Stantec

**Hastings on Hudson
Hydrodynamic Study Part 2 –
Morphodynamic Modeling
Technical Report**

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Table of Contents

1.0   INTRODUCTION

The Former Anaconda Wire and Cable Company Site in the Village of Hastings-on-Hudson (Site) is located along the eastern bank of the Hudson River approximately 21 miles north and upstream of the Battery in New York City, NY, and 5 miles downstream of the Tappan Zee Bridge. The Site encompasses approximately 28 acres and has a history of industrial development dating back to the mid-1800s. Proposed remediation efforts extend into the Hudson River and include sediment dredging and backfill (no net fill), isolation capping (no net fill), installation of a containment bulkhead with backfill behind that bulkhead (net "taking" of approximately 0.83 acres). Relevant remediation efforts adjacent to the river include excavation and backfill, installation of a sloped shoreline, and construction of a compensatory habitat mitigation feature. These planned remediation efforts are detailed in the Preliminary Design Report dated November 29, 2017 (Arcadis) and are represented as the design conditions in this report.

Stantec was commissioned to assess the hydrodynamic and morphodynamic responses to proposed post-remediation conditions. This report summarizes the results of the study, which was carried out in two phases. The first phase was a hydrodynamic study and the second phase was a morphodynamic study.

During Phase I, a fine resolution local hydrodynamic model at the Site (HOH model) nested within a coarse resolution regional hydrodynamic model of the Lower Hudson River (LHR model) was developed using Delft3D. Delft3D is a modelling suite for hydrodynamics, sediment transport, and morphology developed at TU Delft, the Netherlands. The LHR model extends from the Battery upriver to Green Island (250 kilometers from the Battery), which is driven by an hourly time series of water levels at the Battery as the downstream boundary condition and daily time series of discharge at the Green Island as the upstream boundary condition. The hydrodynamics of the LHR model were validated against field observations at several stations along the Hudson River for select time periods in 2005 and 2011. The nested HOH model was verified to yield the same results as the LHR model. For the details of the hydrodynamic model and its validation, please see the report titled *Hastings on Hudson Hydrodynamic Study Part I – Model Setup & Calibration, Stantec, February 19, 2016*, hereafter referred to as the Phase I Report.

The purpose of the Phase II study was to extend the hydrodynamic model developed in Phase I in order to model sediment transport and morphodynamics, and to compare the morphological response (changes in erosion and deposition) in the post-remediation (design) conditions to the pre-remediation (existing) conditions at the Site. Another objective was to predict the time it would take for one foot of natural deposition to occur in the project area, specifically within the remediation dredging areas. This report summarizes the development and validation of the sediment transport and morphodynamic components of the HOH model, and assesses the hydrodynamic and morphodynamic response to the design conditions.

2.0   SITE CONDITIONS

2.1   SEDIMENT TYPE

The most comprehensive sediment environment dataset of the Hudson River is available from the Hudson River Benthic Mapping Project (Nitsche et al. 2005; Bell et al. 2006), which consists of high-resolution multibeam bathymetry, sidescan sonar, and sub-bottom data, as well as over 400 sediment cores and 600 grab samples. Based on these data, Nitsche et al. (2007) described the distribution of sediment types and process-related sedimentary environments for the entire Hudson River estuary. The sediment types at the Site are shown in Figure 1.. The sediments are predominantly mud and sandy mud with some gravel and gravelly sand in the channel. The geotechnical analysis reported by TerraSense, LLC in the Preliminary Design Report – Attachment D also shows mud near the Site. Sediment types in these references are categorized by the percentage of the underlying sediment components (sand, silt, gravel, etc.). For example, based on Nitsche et al. (2007), areas with mud contain less than 10% sand and more than 90% silt. Select physical properties of these underlying sediment components as described by Ralston et al. (2012) are listed in Table 1. Sediment data from Nitsche et al. (2007) and site geotechnical data from TerraSense, LLC were used to parameterize the morphodynamic model.

Table 1: Physical Properties of Sediment Types (Ralston et al. 2012)

Sediment Class	Settling Velocity (mm/s)	Erosion Rate (kg/m^2/s)	Critical Stress for Erosion (N/m^2)
Medium sand (bed)	40.0	1×10^{-4}	0.5
Fine sand (bed)	5.0	1×10^{-4}	0.1
Silt (bed)	0.6	1×10^{-4}	0.05
Silt (River)*	0.1,0.6	1×10^{-3}, 1×10^{-4}	0.05

