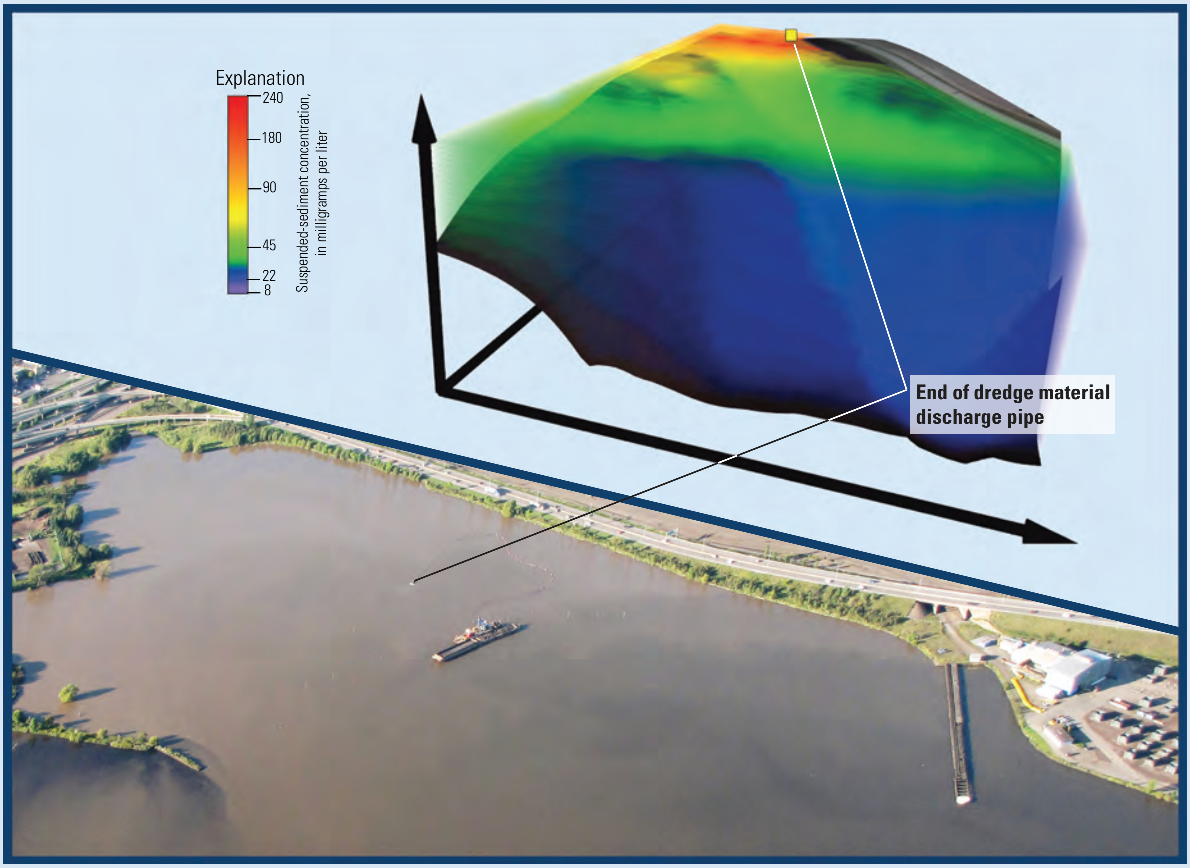
Prepared in cooperation with the U.S. Army Corps of Engineers

Three-Dimensional Visualization Maps of Suspended-Sediment Concentrations during Placement of Dredged Material in 21st Avenue West Channel Embayment, Duluth-Superior Harbor, Duluth, Minnesota, 2015



Scientific Investigations Report 2016–5086

U.S. Department of the Interior
U.S. Geological Survey

Cover illustration: Modified version of figure 13 from this report and 21st Avenue West Channel Embayment of the Duluth-Superior Harbor, Duluth, Minnesota, on September 4, 2015 (photograph provided by U.S. Army Corps of Engineers).

Three-Dimensional Visualization Maps of Suspended-Sediment Concentrations during Placement of Dredged Material in 21st Avenue West Channel Embayment, Duluth-Superior Harbor, Duluth, Minnesota, 2015

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U.S. Department of the Interior
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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2016

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Suggested citation:
Groten, J.T., Ellison, C.A., and Mahoney, M.H., 2016, Three-dimensional visualization maps of suspended-sediment concentrations during placement of dredged material in 21st Avenue West Channel Embayment, Duluth-Superior Harbor, Duluth, Minnesota, 2015: U.S. Geological Survey Scientific Investigations Report 2016–5086, 26 p., http://dx.doi.org/10.3133/sir20165086.

ISSN 2328-0328 (online)

Acknowledgments

The authors would like to thank the U.S. Army Corps of Engineers and Roen Salvage for their assistance with this study. Esther Johnson and Joseph Kreitinger of the U.S. Army Corps of Engineers were integral to the design and implementation of the study. Corey Weston and Daniel Carlson of the U.S. Army Corps of Engineers provided key support for coordinating field aspects of the study.

Gerald Storey, Brent Mason, J. William Lund, Joshua Ayers, Lindsay Hastings, Molly McCool, Chris Sanocki, Michael Roberts, Scott Bennett, and Christopher Ruth of the U.S. Geological Survey and Shon Schooler of the Lake Superior National Estuarine Research Reserve are acknowledged for assistance with data collection. Mark Brigham, Erik Smith, and Paul Reneau of the U.S. Geological Survey are acknowledged for their technical reviews of the report.

Contents

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Appendix Tables

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	feet (ft)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Vertical coordinate information is referenced to the International Great Lakes Datum of 1985 (IGLD 85).

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

®	registered trademark
AOC	Area of Concern
BCF	bias-correction factor
BUI	beneficial use impairment
FNU	formazin nephelometric units
NWIS	National Water Information System
R^2	coefficient of determination
SLR	simple linear regression
SSC	suspended-sediment concentration
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

Three-Dimensional Visualization Maps of Suspended-Sediment Concentrations during Placement of Dredged Material in 21st Avenue West Channel Embayment, Duluth-Superior Harbor, Duluth, Minnesota, 2015

By Joel T. Groten,[1] Christopher A. Ellison,[1] and Mollie H. Mahoney[2]

Abstract

Excess sediment in rivers and estuaries poses serious environmental and economic challenges. The U.S. Army Corps of Engineers (USACE) routinely dredges sediment in Federal navigation channels to maintain commercial shipping operations. The USACE initiated a 3-year pilot project in 2013 to use navigation channel dredged material to aid in restoration of shoreline habitat in the 21st Avenue West Channel Embayment of the Duluth-Superior Harbor. Placing dredged material in the 21st Avenue West Channel Embayment supports the restoration of shallow bay aquatic habitat aiding in the delisting of the St. Louis River Estuary Area of Concern.

The U.S. Geological Survey, in cooperation with the USACE, collected turbidity and suspended-sediment concentrations (SSCs) in 2014 and 2015 to measure the horizontal and vertical distribution of SSCs during placement operations of dredged materials. These data were collected to help the USACE evaluate the use of several best management practices, including various dredge material placement techniques and a silt curtain, to mitigate the dispersion of suspended sediment.

Three-dimensional visualization maps are a valuable tool for assessing the spatial displacement of SSCs. Data collection was designed to coincide with four dredged placement configurations that included periods with and without a silt curtain as well as before and after placement of dredged materials. Approximately 230 SSC samples and corresponding turbidity values collected in 2014 and 2015 were used to develop a simple linear regression model between SSC and turbidity. Using the simple linear regression model, SSCs were estimated for approximately 3,000 turbidity values at approximately 100 sampling sites in the 21st Avenue West Channel Embayment of the Duluth-Superior Harbor. The estimated SSCs served as input for development of 12 three-dimensional visualization maps.

[1]U.S. Geological Survey.

[2]U.S. Army Corps of Engineers.

Introduction

Suspended sediment is a major concern in U.S. waterways because of the role it plays in water quality degradation, navigability, and loss of aquatic habitat (Baker, 1980; U.S. Army Corps of Engineers, 2016a; Minnesota Pollution Control Agency, 2009). Under certain conditions, transport and deposition of suspended sediment fills in navigable waterways, requiring costly dredging operations to maintain commercial shipping (U.S. Army Corps of Engineers, 2016b). The 21st Avenue West Channel Embayment of the Duluth-Superior Harbor (fig. 1) is located in the lower St. Louis River Estuary, which is listed by the International Joint Commission as an Area of Concern (AOC). An AOC is defined as "a geographic area that fails to meet the general or specific objectives of the beneficial-use agreement where such failure has caused or is likely to cause impairment of beneficial use of the area's ability to support aquatic life" (U.S. Environmental Protection Agency, 2016). Nine beneficial use impairments (BUIs) are listed for the lower St. Louis River Estuary AOC, and one of these BUIs is the loss of fish and wildlife habitat (LimnoTech, 2013).

The U.S. Army Corps of Engineers (USACE), Detroit District, initiated a 3-year pilot project in 2013 to place dredged material in support of their navigation mission with the additional benefit of aiding in the restoration of shoreline habitat of the 21st Avenue West Channel Embayment (fig. 1). The goal of the pilot project was to determine the least expensive and environmentally acceptable manner to place Duluth-Superior Harbor dredged material while also contributing to the removal of BUIs to aid in the delisting of the lower St. Louis River Estuary AOC. The 21st Avenue West Channel Embayment was chosen for the pilot project because of its proximity to existing dredged material sources, lack of habitat, and its sheltered location within the Duluth-Superior Harbor (U.S. Army Corps of Engineers, 2014). In coordination with the Minnesota Pollution Control Agency, the USACE implemented best management practices designed to mitigate disbursement of suspended sediment during dredged

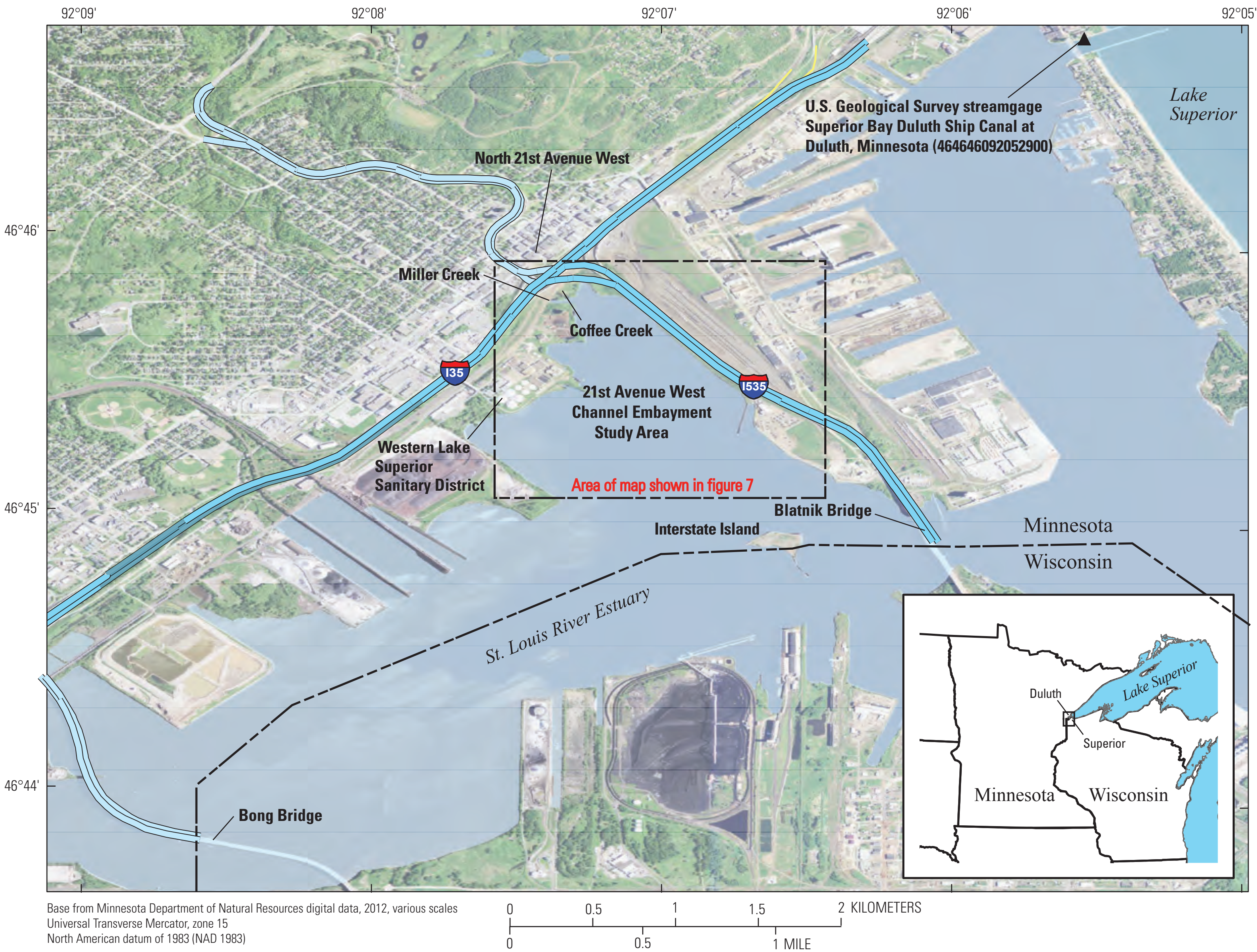

Figure 1. Location of the study area within the 21st Avenue West Channel Embayment of the Duluth-Superior Harbor, Duluth, Minnesota.

material placement operations. This included implementation of various dredged material placement configurations and the employment of a silt curtain for a substantial portion of dredged material placement. Dredge material was hydraulically pumped through a high density polyethylene pipe and was discharged through one of four configurations (figs. 2–5). During portions of dredged material placement, a permeable silt curtain made of a heavy vinyl-coated fabric skirt spanned approximately 500 meters (m) across the 21st Avenue West Channel Embayment and extended from the top of the water column to 0.31–0.61 m above the bottom of the water column (fig. 6).

