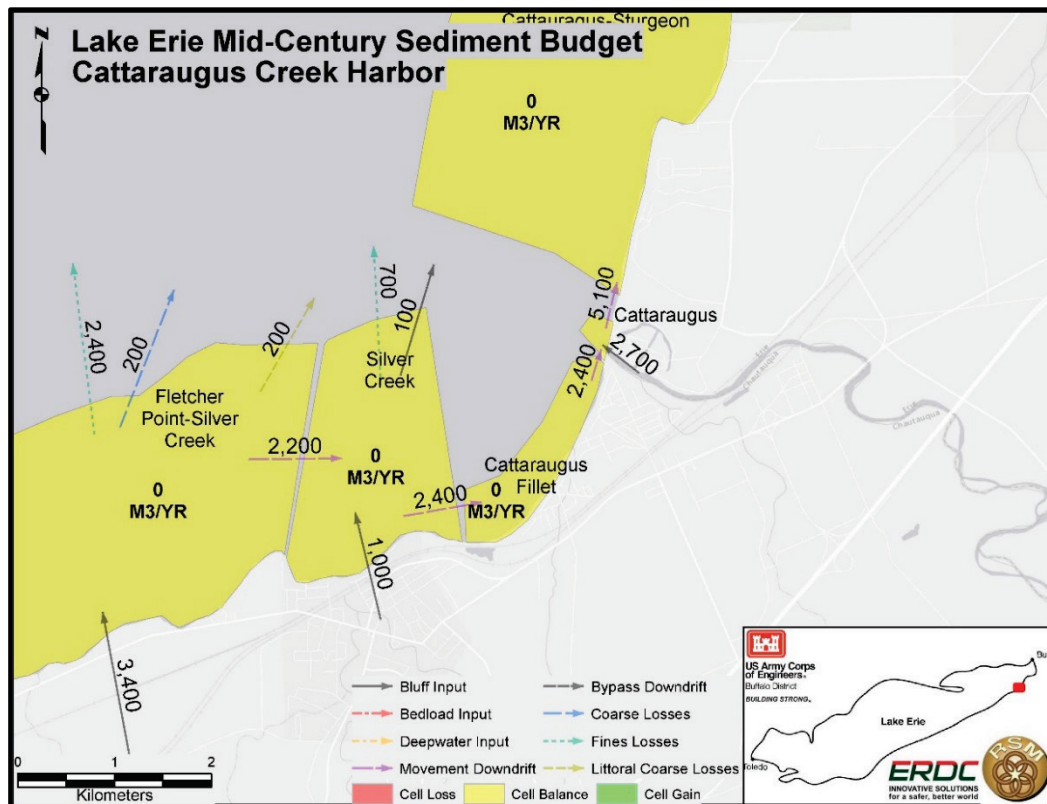


Figure 78. Sediment budget for Cattaraugus Creek Harbor for recent period.

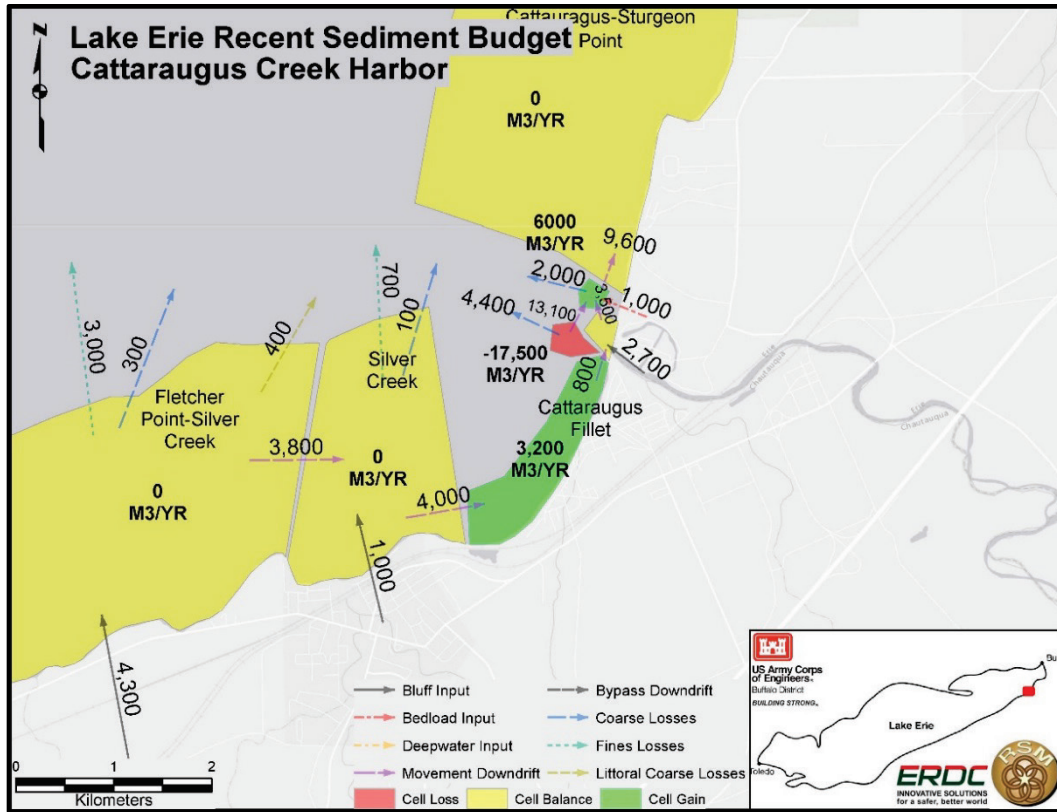
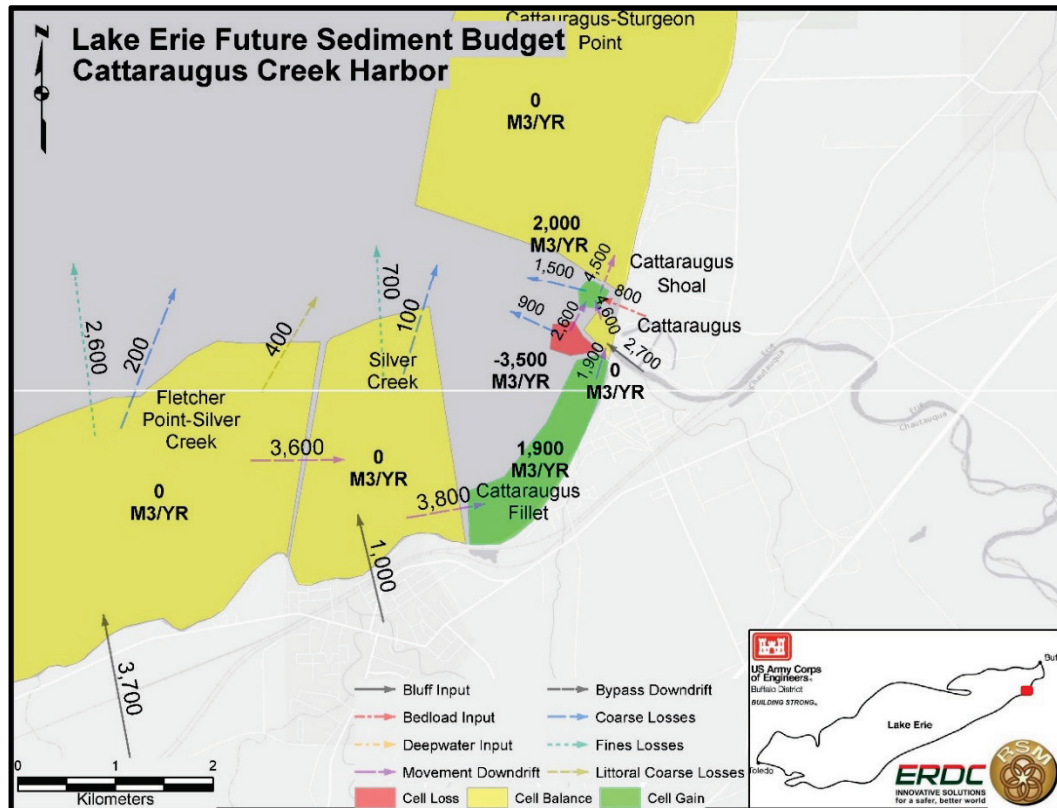


Figure 79. Sediment budget for Cattaraugus Creek Harbor for Future conditions.



10 Bypassing at Harbors/Sinks

Harbor improvements in the Great Lakes began with the earliest settlers and their attempts to maintain navigable channels for trade and safety. Large-scale improvements began in earnest in the early to mid-1800s and have continued to the present. Creek mouths were protected with piers, breakwaters provided shelter from wave action, and dredging of deep-water navigation channels further disrupted sediment transport through the littoral system.

The impact of recent shoreline improvements on the littoral system has been taken into account, and a number of harbors on Lake Erie now require sediment bypassing as part of the permitting process. These harbors provide a good case study and verification for littoral sediment quantity measurements. Knowledge of bypassing quantity is also important with regard to movement of sediments around harbors for computation of downdrift quantities.

White City Park, Cleveland, OH

White City Park is the first littoral drift impoundment east of Cleveland (Figure 80). Records provided by the Buffalo District Regulatory Branch state that up to 765 m³/year of dredging and bypassing are authorized at this location. Actual dredging quantities are not available. Aerial imagery shows little change in shoreline position between the 1974 and 2006 images, so it is assumed that any material being trapped at this location is bypassed to the east.

Cleveland Lakefront State Park, Cleveland, OH

Cleveland Lakefront State Park lies to the east of White City Park (Figure 80). Records provided by the Buffalo District Regulatory branch state that up to 5,350 m³/year of dredging and bypassing is authorized at this location. Actual dredging quantities are not available. A beach-fill project and series of segmented breakwaters were completed after the 1974 aerial, but additional information is not available at this time. It is assumed that any material trapped at this location is bypassed to the east.

Figure 80. White City Park (left) and Cleveland Lakefront State Park (right), Cleveland, OH. Green dots show 1 km reaches used in this study. Photograph taken 03 Feb 2012.



Eastlake Power Plant, East Lake, OH

Eastlake Power Plant is a coal-fired generating station with a water intake located along the shore. Two shore-normal jetties extend into the lake, with the inlet channel curving to the west. To maintain the inlet channel, the Plant performs annual dredging. Placement of dredged material depends on the constituency of the dredged material; finer-grained sediments are disposed offsite while coarser material is placed downdrift (east) of the facility. A breakdown of downdrift placement/offsite disposal is not available. Historical imagery shows minimal infilling of the fillet (Figure 81), so an estimated 1,000 m³ annual accretion rate for the Mid-Century time frame, 800 m³ annual accretion rate for the Recent time frame, and 500 m³ annual accretion rate for the Future time frame is assumed with the remainder of the sediment bypassed to the east. Annual dredging quantities are given in Table 28.

Figure 81. Eastlake Power Plant: 1974 (left) and 2006 (right).



Table 28. Dredging Quantities at Eastlake Power Plant, 2003–2011.

| Year | Volume (m ³) |
|---------|--------------------------|
| 2003 | 18,043 |
| 2004 | 16,056 |
| 2005 | 15,062 |
| 2006 | 0 |
| 2007 | 3,058 |
| 2008 | 5,734 |
| 2009 | 3,823 |
| 2010 | 30,582 |
| 2011 | 3,823 |
| Average | 10,687 |

Mentor Harbor, Mentor, OH

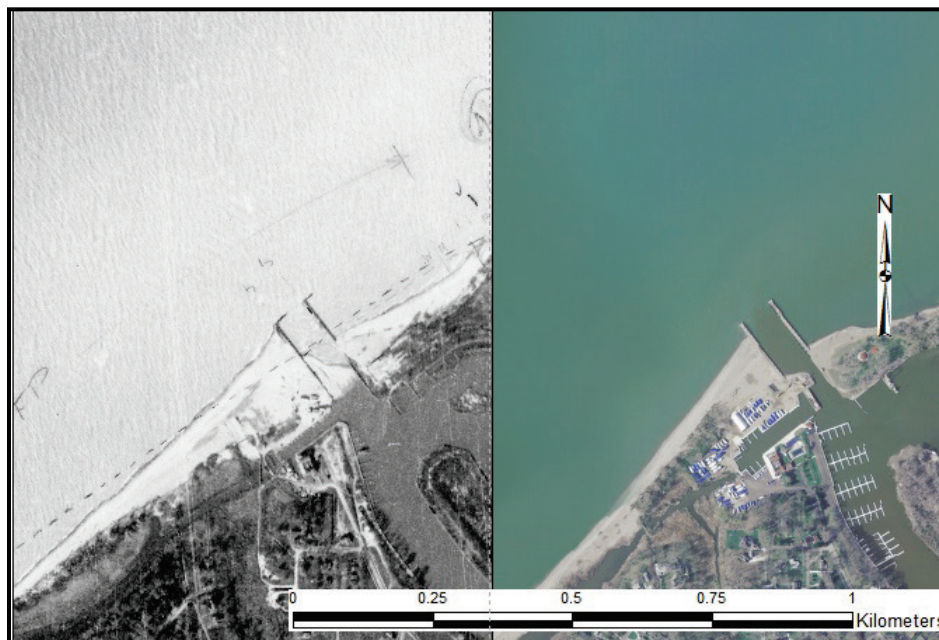
Mentor Harbor is located about half way between the Eastlake Power Plant and Fairport Harbor, OH. Dredging records between 2002 and 2011

indicate an average of 13,520 m³/year of dredging (Table 29). The shoreline has been relatively stable at this site since the 1938 imagery was flown (Figure 82). Thus, an estimated 1,000 m³/year annual accretion rate for the Mid-Century time frame, 750 m³ annual accretion rate for the Recent time frame, and 500 m³ annual accretion rate for the Future time frame is assumed, with the remainder of the sediment bypassed to the east.

Table 29. Dredging Quantities at Mentor Harbor, 2002–2011.

| Year | Volume (m ³) |
|---------|--------------------------|
| 2002 | 12,997 |
| 2003 | 10,704 |
| 2004 | 19,037 |
| 2005 | 10,704 |
| 2006 | 15,903 |
| 2007 | 20,031 |
| 2008 | 15,673 |
| 2009 | 12,615 |
| 2010 | 16,897 |
| 2011 | 6,415 |
| 2012 | 7,754 |
| Average | 13,520 |

Figure 82. Mentor Harbor: 1936 (left) and 2006 (right).



Townline Park Marina, North Perry, OH

The marina at Townline Park in the Village of North Perry, OH, was constructed in 2009. The project included two offshore rubble-mound breakwaters, a shore-connected rubble-mound breakwater, a launch ramp, binwall structures, beach creation, and upland improvements (JJR, LLC 2010). An overview of the marina structures is displayed in Figure 83. As part of the permitting process, the Village of North Perry is required to perform regular surveys to determine sediment accumulation and bypass sand as necessary.

Figure 83. Townline Park Marina, North Perry, OH. Green dot shows study reach no. 325. Photograph 03 Feb 2012.



The first bypass event occurred in 2010, and bypassing takes place multiple times throughout the ice-free season. Annual quantities are given in Table 30. Predicted littoral volumes from bluff erosion are provided in Table 31.

Table 30. North Perry bypass volumes, 2010–2012.

| Year | Volume (m ³) |
|---------|--------------------------|
| 2010 | 9,022 |
| 2011 | 24,026 |
| 2012 | 31,318 |
| 2013 | 24,523 |
| 2014 | 30,123 |
| Average | 23,802 |

Table 31. Predicted littoral volumes at North Perry Marina, OH.

| Time Frame | Littoral Volume (m ³ /year) |
|--------------|--|
| Pre-Armoring | 26,885 |
| Mid-Century | 40,230 |
| Recent | 34,770 |
| Future | 26,645 |

The Future condition is based on the shore armoring that is in place now and is the most relevant condition for comparisons to the North Perry bypassing quantities. The difference in the average quantity of material bypassed and the predicted littoral volume is approximately 2,800 m³ annually, or 11% of the predicted littoral volume. Additionally, dredging quantities have been on the rise since project completion because the town underestimated the volume of material that would need to be bypassed and has been dredging more frequently. The 2011 to 2014 dredging events are more indicative of actual accretion at the harbor.

North East Marina, Northeast, PA

North East Marina was constructed in 1991 and consists of an L-shaped concrete breakwater extending shore-normal for approximately 150 m into the lake before turning to the northeast and running shore-parallel for approximately 200 m (Morang and Melton 2001). A shore-normal breakwater on the east end of the marina provides a small entrance gap at the northeast corner of the facility (Figure 84).

Figure 84. North East Marina, North East, PA. Reach no. 143 is west of the marina. Photograph 19 Jun 2010.



Upon completion of the marina, a bypassing plan was instituted; however, regular bypassing was not initiated until 1994. Bypassing has continued from 1994 to the present. Annual bypassing totals are given in Table 32, and predicted littoral volumes are presented in Table 33.

Table 32. Bypass quantities at North East Marina, 1993–2010 (based on Morang and Melton [2001] with more recent data from Pennsylvania Fish and Boat Commission).

| Year | Volume (m ³) | Year | Volume (m ³) |
|------|--------------------------|---------|--------------------------|
| 1994 | 10,824 | 2003 | 7,920 |
| 1995 | 13,552 | 2004 | 9,649 |
| 1996 | 15,948 | 2005 | 11,572 |
| 1997 | 9,987 | 2006 | 11,747 |
| 1998 | 18,133 | 2007 | 13,403 |
| 1999 | 11,672 | 2008 | 13,199 |
| 2000 | 15,809 | 2009 | 14,516 |
| 2001 | 10,126 | 2010 | 17,391 |
| 2002 | 5,821 | Average | 12,428 |

Table 33. Predicted littoral volumes at North East Marina, PA.

| Time Frame | Littoral Volume (m ³ /year) |
|--------------|--|
| Pre-Armoring | 36,200 |
| Mid-Century | 32,500 |
| Recent | 25,500 |
| Future | 21,900 |

As the Future condition is based on the shore armoring that is in place now, this is the most relevant condition for comparisons to the North East Marina bypassing quantity. The difference in the average quantity of material bypassed and the predicted littoral volume is approximately 9,400 m³/year, or 43% of the predicted littoral volume. This discrepancy may be partially explained due to the small fillet building up to the west of the harbor, primarily in the area beyond the marina property.

Additionally, a majority of the littoral sediment in this area is derived from the erosion of till, which leads to uncertainty in the coarse fraction entering the system from bluff erosion. Also, some sediment that is not quantified may be lost offshore due to redirection around the breakwater.

Sturgeon Point Marina, Evans, NY

Sturgeon Point Marina was constructed in 1988 and consists of a 285 m long West Breakwater extending from shore and a smaller 105 m long East Breakwater (Figure 85). The design documents for the marina predicted an annual bypassing quantity from the updrift fillet of 6,190 m³ and dredging of approximately 2,295 m³ every 5 years from within the harbor (USACE 1987).

Since completion of the marina, actual accretion volumes have been higher than predicted. Dredging records indicate a rate of 7,645 m³ annually bypassed from the updrift fillet and 5,350 m³ annually dredged from within the marina (USACE 2004), or a total of 12,995 m³ annually.

Figure 85. Sturgeon Point Marina, NY. Shale platforms can be seen through the water offshore of the marina. Photograph 25 Sep 2013.



Sediment profiles obtained prior to the construction of the project indicated a high quantity of shale plates within the beach sediments (Figure 86). Soft shales are the dominant bedrock in this region and contribute a large volume to the littoral system. Once eroded from the bedrock, the shale quickly degrades mechanically to finer particles and eventually is lost from the system. There is a short period, however, when the shale makes an important volumetric contribution to the littoral system. Due to the high quantity of shale plates and the short reach between Cattaraugus Creek and Sturgeon Point (approximately 16 km), the shale coarse fraction contribution to the system was increased to between 30% to 50%, with the percentage increasing closer to Sturgeon Point. Predicted littoral volumes at Sturgeon Point due to bluff erosion/bedload from Cattaraugus Creek are given in Table 34.

Figure 86. Excavation in west fillet at Sturgeon Point pre-project construction (16 Nov 1988). Photograph shows high quantity of shale plates in soil column (USACE 2004).



Table 34. Littoral volumes at Sturgeon Point.

| Timeframe | Littoral Volume (m ³ /year) |
|--------------|--|
| Pre-Armoring | 36,400 |
| Mid-century | 10,000 |
| Recent | 12,700 |
| Future | 7,100 |
| Difference: | -300 |
| | -4% |

The predicted littoral volume in the Recent time frame underpredicts the measured littoral volume dredged at Sturgeon Point by 300 m³/year, or 4%. The Recent time frame is used as the basis for comparison at Sturgeon Point due to the high sediment load supplied to the littoral system by the eroding historic shoal at Cattaraugus Creek.

The predicted littoral system at Cattaraugus contributes an additional 6,900 m³/year to the LST rate above the amount predicted in USACE (1987). This increase is due to erosion of the historic shoal and deposition at

the new shoal, as discussed in Section 8. USACE (1987) also underpredicted the LST rate at Sturgeon Point by 6,500 m³/year, indicating that the bluff analysis in the Sturgeon Point Design Document was accurate but the movement of the shoal at Cattaraugus Creek was not predicted. With the historic shoal at Cattaraugus Creek nearly depleted, dredging at Sturgeon Point is expected to decline significantly in the future.

11 Discussion

Overview

Sediment budgets are of increasing value given the ever-greater pressures to manage the lake shoreline with greatly restricted Operations and Maintenance funding. The sediment budget presented here is the most comprehensive attempt yet to compute a budget for the U.S. shoreline of Lake Erie.

This study utilized bluff erosion as the primary driver for sediment inputs into the system, with offshore losses and trapping at Federal harbors as the primary sediment sinks. Historical data were derived from historic charts, dredging records, previous sediment studies, and first-hand experience with the natural processes on Lake Erie.

The bluff erosion measurements could be matched well with harbor accretion or sediment bypassing measurements at most points along the shoreline. However, bluff erosion measurements underpredicted measured sediment volumes at Fairport Harbor by 45% for the Pre-Armoring era, 74% for the Mid-Century period, and 8% for the Recent period (Table 20).

Future data/analysis needs

Shale contribution to the littoral system

A major source of uncertainty in this study is the determination of littoral material contributed by the weathering and erosion of shale bluffs. Shale accounts for the majority of the sediment entering the system in Erie and Chautauqua Counties in New York as well as the western section of Cuyahoga County, OH. Shale also contributes between 25% and 44% of the total sediment influx in Lorain County, OH (Table 35).

A high quantity of shale plates were observed in samples obtained prior to construction of the Sturgeon Point Marina (Figure 86), and field observation in many areas along the New York shoreline verify a significant quantity of eroded/weathered shale on the beaches and in the immediate littoral system. What is unknown is the spatial and temporal scale of the eroded shale as it pertains to the littoral volume. The material

degrades mechanically to very fine particles that can be winnowed out of the littoral system, so the contributions to the littoral system must decrease further from the source. However, the rate at which degradation occurs is unknown. The method of littoral volume determination would benefit greatly from a combined field/laboratory investigation into the process from which shale is weathered, eroded, mechanically degraded, and finally removed from the system as fines.

Measurement of short term adjustment to LST direction

The sediment fluxes represented in this budget reflect long-term littoral transport trends and do not account for short-term storm events and temporary transport direction reversals. The nodal points in central Ohio shift seasonally in response to prevailing wind and wave direction¹. The nodal point at Avon Lake is thought to shift seasonally between Vermilion and Cleveland (a distance of approximately 55 km).

A detailed study in the Vermilion-to-Cleveland reach would be beneficial for understanding the short-term, storm-induced transport.

Till contribution to the littoral system

Till has a highly variable constituency due to its depositional environment. The coarse fraction of till layers can vary dramatically both along a section as well as vertically through the section. A few studies have measured the gradation of the till at various locations along the lake shore (Carter 1977; Knuth 2001). The Buffalo District acquired core samples along the eastern Pennsylvania shore in 1986, but a comprehensive measurement of the constituency of the till throughout the study area would greatly increase the confidence associated with the results of this present study. Multiple samples at each representative location would be necessary to determine an accurate gradation for the till bluffs.

¹ Donald Guy, ODNR, Division of Geological Survey (retired), personal communication, 29 April 2013.

Table 35. Bluff erosion rates by county.

| | Total Shale Volume Eroded (m ³ /year) | | | | Total Bluff Volume Eroded (m ³ /year) | | | | Percentage of Bluff Volume from Shale Contribution | | | |
|---------------------------------------|--|-------------|--------|--------|--|-------------|---------|---------|--|-------------|--------|--------|
| | Pre-Armoring | Mid-Century | Recent | Future | Pre-Armoring | Mid-Century | Recent | Future | Pre-Armoring | Mid-Century | Recent | Future |
| Erie County, OH | 800 | 400 | 400 | 400 | 51,000 | 48,300 | 52,300 | 42,600 | 2% | 1% | 1% | 1% |
| Lorain County, OH | 20,900 | 9,000 | 9,400 | 4,400 | 84,900 | 29,600 | 21,300 | 10,000 | 25% | 30% | 44% | 44% |
| Cuyahoga County, OH-West of Cleveland | 54,700 | 25,200 | 14,900 | 11,800 | 74,700 | 33,000 | 20,100 | 14,300 | 73% | 76% | 74% | 83% |
| Cuyahoga County, OH-East of Cleveland | 600 | 500 | 400 | 200 | 29,300 | 21,700 | 8,100 | 5,100 | 2% | 2% | 5% | 4% |
| Lake County, OH | 0 | 0 | 0 | 0 | 296,600 | 306,500 | 237,200 | 168,000 | 0% | 0% | 0% | 0% |
| Ashtabula County, OH | 400 | 400 | 700 | 700 | 216,800 | 147,700 | 246,800 | 202,100 | 0% | 0% | 0% | 0% |
| PA West of Presque Isle | 0 | 0 | 0 | 0 | 226,200 | 268,200 | 163,100 | 148,500 | 0% | 0% | 0% | 0% |
| PA East of Presque Isle | 28000 | 18200 | 16700 | 15300 | 294700 | 248200 | 198300 | 177700 | 10% | 7% | 8% | 9% |
| Chautauqua County, NY | 123,700 | 29,600 | 36,600 | 35,400 | 248,500 | 65,500 | 72,100 | 68,900 | 50% | 45% | 51% | 51% |
| Erie County, NY | 67,200 | 27,200 | 13,400 | 10,900 | 109,500 | 37,800 | 20,300 | 15,000 | 61% | 72% | 66% | 73% |

Bedload contribution from tributaries

Cattaraugus Creek is the largest contributor of material to the littoral system along the New York lakeshore and for the purposes of this study, was modeled as the only contributor. The majority of sediment load carried by tributaries to Lake Erie is fine grain. Coarse material from the small and intermediate basins can only be expected during high flow events (Buxton 1977).

Processes around Port Clinton sink

The area around Port Clinton is considered as a sink for material coming from both the east and the west. The harbor analysis at Port Clinton did not show large quantities of material accreting, indicating that material is being lost offshore. A more detailed set of surveys at Port Clinton, as well as study into the wave mechanisms present in this area, would help to define the littoral processes.

Ice rafting and loss offshore

Transport of beach and possibly till material offshore as a result of entrainment in ice needs to be further investigated with field studies. It is unknown how much material is carried away from shore and under what circumstances. The results of field studies conducted by Barnes et al. (1993) at Lake Michigan may not be applicable to Lake Erie because of different geology and oceanographic conditions.

12 Conclusions

To calculate a sediment budget, the U.S. shoreline of Lake Erie from Maumee Bay, OH, to Buffalo, NY, was divided into 82 littoral cells. The cells vary in size from multi-kilometer stretches of bluff coast to individual harbors only a few hundred meters wide. Sediment budgets for four periods have been computed:

1. Pre-Armoring (1860s to late-1930s): representing the early development era
2. Mid-Century (late-1930s to late-1970s): representing the mid-twentieth century era of active harbor dredging, but comparatively limited shore protection
3. Recent (late 1970s to 2006-2009): era of extensive suburban development and shore armoring
4. Future: projected sediment inputs and longshore transport.

The budgets were based on computing sediment input into and determining losses from the littoral system. Most of the input along this shore is derived from bluff recession or (west of the Marblehead Peninsula, OH) erosion of low lacustrine deposits. Bluff recession was based on measuring bluff edges on historical maps or geo-referenced aerial photographs. To determine losses, volumes of sand stored in harbor fillets were computed using historical USACE bathymetry charts and historical dredging data. Future sediment budget predictions were based on the bluff recession rates from the Recent time frame (1970s–early 2000s) but with the input volume reduced because of the extensive shoreline armoring that now protects large portions of the coast. Ohio, in particular, is extensively armored.

Uncertainty in the computed sediment budget stems from numerous sources. First, shoreline (or bluff line) definition and detection is not a precise art. Most low shorelines are defined based on water-derived datums such as tide lines. For cliff or bluff-bound water bodies, the bluff edge is often used as a surrogate for the “shoreline” (Boak and Turner 2005). For low shorelines, such as those in western Ohio, potentially one of the most significant sources of error can be the assumption that the feature recorded at one instant in time (i.e., when a photograph was taken

or lidar survey flown) represents a *normal* or *average* condition. The researcher using archival material has little choice but to use whatever materials are available. With bluff edge detection, the bluff is more stable than a water-edge feature and does represent a more average condition. However, as documented above, interpretation is difficult in locations where the bluff edge is obscured by trees, poor lighting conditions, or urban overlay.

Second, the stratigraphy of the Lake Erie bluffs is not precisely known kilometer by kilometer. In this report, the proportion of till versus bedrock versus lacustrine material was interpreted from stratigraphic cross sections, but these were interpretations based on surveys and field notes from various field workers. Ideally, a new stratigraphic survey would have been conducted, but this would have entailed a significant cost and time burden. Even continuous photographic coverage of the shore is of limited value because of features that obscure the underlying sediment (trees and vegetation, urban construction) and because of the difficulty in scaling geology on oblique photography.

Third, the percentage of coarse versus fine grain sediment in the till along the lakeshore varies greatly. These data need better definition. A field-sampling program would be very beneficial.

Fourth, there is inherent uncertainty in the measurement of sediment accumulation at the harbor structures. Uncertainty results from potential cartographic errors in the initial mapping (in many cases in the mid-1800s), varying degrees of accuracy of data, limits in data sources, and generalization of topographic features as a result of the 3D mapping.

Potential sources of error have been minimized to a great extent but will always exist with historic data. Future projections could be refined and errors reduced with the addition of future high-resolution data sets used for computation. Some repeated high-resolution data sets are becoming available via lidar overflights. However, recent data collection was conducted when the study area was subject to high suspended sediment loads as well as algal blooms, thus limiting the ability of the sensor to capture bathymetric data. The Buffalo District has collected high-resolution bathymetry at Federal harbors, but these data sets are generally limited to dredged areas in the Federal channel and are of little use to this study. Dredging quantities were also investigated, but the constituency and the sources of the material (riverine vs. littoral) are unknown and of little use in determining littoral volumes.