*Properties where salinity < 0.5 psu (practical salinity units). Sediment from the river has a slower settling velocity and higher erosion rate in fresh water to represent non-flocculated particles, and it has properties equal to the silt fraction of the bed where salinity > 0.5 psu
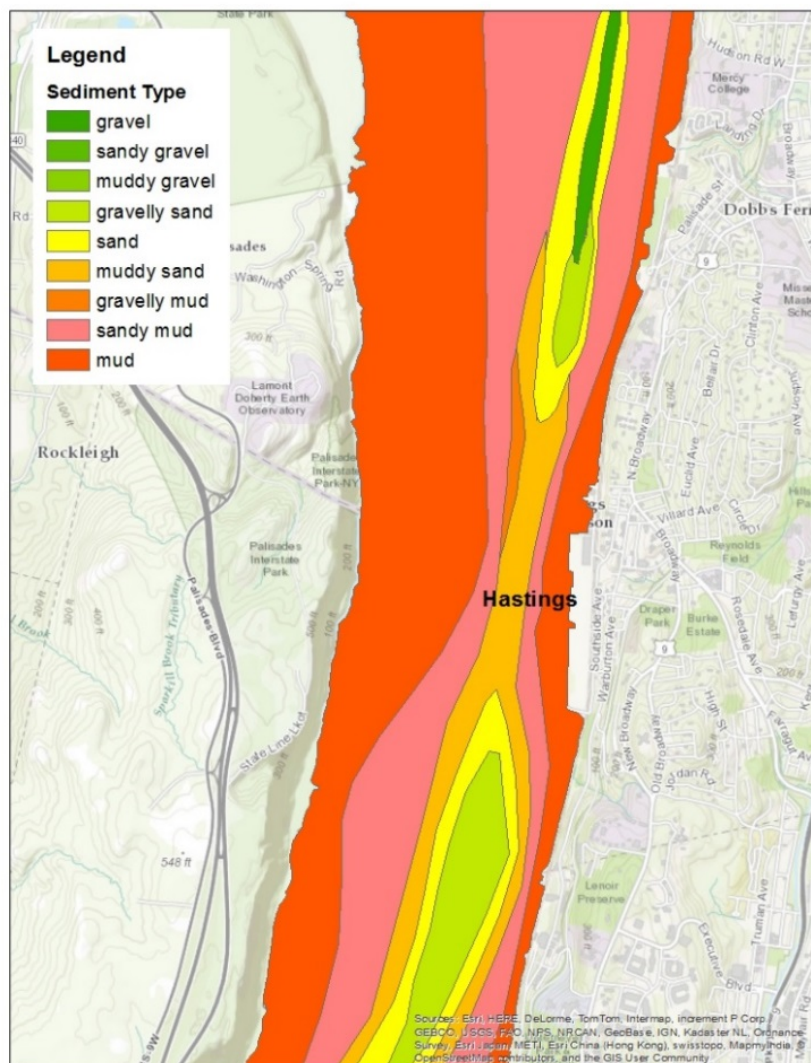
Figure 1. Sediment types at the Site (Nitsche et al. 2007)

2.2 SUSPENDED SEDIMENT CONCENTRATION

There is a relative sparsity of available suspended sediment concentration (SSC) data near the Site; therefore, the investigation of the SSC relied on literature reviews. Ralston and Geyer (2009) presented a tidally averaged model of estuarine dynamics for the estimation of sediment transport in the Hudson River estuary. The Site is at approximate river mile 21, very close to the 21.7 miles location. Figure 2. shows the multiple year (1999-2002) SSC time series at locations that are 13.7 miles and 21.7 miles upstream from the Battery, which are partially validated against the field observations, which are shown in colored dash line. The monthly trend of the SSC is characterized by a lower peak and higher peak, corresponding to neap and spring tide, respectively. The seasonal trend at this sample location is characterized by a

parabolic shape with lower SSC during summer and higher SSC in Spring and late Fall, which corresponds to the seasonal variation of upstream freshwater discharge (i.e., lower fresh water volume during summer and higher volume during spring and fall). The intra-annual pattern is consistent among the 4-year time series, substantiating that this data is appropriate to be used to validate the HOH model.
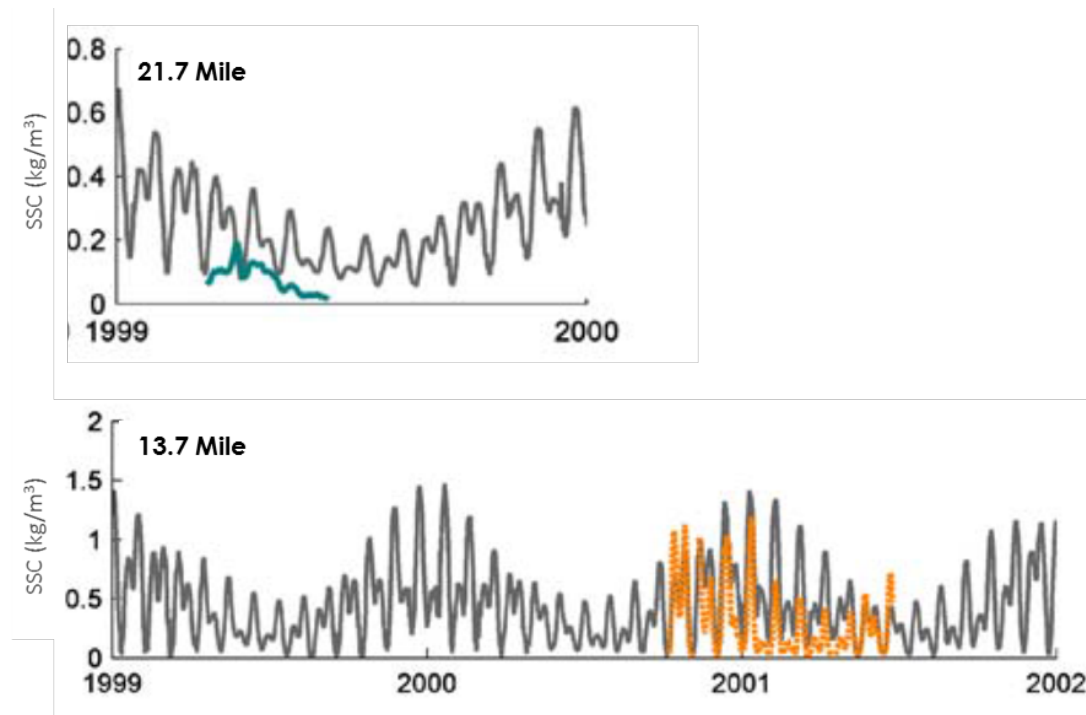
Figure 2. Suspended sediment concentration (SSC) in kg/m3 at river mileage 21.7 (top) and 13.7 (bottom) from the Battery (cited from Ralston et al. 2009). Grey line indicates model results while colored dashed line indicates observation from acoustic backscatter profiles