In 2014 and 2015, the U.S. Geological Survey (USGS), in cooperation with USACE, collected approximately 230 water samples at selected sites in the 21st Avenue West Channel Embayment for analysis of suspended-sediment concentration (SSC). The USGS also collected approximately 3,000 turbidity measurements at approximately 100 sites (fig. 7) in 2015. Data collection was designed to quantify the horizontal and vertical distribution of SSCs during placement of dredged material. Data collected during 2014 and 2015 were used to develop a simple linear regression (SLR) model between SSC and turbidity. Rasmussen and others (2009) and Lietz and Debiak (2005) reported that when the magnitude of turbidity is proportional to SSC, then the turbidity-SSC relation can be quantified through an SLR model. The SLR model was used to predict SSCs from the measured turbidity values at each site. Using these data, 12 three-dimensional visualization maps were generated to elucidate the distribution of SSCs under the following conditions: (1) before placement of dredged materials, (2) during placement of dredged materials using four dredged-material placement configurations without a silt curtain, (3) during placement of dredged materials with a silt curtain, and (4) after placement of dredged materials ceased.

Purpose and Scope

The purpose of this report is to document the vertical and horizontal displacement of suspended sediment before, during, and after placement of dredged material in the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor, Duluth, Minnesota. Specifically, this report presents a series of 12 three-dimensional visualization maps of SSCs from July to November 2015. This report includes descriptions of the study area, methods of data collection, development of an SLR model, and the three-dimensional map interpolation of predicted SSC values.

Description of the Study Area

The cities of Duluth, Minnesota (population 86,238), and Superior, Wisconsin (population 26,705) are port towns on Lake Superior (U.S. Census Bureau, 2016). The 21st Avenue West Channel Embayment (study area) is in the lower St. Louis River Estuary, which is the largest U.S. tributary to

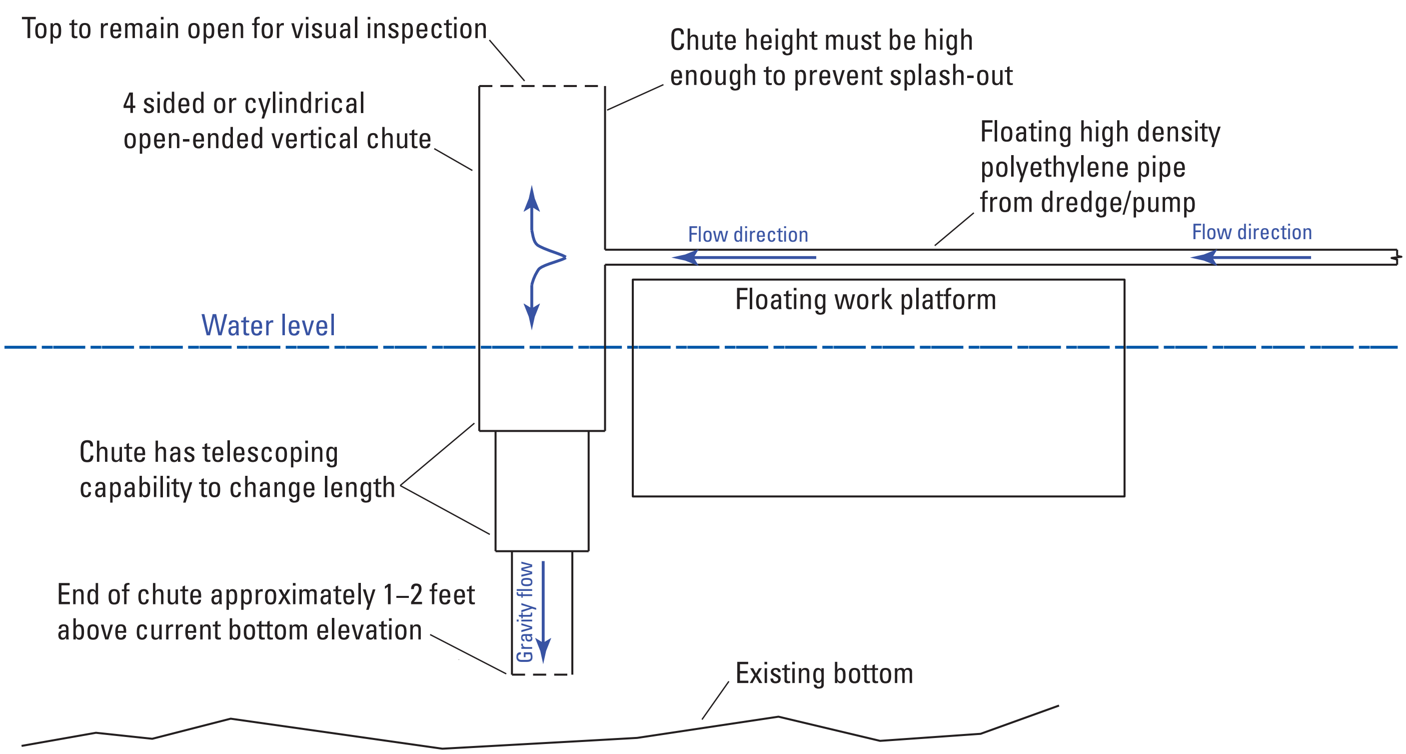

Figure 2. Configuration one schematic (image provided by U.S. Army Corps of Engineers).

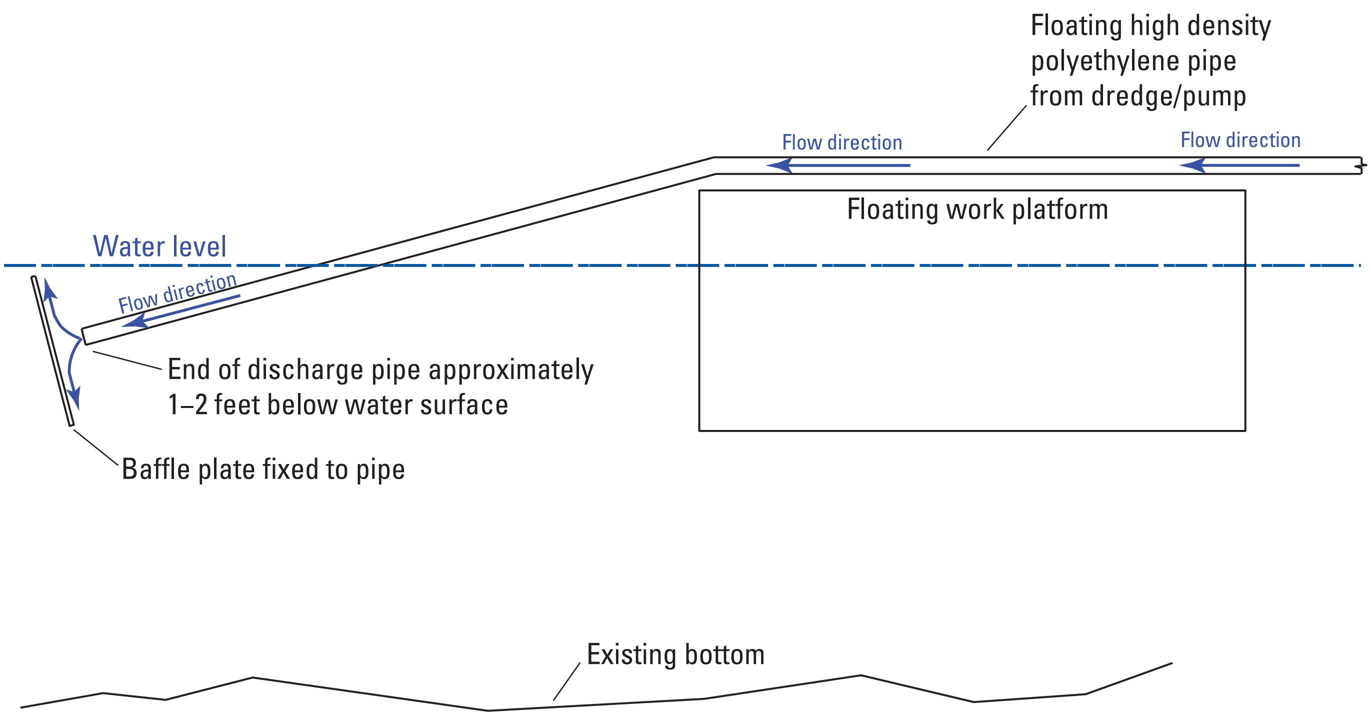

Figure 3. Configuration two schematic (image provided by U.S. Army Corps of Engineers).

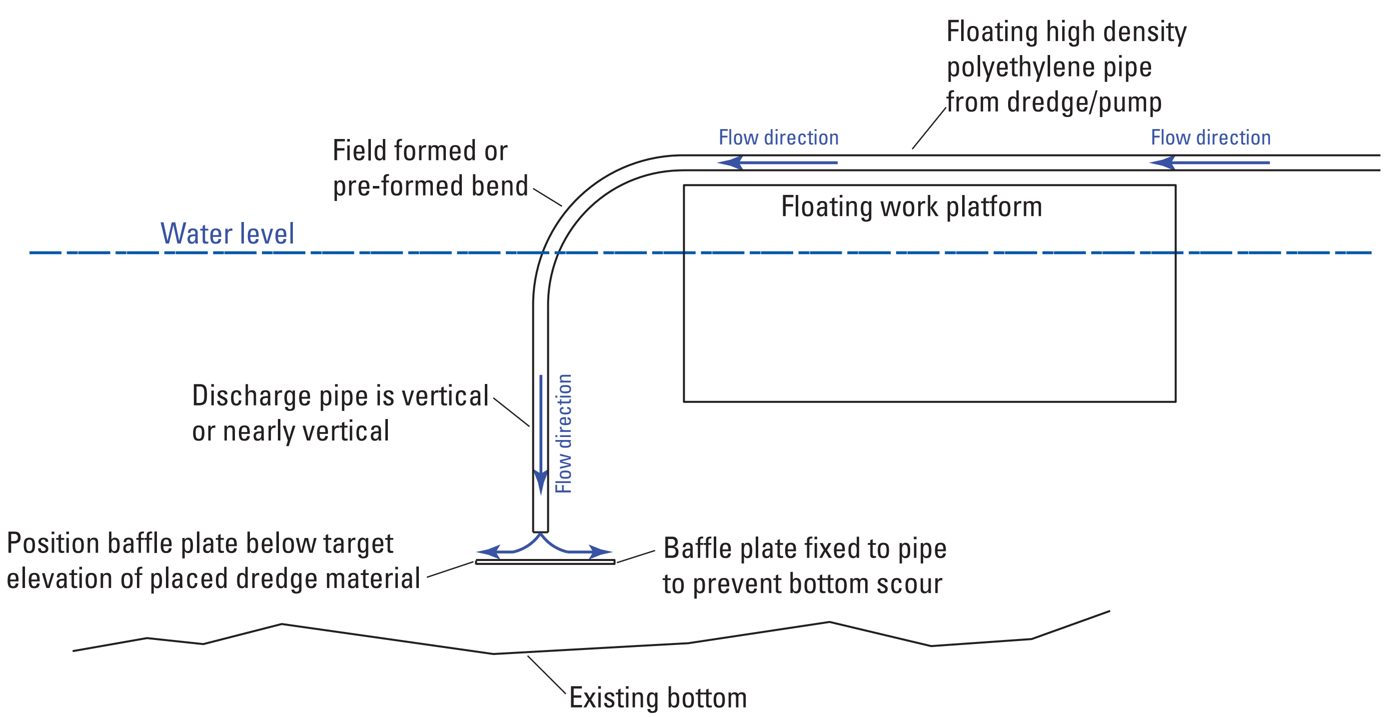

Figure 4. Configuration three schematic (image provided by U.S. Army Corps of Engineers).