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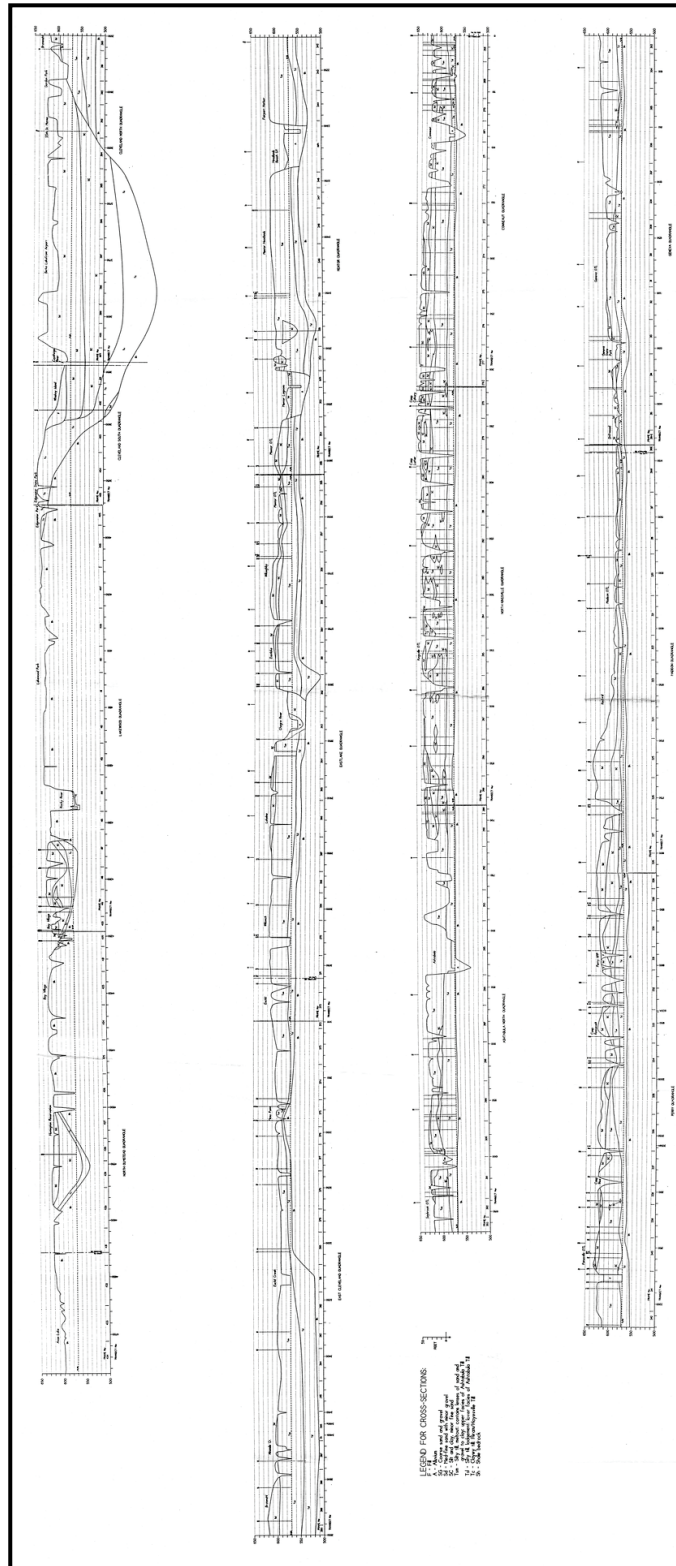
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Appendix A: Bluff Stratigraphy – New York and Ohio

Figure A-1, from Geier and Calkin (1983), is a cross section of the stratigraphy of the coastal bluffs of Lake Erie in New York State. This is similar to a view that a person would see cruising parallel to the shoreline on a boat. The origin of this plot may be Geier's M.A. thesis (Geier 1983). Similar cross sections were not available for Pennsylvania.

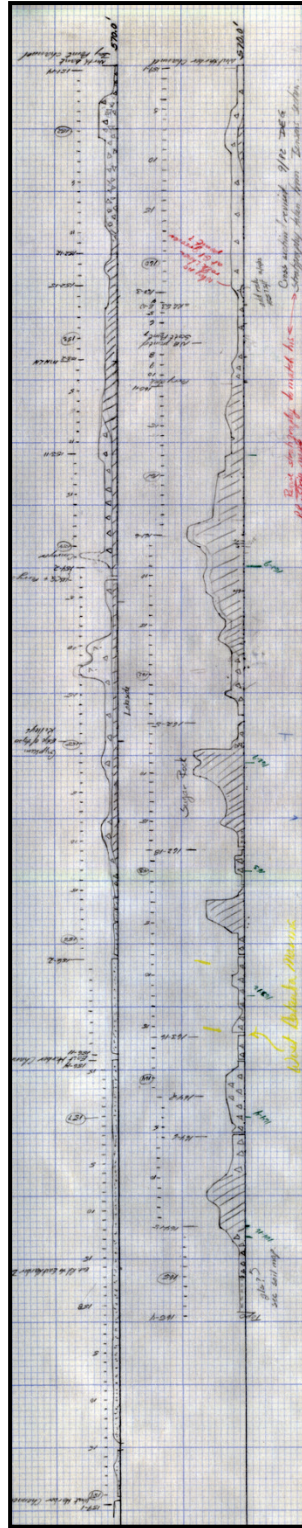
For the Ohio shoreline, the ODNR supplied cross sections from published reports and unpublished manuscripts (Figures A-2 and A-3).

Figure A-2. Cross sections of eastern Ohio bluffs (after Stone et al.¹). The Cleveland urban area with its armored coast is not shown.



¹Stone, B. D., R. R. Pavey, J. A. Fuller, and D. S. Foster. Unpublished report. Map of surficial surface materials in the Lake Erie coastal area, northeastern Ohio. U.S. Geological Survey Open-File Report. Denver, CO: U.S. Geological Survey Publications Warehouse.

Figure A-3. Cross sections from Ottawa-Lucas counties (provided by ODNR). Contrast enhanced from original scan using Photoshop Elements software version 8.



Appendix B: Complete Lake Erie Sediment Budget

The following figures (Figures B-1 through B-60) show the sediment budgets for the four time periods (a) Pre-Armoring, (b) Mid-Century, (c) Recent, and (d) Future along the southern Lake Erie shoreline of the United States. The figures begin at Maumee Bay at the west end of Lake Erie (just west of Toledo Harbor, OH) and proceed eastward to the Sturgeon Point/Buffalo, NY, region.

Figure B-1. Toledo to Locust Point Pre-Armoring sediment budget.

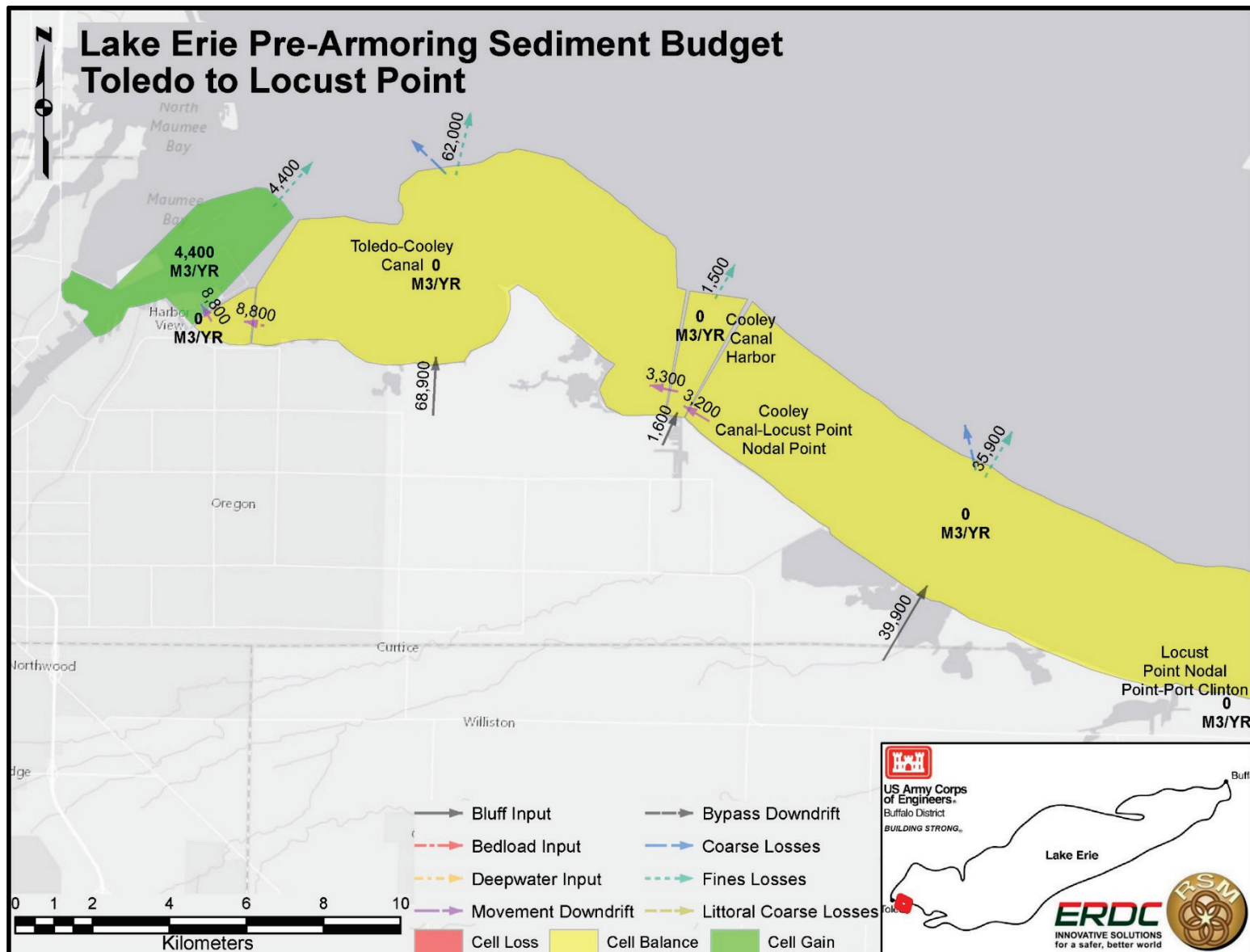


Figure B-2. Toledo to Locust Point Mid-Century sediment budget.

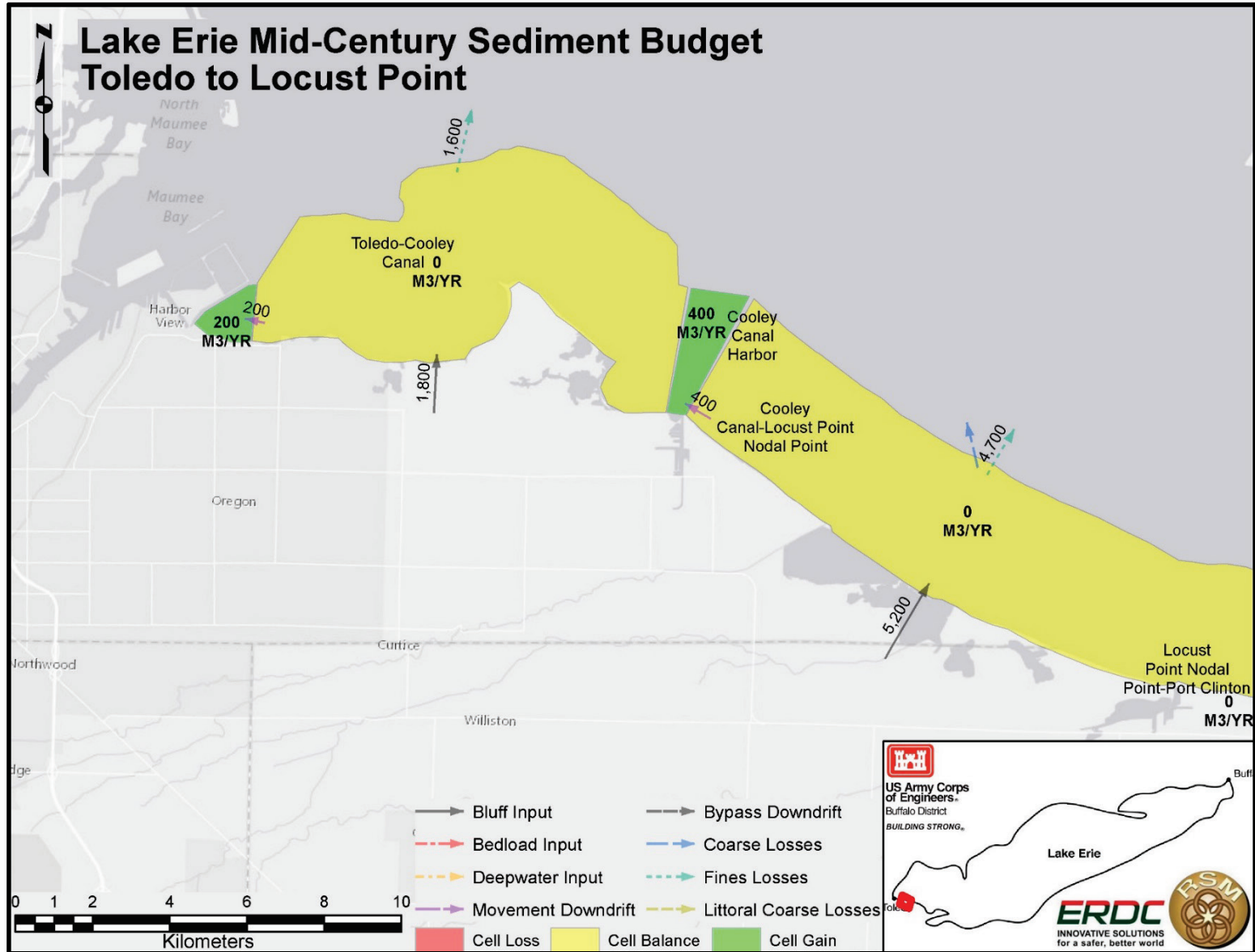


Figure B-3. Toledo to Locust Point Recent sediment budget.

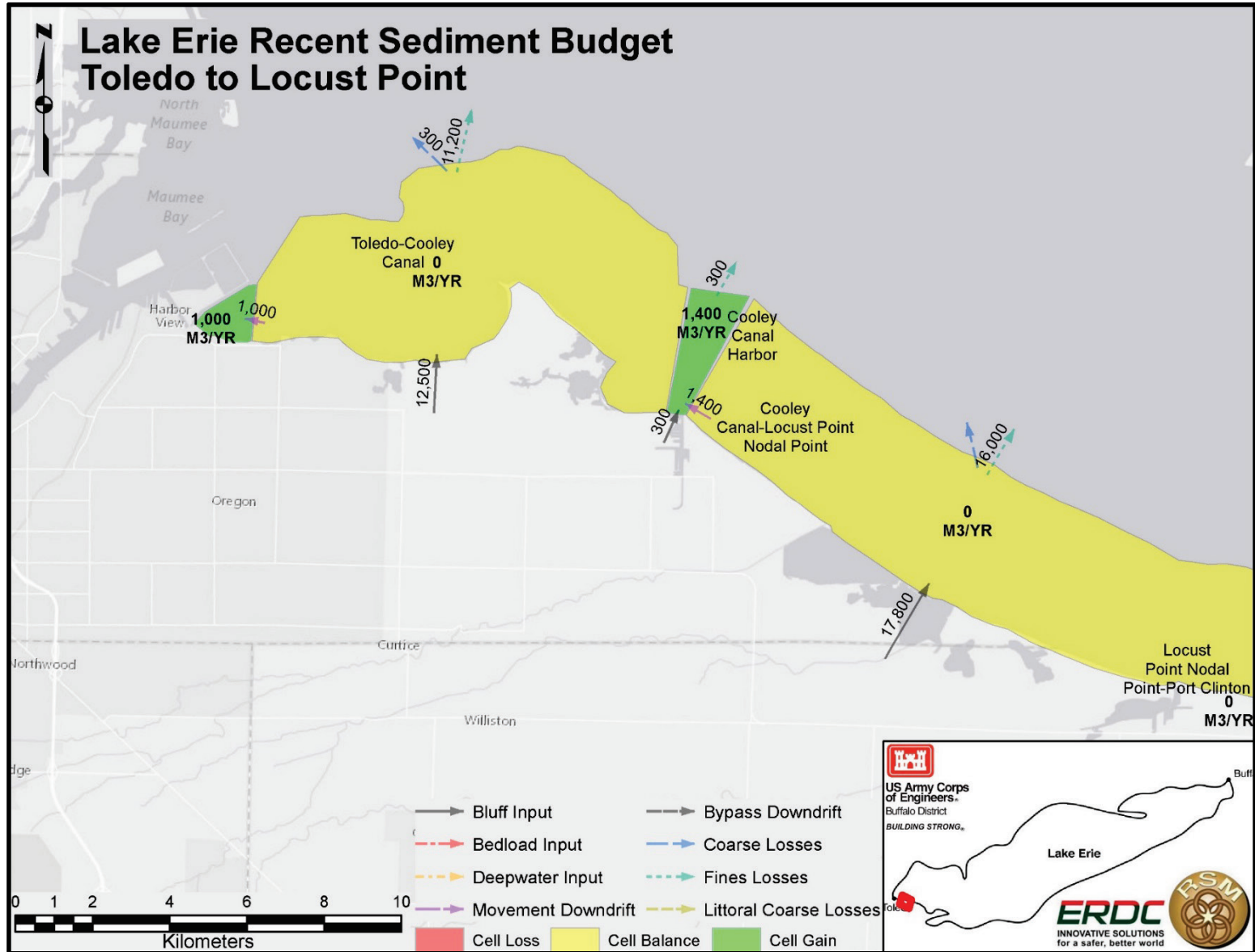


Figure B-4. Toledo to Locust Point Future sediment budget.

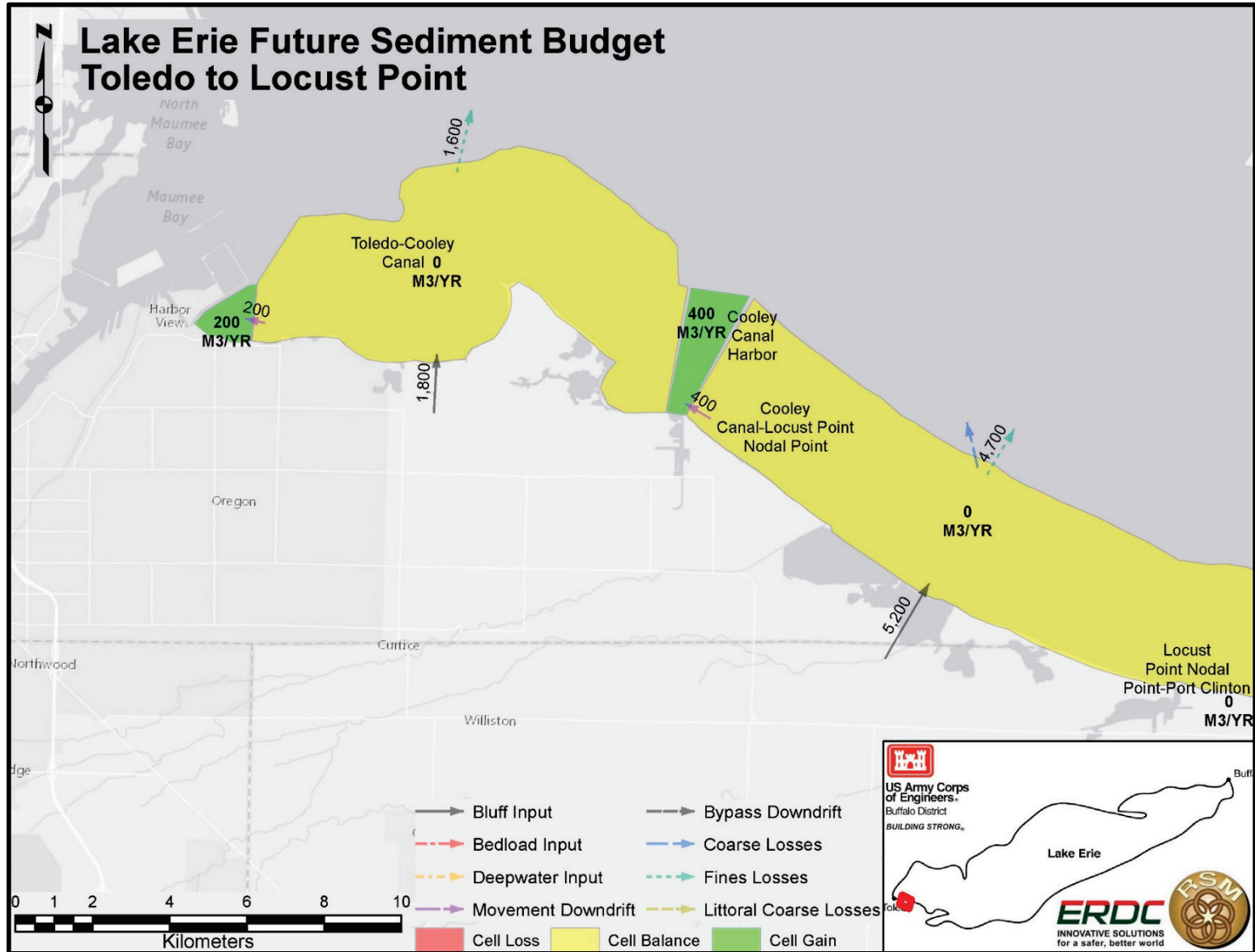


Figure B-5. Locust Point to Sandusky Pre-Armoring sediment budget.

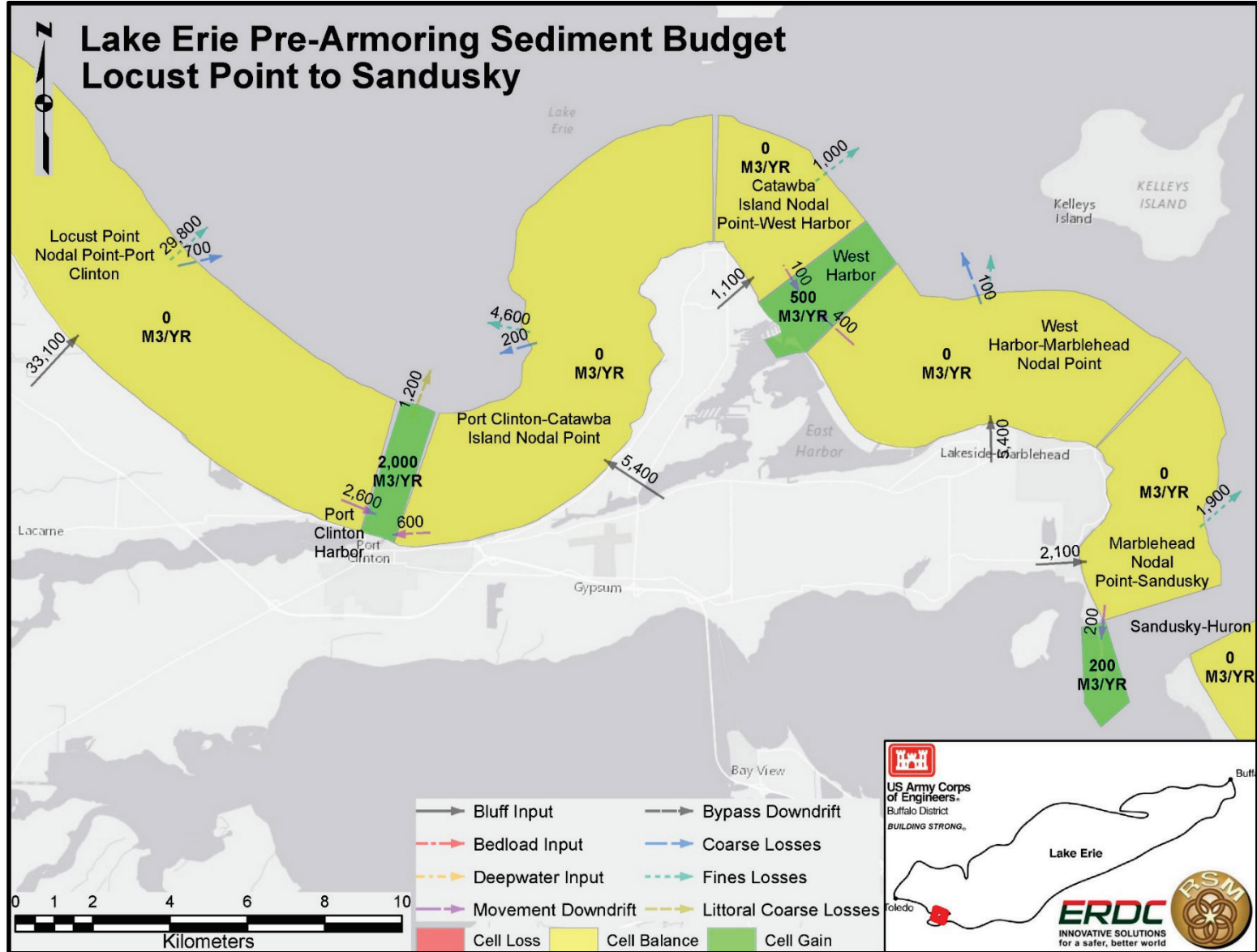


Figure B-6. Locust Point to Sandusky Mid-Century sediment budget.

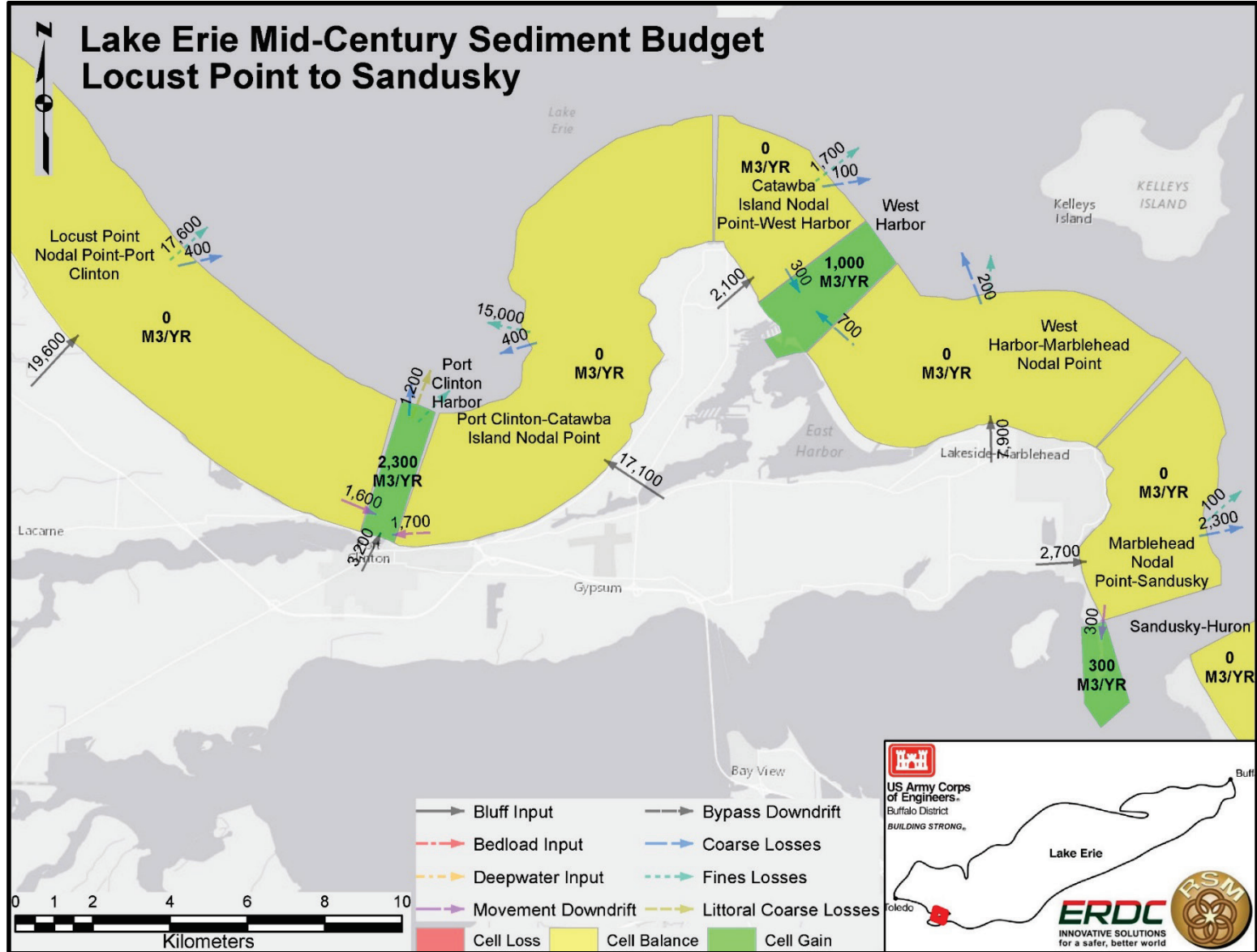


Figure B-8. Locust Point to Sandusky Future sediment budget.

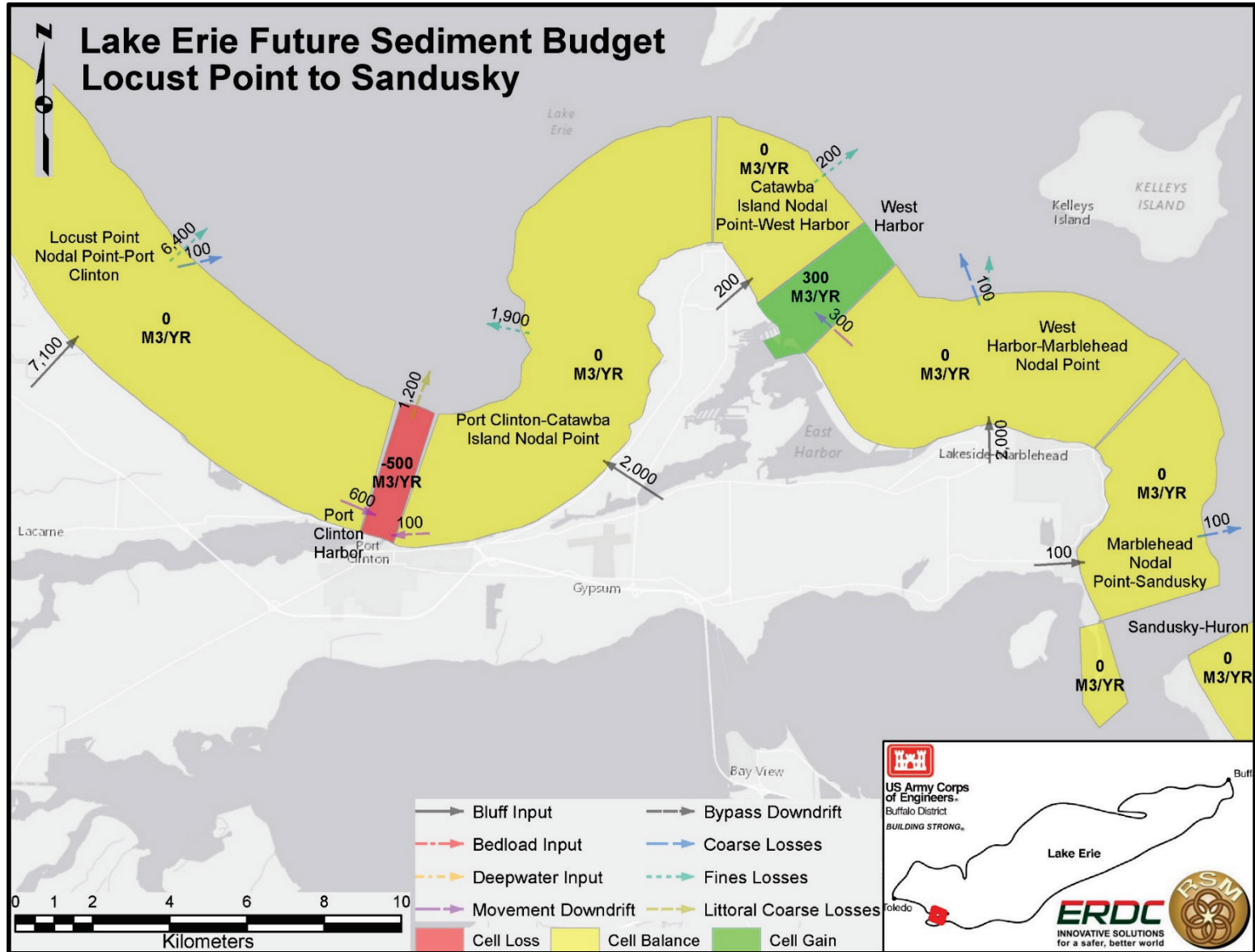


Figure B-9. Sandusky to Beaver Park Marina Pre-Armoring sediment budget.