2.3   SEDIMENTARY ENVIRONMENT

Nitsche et al. (2007) also presented the sedimentary environment of the lower Hudson River, which is shown in Figure 3. for the area near the Site. Deposition has generally occurred at the shoal areas along both banks, while erosion has occurred from the shoal towards the center of the river. Some areas in the center of the river are dynamically balanced (both erosion and deposition are occurring). This corresponds to: 1) the predominant sand and gravel sediment types which, given the hydrodynamics, are barely erodible, and 2) the presence of fine particles constantly in motion (Figure 1.).
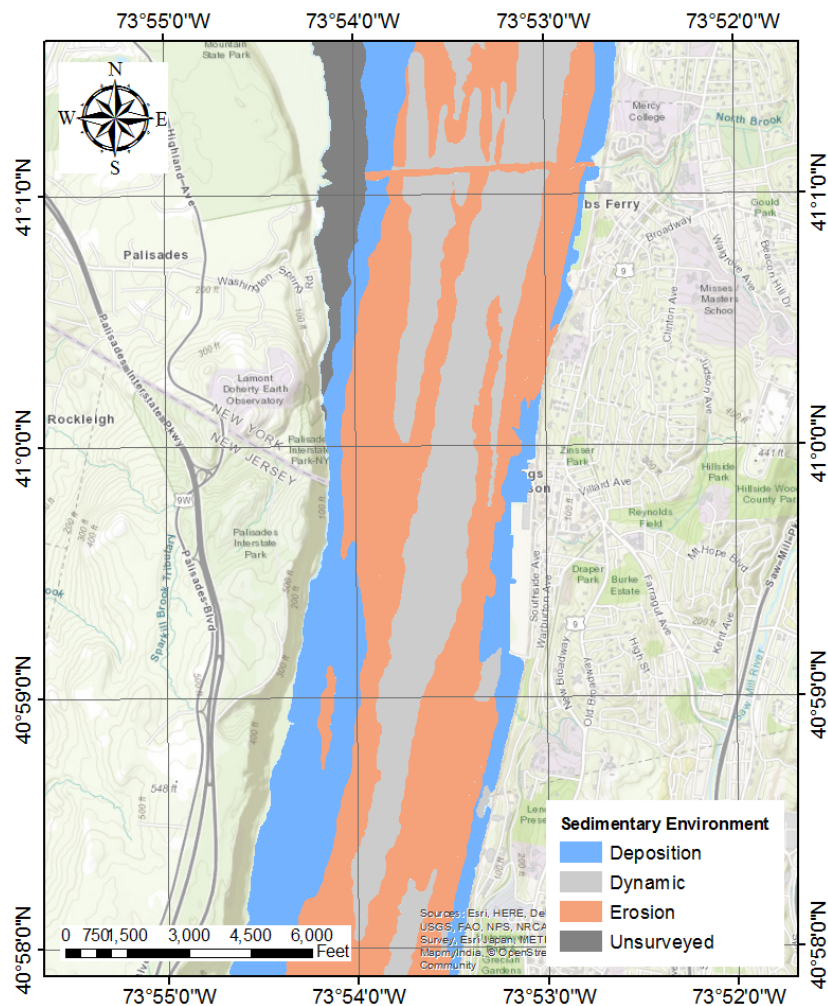
Figure 3. Sedimentary Environment at the Site (Nitsche et al. 2007)