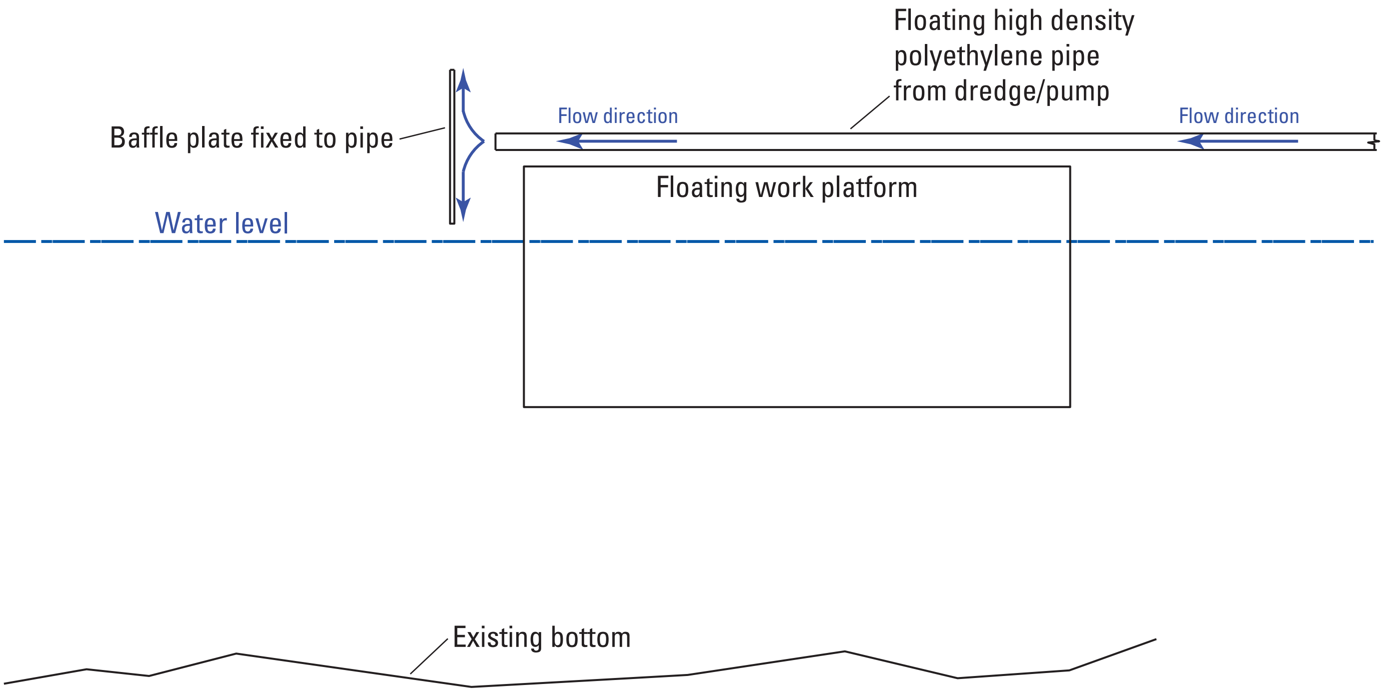

Figure 5. Configuration four schematic (image provided by U.S. Army Corps of Engineers).

Figure 6. Silt curtain within the 21st Avenue West Channel Embayment of the Duluth-Superior Harbor, Duluth, Minnesota, on October 29, 2015 (photograph provided by U.S. Army Corps of Engineers).

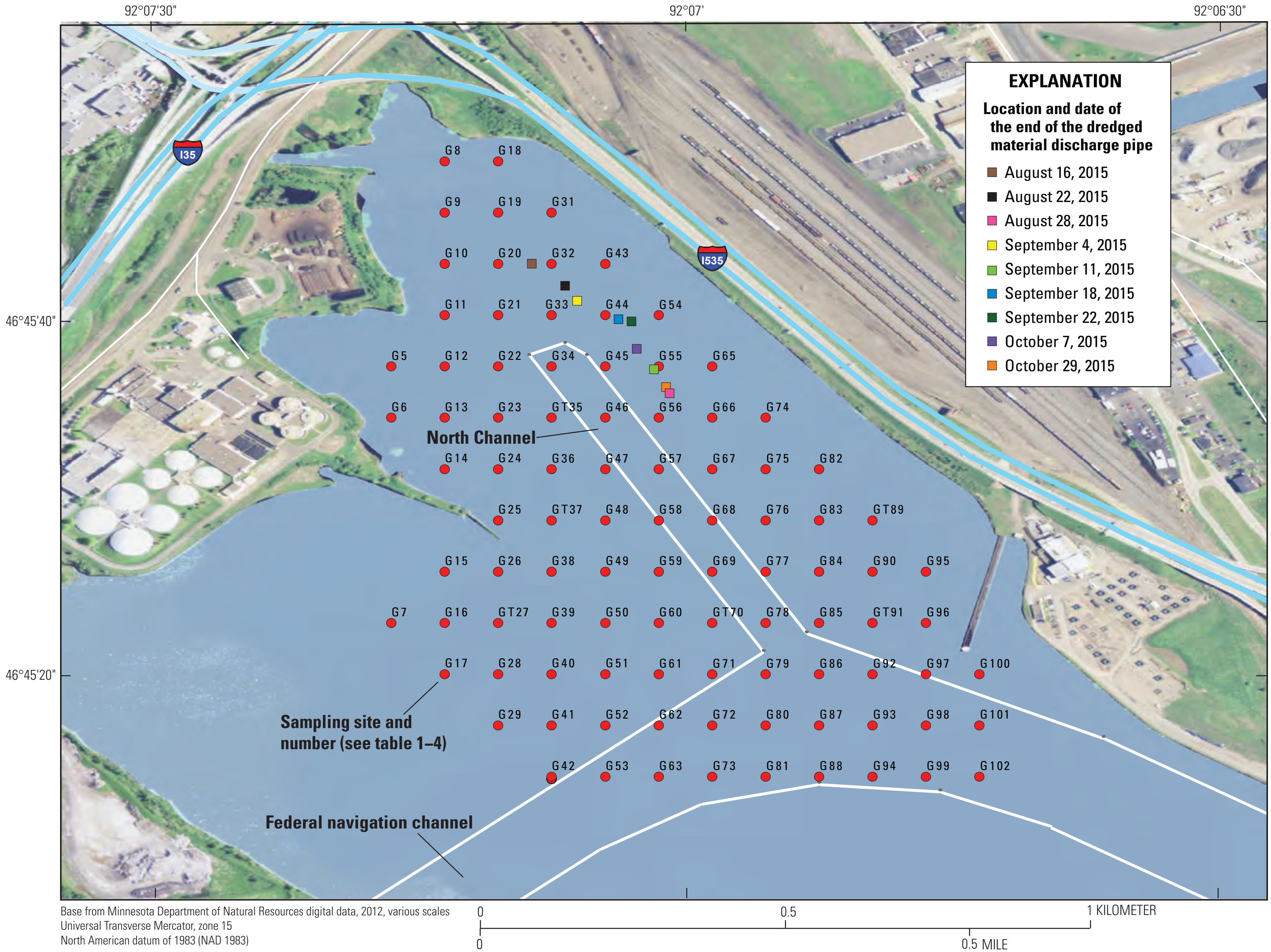

Figure 7. Selected sampling sites used for generation of three-dimensional suspended-sediment concentration maps during 2015 within the 21st Avenue West Channel Embayment of the Duluth-Superior Harbor, Duluth, Minnesota.

Lake Superior (The Nature Conservancy, 2016). The size of the contributing watershed to the study area is approximately 9,582 square kilometers (km^2) (Lorenz and others, 2009), and the size of the study area is approximately 2 km^2 (Host and others, 2013). The study area receives wastewater effluent from the Western Lake Superior Sanitary District (fig. 1) along a point in the southeast direction from the wastewater treatment plant, and Miller and Coffee Creeks also discharge into the northernmost bay.

One primary Federal navigation channel is within the 21st Avenue West Channel Embayment along with a decommissioned deep-water channel that hereafter will be referred to as the North Channel (fig. 7). The North Channel bisects the study area and extends into the Federal navigation channel. The North Channel extends toward the northernmost bay, but sections were filled in with dredged material during the USACE pilot project. Interstate Island (fig. 1) is located to the southeast of the study area and was created from dredged material. Interstate Island is maintained as a Wildlife Management Area by the Minnesota Department of Natural Resources (St. Louis River Estuary, 2016).

The nearest streamgage is located at Superior Bay Duluth Ship Canal in Duluth, Minnesota (USGS station 464646092052900) (fig. 1). The elevation of the water surface (stage readings) are recorded every 15-minutes, and preliminary data are available at http://waterdata.usgs.gov/mn/nwis/uv?site_no=464646092052900. The reference datum for water surface is the International Great Lakes Datum of 1985.

Methods of Data Collection and Analysis

Data collection was designed to quantify horizontal and vertical distribution of SSCs within the 21st Avenue West Channel Embayment. Approximately 100 monitoring sites (fig. 7) were established in the embayment from which SSC and turbidity measurements were collected. Each site consisted of one to four depths from which samples or measurements were collected vertically.

Depth-integrated samples were collected with a Kemmerer (Wildco® Product Number 1520-A45, Yulee, Florida; Shelton, 1994). A YSI Inc. (Xylem Inc.®) model 6136 turbidity sensor and a YSI model 6920 V2 sonde were used to measure turbidity. Turbidity sensors were calibrated to three YSI standards (0, 126, and 1,000 formazin nephelometric units [FNU]) in the morning before collection of turbidity measurements. Turbidity measurements and corresponding SSC samples were collected at the same depth, time, and location (table 1–1 in appendix 1). Sequential replicate SSC samples were collected immediately after the primary water sample to assess variability of SSC measurements (table 1–2 in appendix 1). The overall mean absolute relative percent difference between primary and sequential replicate samples was 12 percent, with some sites having noticeably higher relative percent differences than others (table 1–2 in appendix 1). Sites with higher differences between primary and replicate samples most likely are associated with unstable site conditions.

Water samples collected in 2014 and 2015 were transported to the USGS sediment laboratory in Iowa City, Iowa, and analyzed for SSCs according to procedures in Guy (1969). SSC was reported in milligrams per liter, and turbidity was reported in FNU. The results of USGS sampling are presented in table 1–1 in appendix 1; the results also are stored in the USGS National Water Information System (NWIS) and are available at http://waterdata.usgs.gov/nwis (U.S. Geological Survey, 2016).

Turbidity data were collected in 2014 and 2015 at multiple sites and depths and are available at http://waterdata.usgs.gov/nwis (U.S. Geological Survey, 2016). In 2014, turbidity data were collected at three depths in the water column if the water depth was 3.05 m or greater. Measurements were collected at 0.31 m below the water surface, at mid-depth, and 0.31 m above the bottom of the estuary. If the total depth was less than 3.05 m but equal to or greater than 1.53 m, then two turbidity measurements were collected at 0.31 m below the water surface and 0.31 m above the bottom of the estuary. If the depth was less than 1.53 m, then one turbidity measurement was collected at mid-depth.