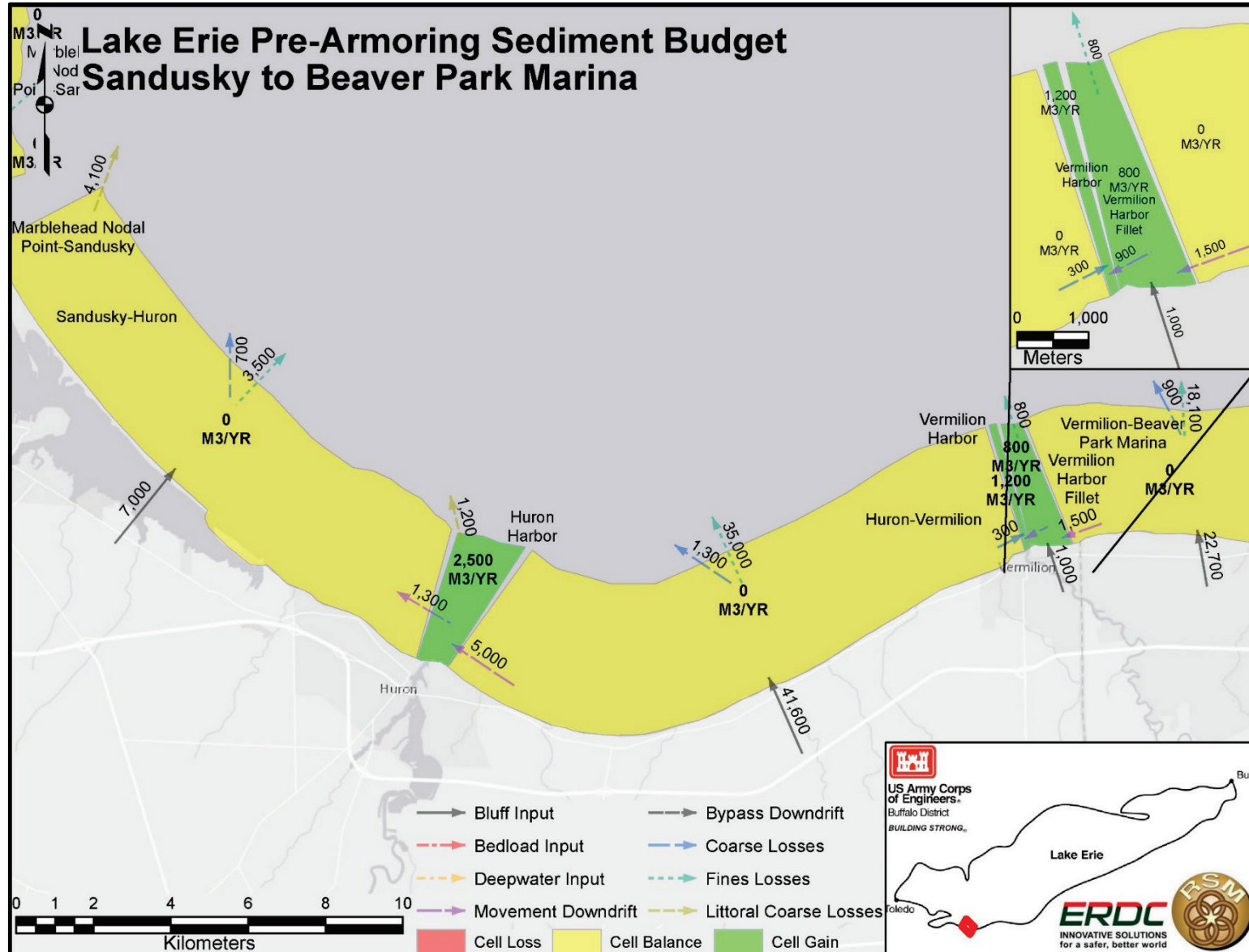


Figure B-10. Sandusky to Beaver Park Marina Mid-Century sediment budget.

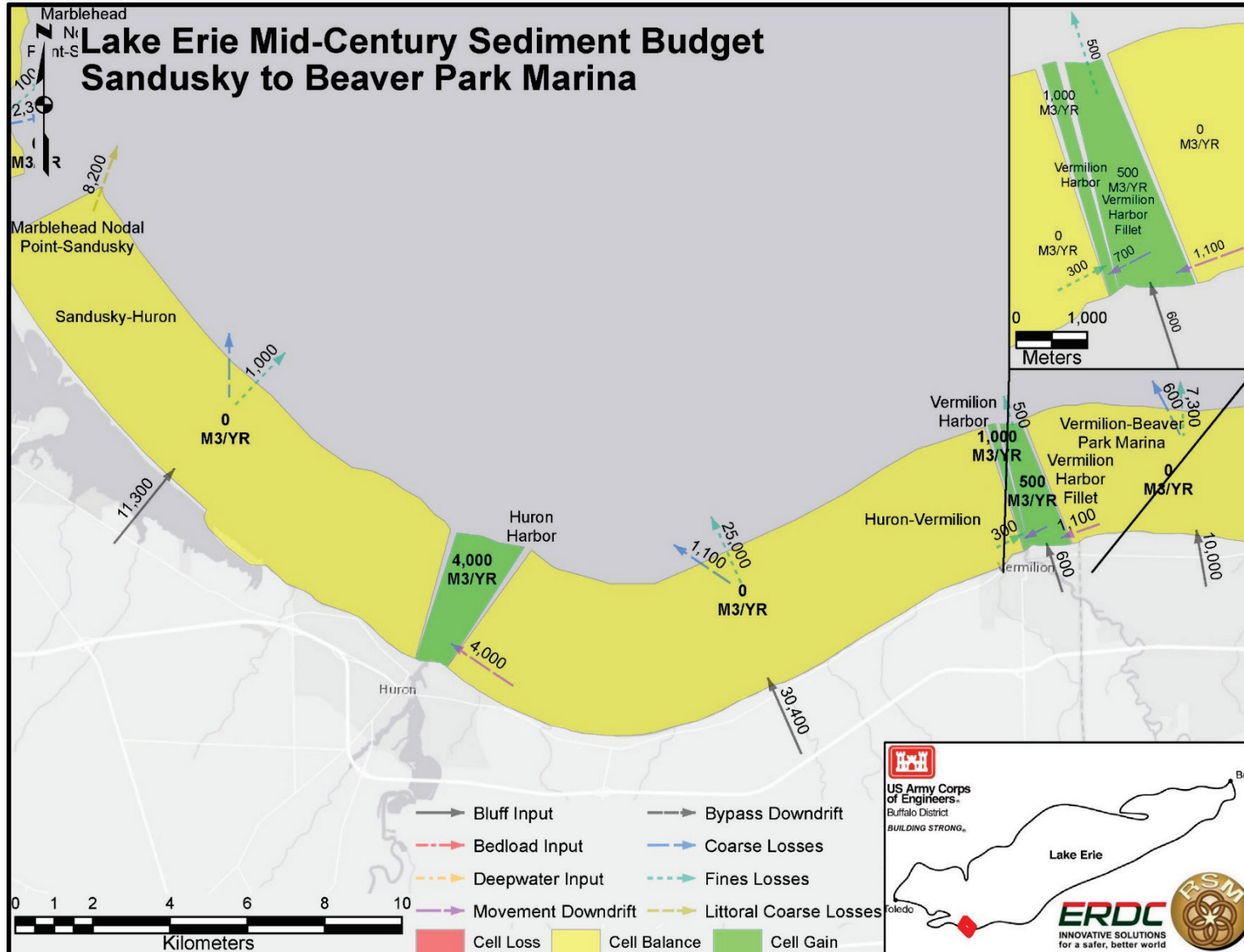


Figure B-11. Sandusky to Beaver Park Marina Recent sediment budget.

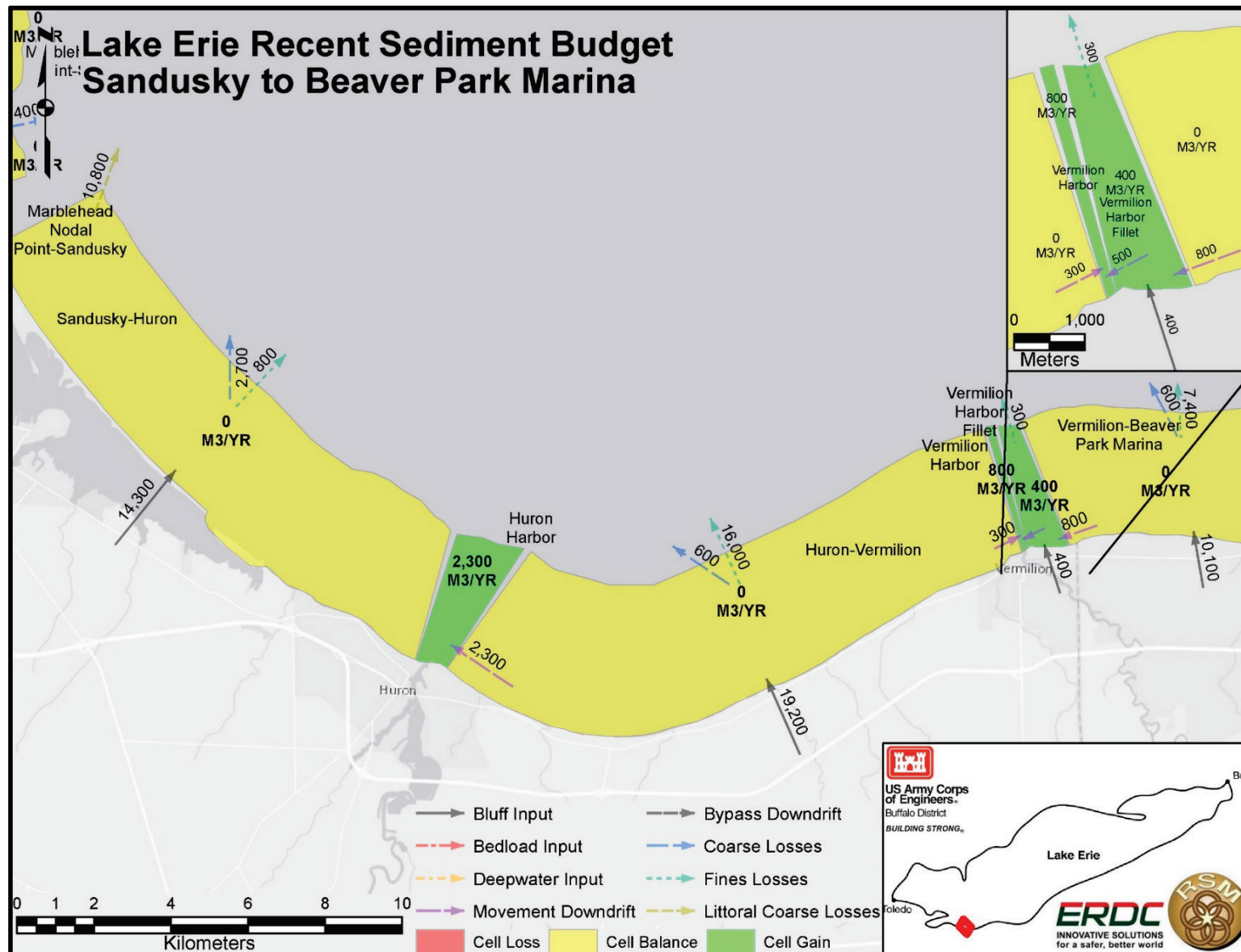


Figure B-12. Sandusky to Beaver Park Marina Future sediment budget.

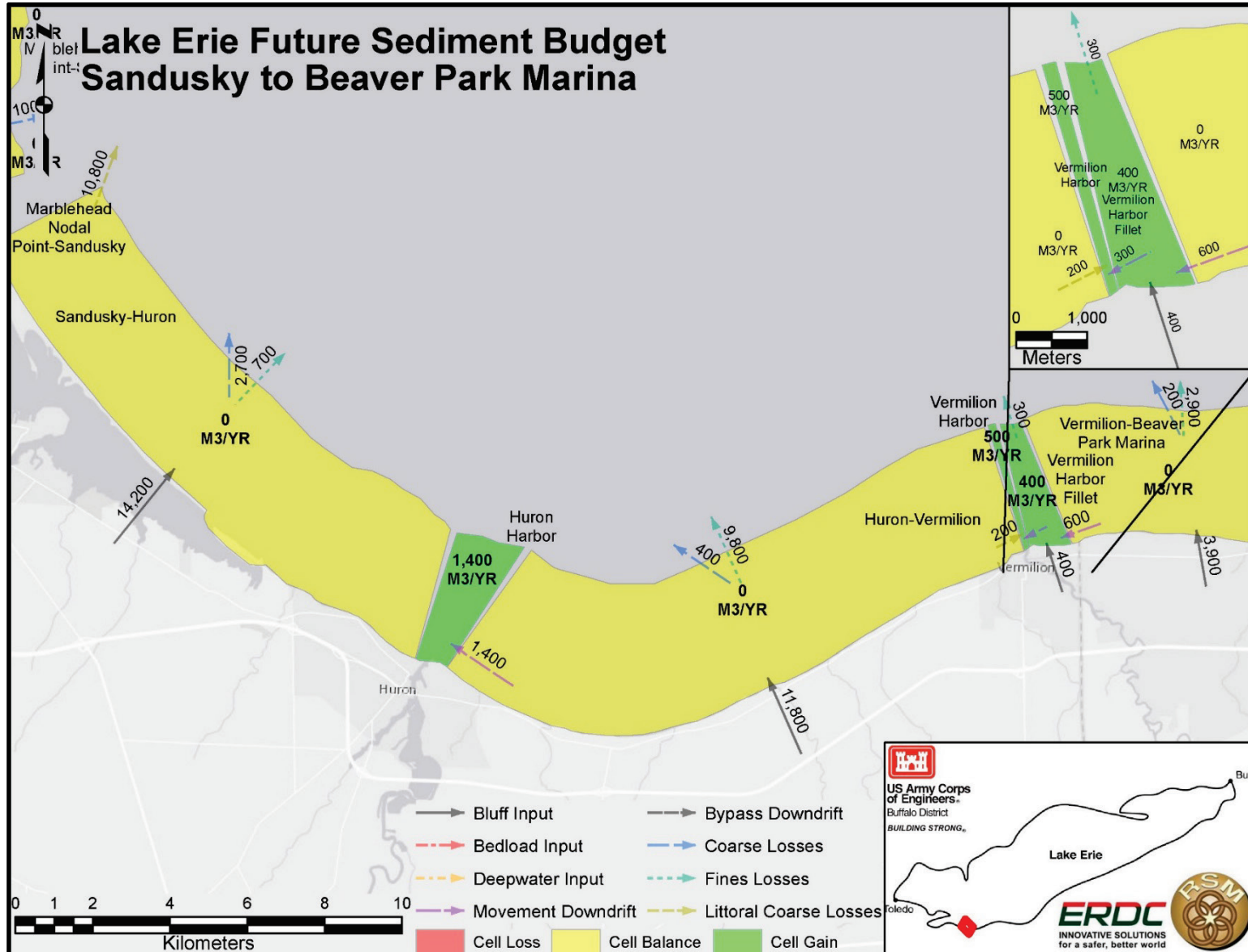


Figure B-13. Beaver Park Marina to Avon Lake Nodal Point Pre-Armoring sediment budget.

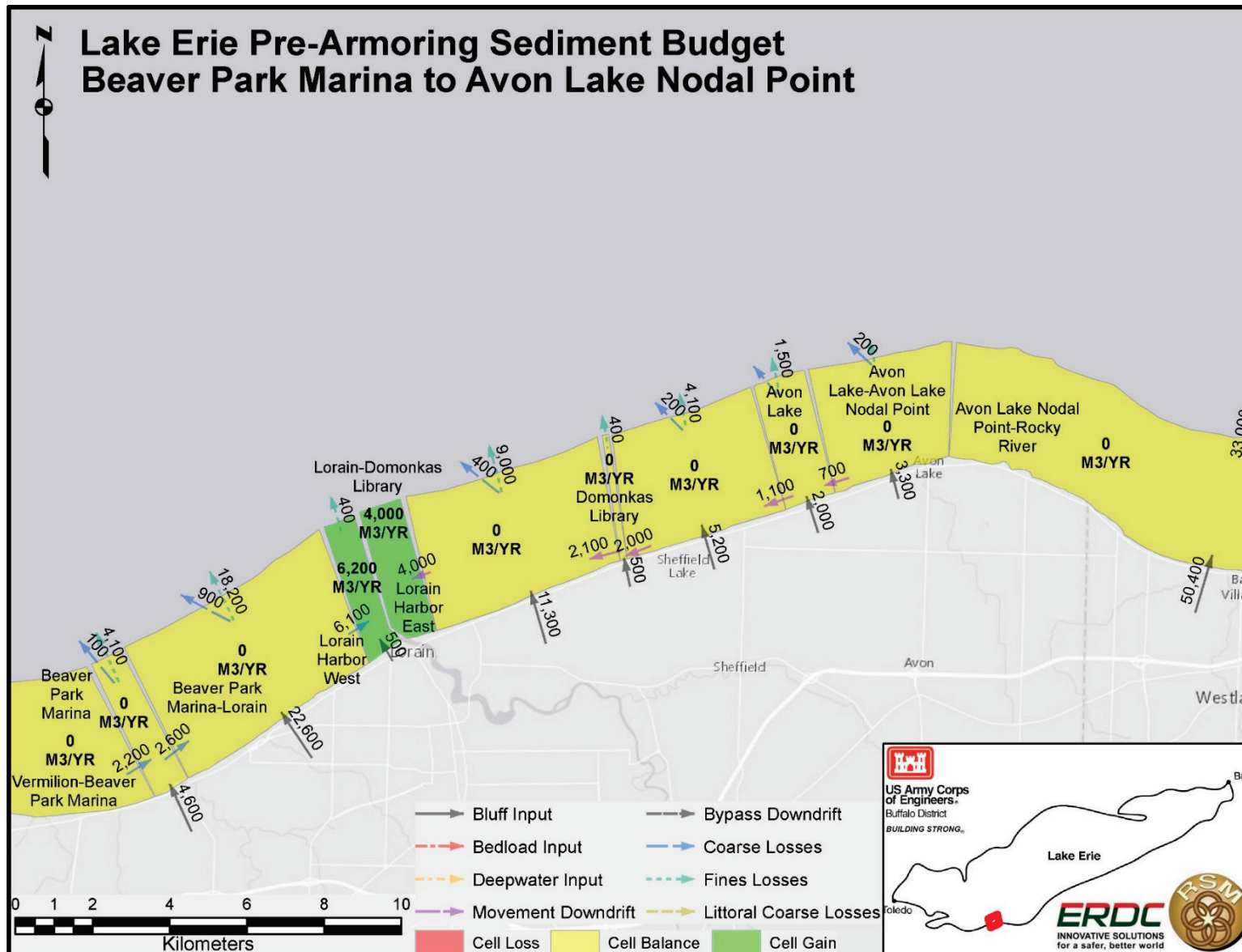


Figure B-14. Beaver Park Marina to Avon Lake Nodal Point Mid-Century sediment budget.

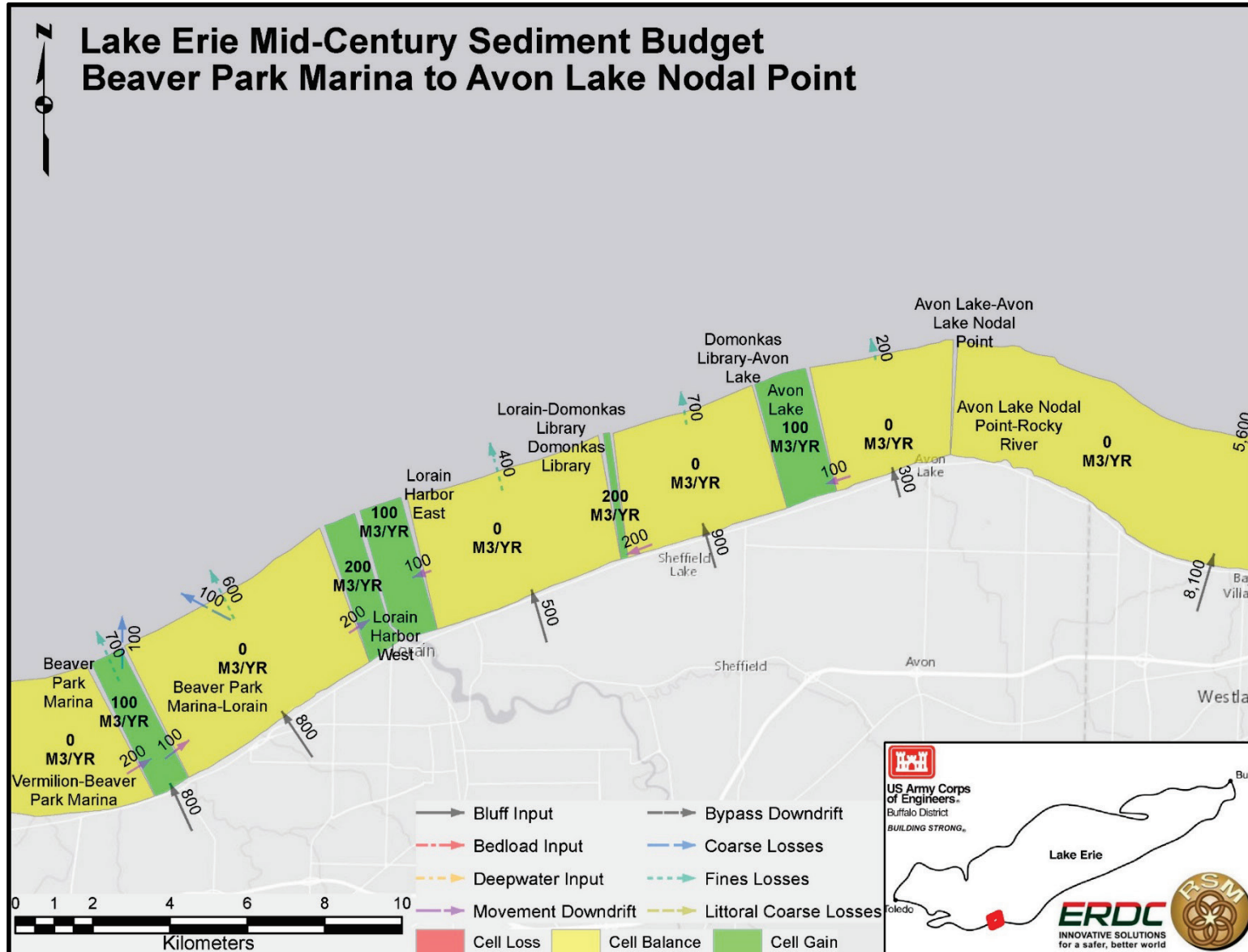


Figure B-15. Beaver Park Marina to Avon Lake Nodal Point Recent sediment budget.

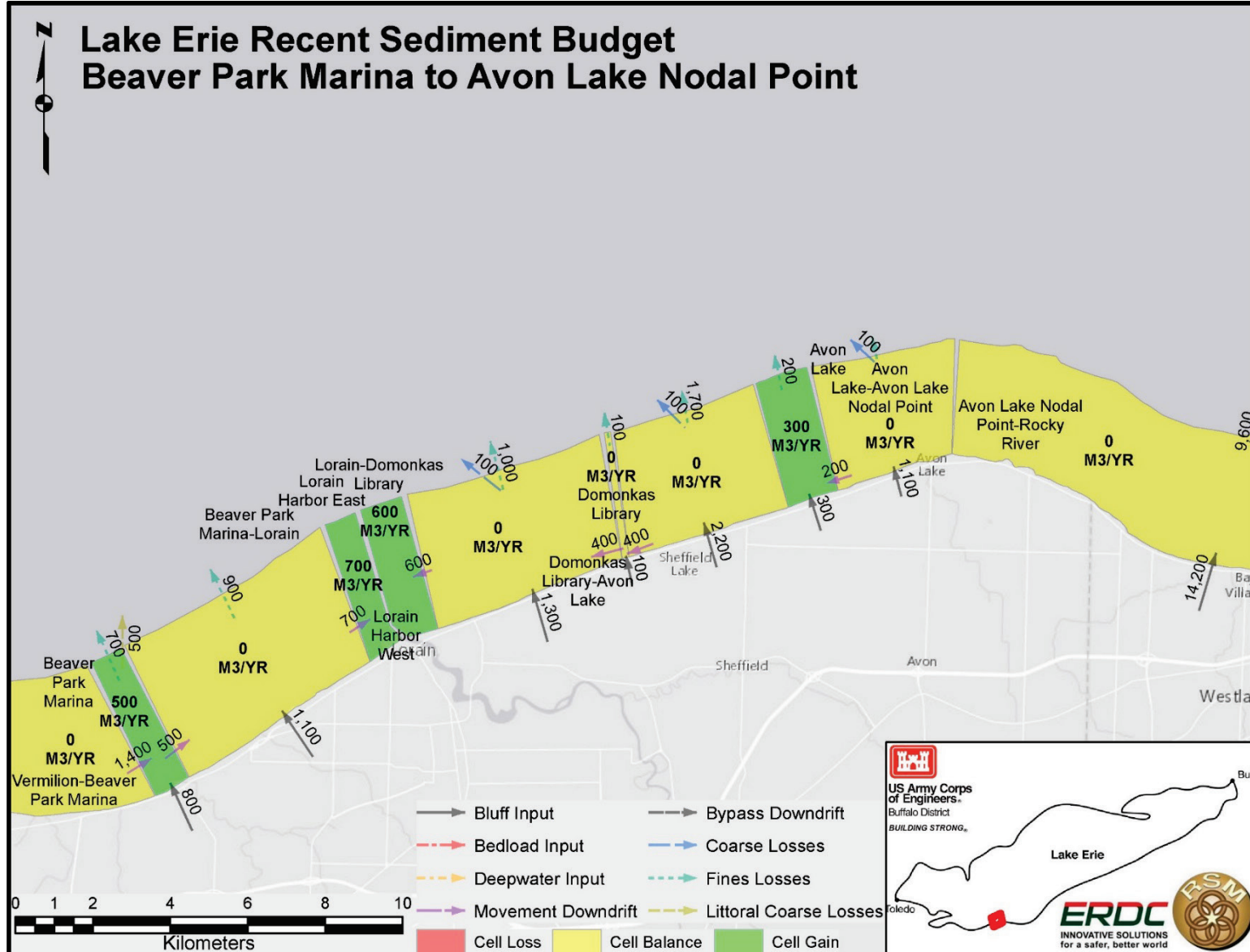


Figure B-16. Beaver Park Marina to Avon Lake Nodal Point Future sediment budget.

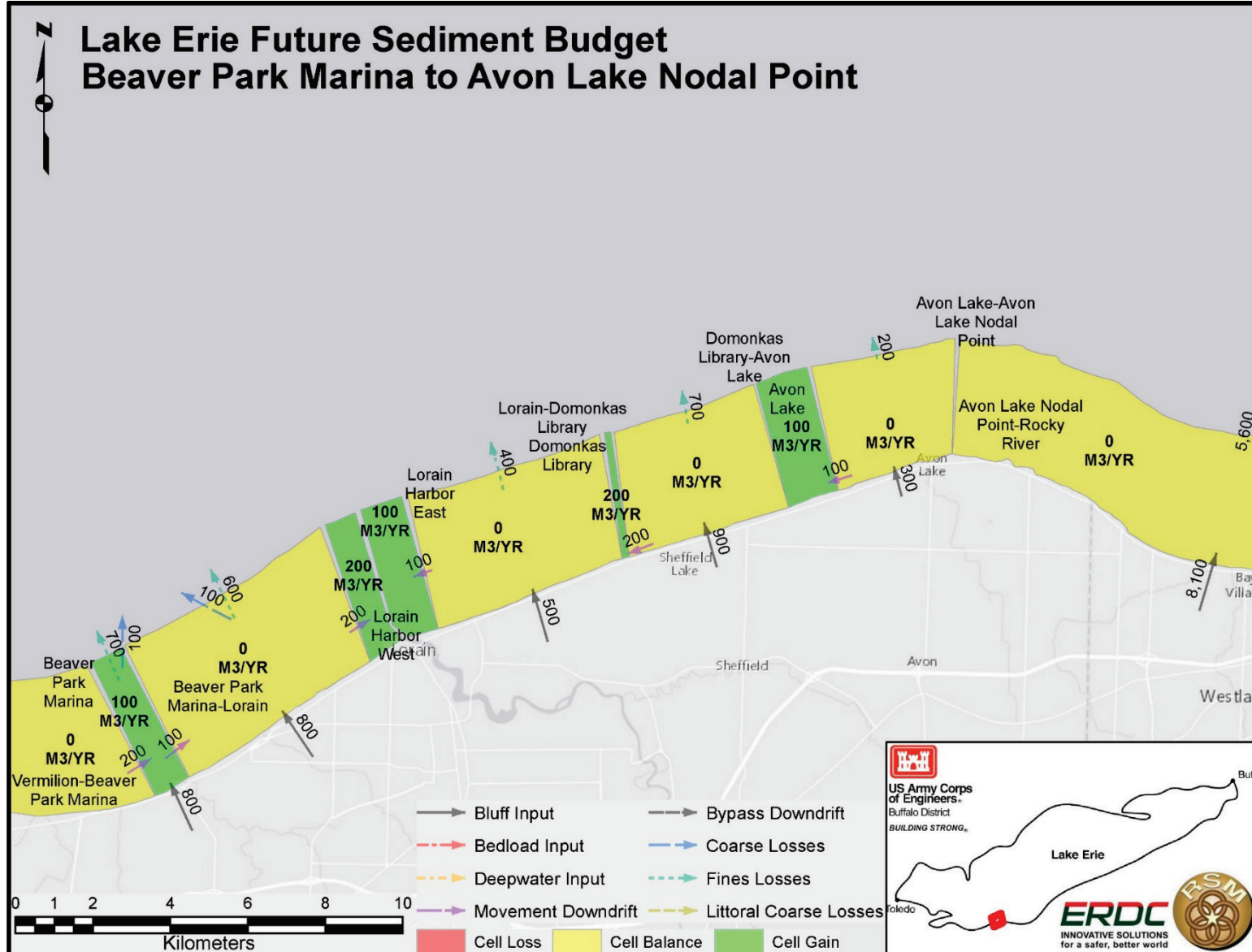


Figure B-17. Avon Lake Nodal Point to Cleveland Pre-Armoring sediment budget.