3.0   DEVELOPMENT OF MORPHODYNAMIC MODEL

3.1   MESH REFINEMENT

Each mesh cell in a numerical model represents a computational node where hydrodynamic and sediment characteristics are calculated. The HOH mesh was further refined during the development of the morphodynamic model to provide greater resolution in the project area, including but not limited to the proposed bulkhead and the proposed remediation dredging areas, as shown in Figure 4.. The mesh captures those planned ("design") features at a minimal resolution of 10 meters (m).
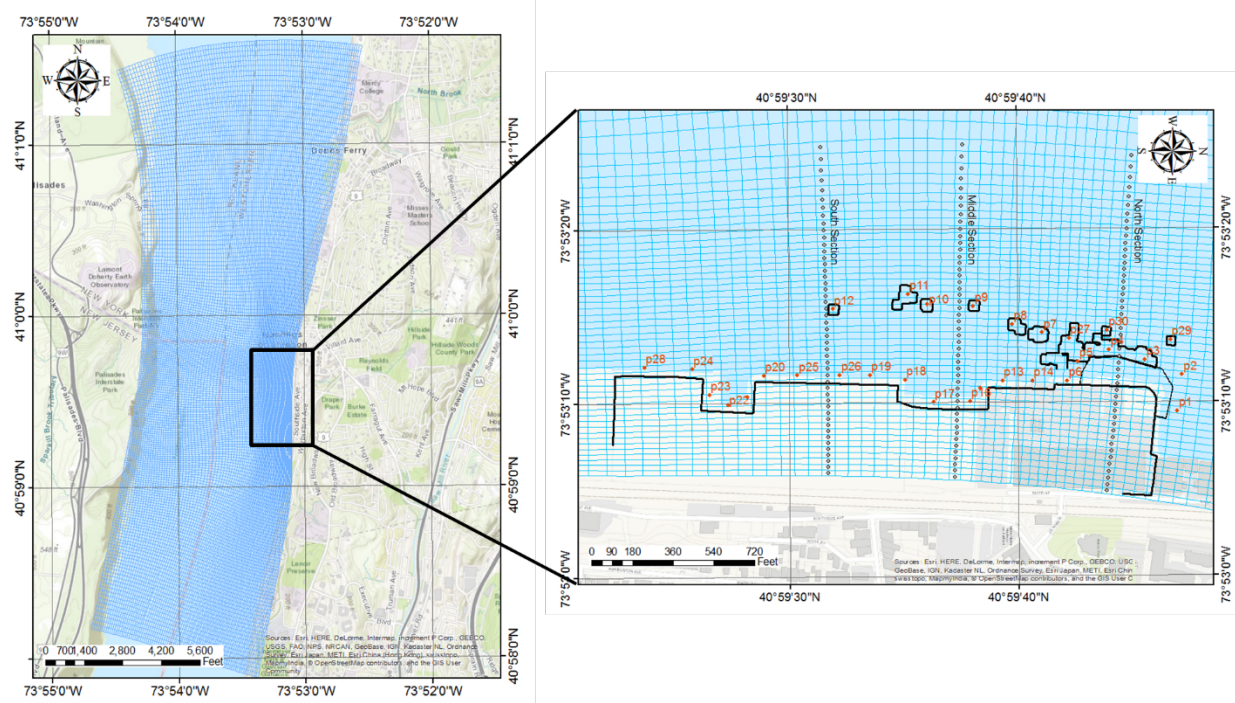
Figure 4. Refined computational mesh for HOH model

3.2 PARAMETERS

Existing substrate at the Site along the shorelines is composed of mud or sandy mud; the predominant sediment types directly adjacent to and within the channel are gravelly sand and gravel. As mentioned in Section 2.1, mud is defined as less than 10% sand and sandy mud is defined as greater than 10% sand. Due to the small fraction of sand and uncertainty of the precise percentage, this study primarily focused on mud, where the fraction of sand contained in the bed material was accounted for by using spatially varying critical shear stress. A limitation of this approach is that the result may be less accurate if the fraction of sand increases dramatically within the time period of interest, which in turn may impact the value of the critical shear stress. This is not expected to be a concern for this study, as any changes in shear stress are likely to be small, based on the small fraction of sand in the mud at the Site.

Based on the sediment environment, the HOH model was initialized to represent the existing condition with only mud available at areas with mud and sandy mud. According to the parameters used in Ralston et al. (2012) as listed in Table 2, a constant settling velocity W_s of 0.6 mm/s was assumed, since the salinity within the HOH model domain is always greater than 0.5 practical salinity units (psu). A spatially uniform erosion rate $M_{Delft3D}$ of 0.5×10^{-4} kg/m²/s was used, which accounts for the difference in definition of erosion rate between Delft3D and Ralston et al. (2012), i.e.,

$$M_{Delft3D} = M_{Ralston}(1-n),$$

where n is the porosity. The spatially varying critical shear stress for erosion and deposition accounting for different fractions of sand at the different areas was used. The base value corresponds well to the value used in Ralston and Geyer (2009), where the critical velocity for erosion is 0.5 m/s. Table 2. summarizes the sediment parameters used in the study.

Table 2. Range of Sediment Parameter Values in the HOH Model

Parameters	Range of Values
Settling velocity	0.6 mm/s
Erosion rate	0.5×10^{-4} kg/m²/s
Critical shear stress for erosion	$0.15 - 0.18$ N/m²
Critical shear stress for deposition	$0.07 - 0.09$ N/m²

3.3   BOUNDARY CONDITIONS

As described in the Phase I report, the HOH model is driven by times series of water levels and velocities at the downstream and upstream boundaries, respectively, which are obtained from the regional LHR model. Boundary conditions for the entire year of 2011 were generated using the LHR model for two reasons: 1) hydrodynamics (water level and current) of the LHR model were validated at several stations along the Hudson River, including one station near the Site where high quality data are available; and 2) annual time series of SSC can be produced to verify the monthly and seasonal trends and the magnitude of the SCC against the study by Ralston and Geyer (2009).

3.4   MODEL VALIDATION

In the absence of direct field observations of the SSC or quantitative morphological change at the Site, the study of long-term sediment transport in the lower Hudson River estuary by Ralston and Geyer (2009) was used for model verification. They presented long-term time series of SSC at several locations along the Hudson River that are partially validated against short periods of field observations. Subsequently, Ralston et al. (2012) performed a more comprehensive numerical study of sediment transport and morphological changes in the entire lower Hudson River and demonstrated the morphological change of

the lower Hudson River at the tidal timescale. These two studies provided valuable information to verify the HOH model qualitatively and quantitatively.