In 2015, additional turbidity measurements were collected for depths less than 3.35 m. This change was incorporated into the sampling plan to improve understanding of SSCs at shallower depths. If the water depth was 3.35 m or greater, then four turbidity measurements were collected at depths below the water surface of 0.31, 2.14, 3.05, and at 0.31 m above the bottom of the estuary. If the water depth was less than 3.35 m but greater than 3.05 m, then three turbidity measurements were collected below the water surface at 0.31, 2.14, and 3.05 m. If the water depth was less than 3.05 m but greater than 2.44 m, then turbidity measurements were collected at 0.31 and 2.14 m below the water surface. If the water depth was 2.44 m or less but equal to or greater than 0.92 m, then measurements were collected at 0.31 m below the water surface and at 0.31 m above the estuary bottom. If the depth was less than 0.92 m, then one measurement was collected at 0.31 m below the surface.

Model Development

Approximately 230 SSC and corresponding turbidity values were used for SLR model development (table 1–1 in appendix 1). During model development, eight outliers were removed (four SSC values and the four corresponding turbidity values) from the model development (table 1–3 in appendix 1). The four samples associated with the outliers were collected in proximity to the end of the dredged material discharge pipe (table 1–3 in appendix 1). These unusual measurements (outliers) may have been caused by rapidly changing SSCs near the end of the dredged material discharge pipe (fig. 7). The simultaneous collection of the SSC sample and associated turbidity measurement from the same volume of water near the end of the discharge pipe, which was being inundated with sediment directly from the discharge pipe, likely resulted in the observed discrepancies between the two measurements.

An SLR model was developed using SSC samples and turbidity measurements collected in 2014 and 2015 (table 1–1 in appendix 1; U.S. Geological Survey, 2016). The SLR model was then used to predict SSC from the measured turbidity values collected at selected sites in 2015 (table 1–4 in appendix 1). The SSC and turbidity values were log-transformed (base-10 logarithms) to normalize the data to meet the assumptions of the SLR model in order to reduce heteroscedasticity and skewness of the residuals (Helsel and Hirsch, 2002). Log-transformed data were used to develop an SLR equation using the S-Plus statistical package (TIBCO® Software Inc., 2010). Diagnostics for the model included a residual normal quantile-quantile plot (also known as a QQ plot; Chambers and others, 1983) and removing unusual measurements (outliers). Model variance was evaluated by plotting residual and response values against fitted values. A bias-correction factor (BCF) (Duan, 1983) was applied to the data after they were retransformed into the original units (Miller, 1951; Koch and Smillie, 1986). The following model was used to predict SSC from turbidity:

$$SSC = 10^{\beta_0} * Turb.^{\beta_1} * BCF \tag{1}$$

where

SSC is suspended-sediment concentration, in milligrams per liter;

β_0 is the intercept;

$Turb.$ is turbidity, in formazin nephelometric units;

β_1 is the slope; and

BCF is the bias-correction factor.

Relation between Suspended-Sediment Concentrations and Turbidity

The relation between SSC and turbidity for the 2014 and 2015 dataset is illustrated in figure 8. The resulting SLR equation follows:

$$SSC = 1.1876 * Turb.^{0.8872} * 1.04 \tag{2}$$

where

SSC is suspended-sediment concentration, in milligrams per liter; and

$Turb.$ is turbidity, in formazin nephelometric units.

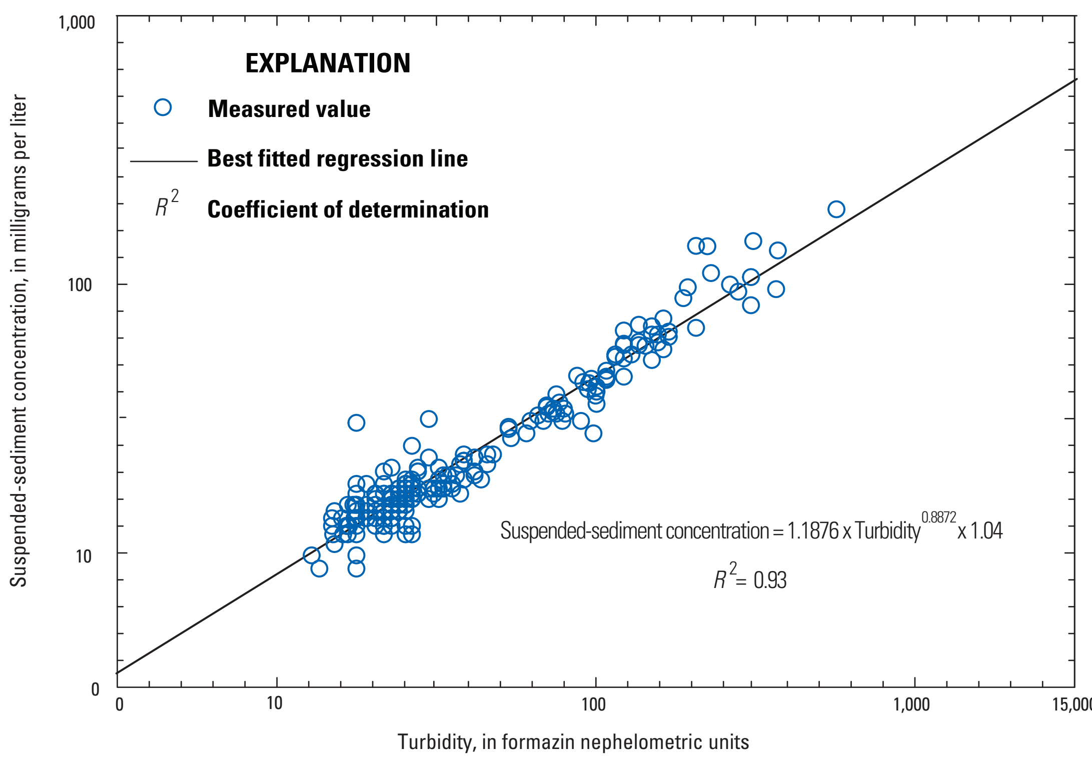

Figure 8. Relation between suspended-sediment concentration and turbidity for selected sites in the 21st Avenue West Channel Embayment, Duluth-Superior Harbor, 2014 and 2015.

The SLR equation had a p-value less than 0.01 and a coefficient of determination (R^2) of 0.93, which indicate a strong, significant relation between SSC and turbidity.

Using the SLR equation (equation 2), SSCs were predicted for approximately 3,000 turbidity values collected on 12 dates in 2015 at the sampling sites in the 21st Avenue West Channel Embayment of the Duluth-Superior Harbor (table 1–4 in appendix 1). The estimated SSCs served as input for development of 12 three-dimensional visualization maps as described in the following subsection.

Generation of Three-Dimensional Visualization Maps

A total of 12 three-dimensional visualization maps were created using three-dimensional visualization software Voxler®4 (Golden Software, LLC, 2012). Voxler®4 was used to display Universal Transverse Mercator (UTM) easting, northing, and elevation coordinates (x, y, and z dimensions, respectively) and predicted SSC values for 12 dates in 2015 (table 1–4 in appendix 1). Between 244 and 261 predicted SSC values for each of 12 dates for approximately 100 sites (fig. 7) were used to generate the three-dimensional visualization maps. One to four SSC values at various depths were assigned to each of the sites during map generation. The data collected in 2015 are referenced horizontally to the North American Datum of 1983 using UTM projection Zone 15N. During each of the 12 sampling days in 2015, 15-minute stage readings from the USGS streamgage at Superior Bay Duluth Ship Canal at Duluth, Minnesota (station 464646092052900) were averaged over each sampling day to obtain the surface-water elevation. Elevations associated with SSC values were determined by subtracting the measured sampling depths from the surface-water elevation.

A sequence of five steps was used to generate the three-dimensional visualization maps. The first step entailed using 2015 data to create a horizontal and vertical (x, y, and z) grid of the bottom of the estuary using elevation software Surfer®13 (Golden Software, LLC). The second step was to create a visual display of the elevation grid of the bottom of the estuary using Voxler®4. The third step was to overlay a georeferenced Google Earth (Google Earth, 2016) aerial photograph (image from August 2010) above the elevation grid of the estuary bottom. The fourth step entailed interpolating SSC data between the sampling sites using Voxler®4 and the inverse distance method using the following equations (Franke, 1982):

$$\hat{C}_j = \frac{\sum_{i=1}^{n} \frac{C_i}{h_{ij\beta}}}{\sum_{i=1}^{n} \frac{1}{h_{ij\beta}}} \text{, and} \tag{3}$$

$$h_{ij} = \sqrt{d_{ij}^2} + \delta^2 \tag{4}$$

where

$\hat{C}_j$ is the interpolated value for grid node j,
i is the first grid point,
n is the total number of grid points,
h_{ij} is the effective separation distance between grid node j and the neighboring point i,
C_i are the neighboring points,
d_{ij}^2 is the squared distance between grid node j and the neighboring point i,
β is the power or weighting parameter, and
δ is the smooth parameter (Franke, 1982).

The fifth and final step involved displaying the location of the dredged material placement discharge pipe and the location of the silt curtain.

Three-Dimensional Visualization Maps of Suspended-Sediment Concentrations and Limitations

The visualization maps were generated to elucidate the distribution of SSC under four conditions: (1) before placement of dredged materials (fig. 9), (2) during placement of dredged materials using four dredged-material configurations (figs. 2–5) without a silt curtain (figs. 10–14), (3) during placement of dredged materials with a silt curtain (figs. 15–18), and (4) after dredged material placements ceased (figs. 19 and 20). Three-dimensional visualization maps are valuable for assessing the spatial displacement of SSC during dredged material placement in open waters. Three-dimensional visualization maps also provide an effective tool to support the design of projects requiring placement of dredged material in open water, and such projects aid in the delisting of the lower St. Louis River Estuary from the International Joint Commission's AOC.

A limitation of the Voxler®4 software is its inability to recognize and account for the presence of physical obstructions between interpolated data points. For example, if a physical obstruction (such as a shoreline) is present between sites with predicted SSC values, then Voxler®4 will continue to interpolate SSC values through the obstruction as if it does not exist. The limitation is a concern because SSC values were interpolated and displayed for portions of the study area where a physical obstruction was present; thus, interpolated points near the shoreline and near the estuary bottom should be closely inspected to ensure obstructions are not present.

The three-dimensional visualization maps presented in this report should not be used for permitting, navigation, or other legal purposes. The USGS provides these maps as a reference and planning tool and users are cautioned to carefully consider the use of the maps before making decisions that concern personal or public safety or before the conduct of business that involves substantial monetary or operational consequences. The USGS assumes no legal liability or responsibility resulting from the use.