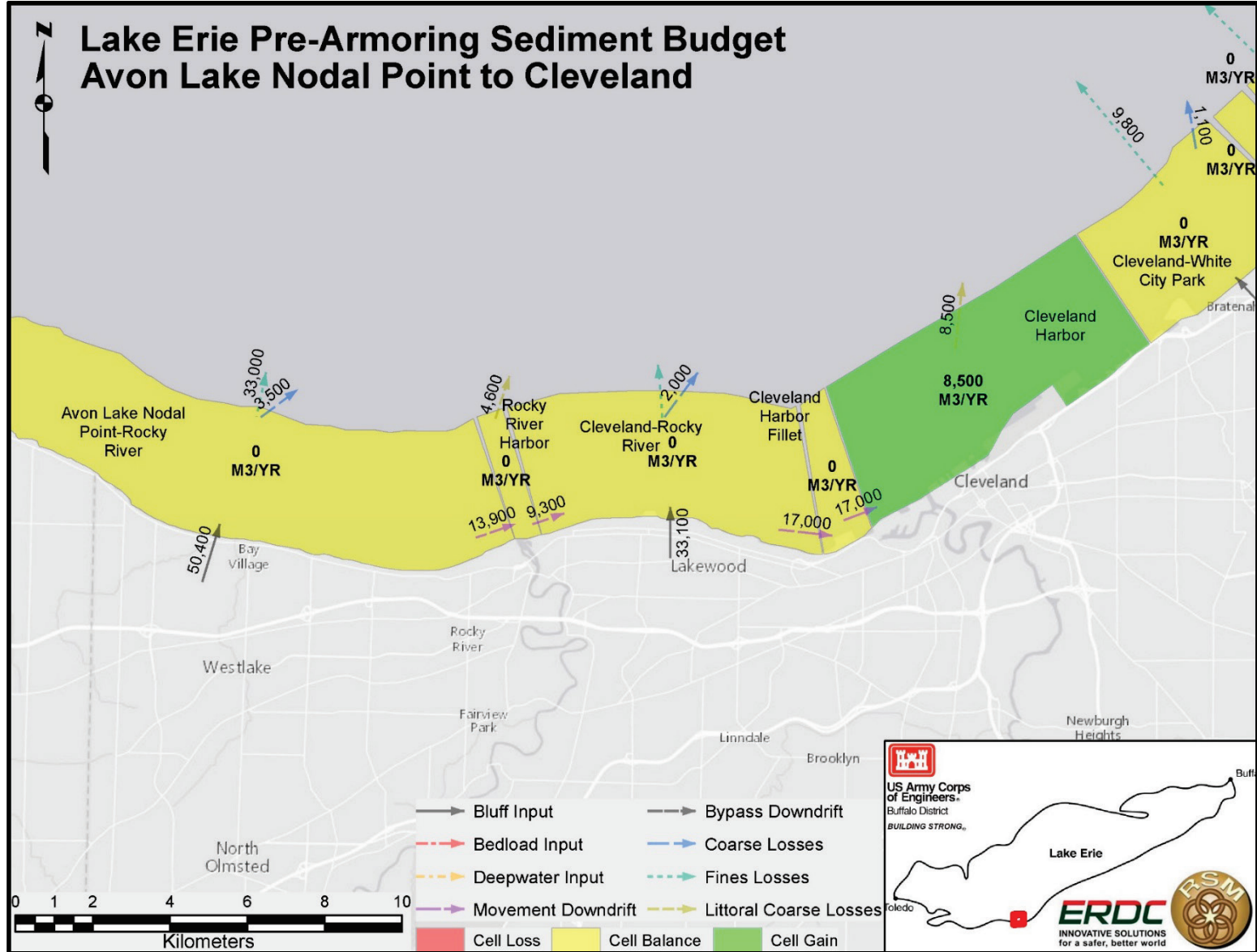


Figure B-18. Avon Lake Nodal Point to Cleveland Mid-Century sediment budget

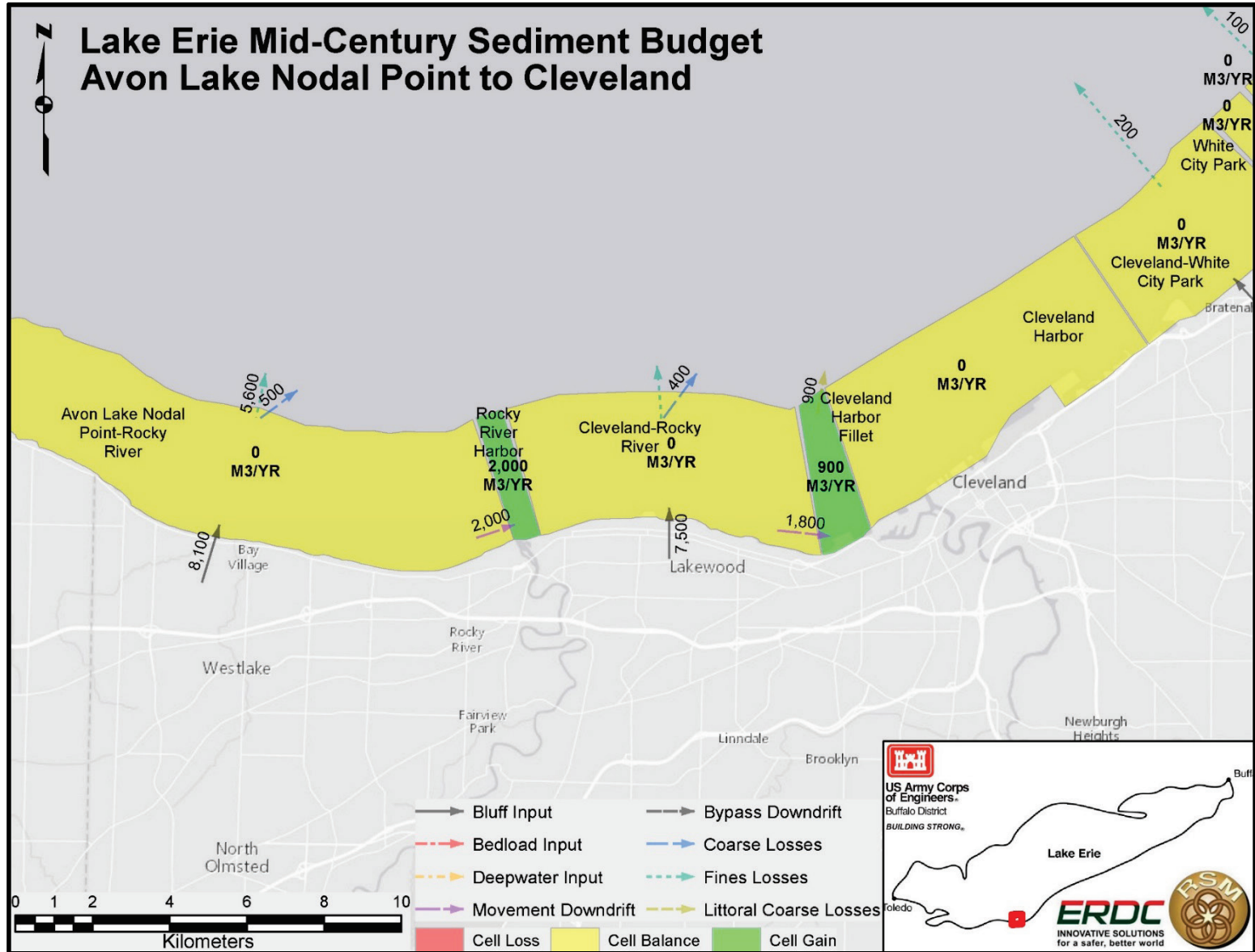


Figure B-19. Avon Lake Nodal Point to Cleveland Recent sediment budget.

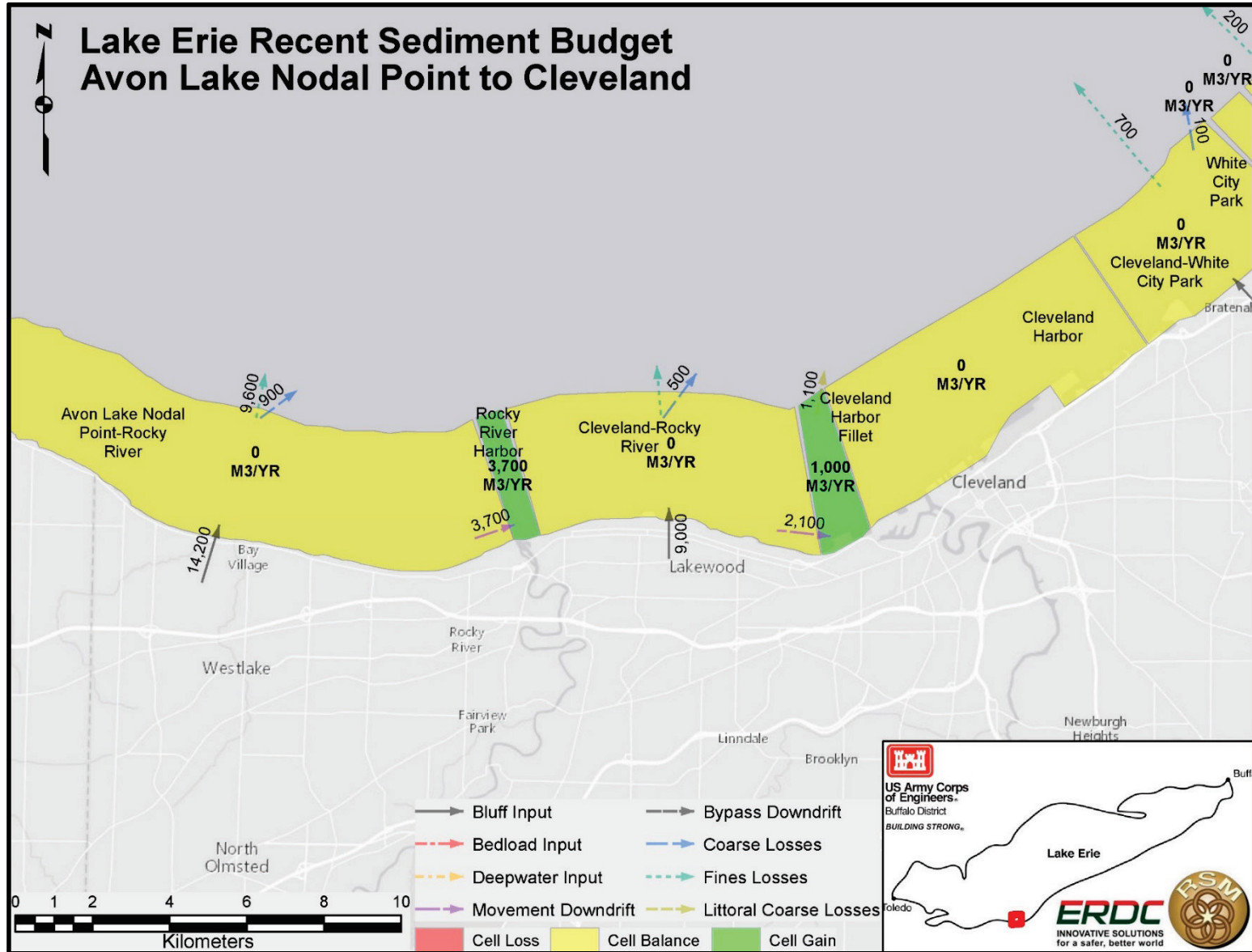


Figure B-20. Avon Lake Nodal Point to Cleveland Future sediment budget.

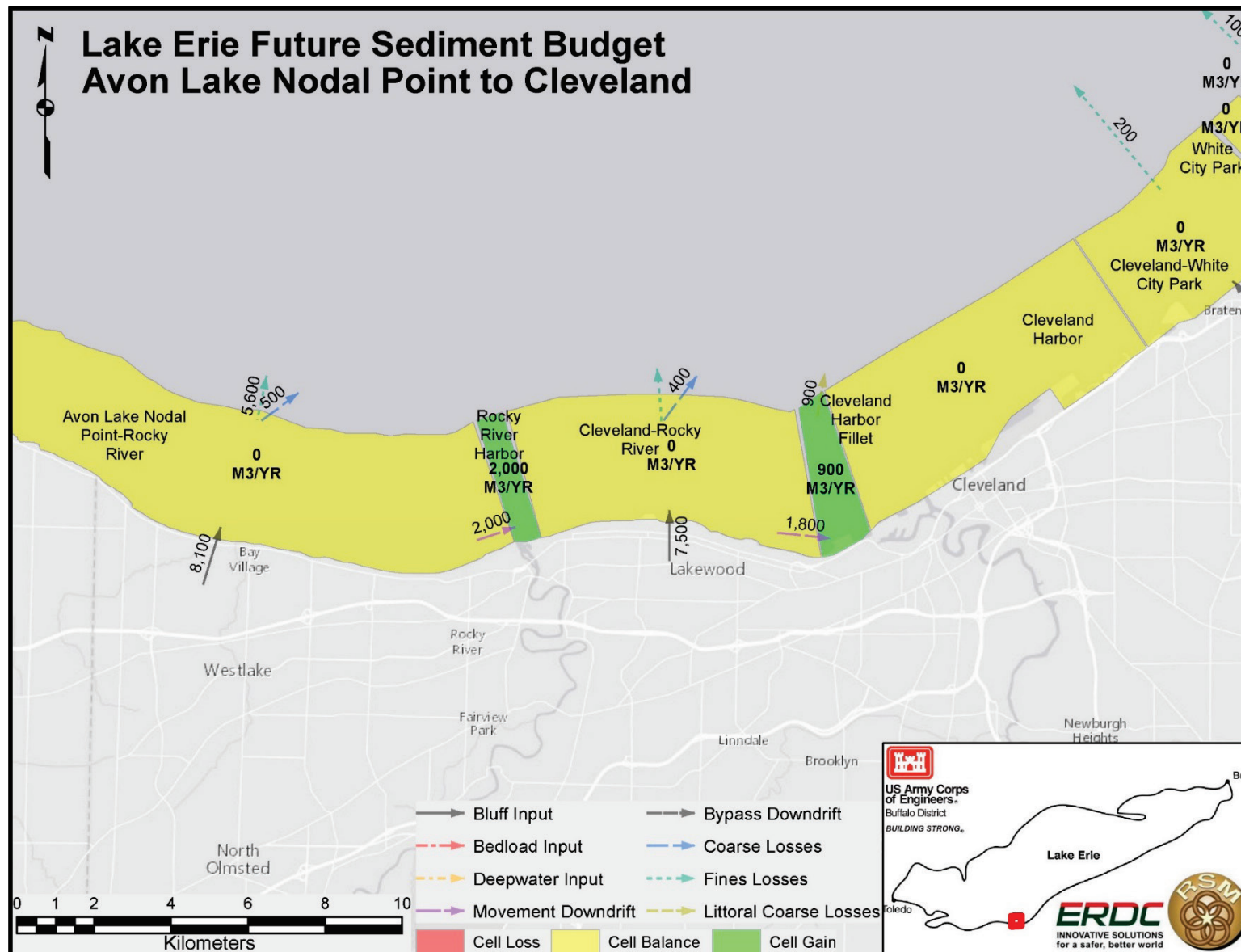


Figure B-21. Cleveland to Eastlake Pre-Armoring sediment budget.

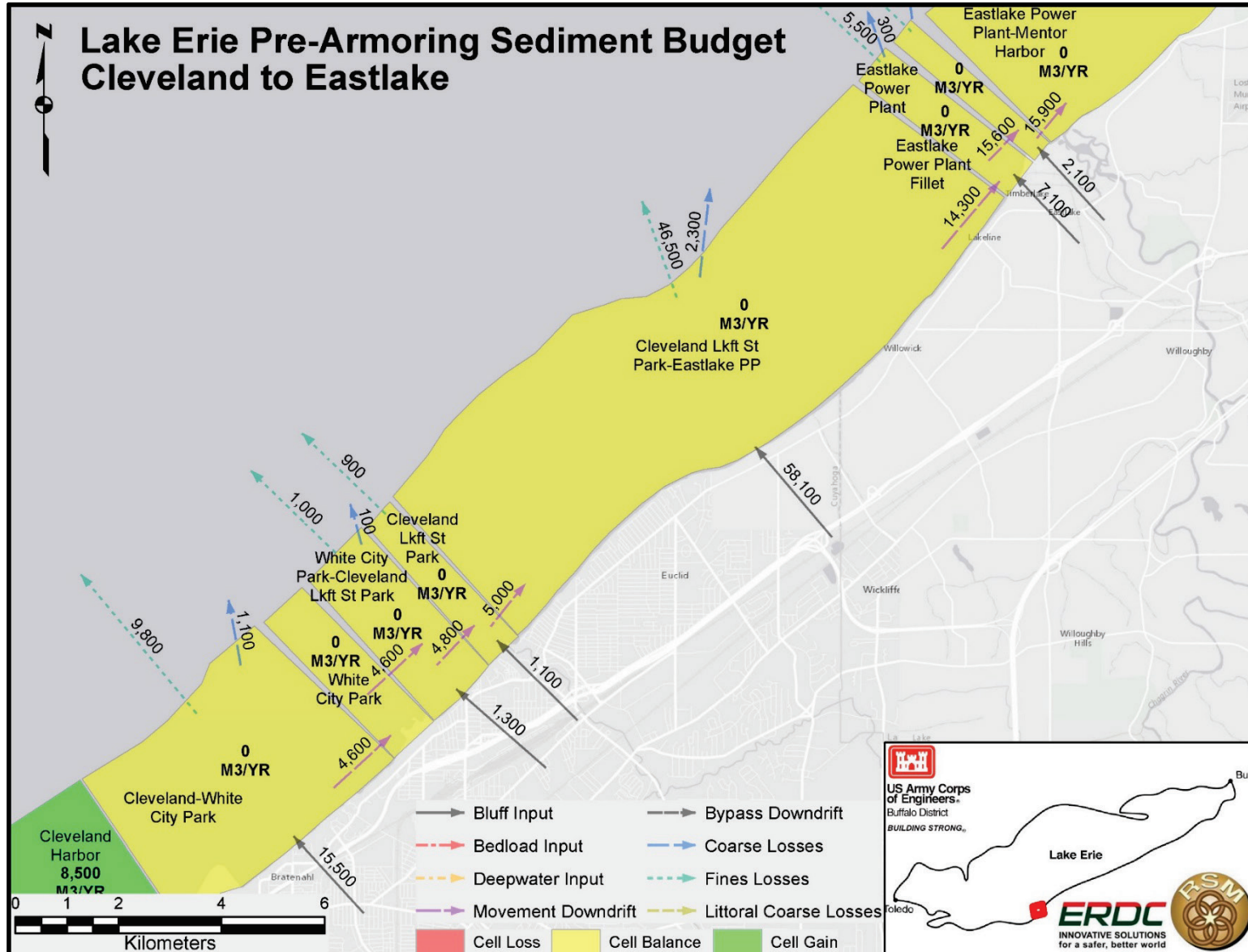


Figure B-22. Cleveland to Eastlake Mid-Century sediment budget.

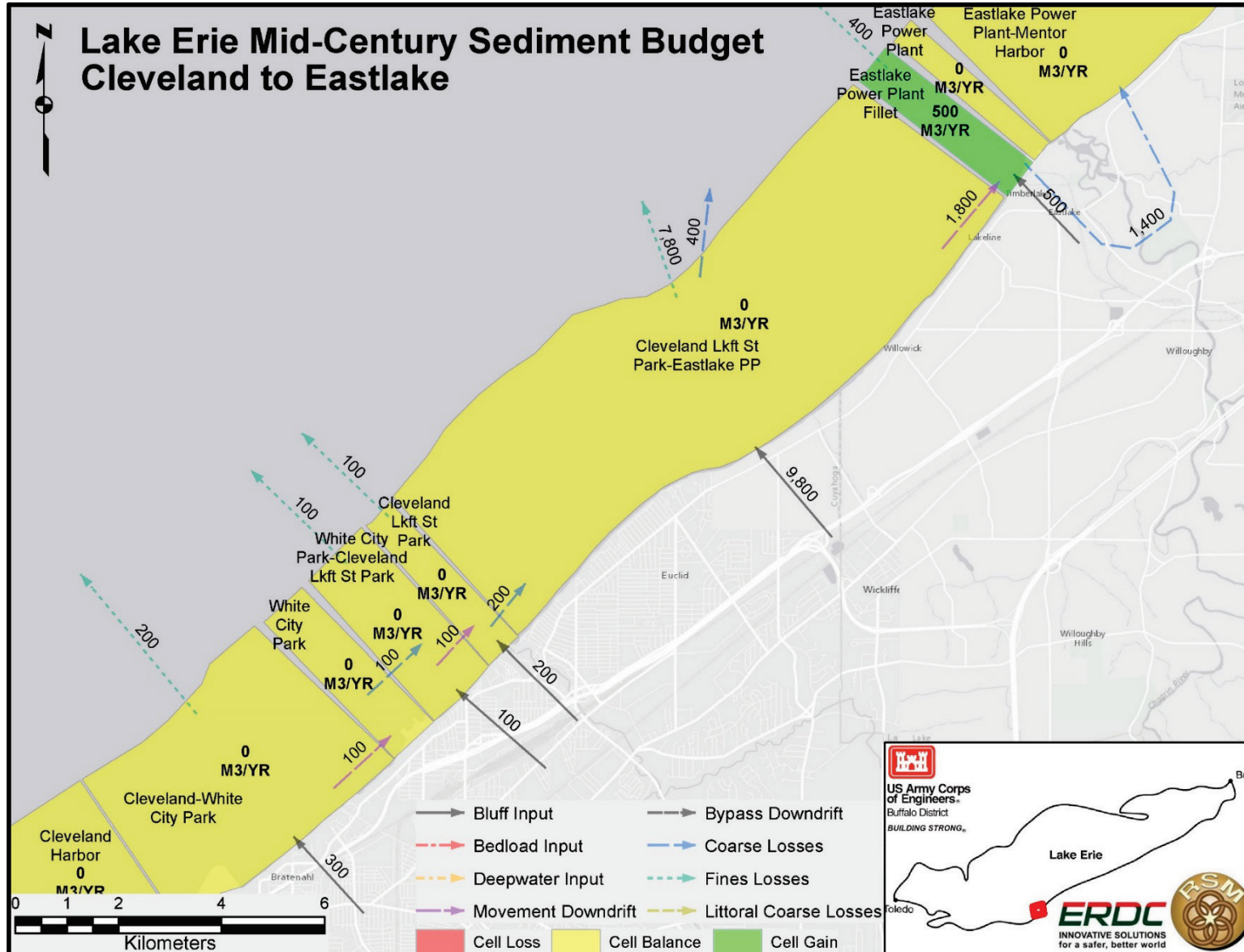


Figure B-23. Cleveland to Eastlake Recent sediment budget.

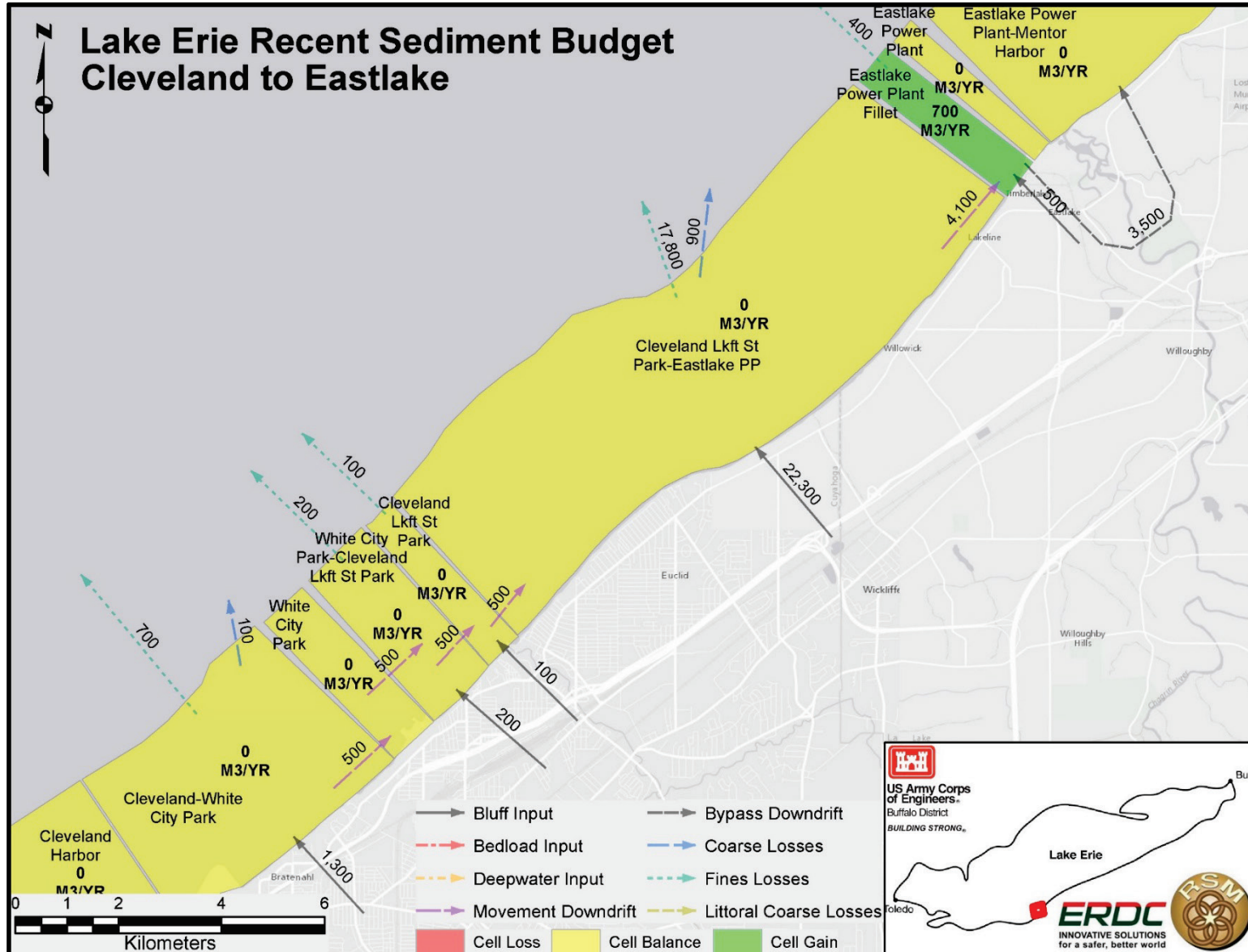


Figure B-24. Cleveland to Eastlake Future sediment budget.

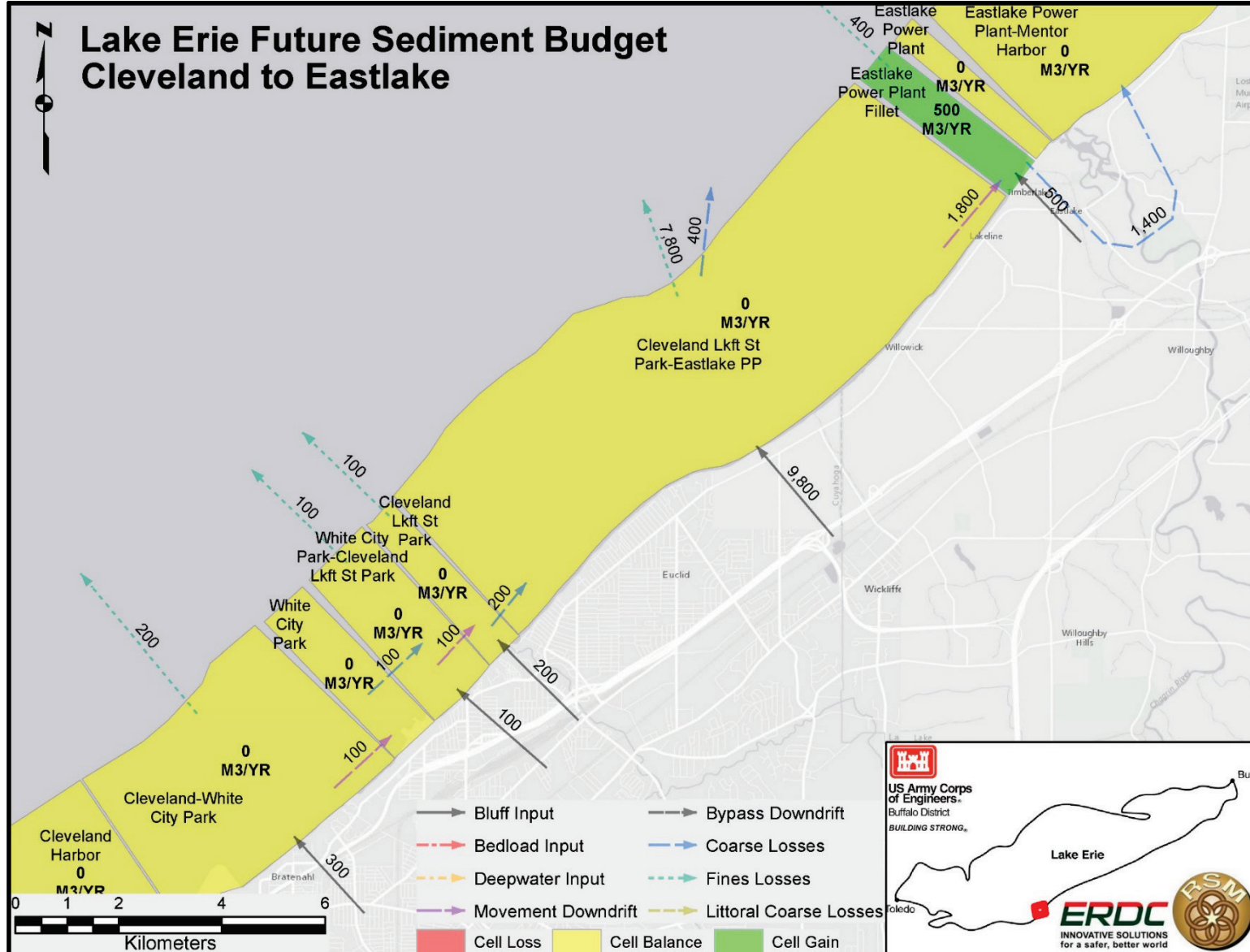


Figure B-25. Eastlake to Fairport Pre-Armoring sediment budget.