Similar to Ralston and Geyer (2009), hourly time series of SSC generated by the HOH model for the entire year of 2011 was plotted in Figure 5., which shows that the HOH model captured both the monthly and seasonal variations of SSC as described in Section 2.2. One discrepancy between the two models is that the envelope of the peak SSC variations presented in Ralston and Geyer (2009) shows a smooth parabolic shape, whereas that same trend is not as smooth in the HOH model. The smooth parabolic shape in Ralston and Geyer is likely due to the use of a tidal and cross-sectional average model in that model, which failed to capture the detailed variations. The trend shown in Figure 2. from field observations supports the less smooth trend in the HOH model. Quantitatively, the magnitude of the SSC in 2011 predicted by the HOH model in terms of peak envelope ranged from 0.24 to 0.51 kg/m^3, whereas that presented in Ralston and Geyer (2009) for 1999 at a station about 2 kilometers upstream from the site, as shown in Figure 2, ranged from 0.23 to 0.70 kg/m^3.
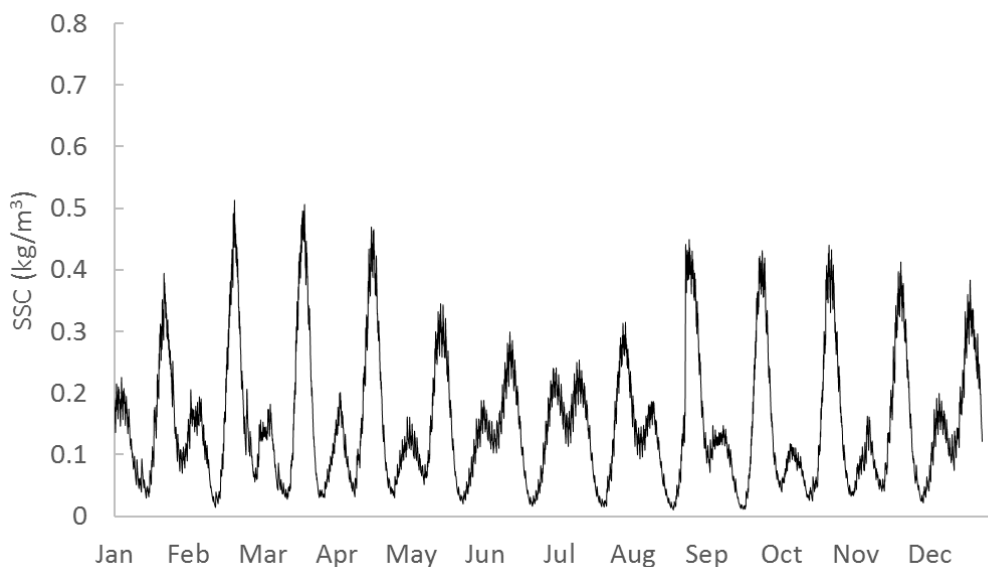
Figure 5. Time series of SSC at the Site from the HOH model (2011)

Figure 6. shows the erosion and deposition patterns after a 1-year model simulation under existing conditions. The blue or cool colors signify deposition and the red or warm colors signify erosion. The sedimentary environment described in Nistche et al. 2007, based on field observations, are indicated by the solid blue lines and text labels. The shoreline and planned / design remediation dredge areas are shown as black lines for reference.

As seen in FigureFigure 6., the model predicts deposition along the river bank to a distance of approximately 400 feet from the shoreline, with areas farther than 400 feet from the shoreline experiencing erosion. This is generally qualitatively consistent with the sedimentary environment

observed in the field as described by Nitsche et al. (2007). Particularly, the transition areas from erosion to deposition (as indicated by light colors) match well with the boundary (solid blue line) between erosion and deposition zones presented in Nitsche. Ralston et al. 2012 also showed that in the lower Hudson River estuary, the channel is generally erosional, and the shallow areas along the river bank are depositional. Quantitively, the overall maximum sedimentation predicted by Ralston et al. 2012 ranges from 0.2 mm (Haverstraw) to 0.4 mm (George Washington Bridge) at the tidal timescale, which equates to 2.3 to 4.6 feet annually based on a simple linear extrapolation. The overall maximum annual deposition predicted by the HOH model is about 2.6 feet, consistent with Ralston.