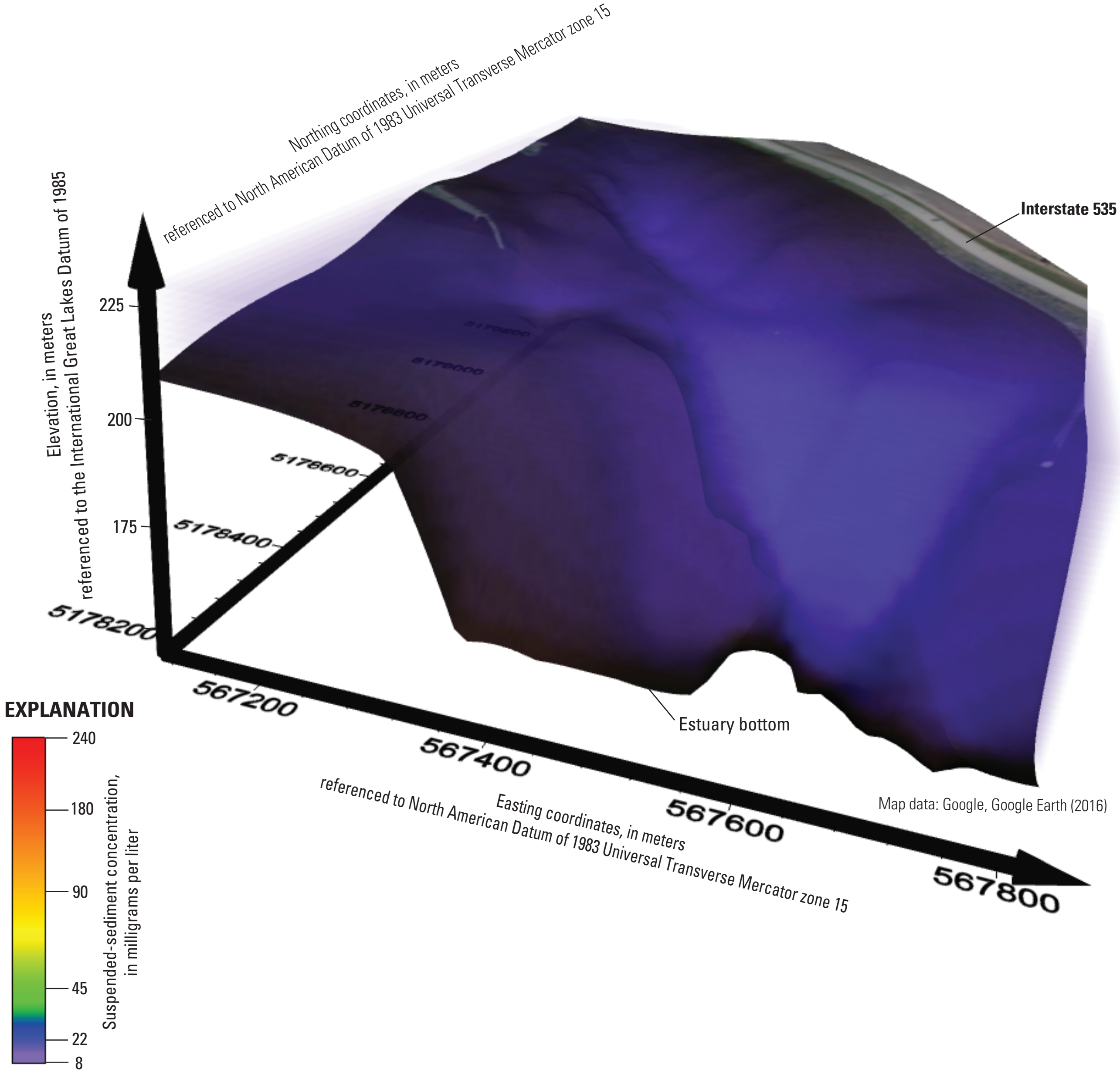

Figure 9. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on July 21, 2015, before placement of dredged materials.

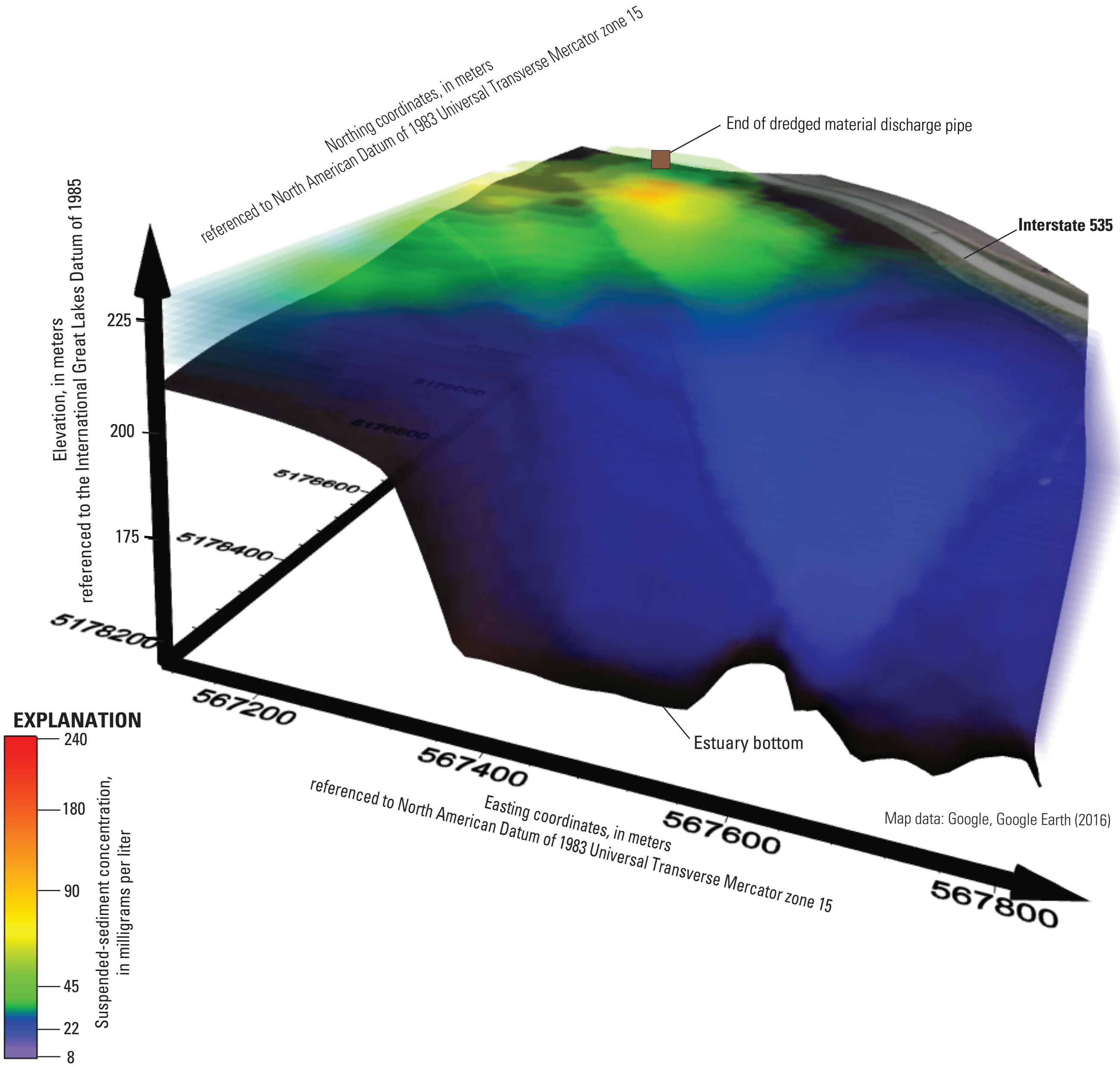

Figure 10. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on August 16, 2015, during placement of dredged materials with configuration one and without a silt curtain.

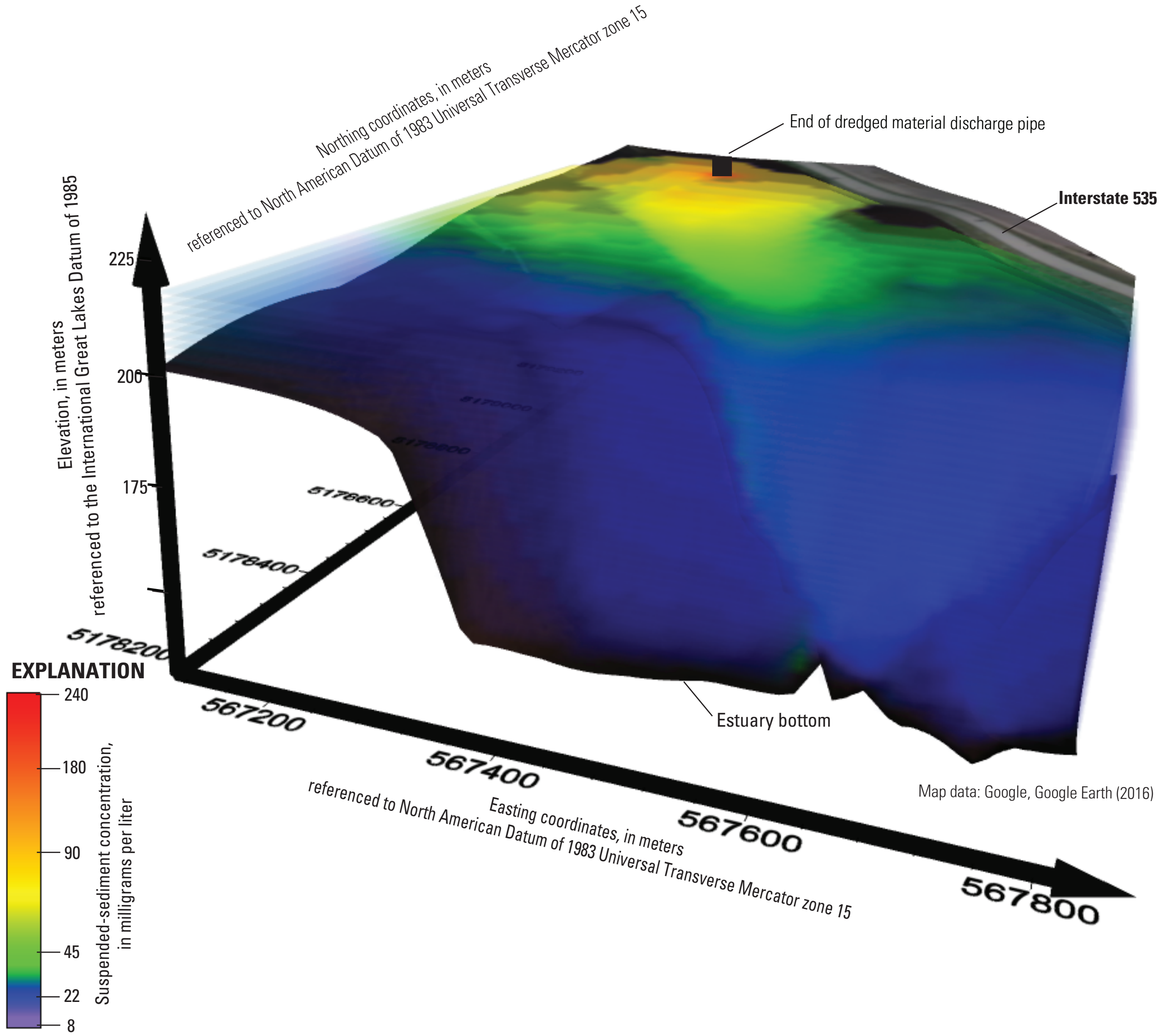

Figure 11. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on August 22, 2015, during placement of dredged materials with configuration two and without a silt curtain.

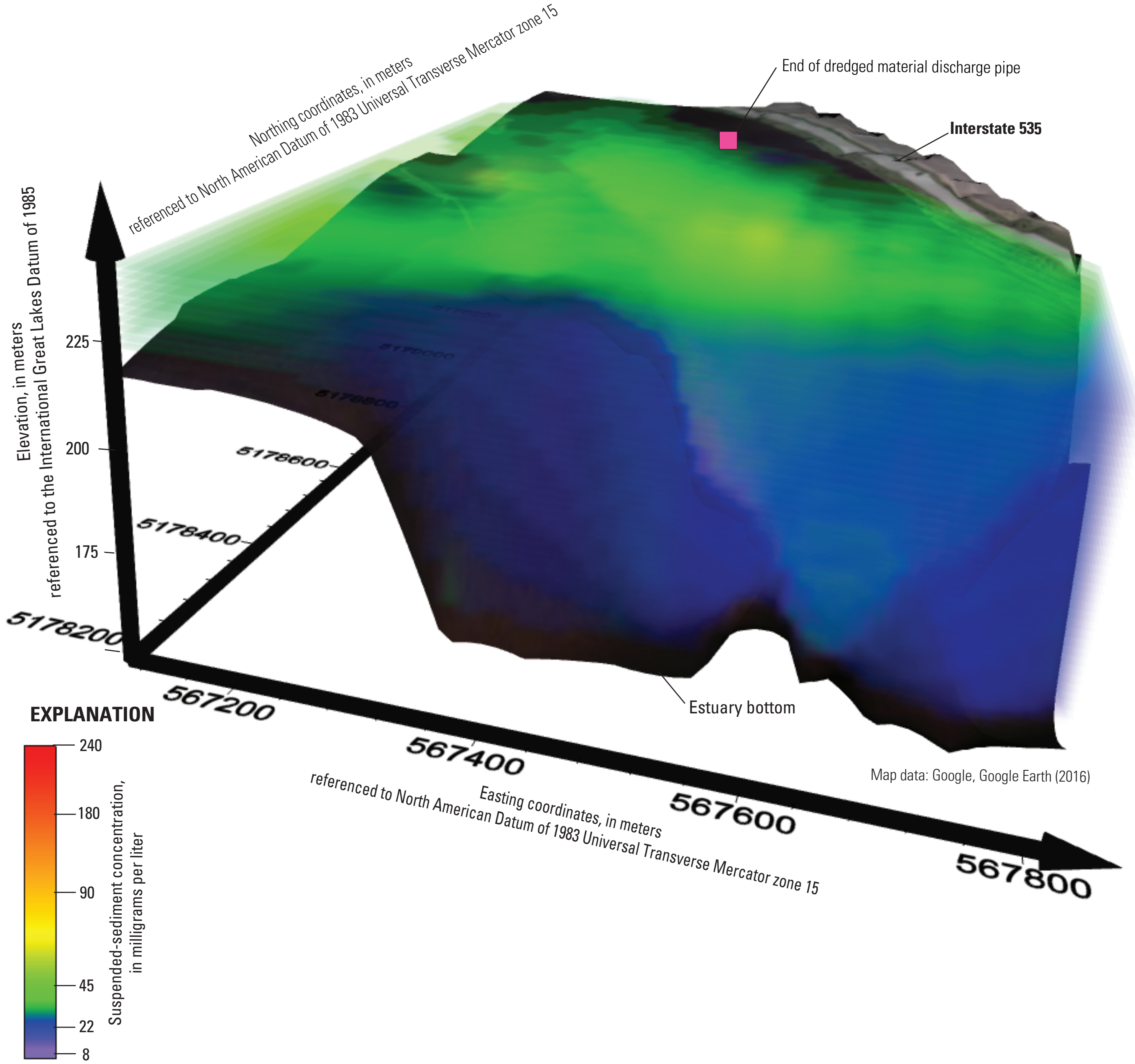

Figure 12. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on August 28, 2015, during placement of dredged materials with configuration three and without a silt curtain.