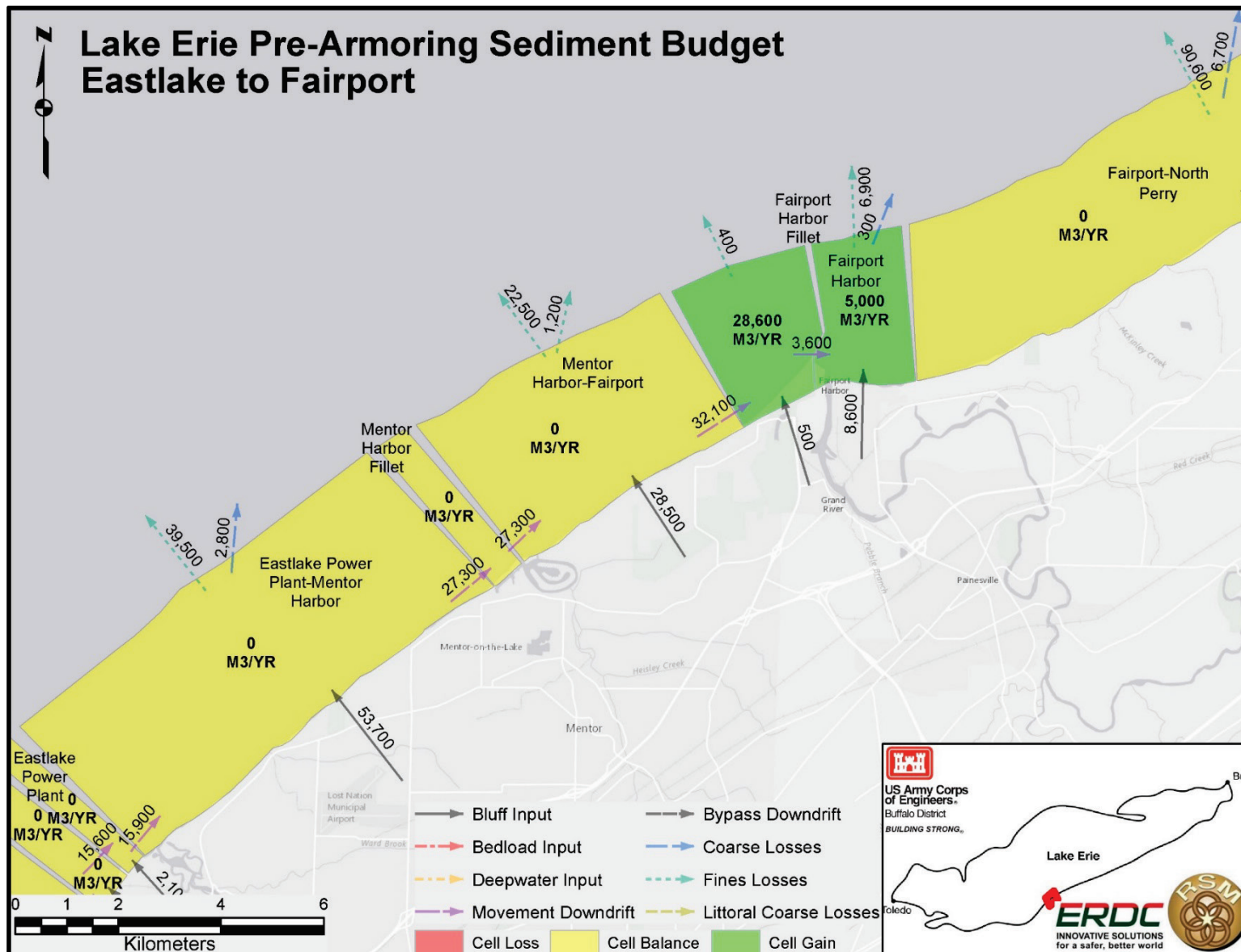


Figure B-26. Eastlake to Fairport Mid-Century sediment budget.

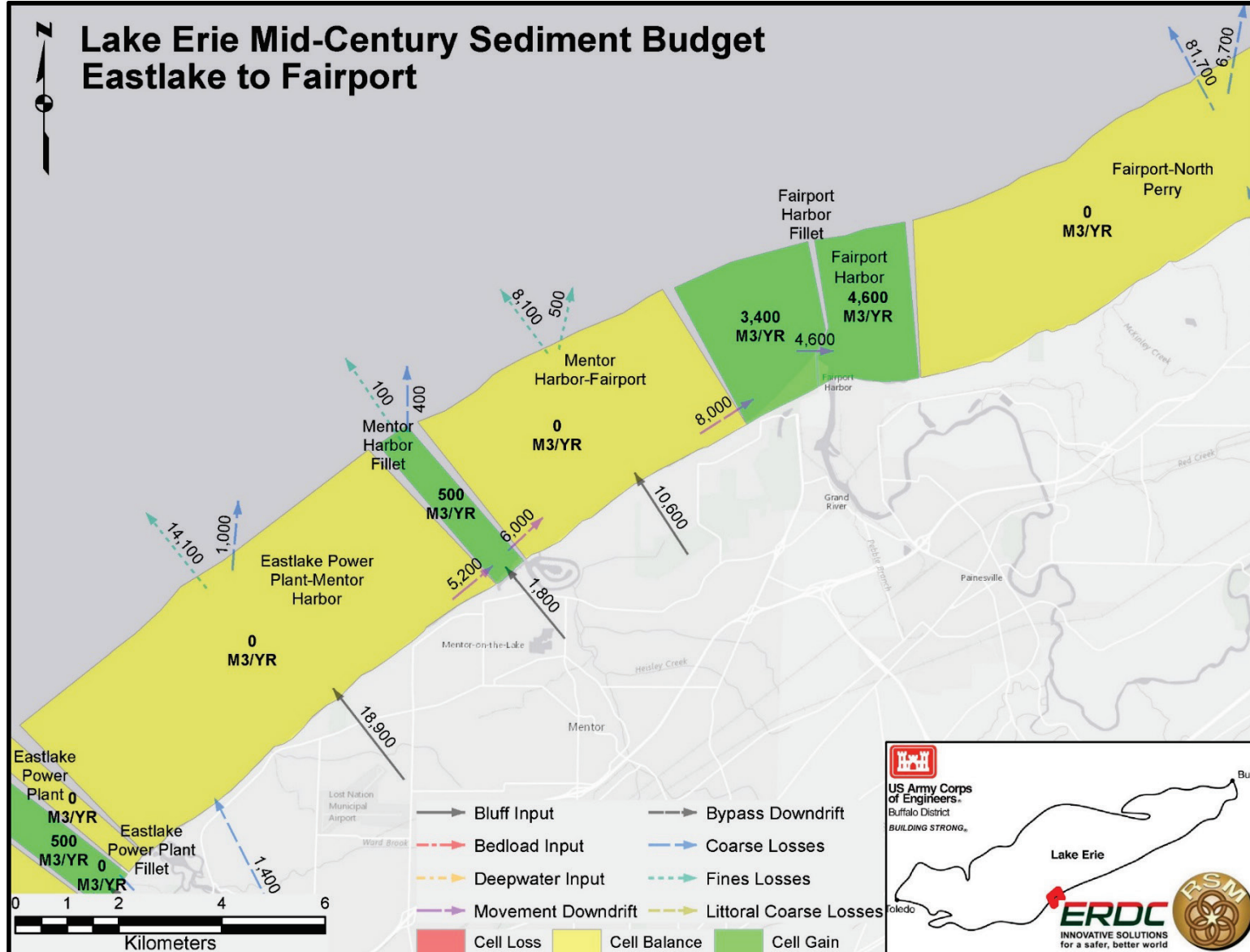


Figure B-27. Eastlake to Fairport Recent sediment budget.

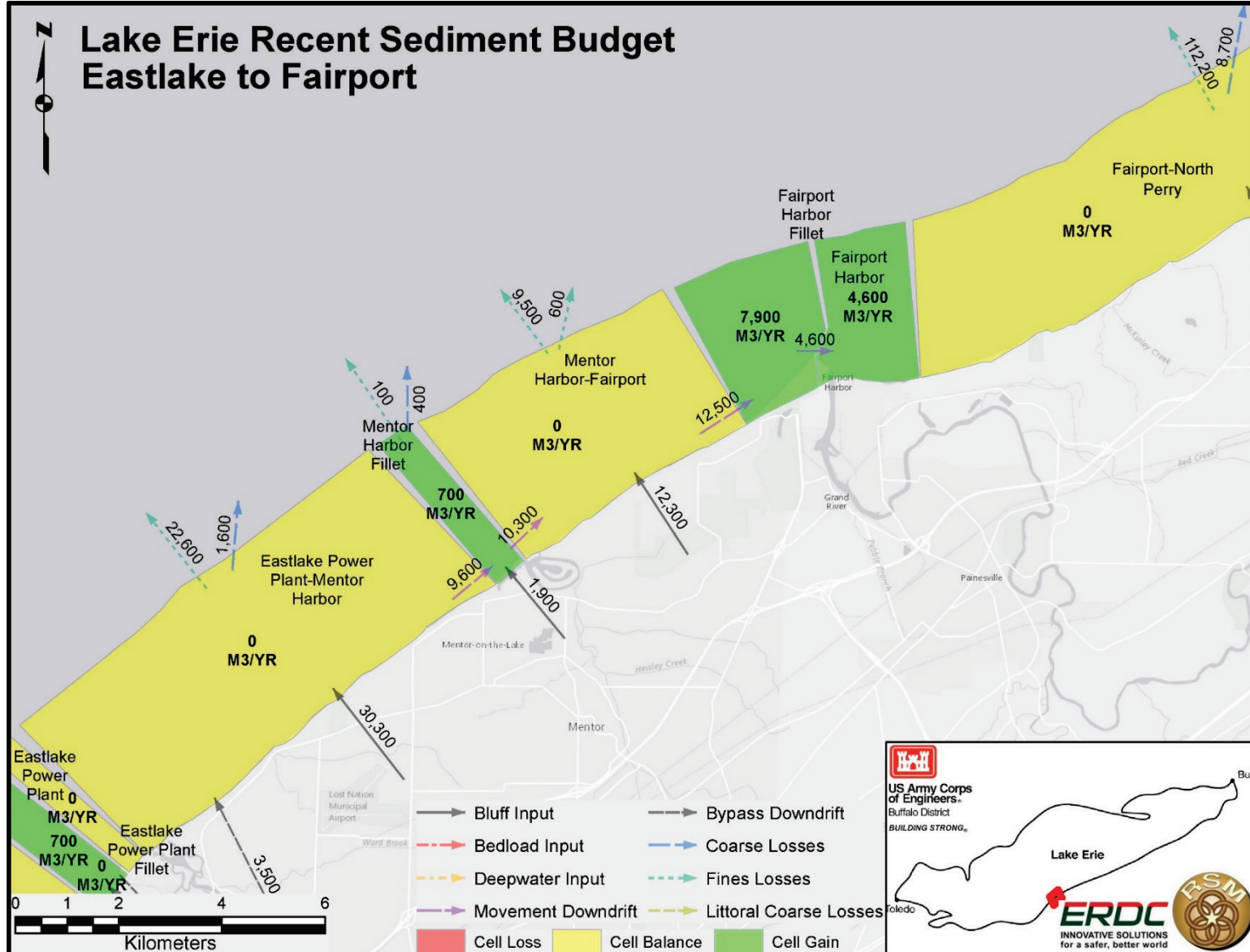


Figure B-28. Eastlake to Fairport Future sediment budget.

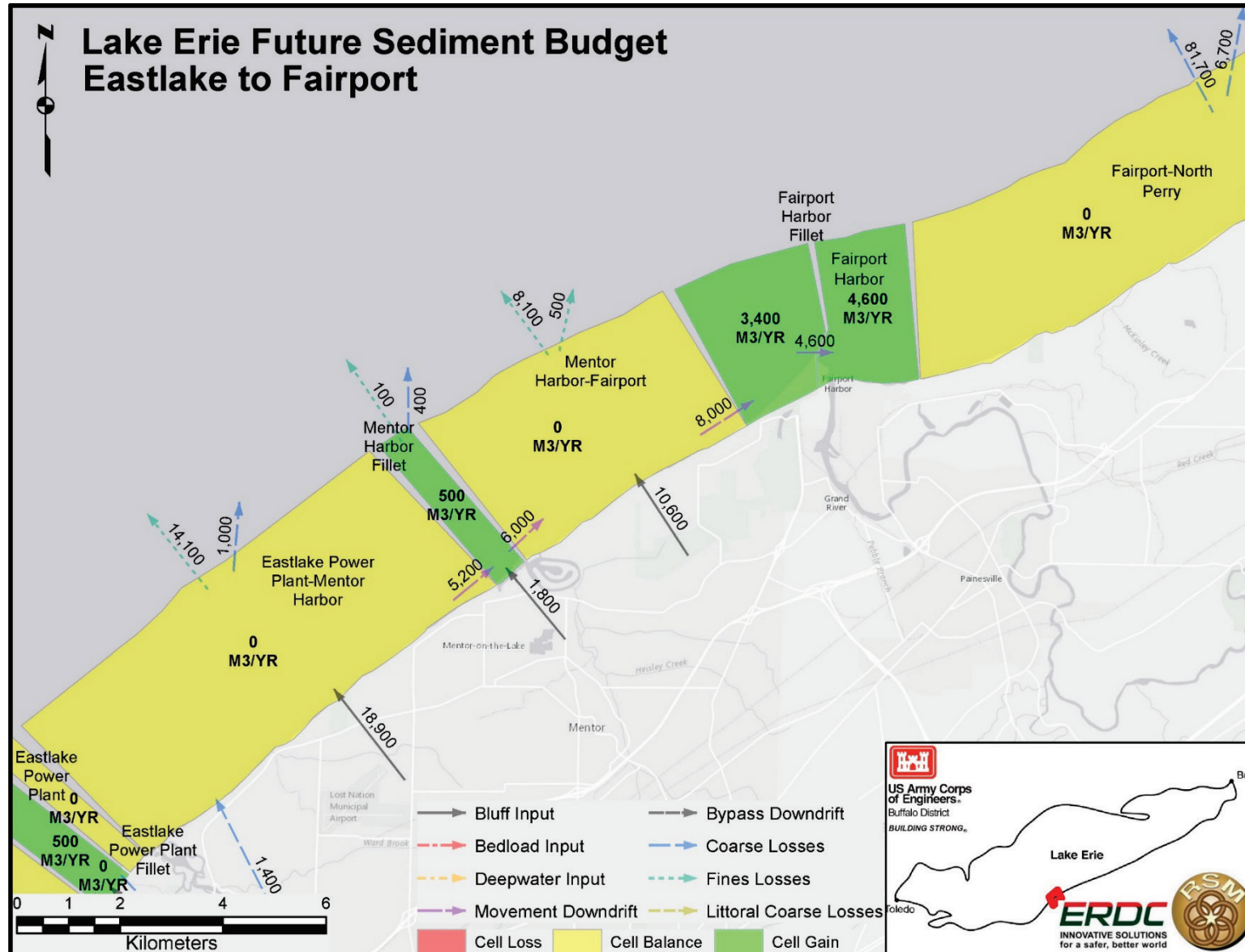


Figure B-29. Fairport to Geneva-on-the-Lake Pre-Armoring sediment budget.

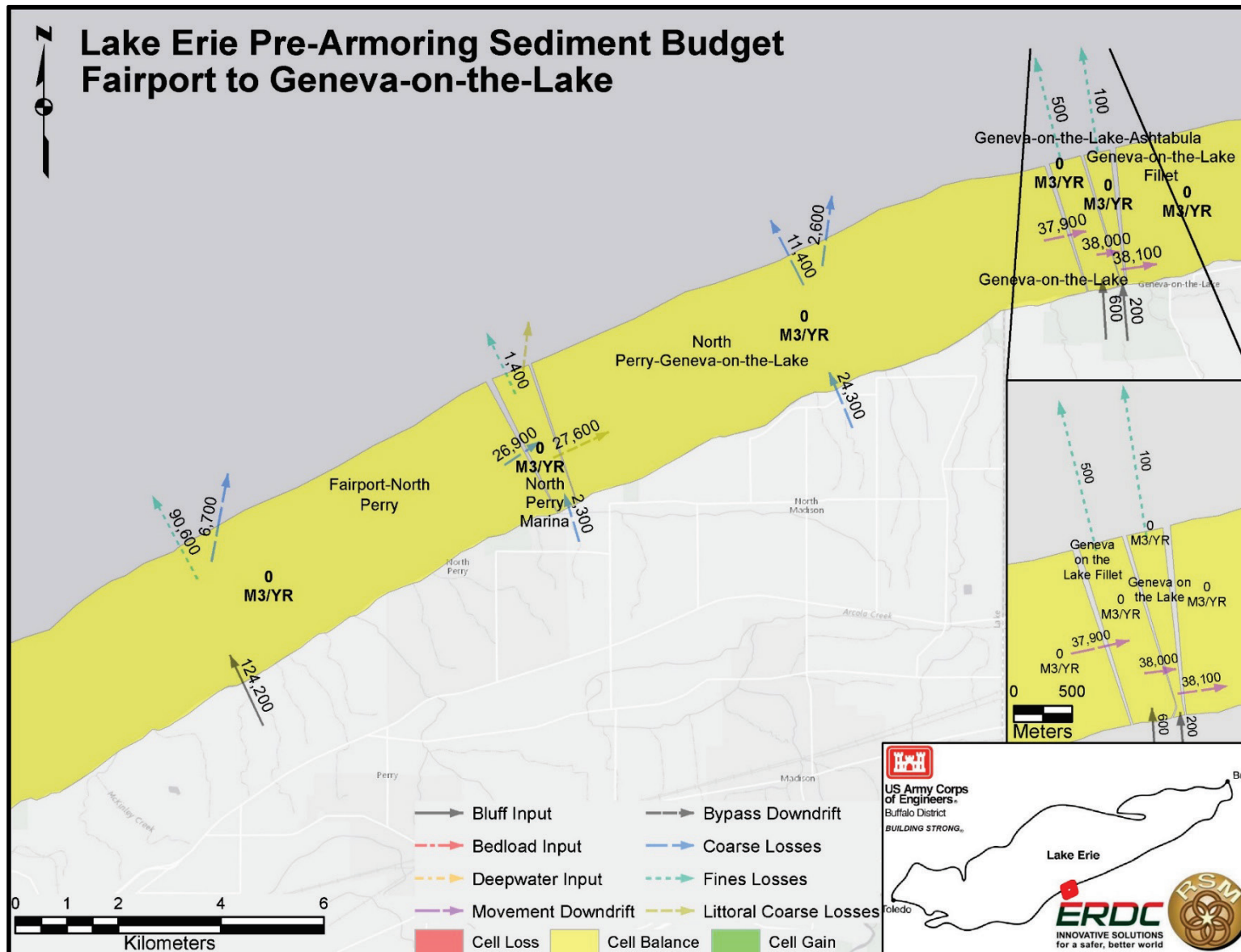


Figure B-30. Fairport to Geneva-on-the-Lake Mid-Century sediment budget.

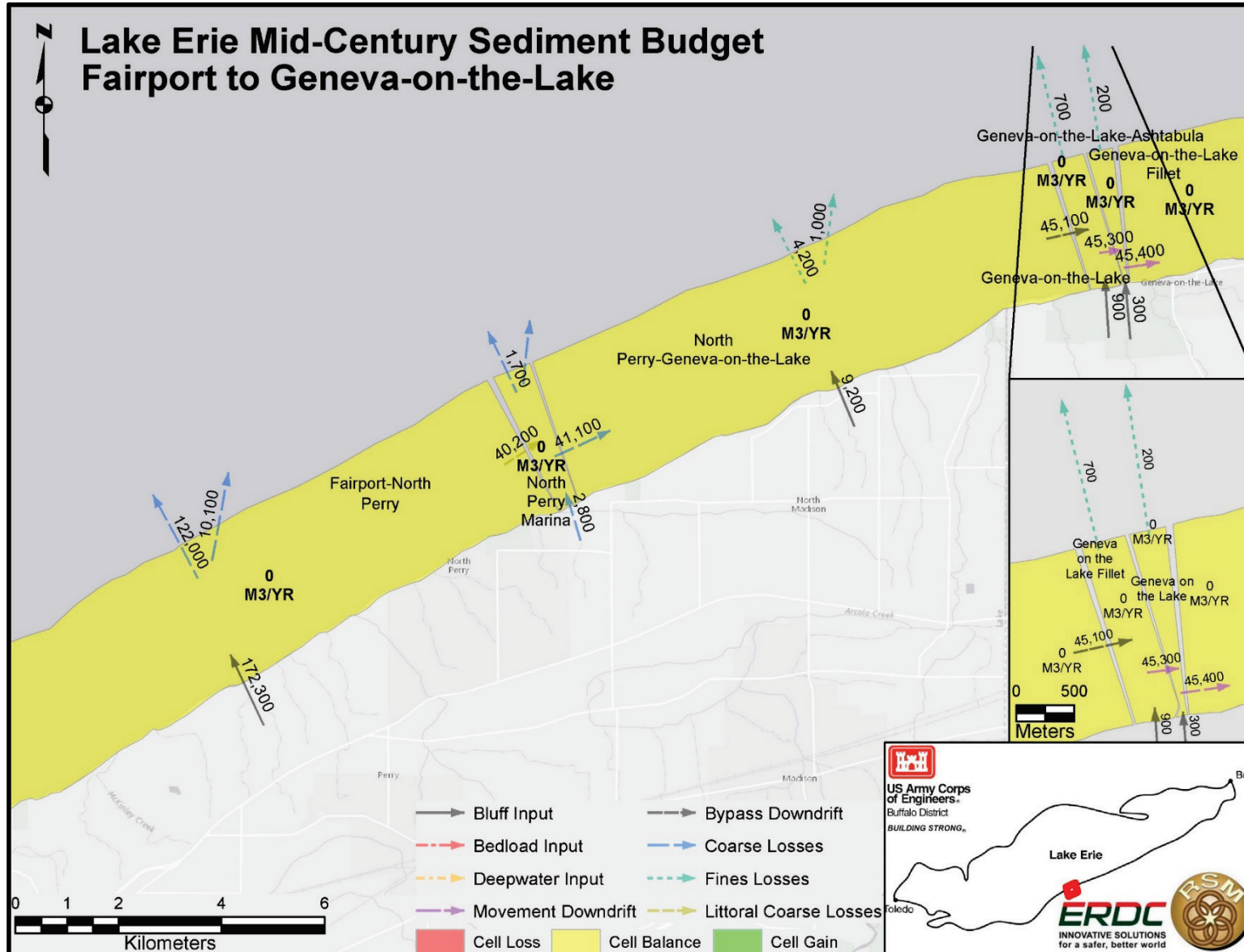


Figure B-31. Fairport to Geneva-on-the-Lake Recent sediment budget.

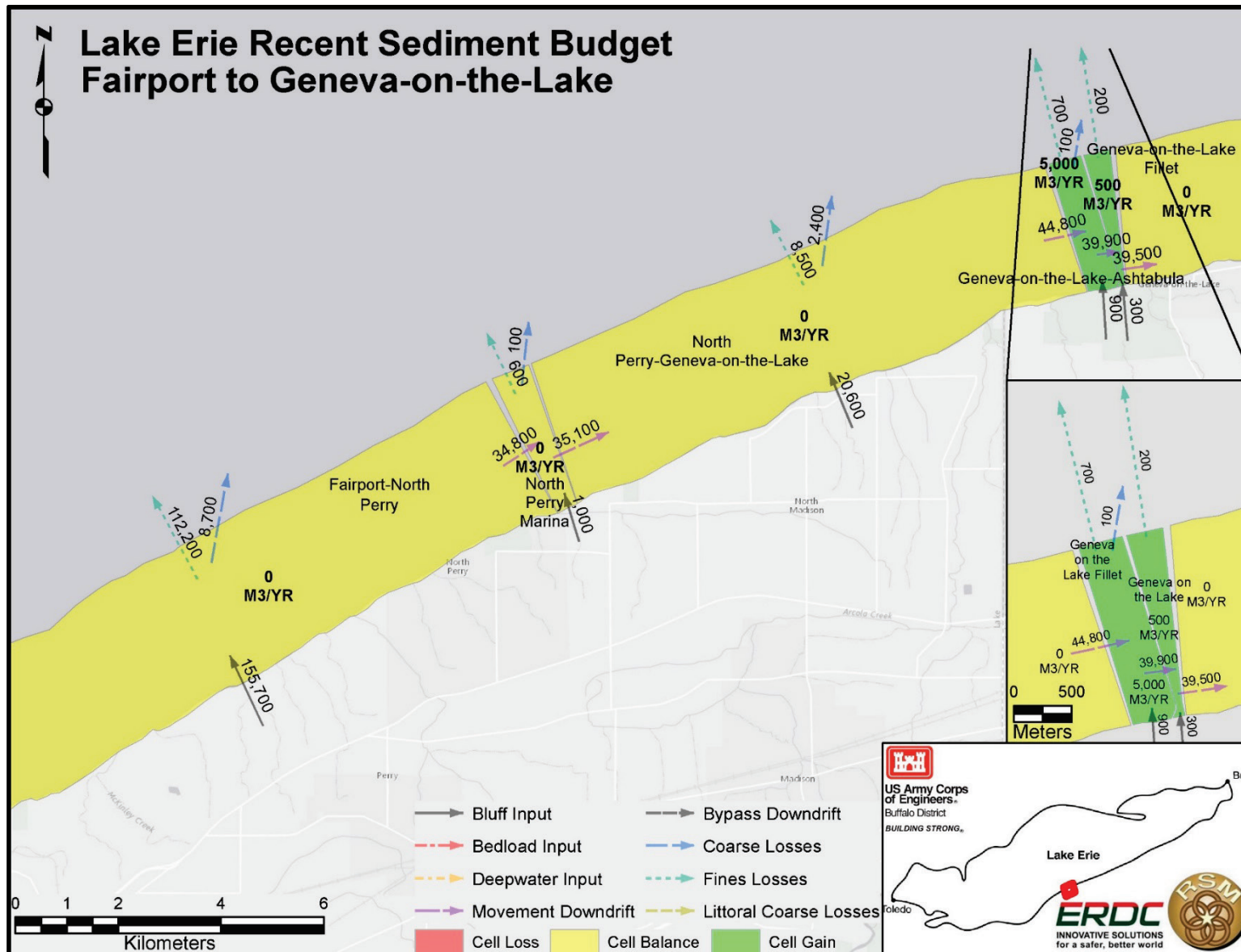


Figure B-32. Fairport to Geneva-on-the-Lake Future sediment budget.

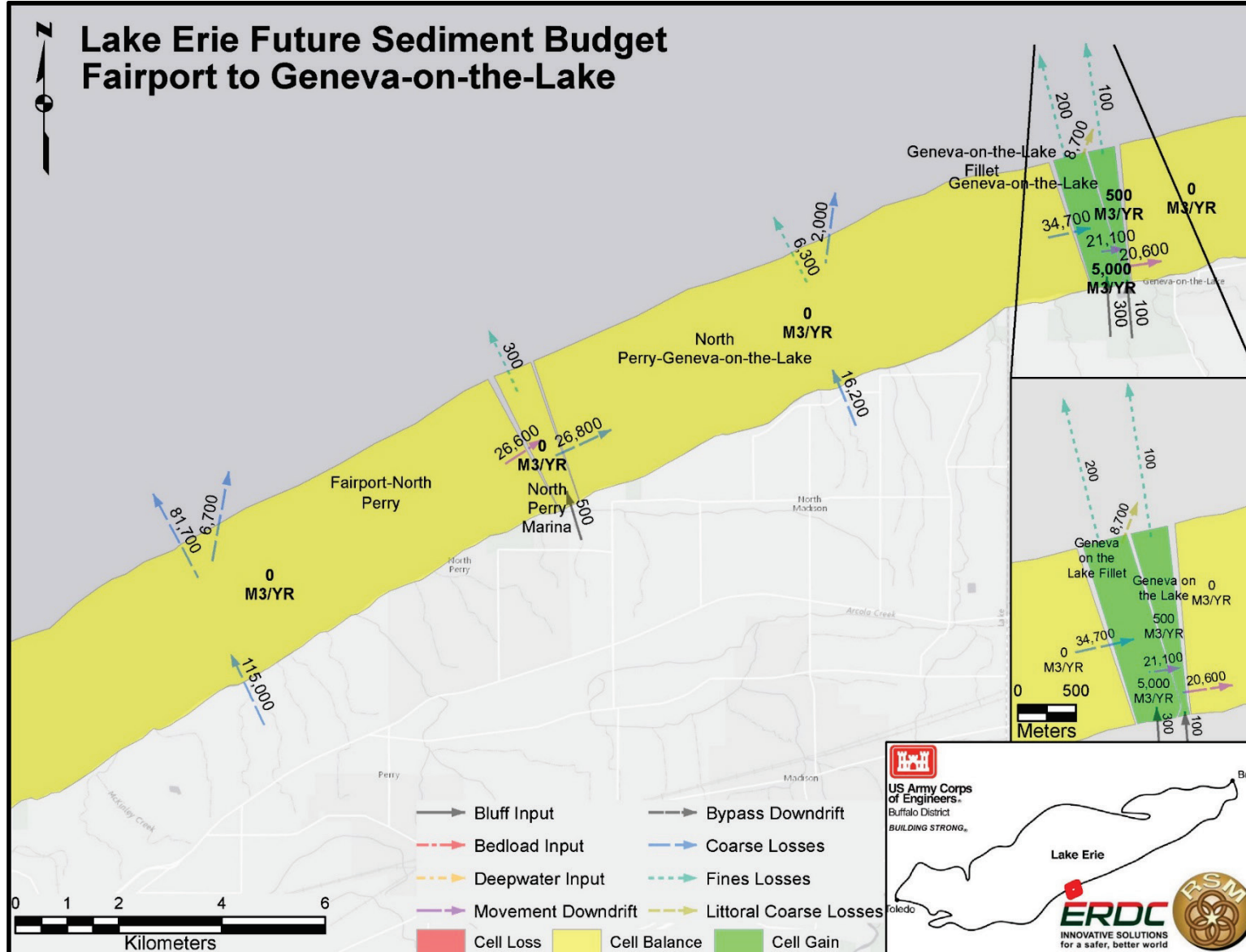


Figure B-33. Geneva-on-the-Lake to Conneaut Pre-Armoring Sediment Budget.