In general, the model produces results that are consistent with field observation and previous studies.
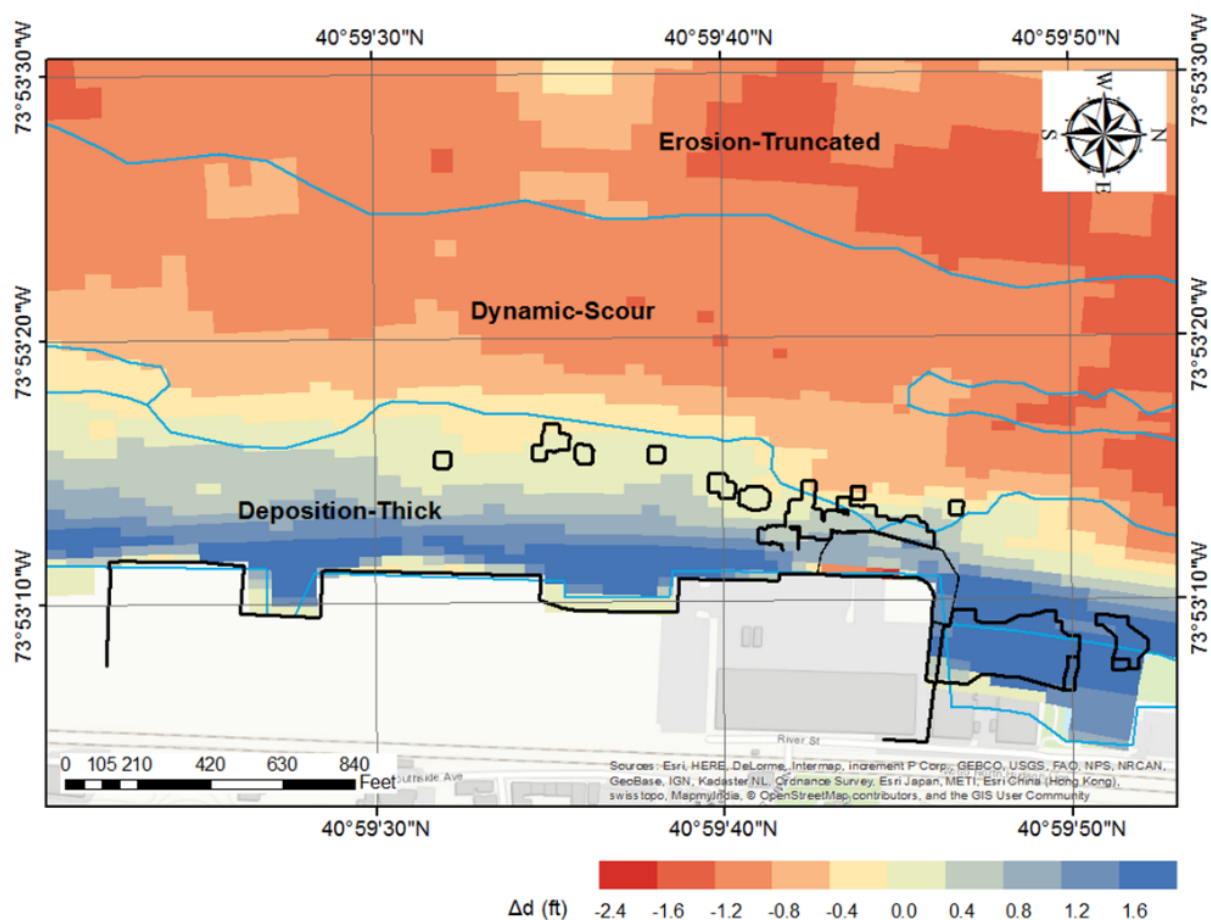
Figure 6. Erosion and deposition pattern after 1-year simulation under existing conditions by HOH model. Sedimentary environment from Nistche et al. 2001 indicated by blue lines and text.

4.0 DESIGN VERSUS EXISTING CONDITIONS

To assess the hydrodynamic and morphodynamic responses to the design conditions, the verified HOH model was applied to the design conditions. The bathymetric grid was developed to reflect the design conditions, which include: the sloped shoreline; the bulkhead alignment with the proposed crest elevations; and the planned remediation dredge areas, assuming backfill to one foot below the existing grades. A thin dam was also used for the bulkhead alignment to model the vertical bulkhead to which flow can only move parallelly. All model parameters were kept the same as the existing conditions. Similar to the model runs for existing conditions described above, a 1-year simulation under design conditions was performed, and the results were compared with existing conditions. The results and comparisons are provided in Section 4.1, which considers shear stresses, and in Section 4.2, which considers erosion and deposition patterns.
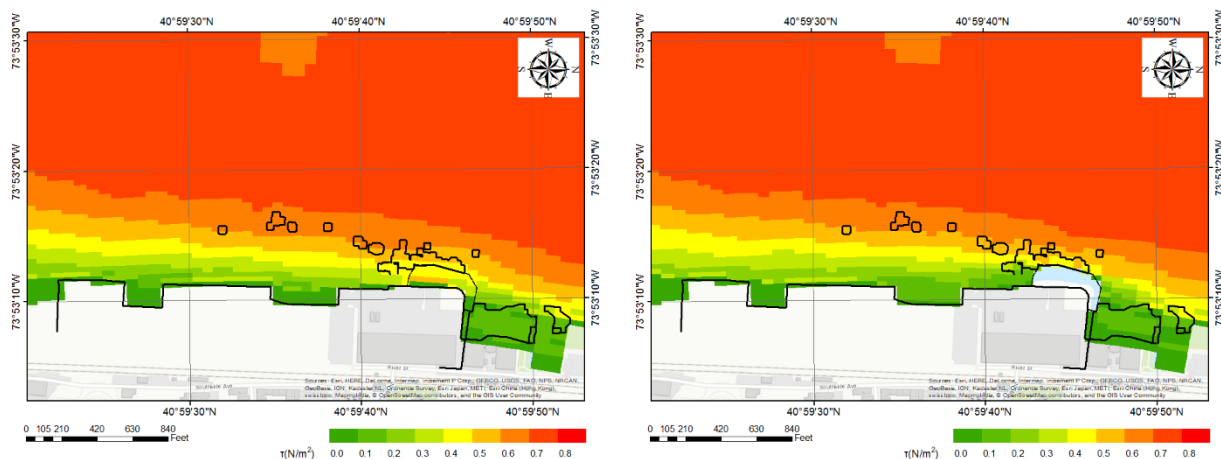
4.1 SHEAR STRESSES