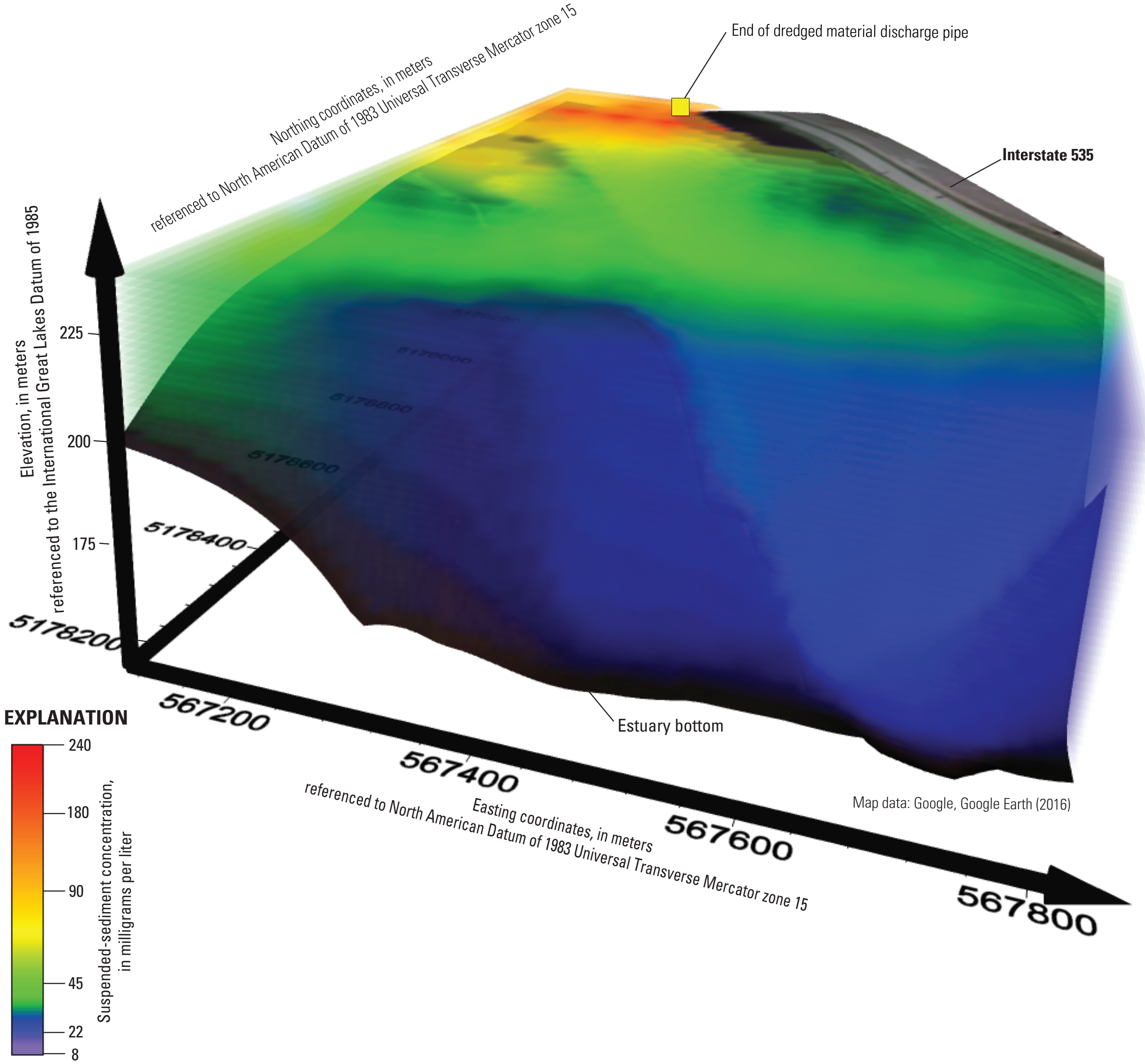

Figure 13. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on September 4, 2015, during placement of dredged materials with configuration four and without a silt curtain.

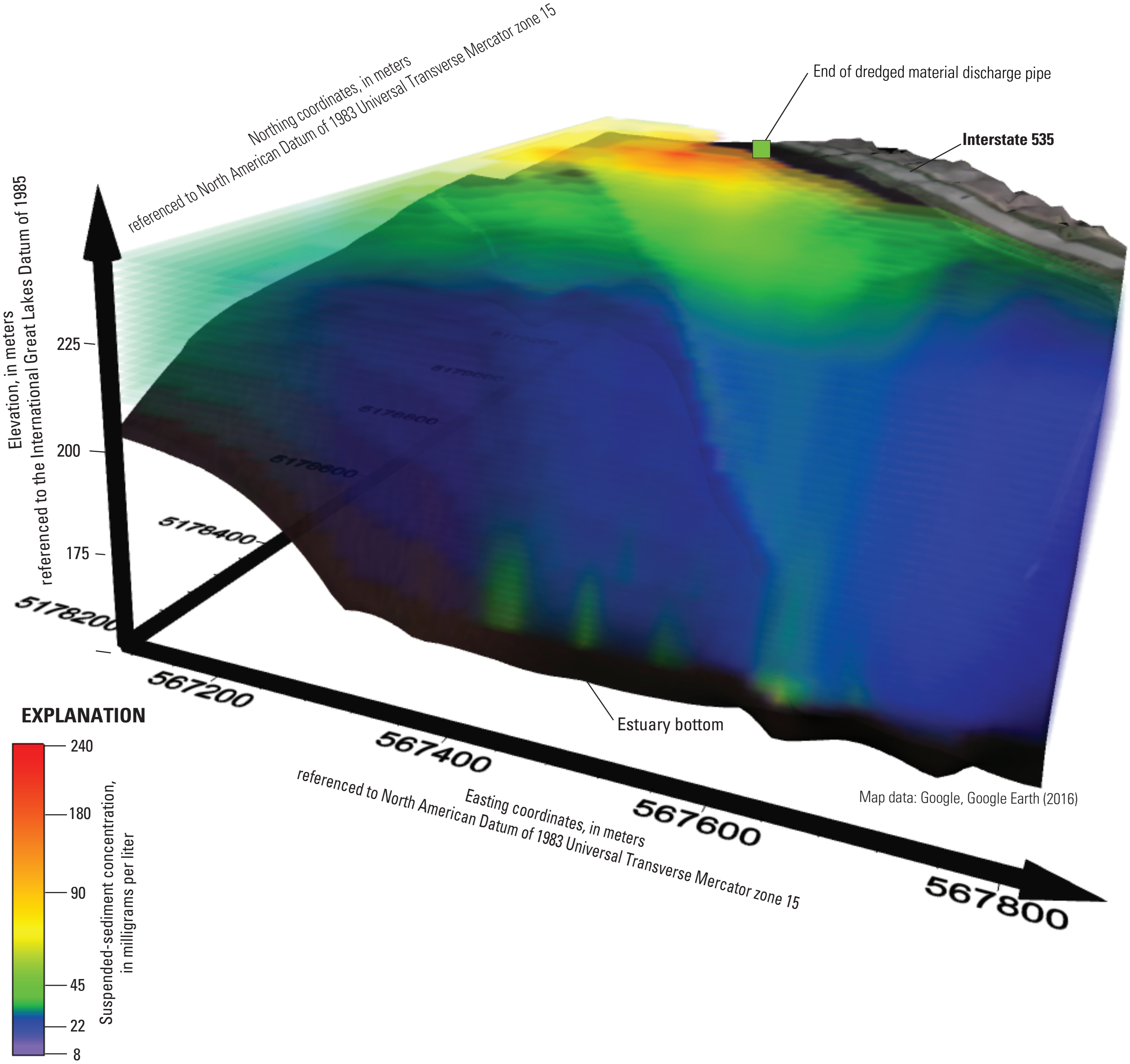

Figure 14. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on September 11, 2015, during placement of dredged materials with configuration four and without a silt curtain.

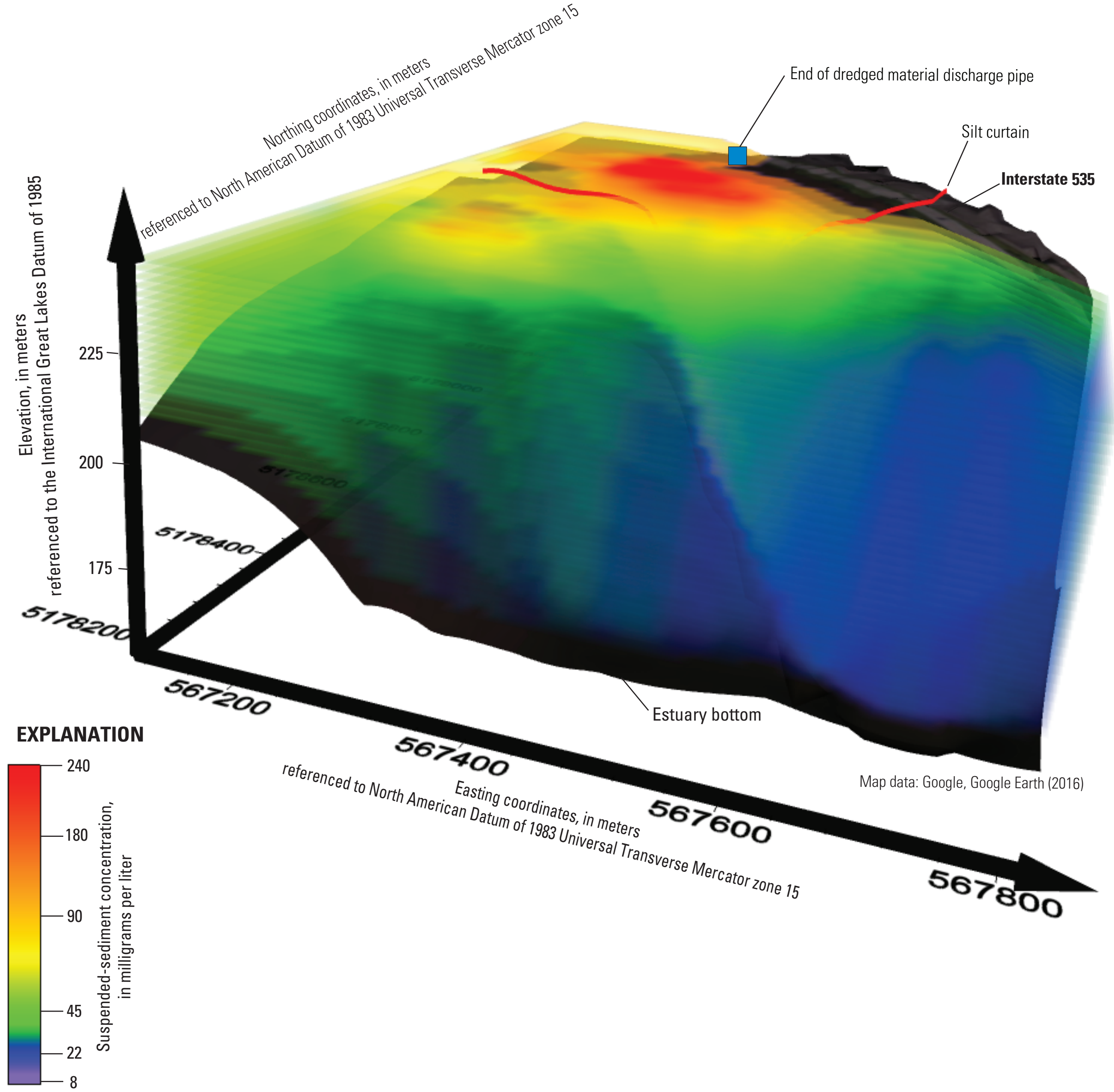

Figure 15. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on September 18, 2015, during placement of dredged materials with configuration four and with a silt curtain.