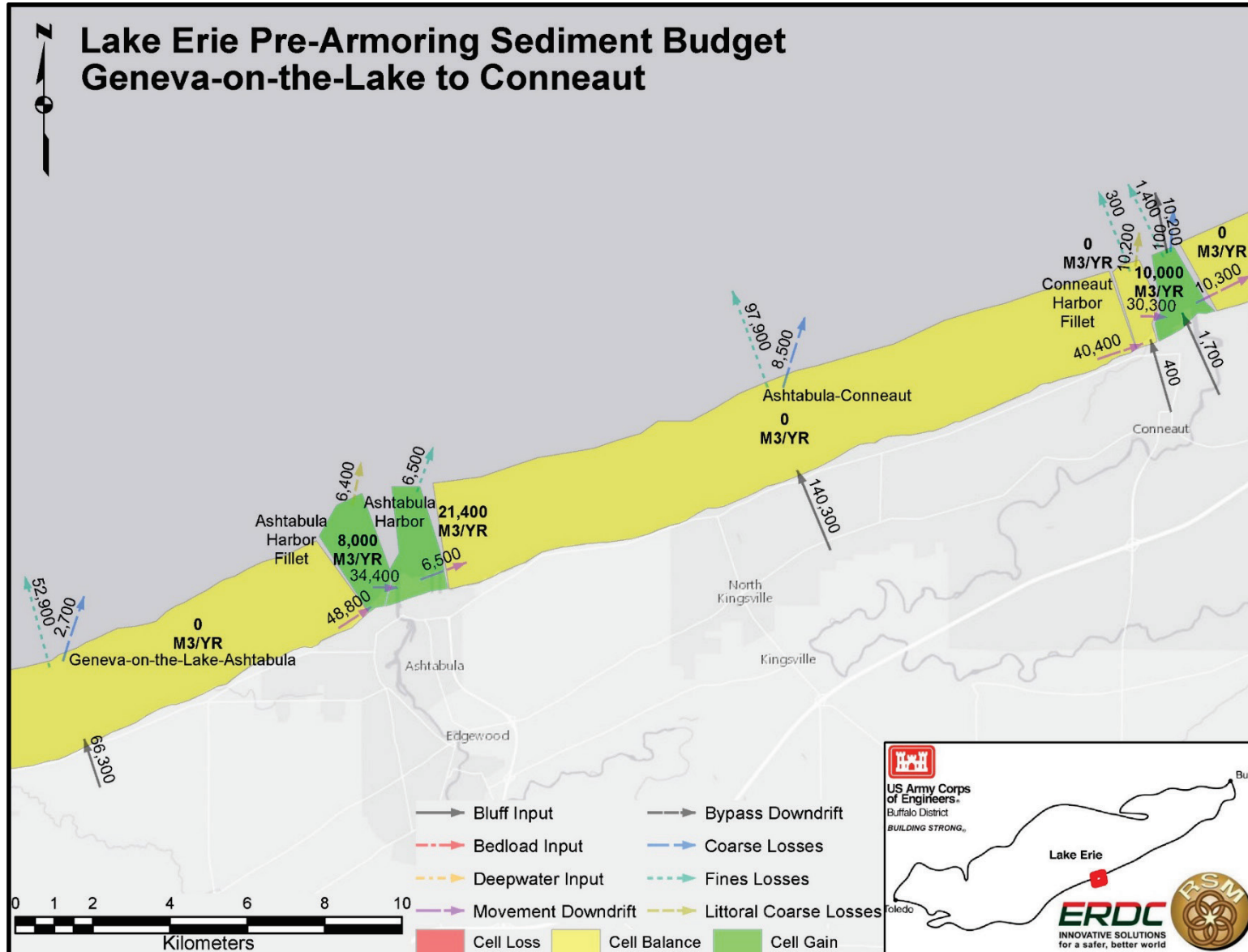


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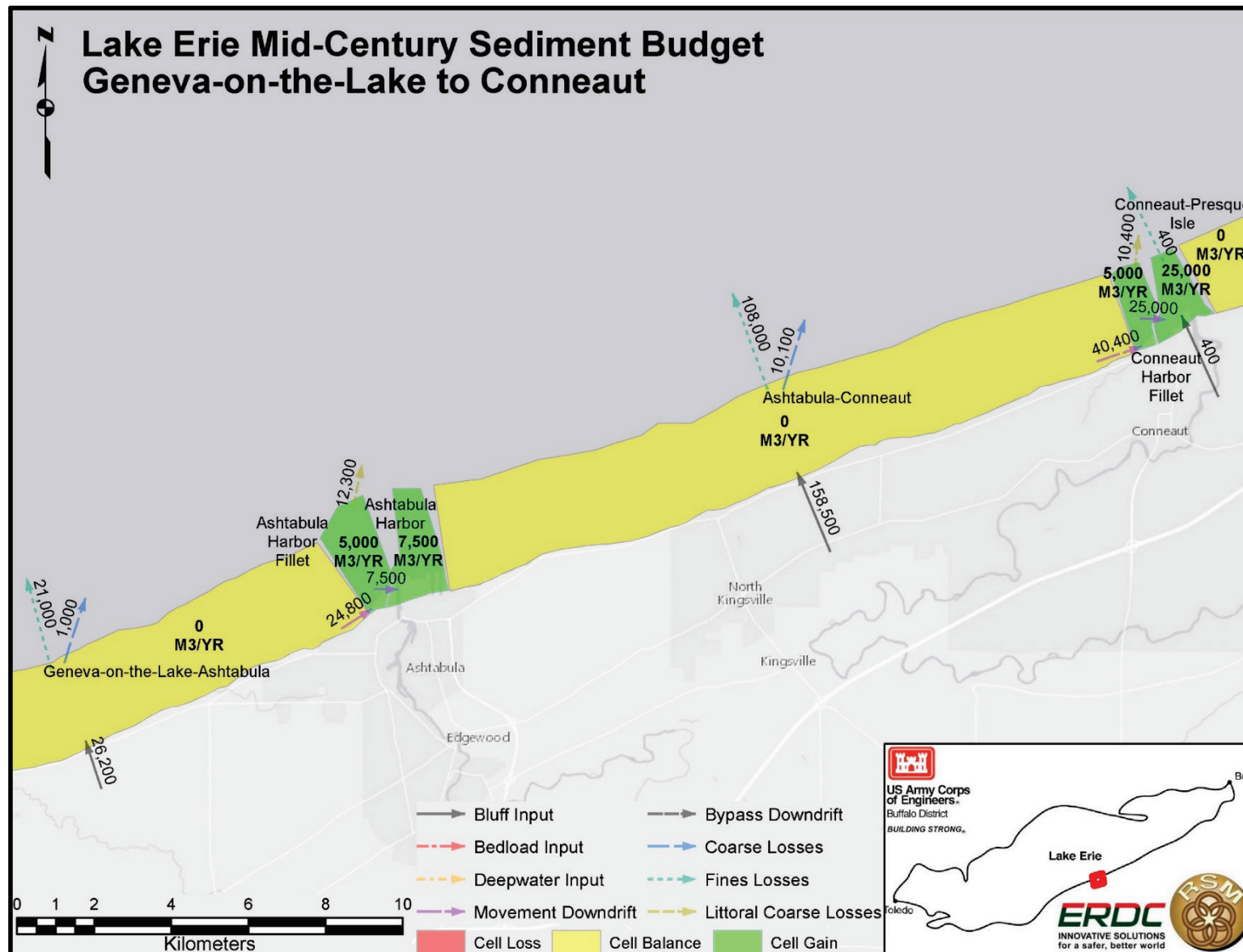


Figure B-35. Geneva-on-the-Lake to Conneaut Recent Sediment Budget.

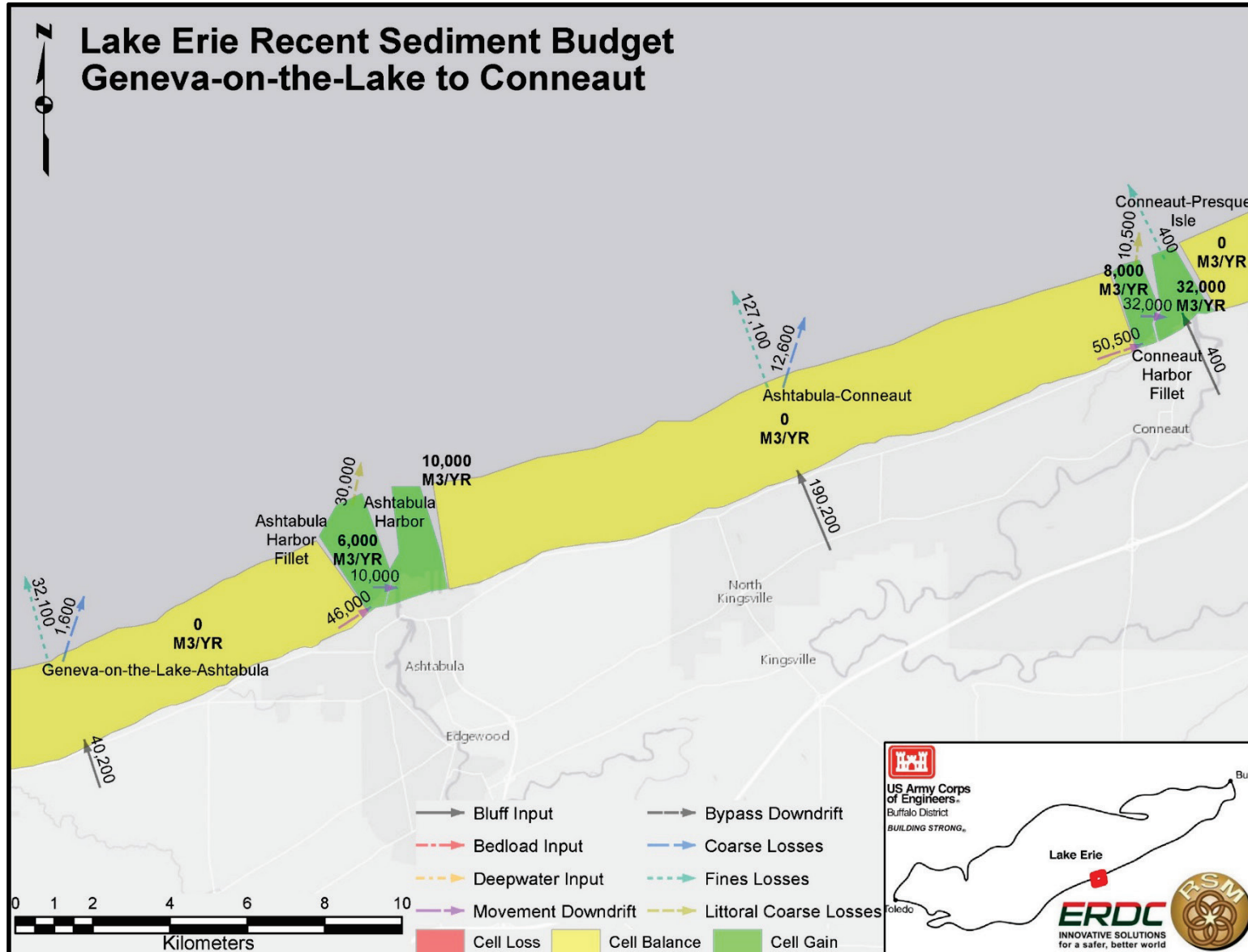


Figure B-36. Geneva-on-the-Lake to Conneaut Future Sediment Budget.

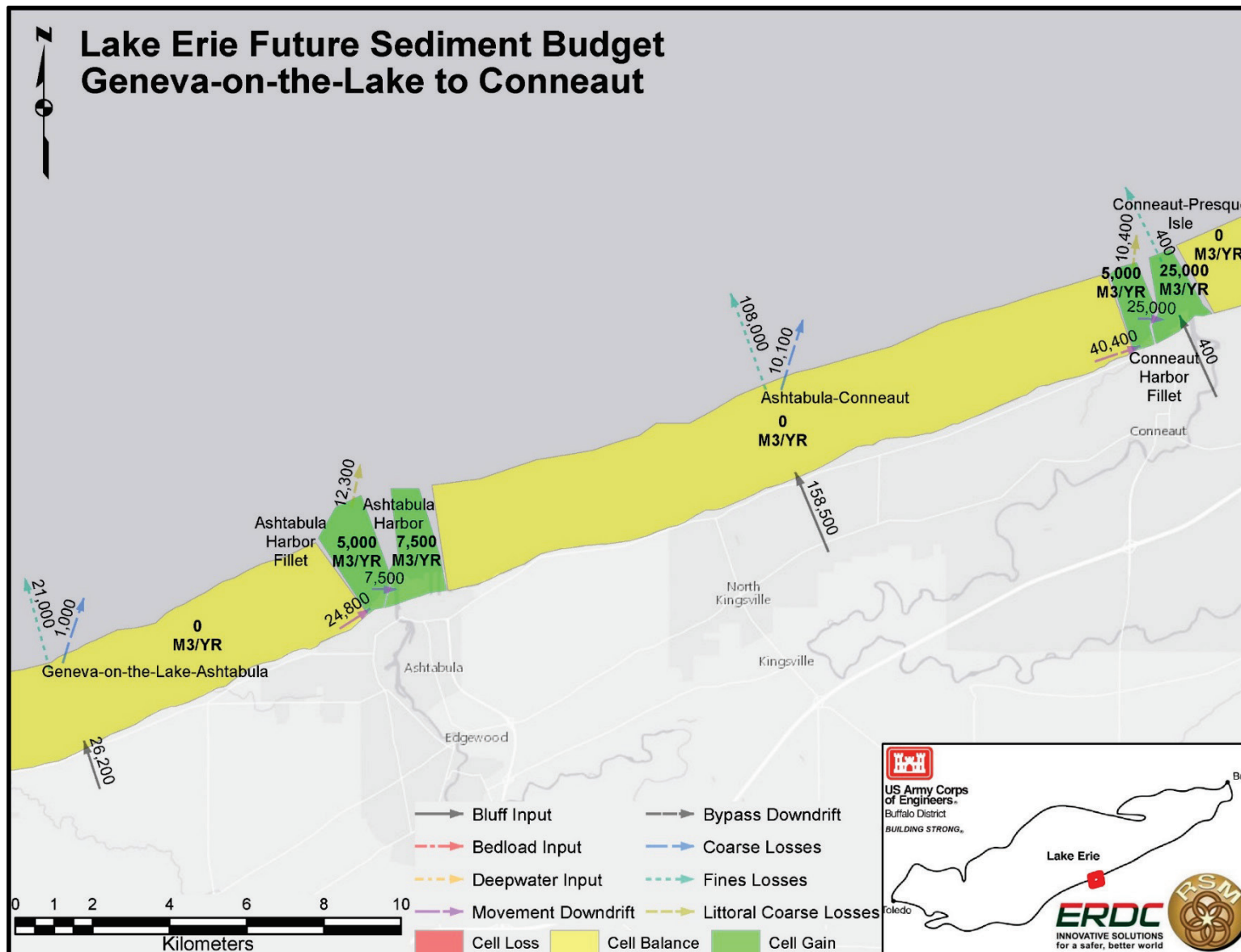


Figure B-37. Conneaut to Presque Isle Pre-Armoring sediment budget.

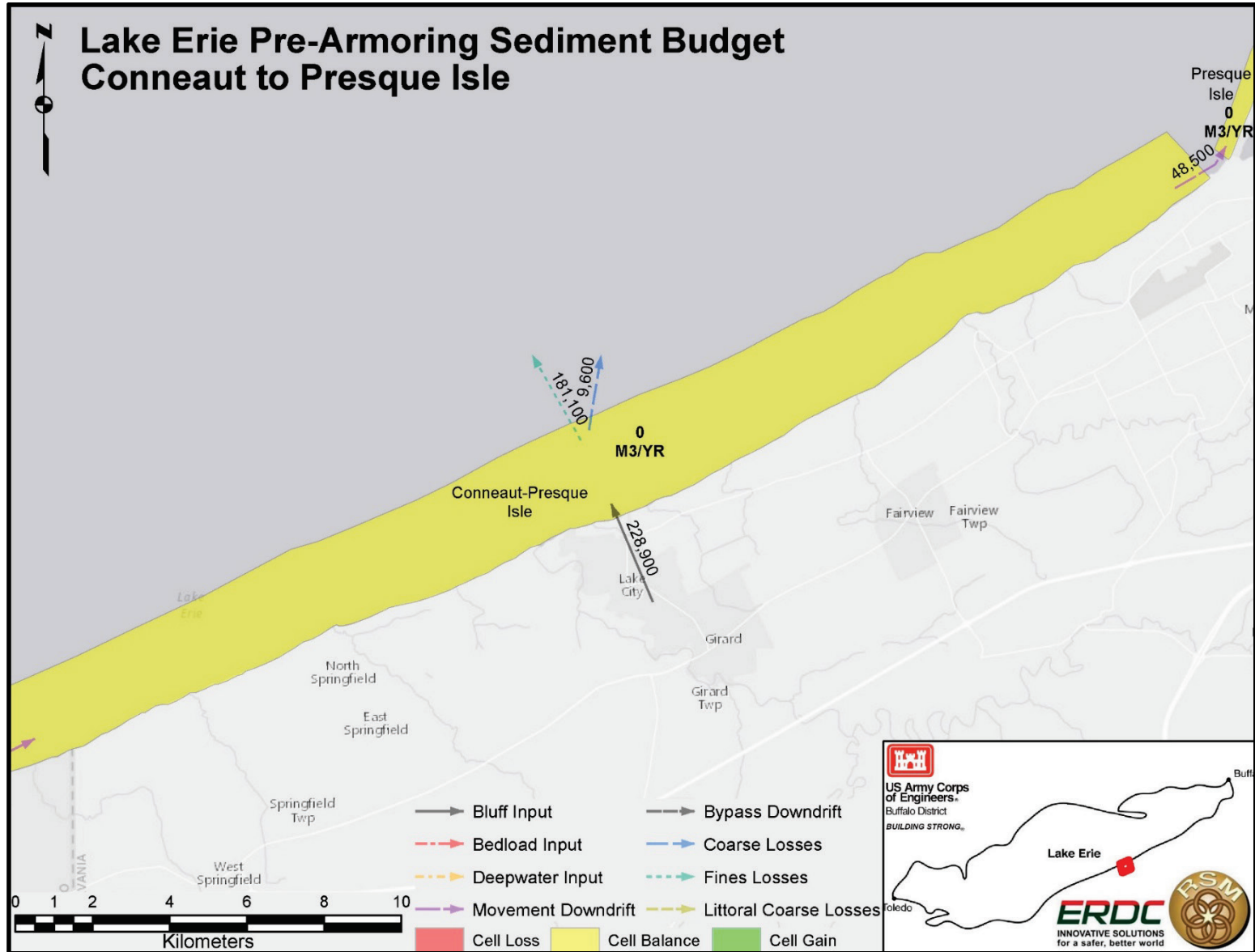


Figure B-38. Conneaut to Presque Isle Mid-Century sediment budget.

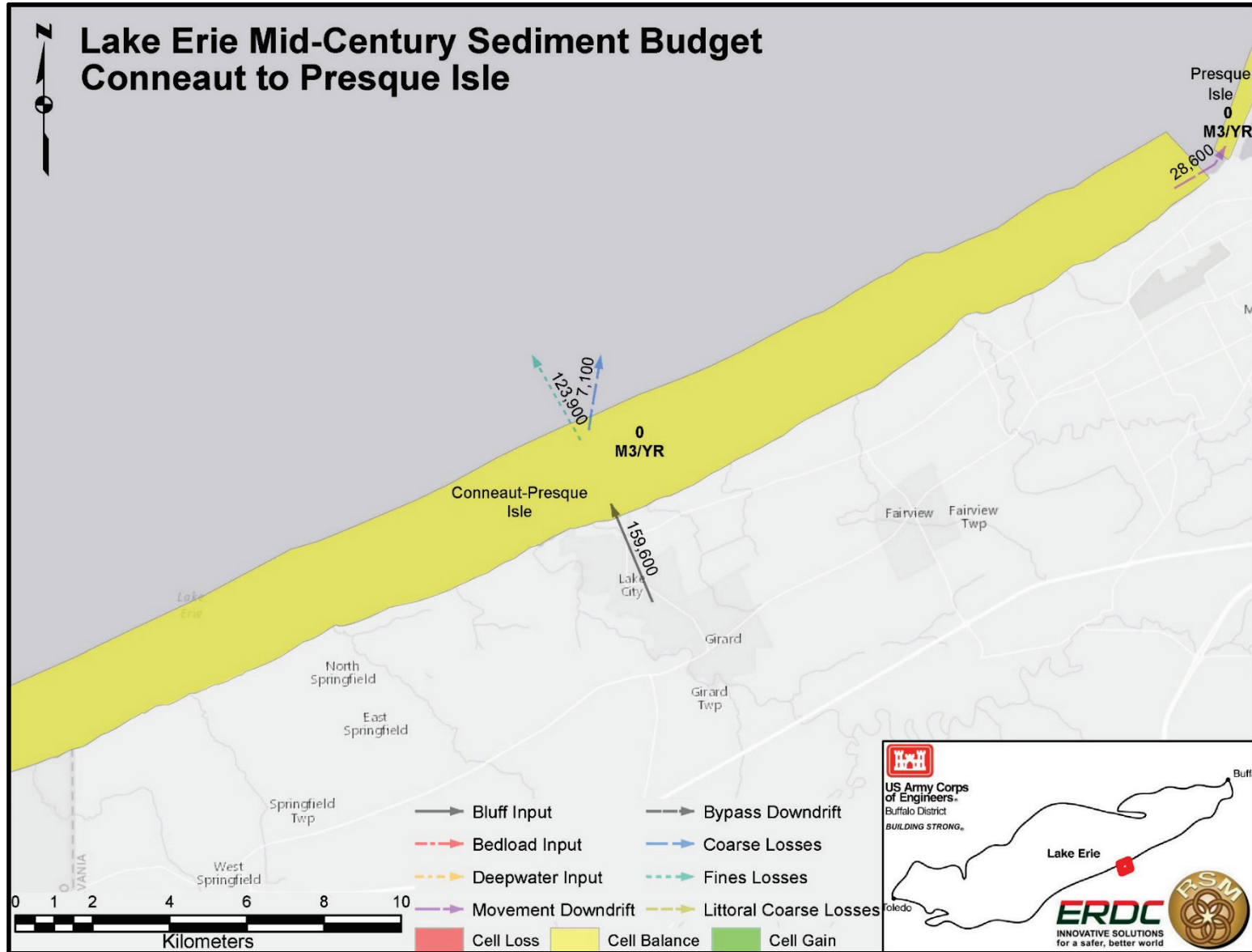


Figure B-39. Conneaut to Presque Isle Recent sediment budget.

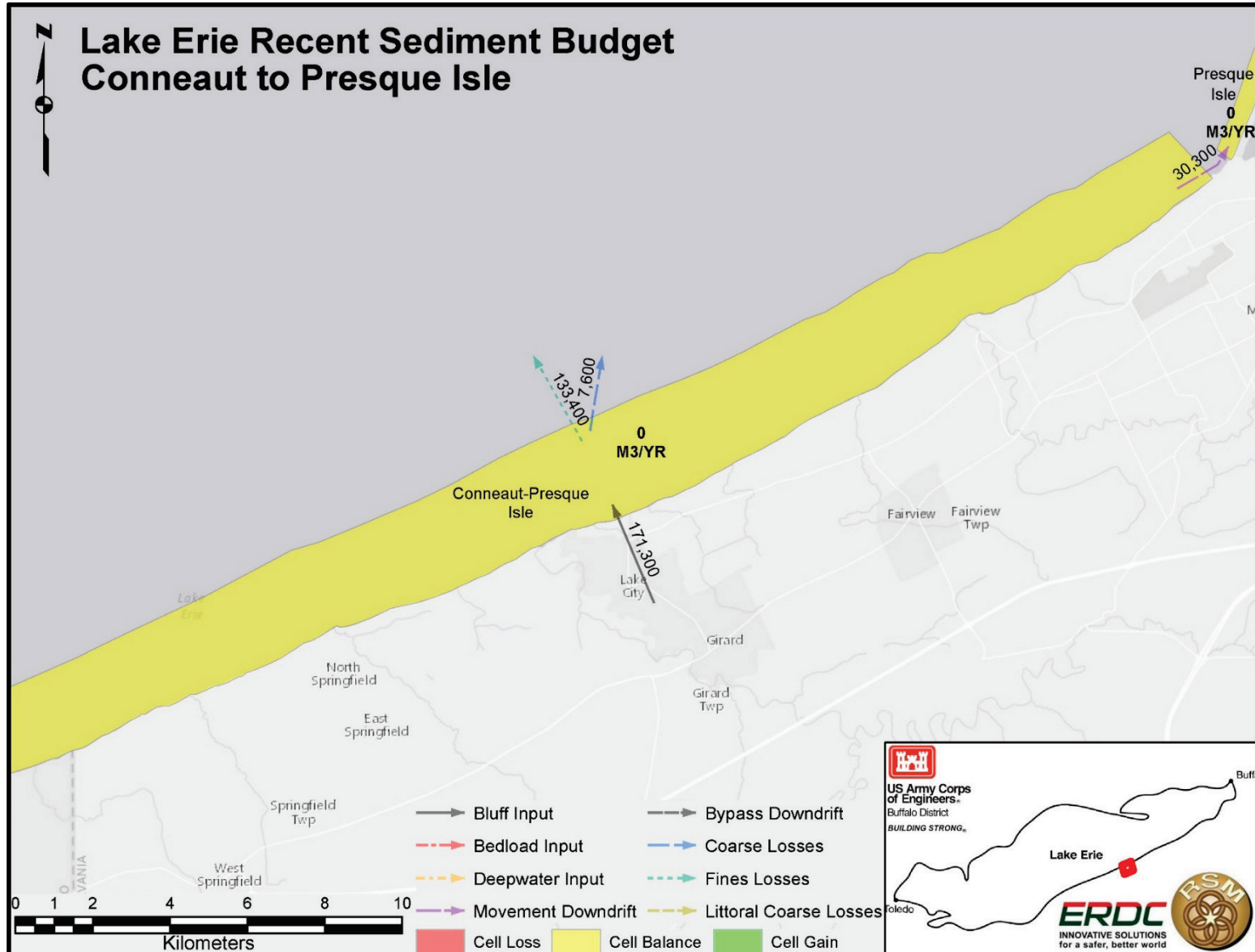


Figure B-40. Conneaut to Presque Isle Future sediment budget.

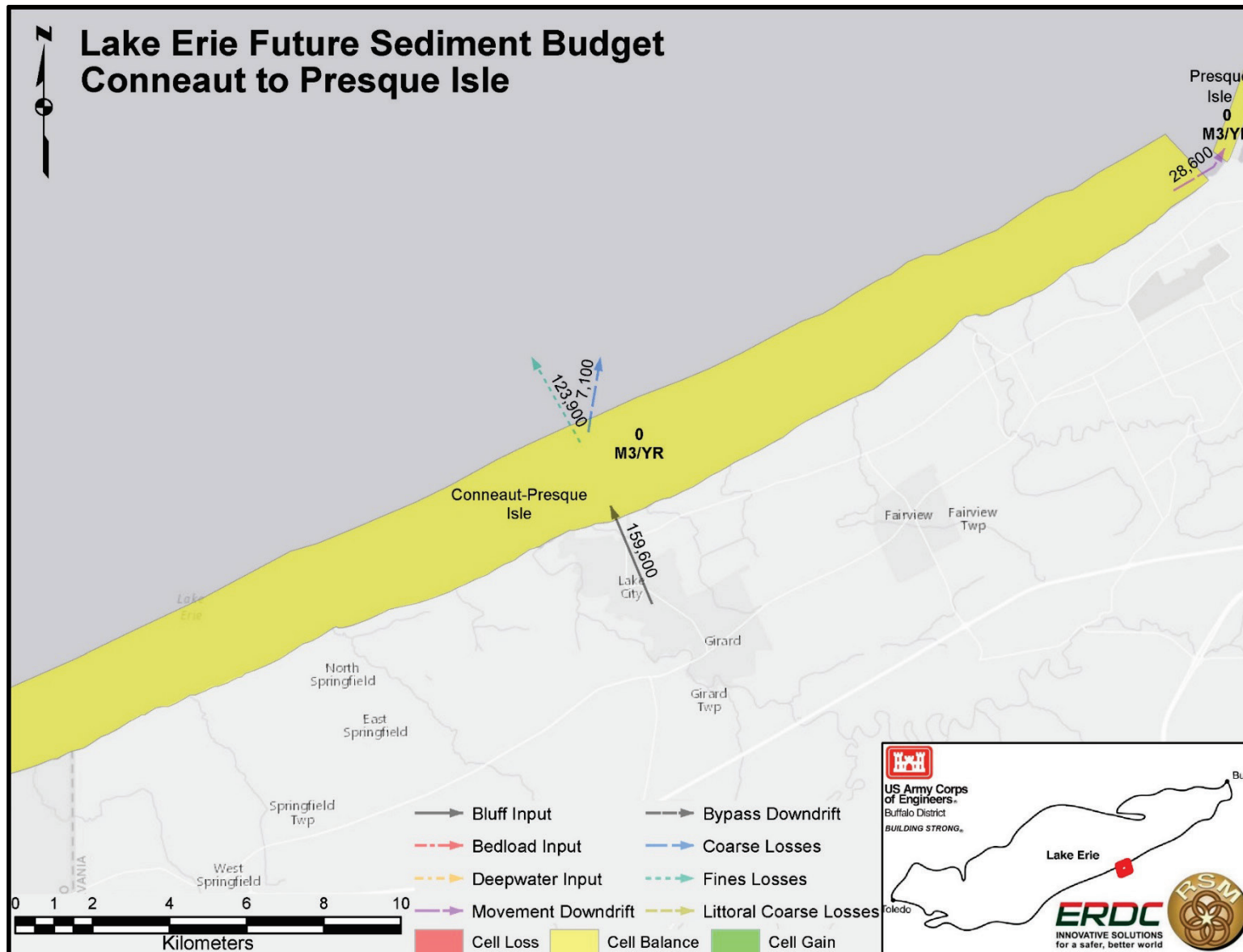


Figure B-42. Presque Isle to North East Mid-Century sediment budget.

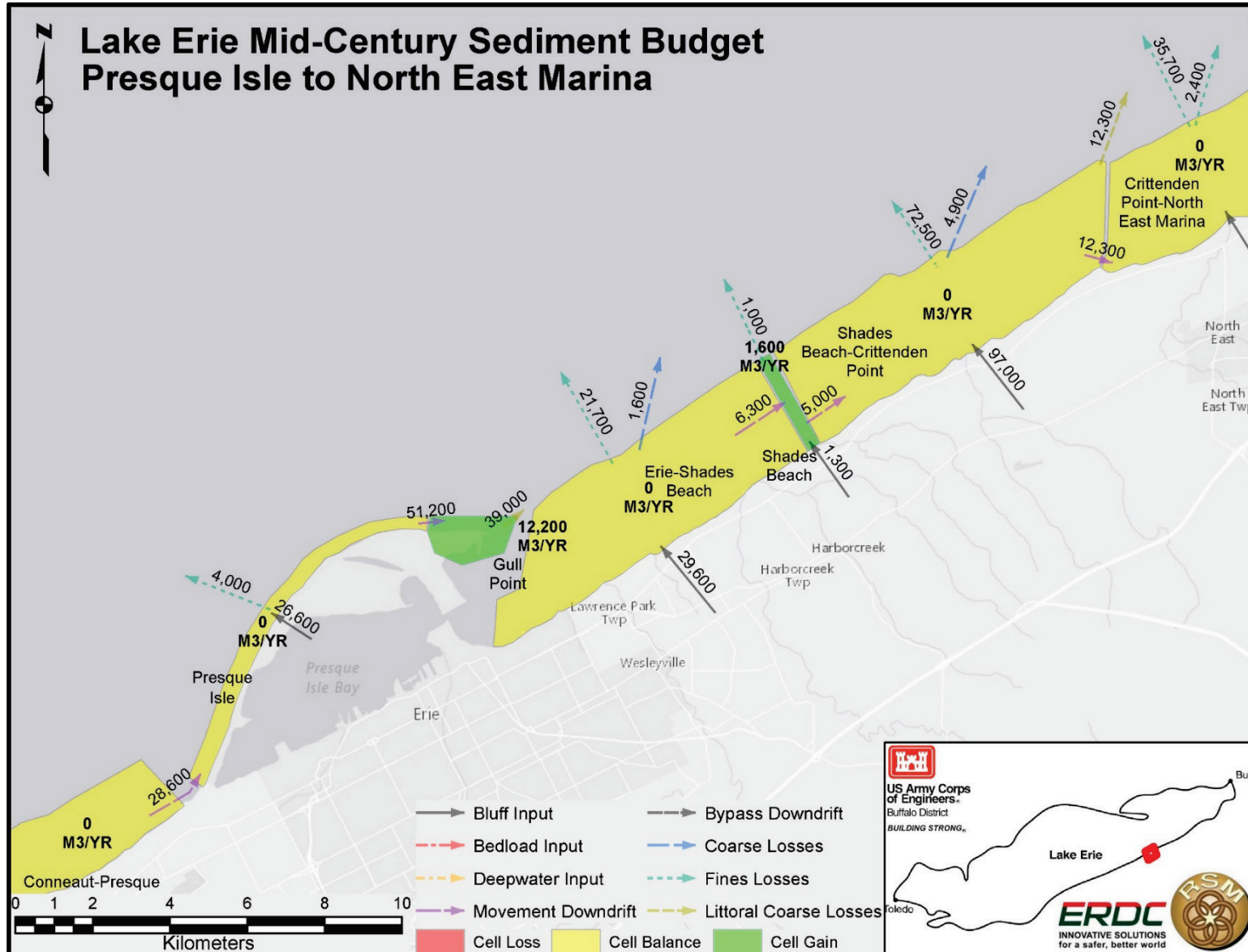


Figure B-43. Presque Isle to North East Recent sediment budget.