Shear stresses at design and existing conditions were compared. The maximum shear stresses at ebb tide (when flow goes downstream to the south) under the existing and design conditions are shown in Figure 7.; the difference between the two is shown in Figure 8.. As shown in the figures, the overall change is small except for immediately adjacent to the south edge of the bulk alignment, where the maximum shear stress is reduced from roughly 0.4 N/m^2 to 0.1 N/m^2. Similarly, the maximum shear stresses at flood tide (when flow goes upstream to the north) under the existing and design conditions are shown in Figure 9; the difference between the two is shown in Figure 10. During flood tide, the bulkhead reduces flow primarily near the north edge of the bulkhead alignment, therefore the shear stresses are reduced roughly from 0.3 N/m^2 to 0.1 N/m^2. This change is likely due to the physical obtrusion of the proposed bulkhead which reduces the flow downstream and upstream (i.e., north during flood tide and south during ebb tide). Smaller changes along the sloped shoreline and boat slips were also observed, which correspond to the planned changes in bathymetry in these areas under design conditions, i.e., current deposits will be removed in these areas, lowering the elevation.

As a response to the change of shear stresses, most changes in erosion and deposition patterns compared to the existing conditions are likely to occur in areas immediately adjacent to the bulkhead.

Figure 7. Maximum shear stress at ebb tide under the existing (left) and design (right) conditions
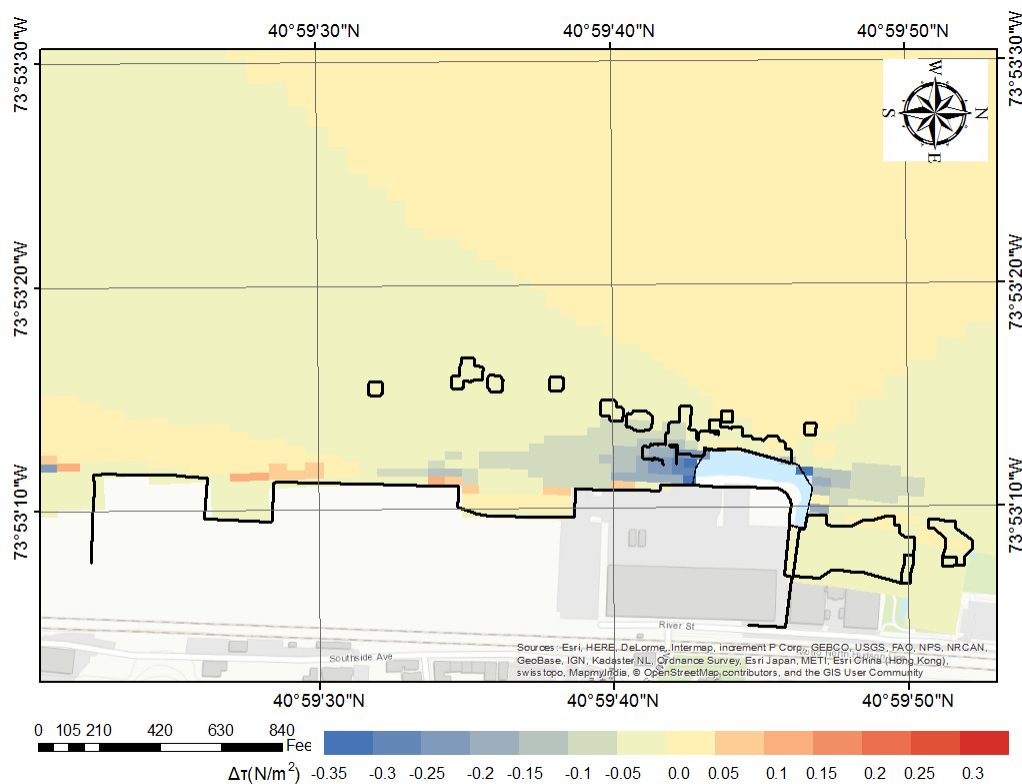
Figure 8. Difference in maximum shear stress at ebb tide between the existing and design conditions
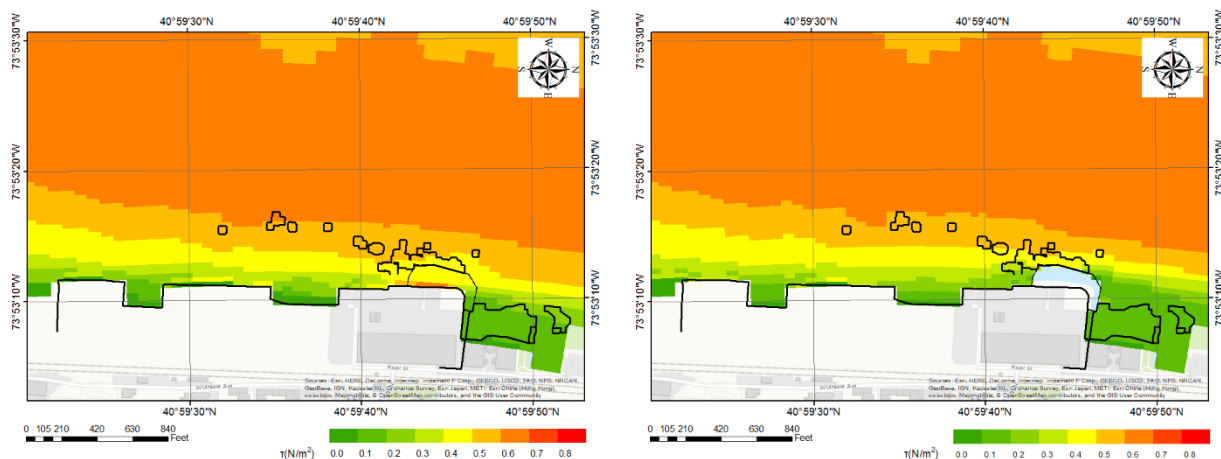
Figure 9. Maximum shear stress at flood tide under the existing (left) and design (right) conditions
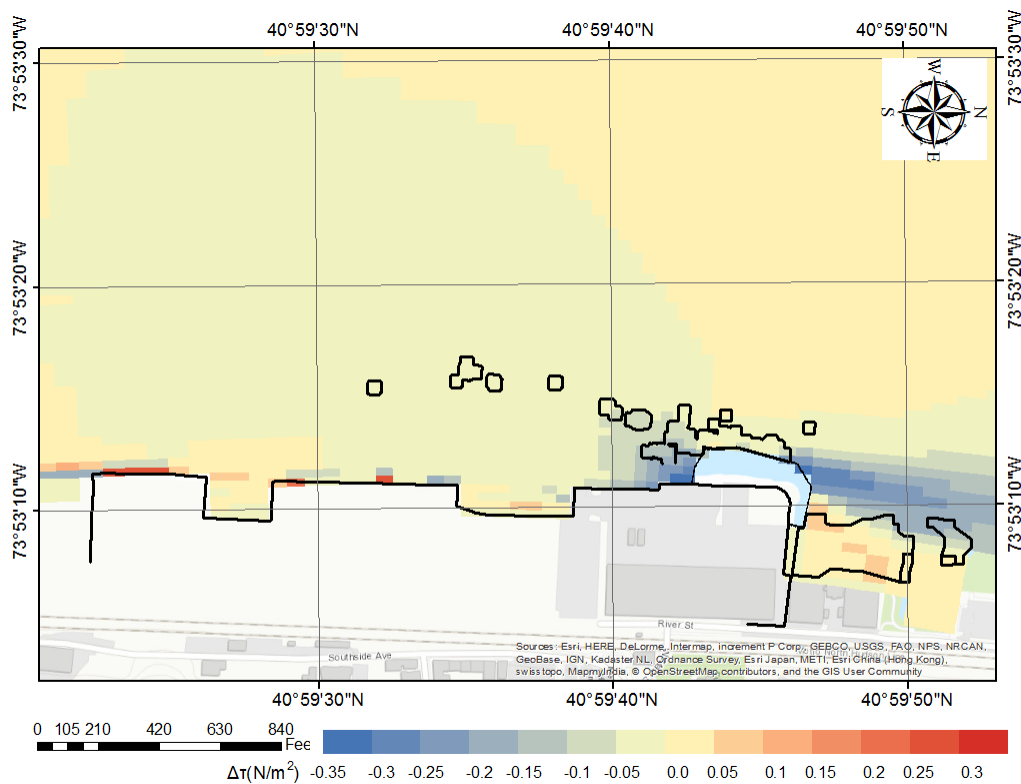
Figure 10. Difference in maximum shear stress at flood tide between the existing and design conditions