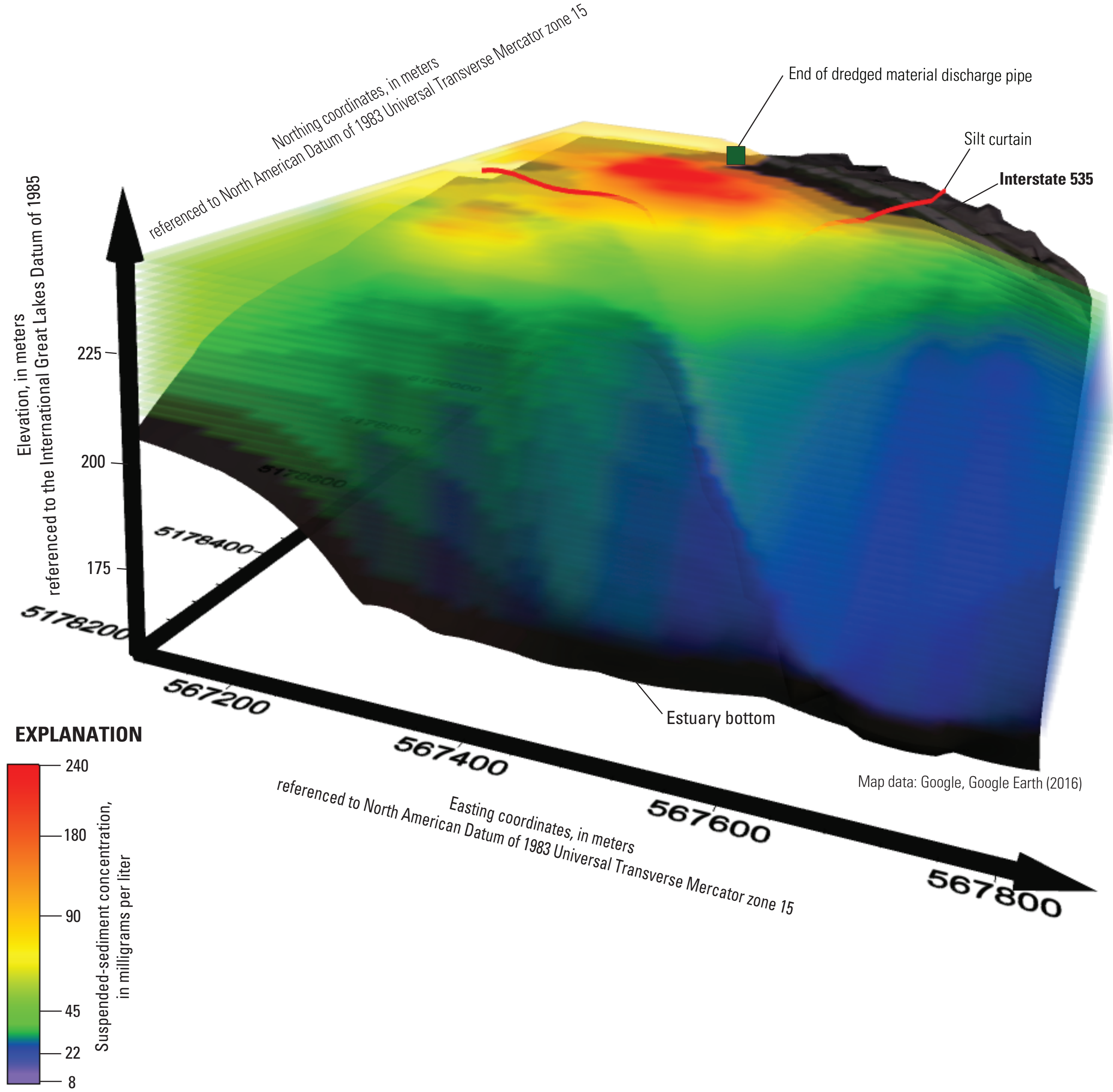

Figure 16. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on September 22, 2015, during placement of dredged materials with configuration four and with a silt curtain.

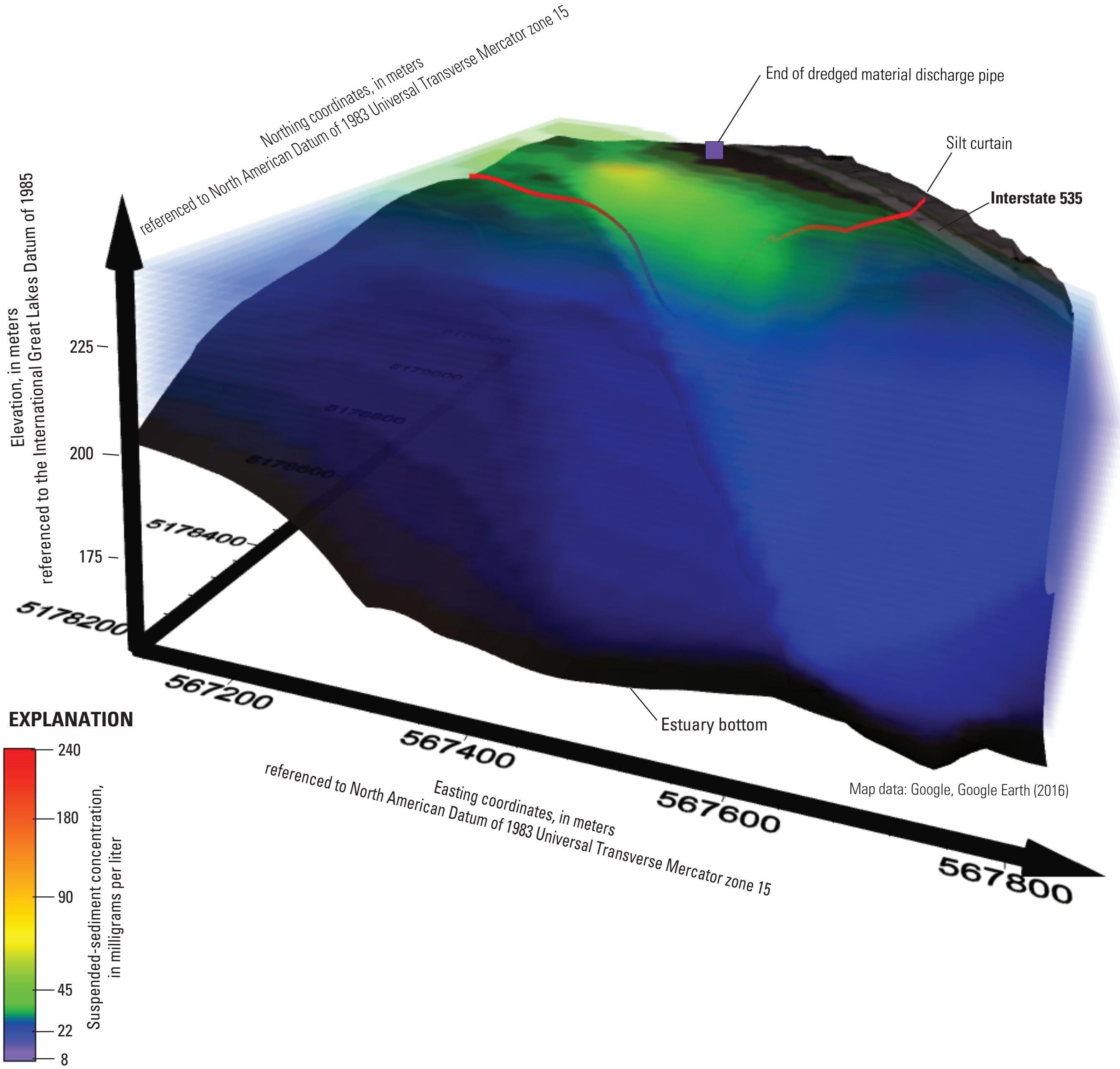

Figure 17. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on October 7, 2015, during placement of dredged materials with configuration four and with a silt curtain.

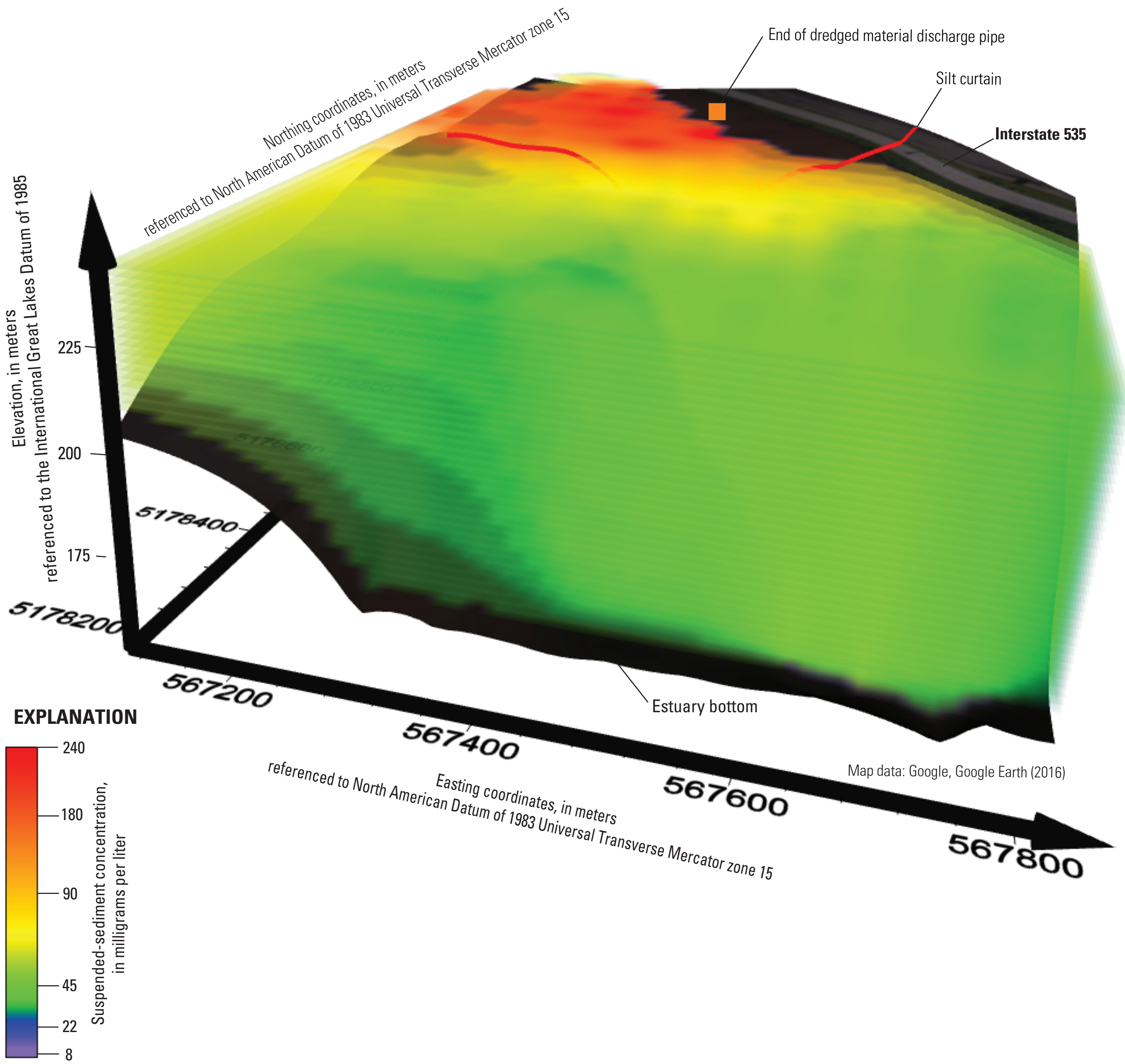

Figure 18. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on October 29, 2015, during placement of dredged materials with configuration four and with a silt curtain.