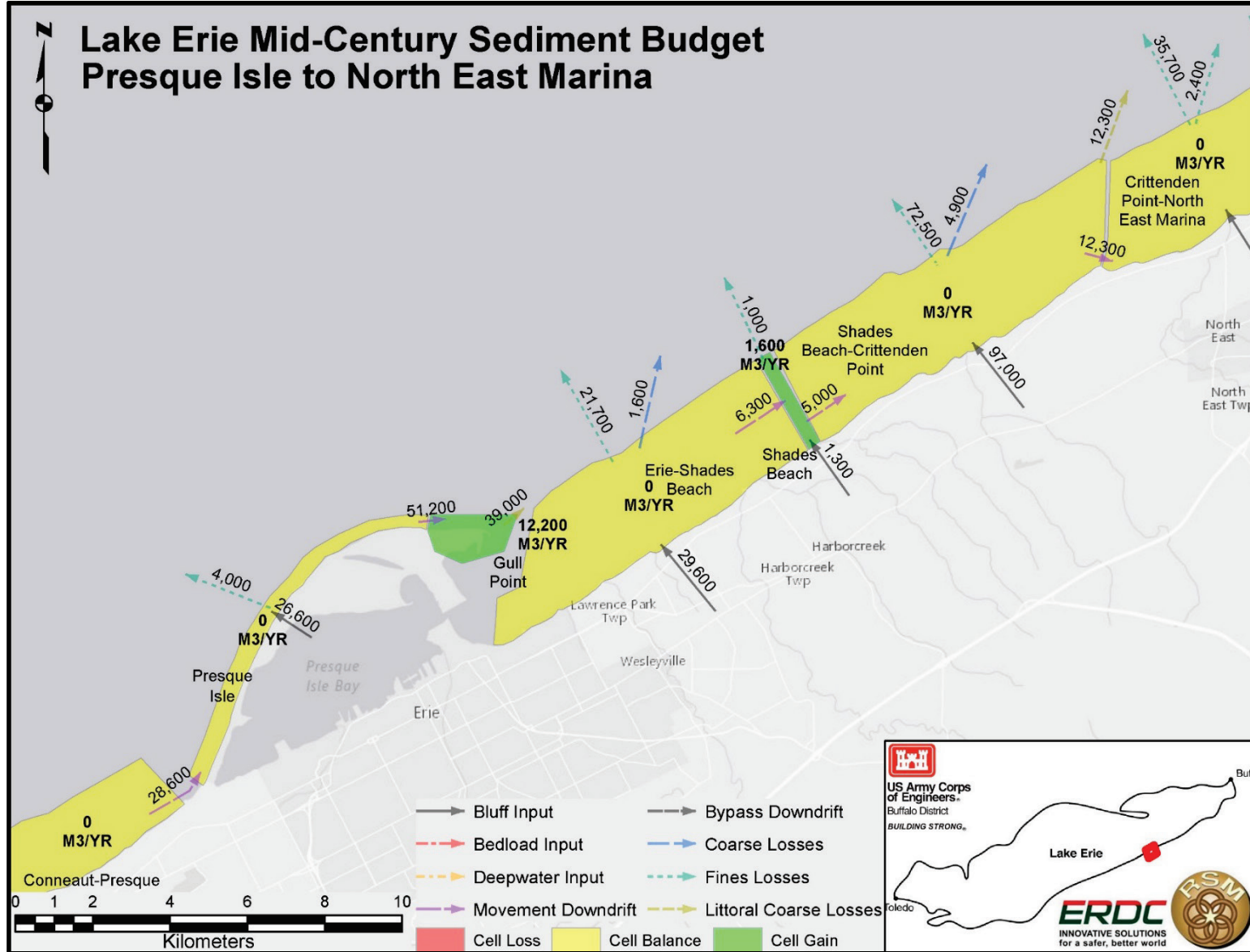


Figure B-44. Presque Isle to North East Future sediment budget.

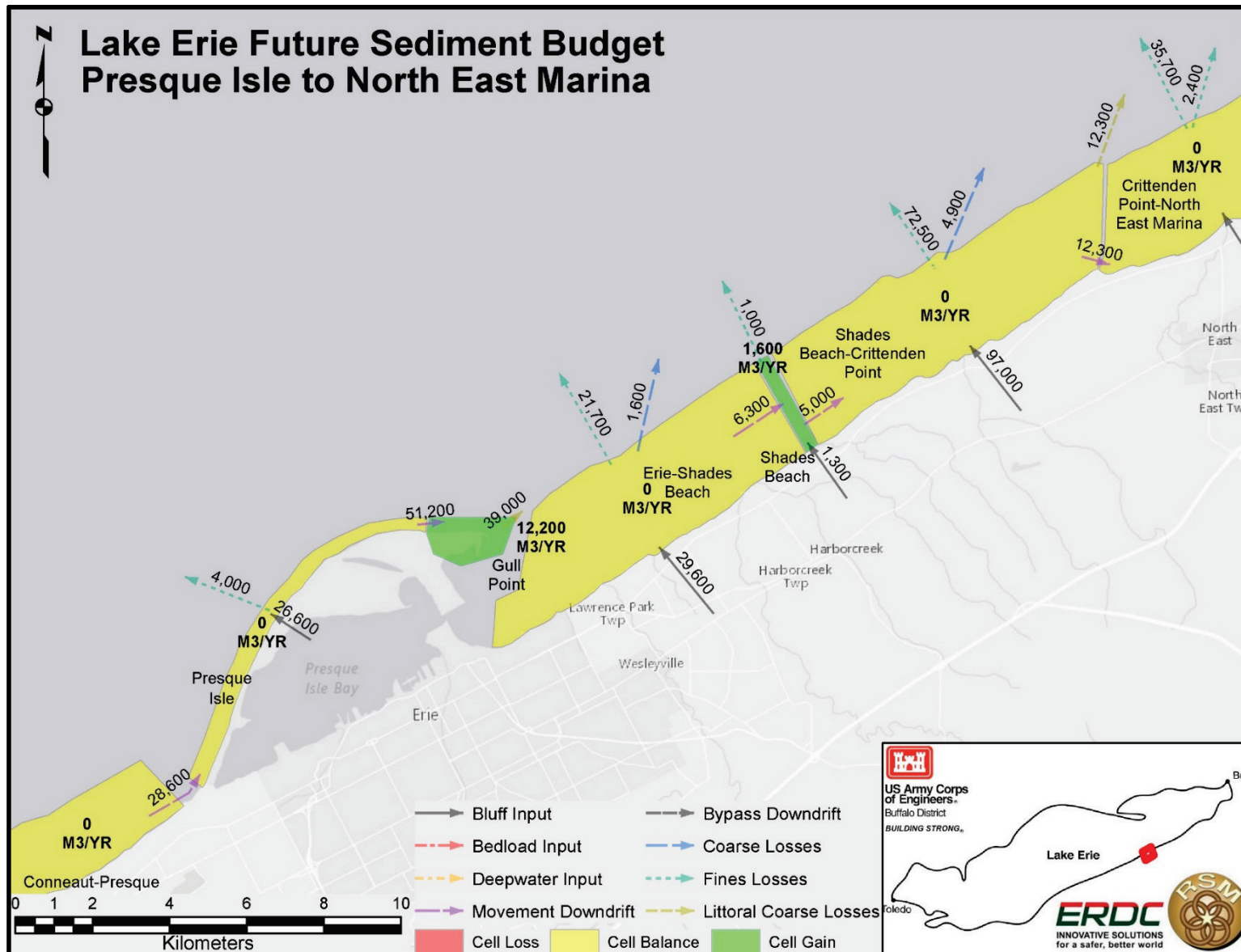


Figure B-45. North East to Barcelona Pre-Armoring sediment budget.

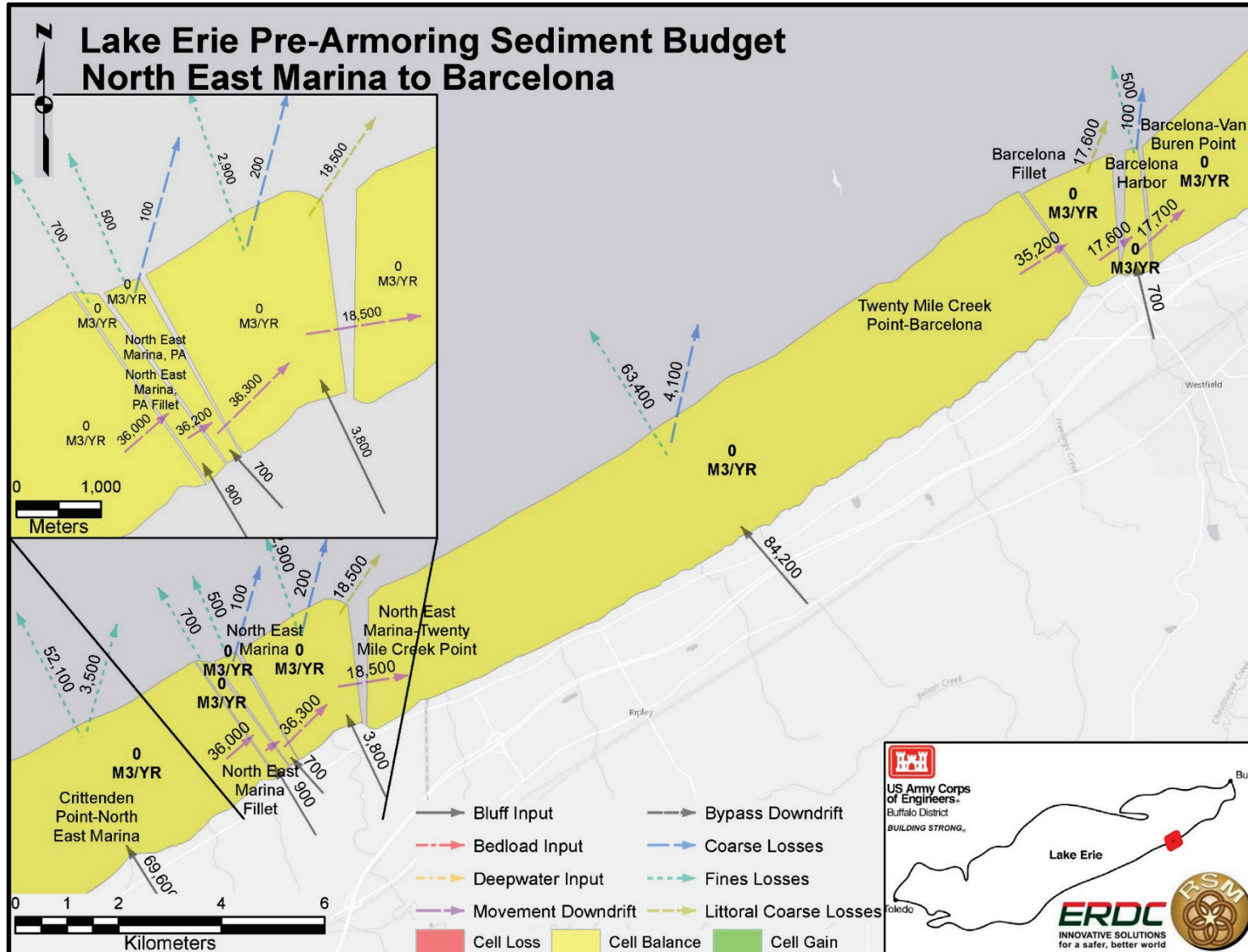


Figure B-46. North East to Barcelona Mid-Century sediment budget.

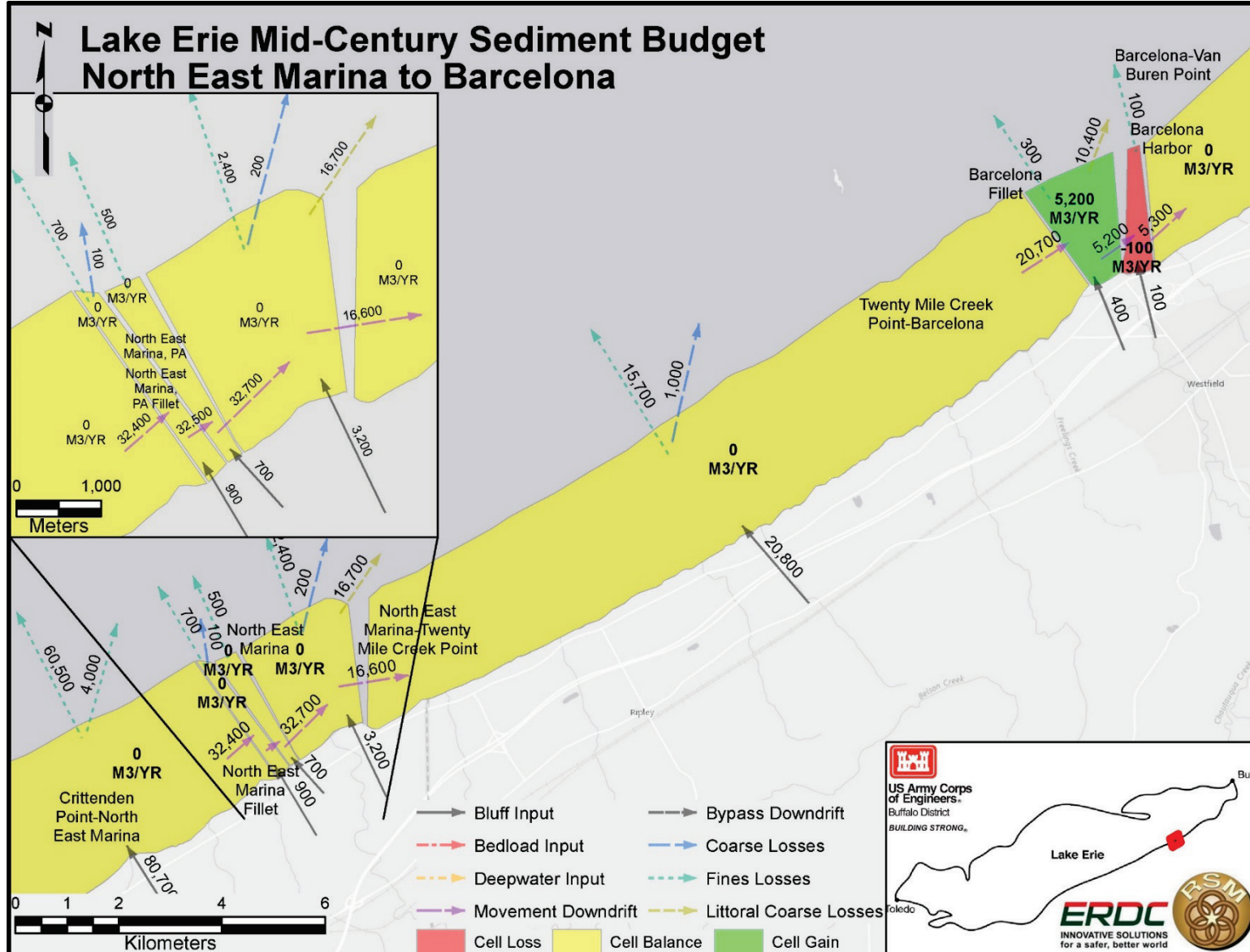


Figure B-47. North East to Barcelona Recent sediment budget.

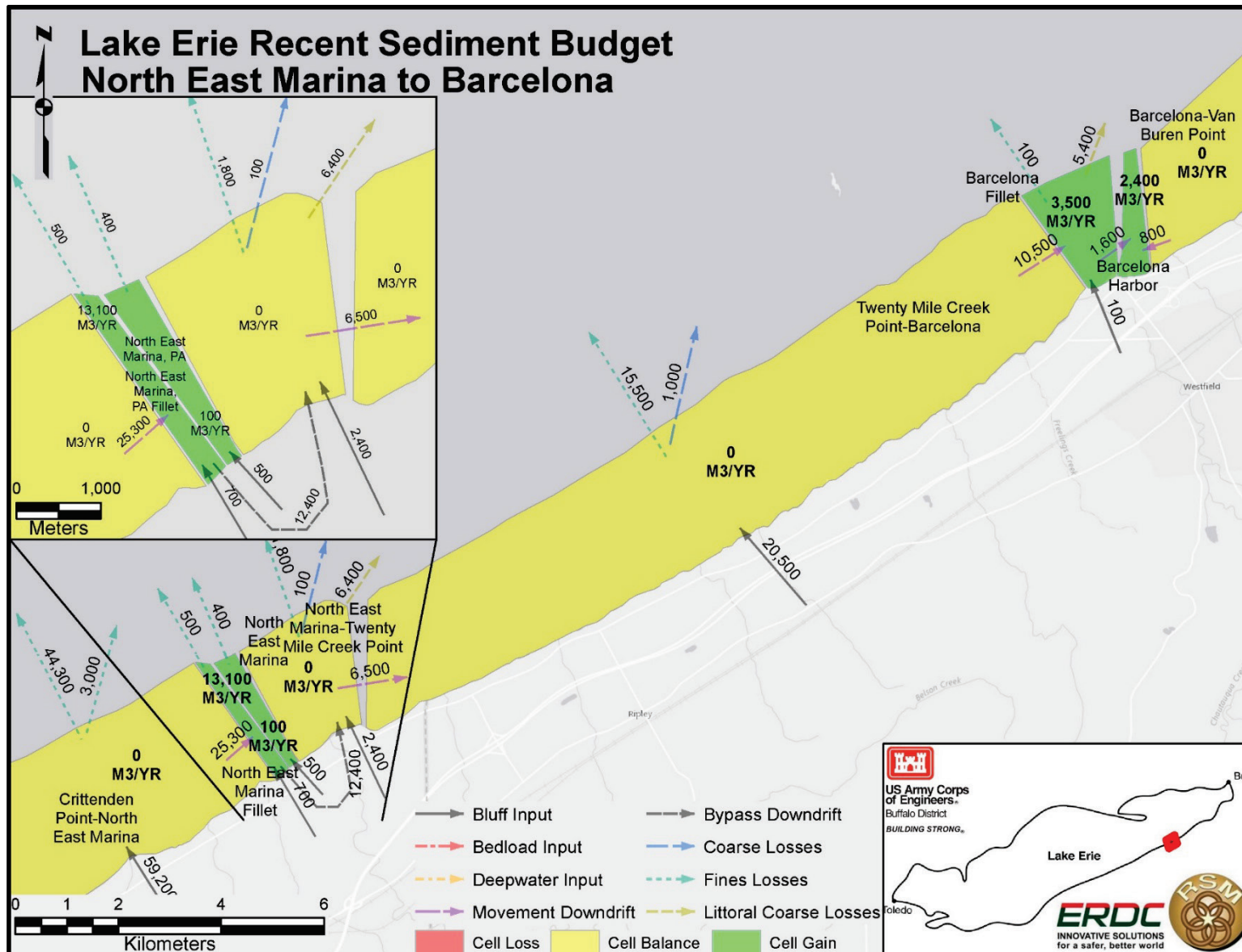


Figure B-48. Northeast to Barcelona Future sediment budget.

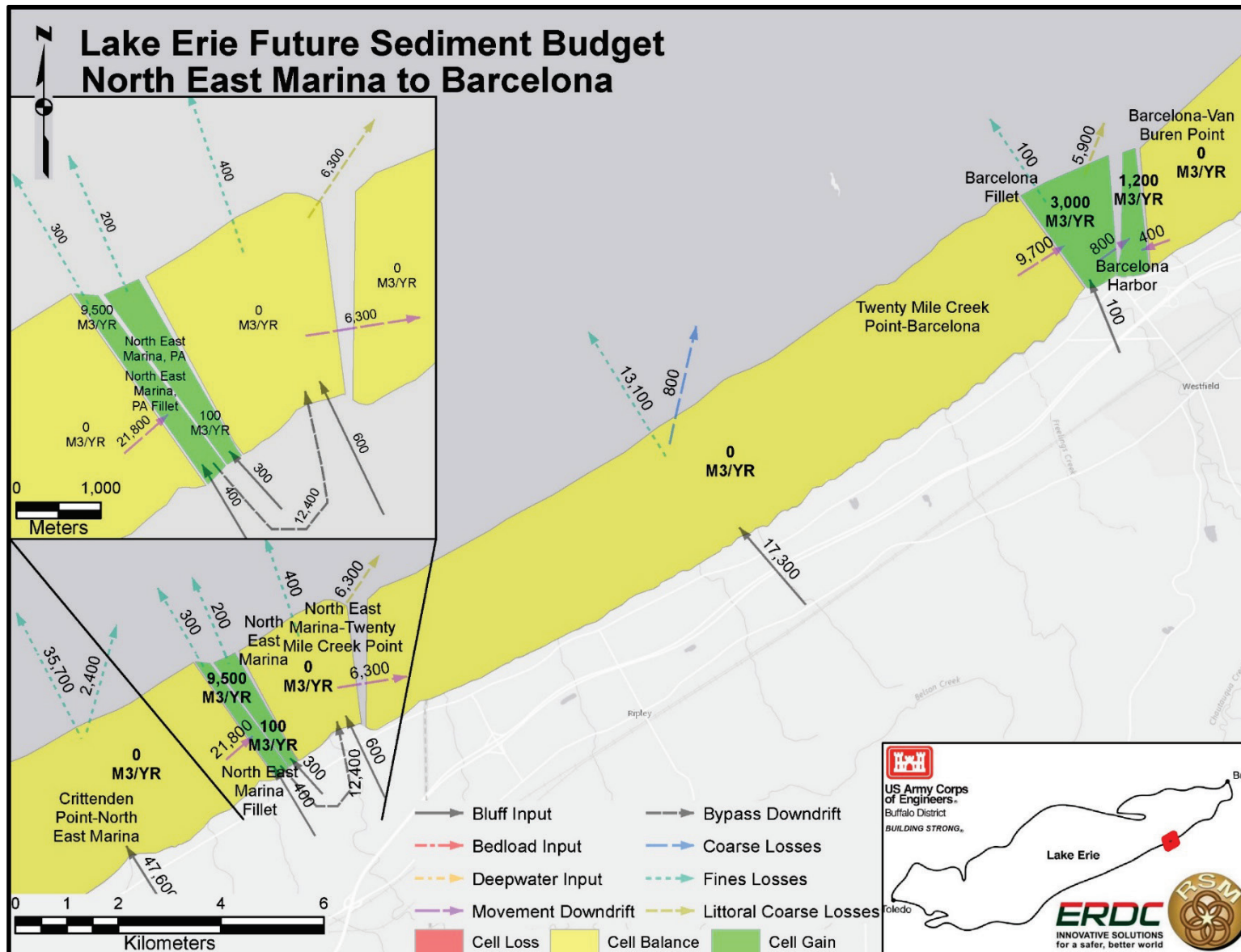


Figure B-49. Barcelona to Dunkirk Pre-Armoring sediment budget.

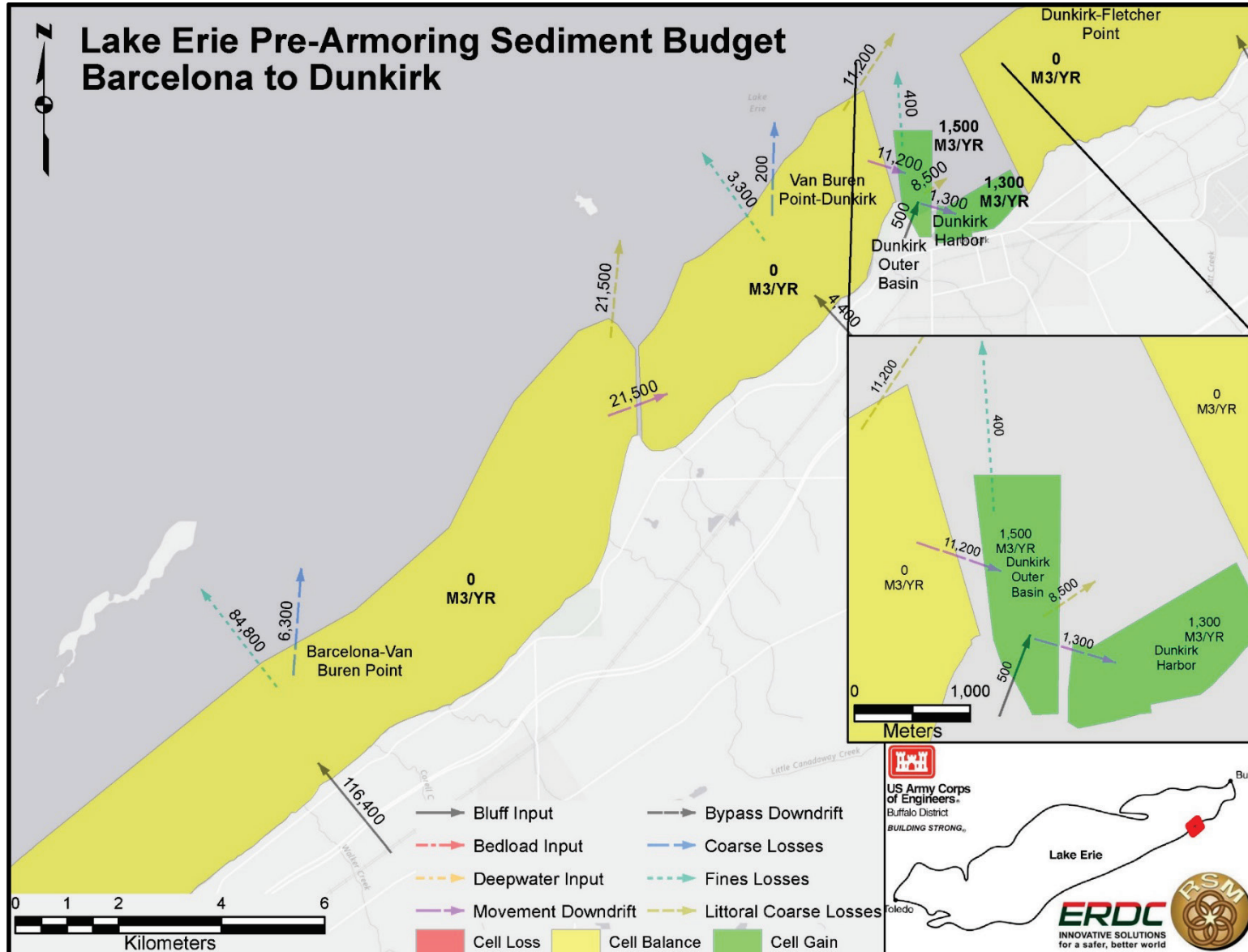


Figure B-50. Barcelona to Dunkirk Mid-Century sediment budget.

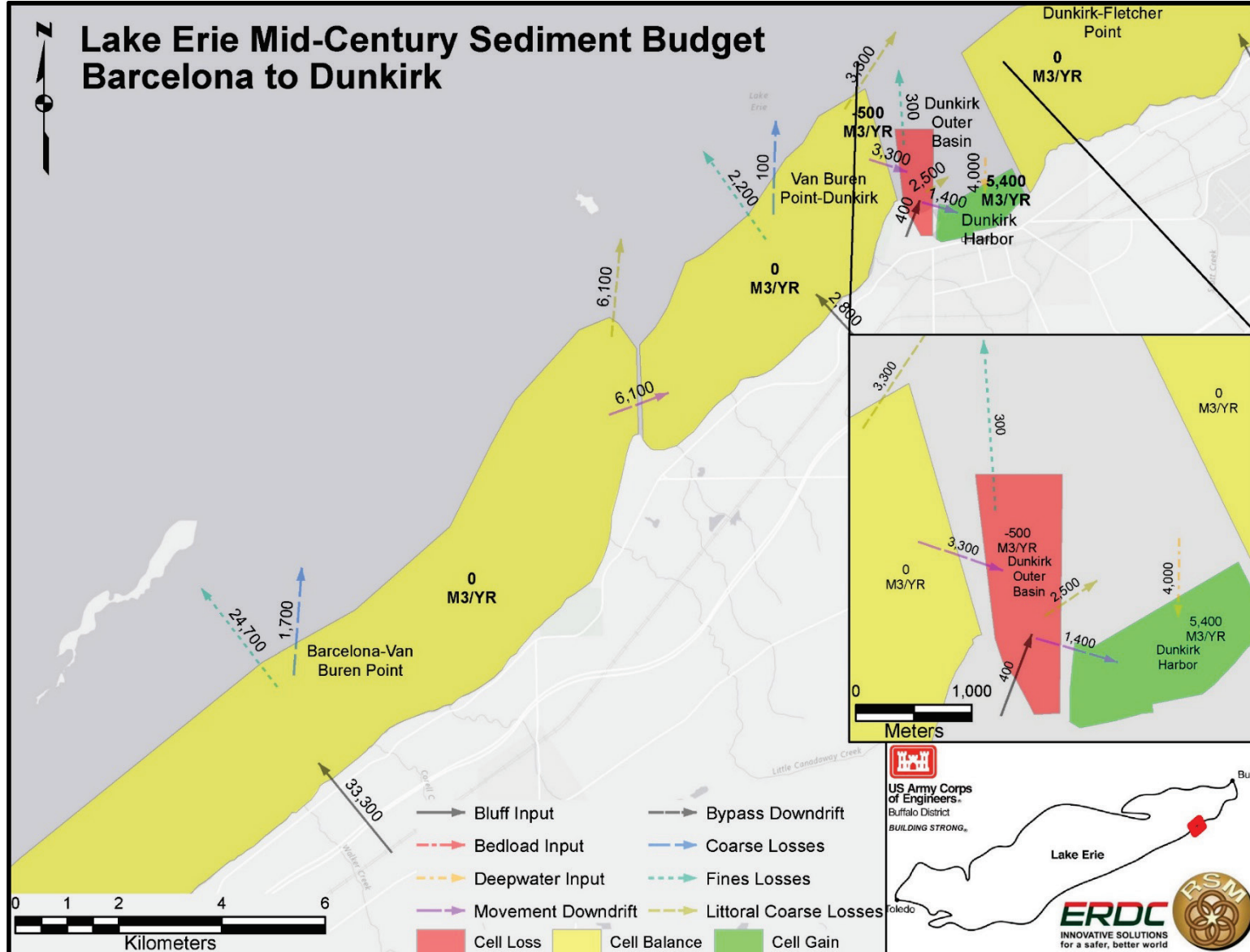


Figure B-51. Barcelona to Dunkirk Recent sediment budget.

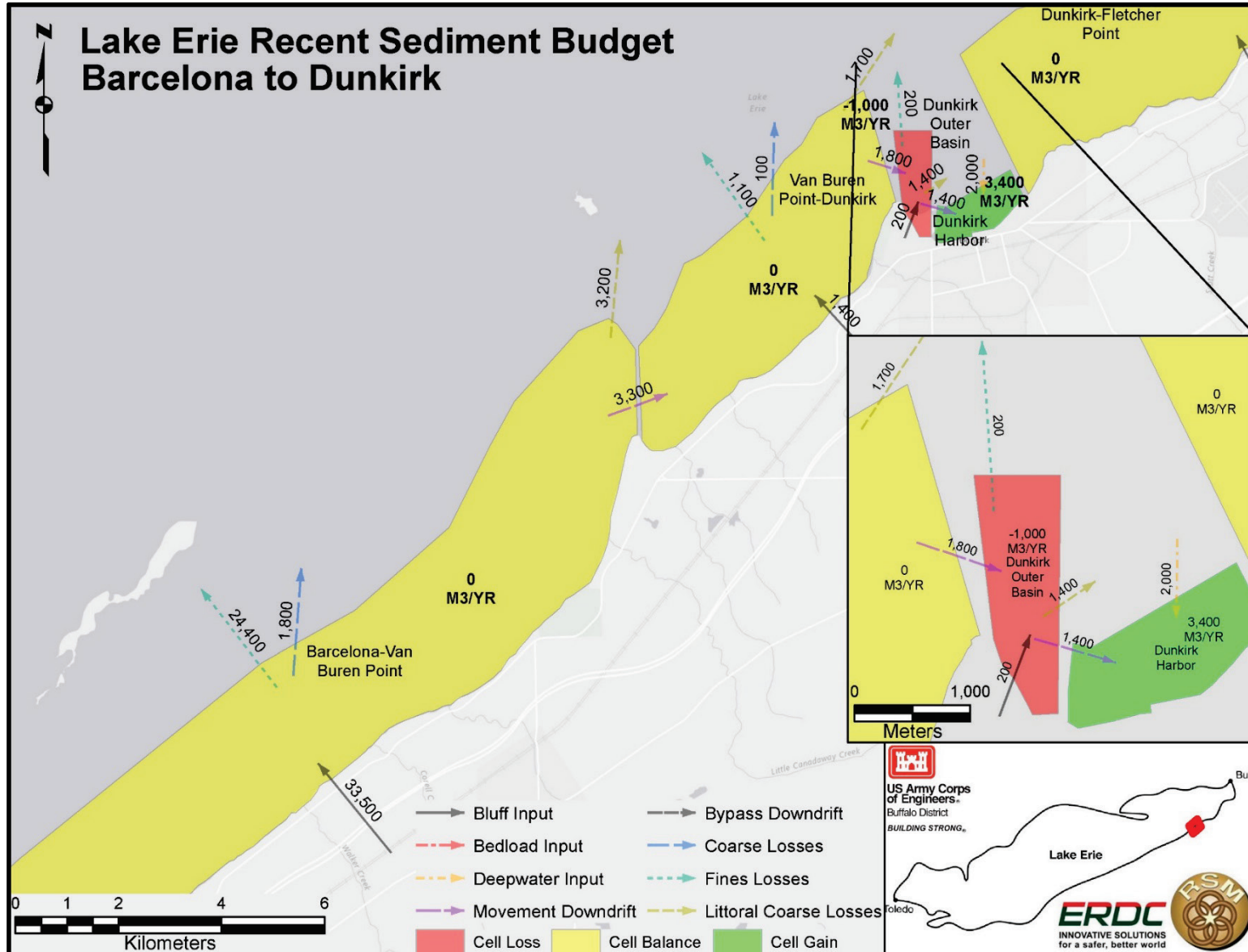


Figure B-52. Barcelona to Dunkirk Future sediment budget.

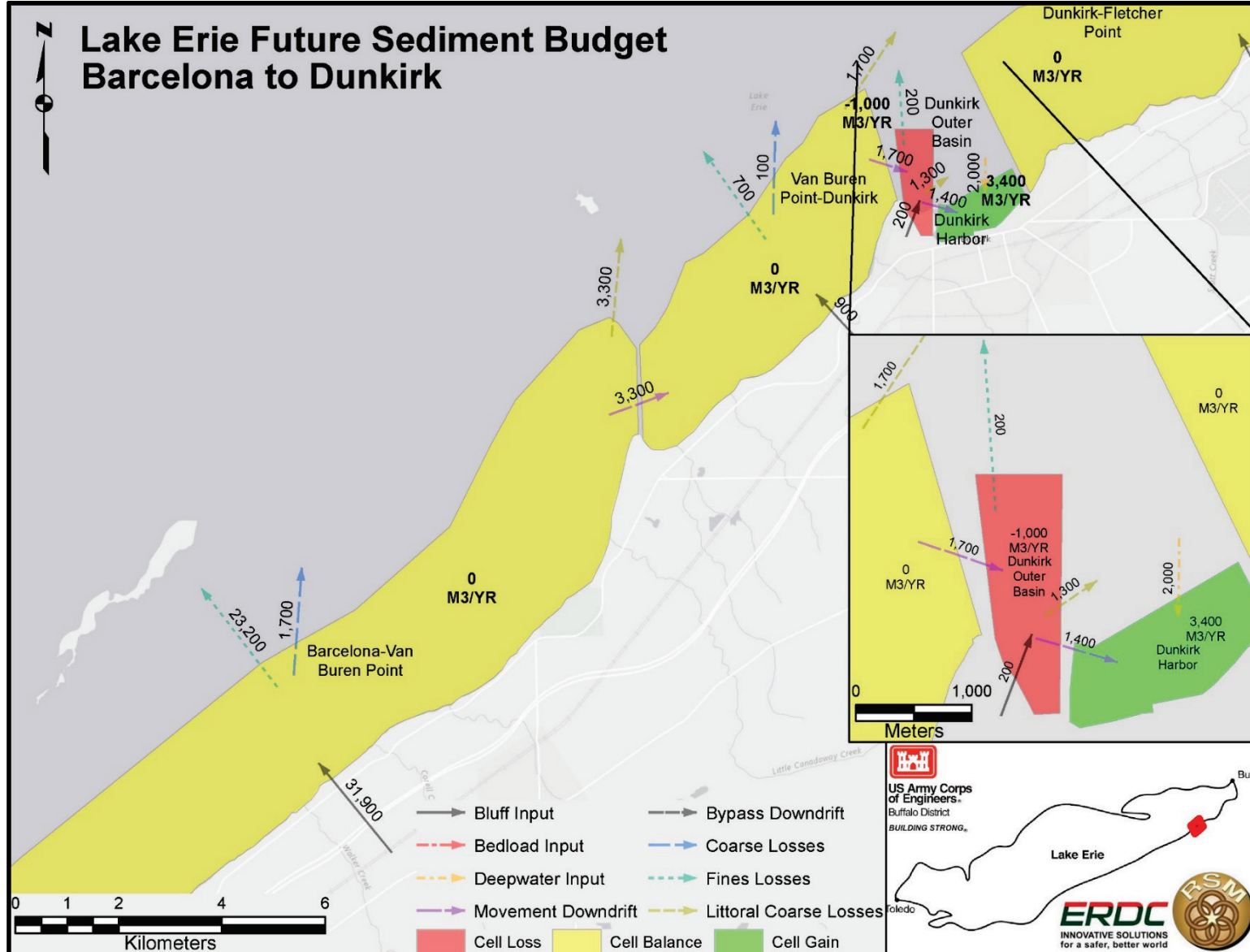


Figure B-53. Dunkirk to Cattaraugus Pre-Armoring sediment budget.

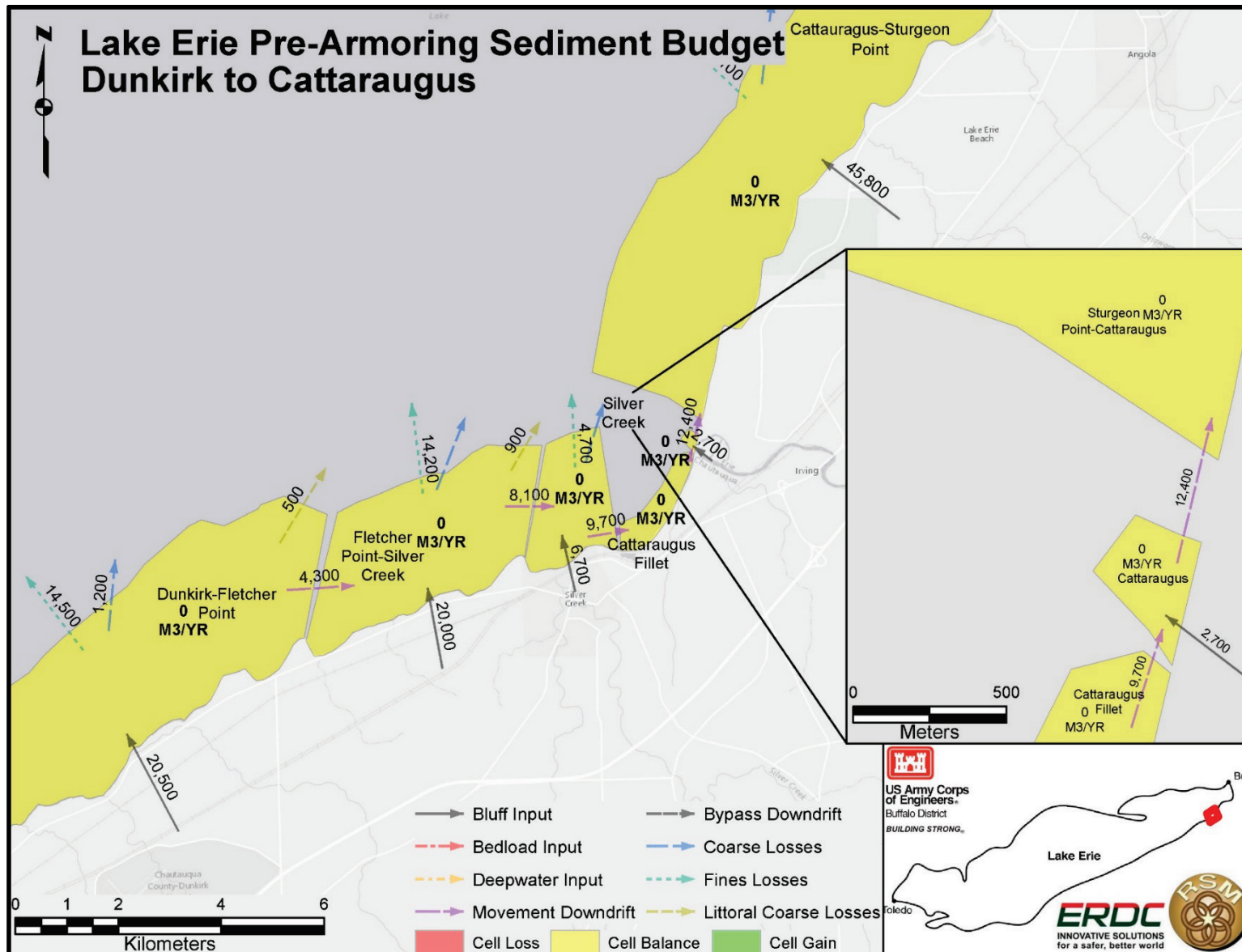


Figure B-54. Dunkirk to Cattaraugus Mid-Century sediment budget.

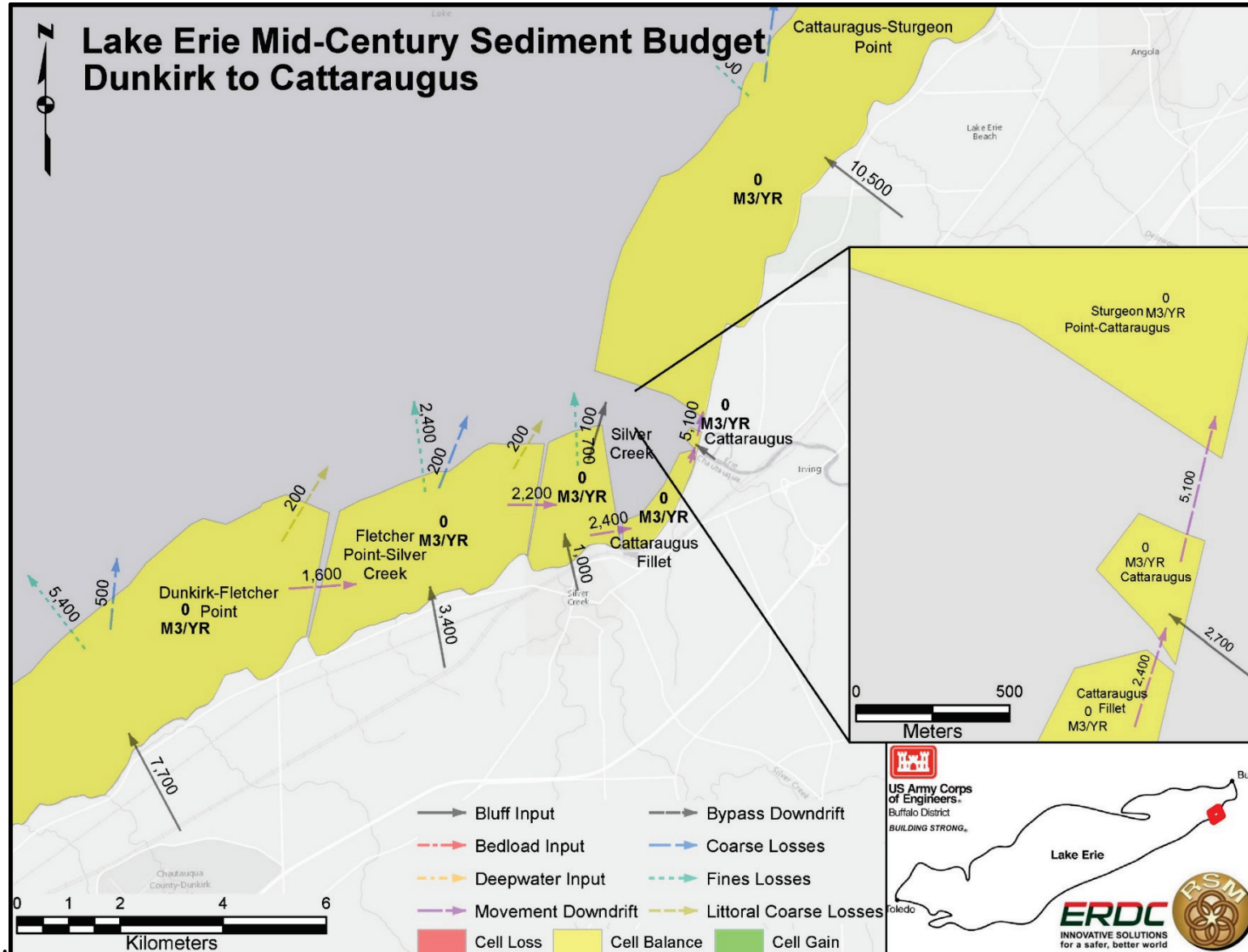


Figure B-55. Dunkirk to Cattaraugus Recent sediment budget.

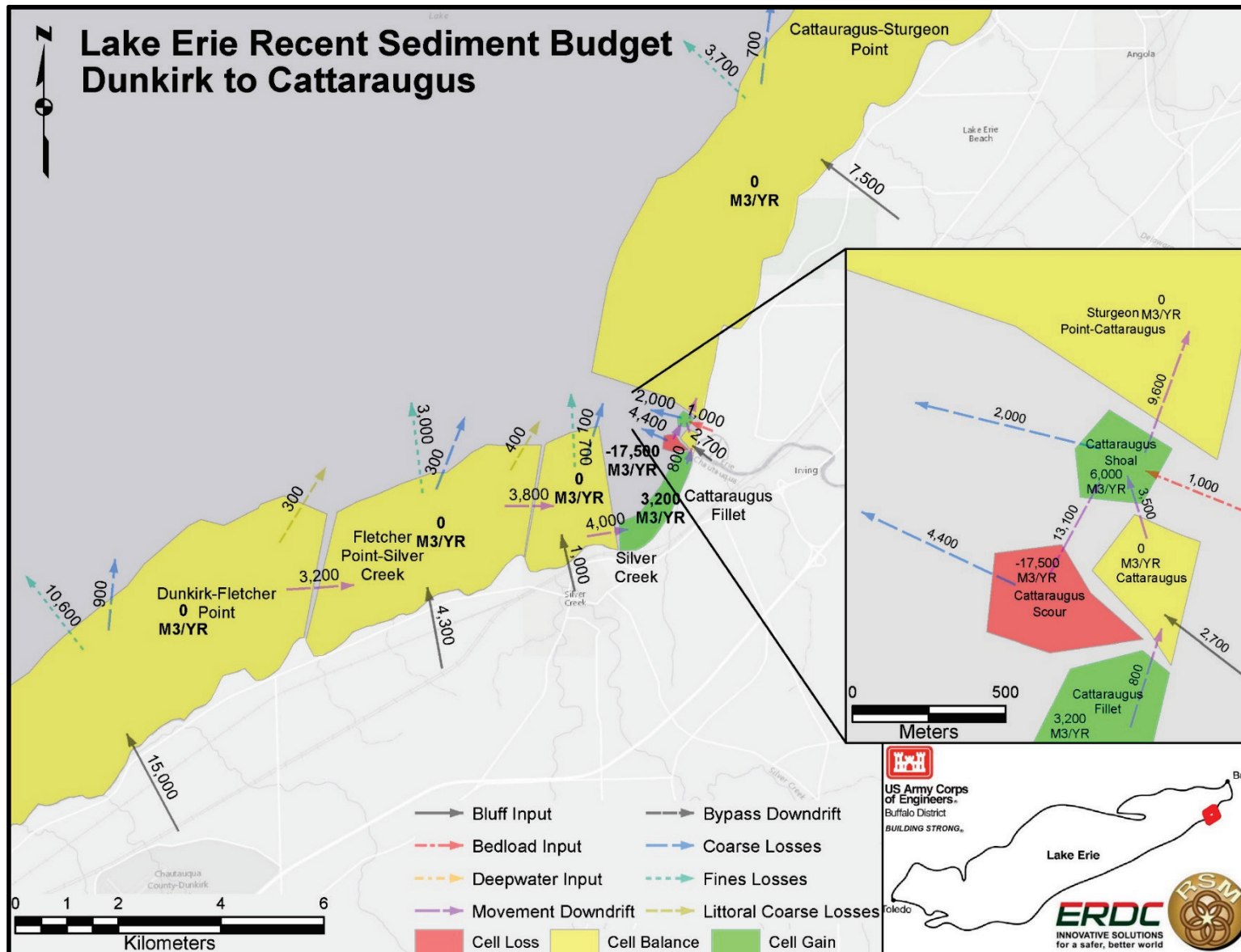


Figure B-56. Dunkirk to Cattaraugus Future sediment budget.

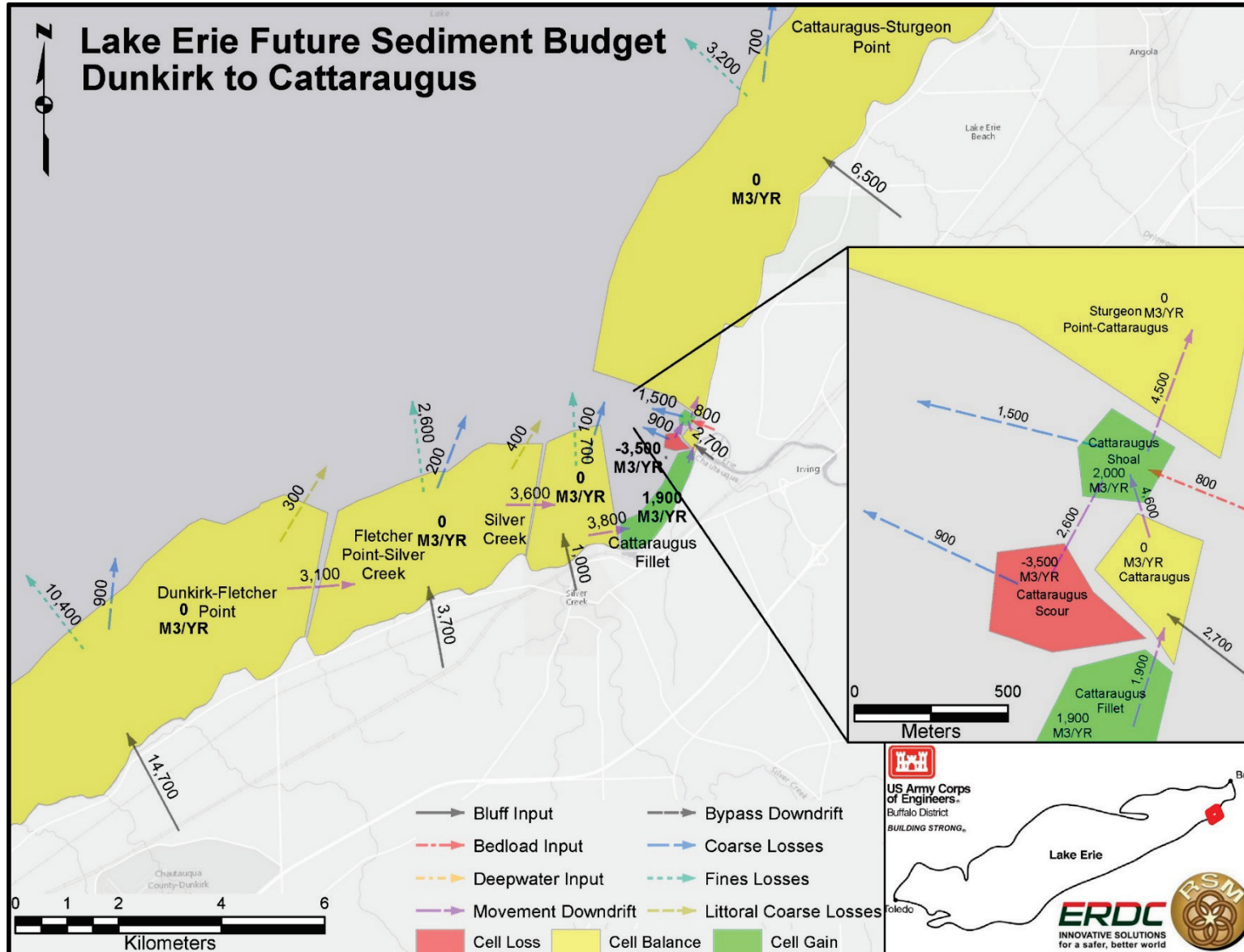


Figure B-58. Cattaraugus to Buffalo Mid-Century sediment budget.

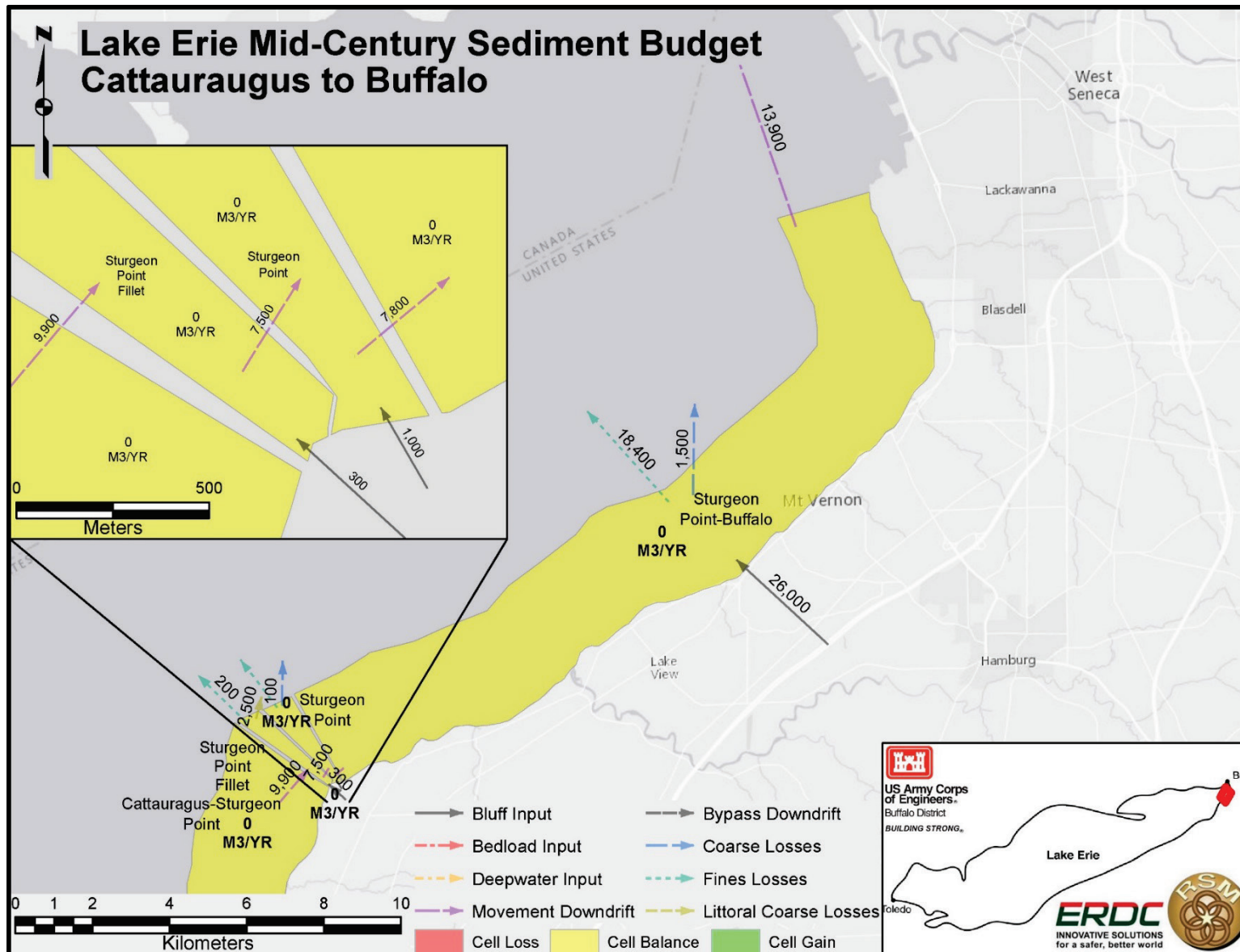
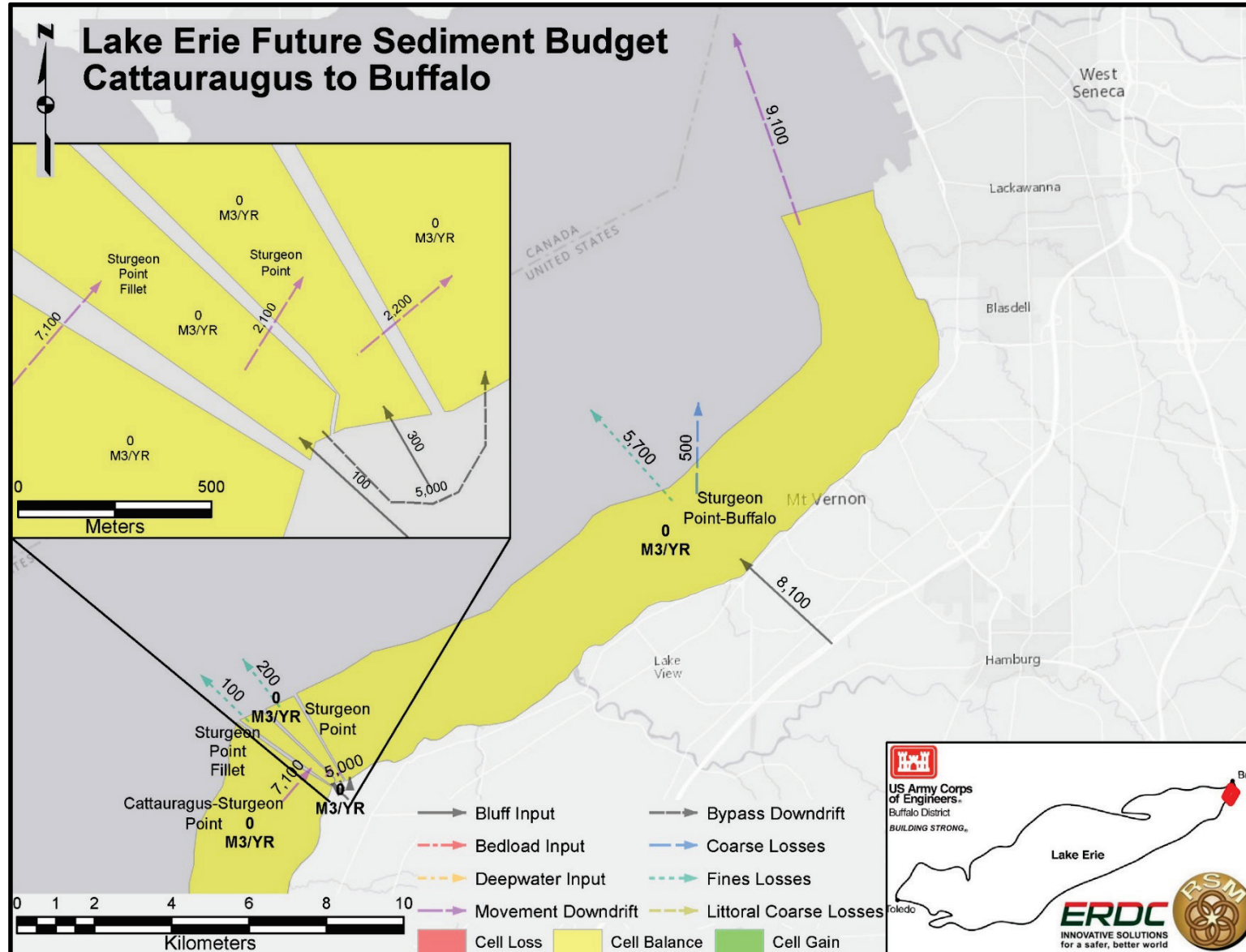


Figure B-60. Cattaraugus to Buffalo Future sediment budget.



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14. ABSTRACT
A sediment budget was developed for the U.S. shoreline of Lake Erie from Maumee Bay, OH, to Buffalo, NY, covering four time frames: (a) Pre-Armoring of the shoreline (1860s–1930s), (b) Mid-Century (mid-twentieth century, 1930s–1970s), (c) Recent era (1970s–2000s), and (d) Future expected conditions (2010+). Sources of data included historic U.S. Army Corps of Engineers Lake Survey charts, aerial photographs, and lidar survey data. The Ohio Department of Natural Resources provided historical recession lines for Ohio. The Pennsylvania Department of Conservation, Natural Resources, and the U.S. Geological Survey supplied historical bluff lines for Pennsylvania.

Analysis of harbor sedimentation and sediment bypassing provides verification of the volume of sediment calculated from bluff recession measurements. These volumes were consistent with harbor sedimentation or sediment bypassing measurements at most points along the shoreline, with the exception of underpredicting sediment volumes at Fairport Harbor, OH.

Most reaches show a decrease in bluff-supplied sediment over time. The decrease is a result of greater bluff armoring during the twentieth century, particularly after the 1970s. For New York and eastern Pennsylvania, the future projected sediment supply from bluffs is similar or slightly less than from the recent era. But in Ohio, the future supply is projected to decrease in most areas because of the almost complete armoring of the Ohio shore.

For the predicted future conditions, total eroded bluff volume will range from 15,000 cubic meters per year in Erie County, NY, to 200,000 cubic meters per year in Ashtabula County, OH.

15. SUBJECT TERMS
Bluff lines, Coast changes, Lake Erie, Regional Sediment Management, Sediment budget, Sediment Budget Analysis System (SBAS), Sediment control, Sediment transport, Shorelines--Monitoring

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