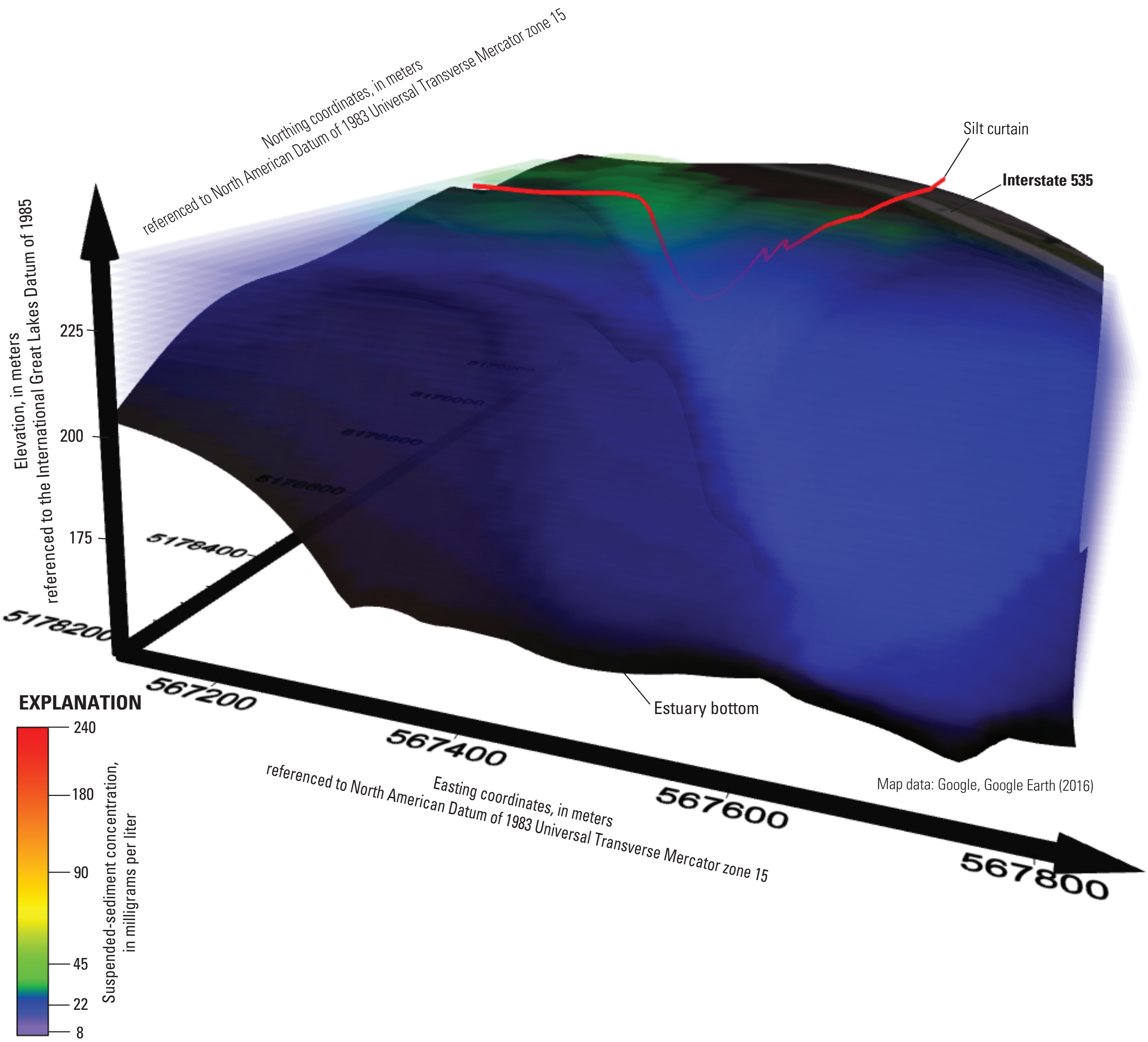

Figure 19. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on November 6, 2015, 24 hours after placement of dredged materials ceased.

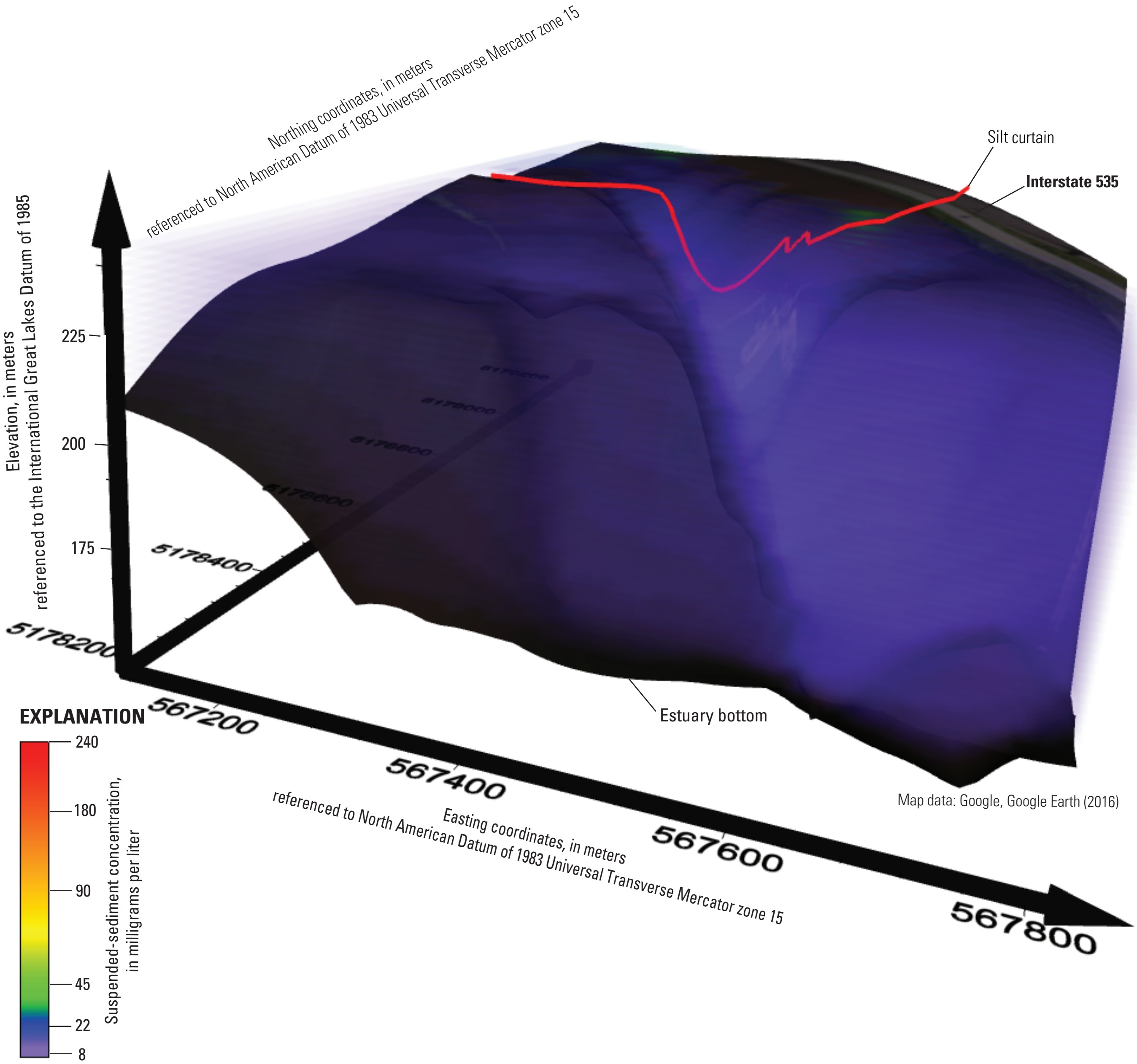

Figure 20. Three-dimensional suspended-sediment concentration map of the study area within the 21st Avenue West Channel Embayment in the Duluth-Superior Harbor on November 8, 2015, 72 hours after placement of dredged material ceased.

Summary

Excess sediment in rivers and estuaries poses serious environmental and economic challenges. The U.S. Army Corps of Engineers (USACE) routinely dredges sediment in Federal navigation channels to maintain commercial shipping operations. The 21st Avenue West Channel Embayment in the Duluth-Superior Harbor is located in the lower St. Louis River Estuary, which is listed by the International Joint Commission as an Area of Concern (AOC). In 2013, the USACE, Detroit District, initiated a 3-year pilot project to place dredged material in support of their navigation mission with the additional benefit of aiding in the restoration of shoreline habitat of the 21st Avenue West Channel Embayment. The goal of the pilot project was to determine if dredged material could be used to aid in the improvement of aquatic habitat, which will contribute to the delisting of sites from the lower St. Louis River Estuary AOC. In 2014 and 2015, the U.S. Geological Survey, in cooperation with USACE, collected suspended-sediment concentrations (SSCs) and turbidity measurements at approximately 100 selected sites with the objectives of quantifying the horizontal and vertical distribution of SSC during placement of dredged material. These data are useful for evaluating the effectiveness of various dredged material placement configurations as well as the efficacy of a silt curtain in mitigating the disbursement of suspended sediment.

Data collected in 2014 and 2015 were used to develop a simple linear regression (SLR) model between SSC and turbidity. The SLR model was used to generate an SLR equation to predict SSC at each of the sites where turbidity measurements were collected in 2015. Using the predicted SSC values, 12 three-dimensional visualization maps were generated to elucidate the distribution of SSC under four conditions: (1) before placement of dredged materials, (2) during placement of dredged materials using four dredged-material placement configurations without a silt curtain, (3) during placement of dredged materials with a silt curtain, and (4) after placement of dredged materials ceased. Three-dimensional visualization maps are valuable for assessing the spatial displacement of suspended sediment during dredged material placements and provide an effective tool to support the design of projects requiring placement of dredged material in open water; such projects aid in the delisting of the lower St. Louis River Estuary from the International Joint Commission's AOC.

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Appendix 1

A summary of sampling sites at which suspended-sediment samples were collected and turbidity values were measured during 2014 and 2015 are provided in table 1–1. Approximately 230 suspended-sediment concentrations (SSC) and corresponding turbidity values were used in simple linear regression model development. Table 1–1 is presented as a Microsoft Excel® spreadsheet (http://dx.doi.org/10.3133/sir20165086).

Table 1–1. Summary of turbidity and suspended-sediment concentrations used for calibration of the simple linear regression model for sampled sites in the 21st Avenue West Channel Embayment, Duluth-Superior Harbor, 2014 through 2015.

Results of primary and sequential replicate samples for SSC collected during 2014 and 2015 are provided in table 1–2. This table also provides the relative percent difference between the primary and sequential replicate samples. Table 1–2 is presented as a Microsoft Excel® spreadsheet (http://dx.doi.org/10.3133/sir20165086).

Table 1–2. Results of quality-assurance samples for suspended-sediment concentrations in the 21st Avenue West Channel Embayment, Duluth-Superior Harbor, 2014 through 2015.

Turbidity and SSC outliers collected during 2014 and 2015 are provided in table 1–3. Outliers were not included in the simple linear regression model development. Table 1–3 is presented as a Microsoft Excel® spreadsheet (http://dx.doi.org/10.3133/sir20165086).

Table 1–3. Turbidity and suspended-sediment concentrations outliers collected in the 21st Avenue West Channel Embayment, Duluth-Superior Harbor, 2014 through 2015.

A summary of selected sampling sites at which turbidity was measured during 2015 is provided in table 1–4. This table also provides the predicted SSC values based on measured turbidity values from 96 sites for 12 dates in 2015 that were used for generation of three-dimensional concentration maps.Table 1–4 is presented as a Microsoft Excel® spreadsheet (http://dx.doi.org/10.3133/sir20165086).

Table 1–4. Information on selected sampling sites in the 21st Avenue West Channel Embayment, Duluth-Superior Harbor, 2015, and predicted suspended-sediment concentrations for 12 dates in 2015 during which turbidity was measured.

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Groten and others—**Three-Dimensional Visualization Maps of Suspended-Sediment Concentrations during Placement of Dredged Material**—Scientific Investigations Report 2016–5086

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20165086