4.2   EROSION AND DEPOSITION PATTERNS

The erosion and deposition patterns under the existing and design conditions are shown in Figure 11 and the difference between the two is shown in Figure 12. The change in erosion and deposition patterns were generally limited to directly south and north of the proposed bulkhead, where shear stresses are reduced as described in Section 4.1. This change is likely due to the physical obtrusion of the proposed bulkhead which reduces the flow downstream and upstream (i.e., north during flood tide and south during ebb tide).

There is a slight increase of erosion or decrease of deposition just in front of the bulkhead to the west, due to slightly contracted flow caused by the bulkhead. Smaller changes along the sloped shoreline and boat slips were also observed with increased deposition, which correspond to the planned changes in bathymetry in these areas under design conditions, i.e., current deposits will be removed in these areas, lowering the elevation.

A key objective of this modeling effort was to investigate the time required for one foot of deposition to occur naturally in the project area, particularly in the remediation dredging areas. Table 3Table 3 summarizes the predicted deposition in feet after 1-year of simulation along with the extrapolated time for one foot of deposition to occur in the remediation dredging areas. The dredging areas are shown in the accompanying figure. The depth and time estimates are bracketed by values of +/- 30%, reflecting the potential uncertainty of these values, with respect to change in rate of bathymetry change. The model predicts that in most areas one foot of deposition will occur in less than two years. It also predicts that one foot of deposition will occur in less than one year in Old Marina and Kinnally Cove. This time period is considered reasonable in the context of the OU-2 ROD, which allows for natural deposition of the last foot of sediment within dredging areas meeting this condition. Northwest deepwater areas near the bulkhead and areas in deeper water may require a longer time for one foot of deposition to occur and will generally be experiencing erosional forces, particularly those further away from the shoreline. It should be noted that those erosional forces currently exist and would be only increased slightly by the presence of the bulkhead.
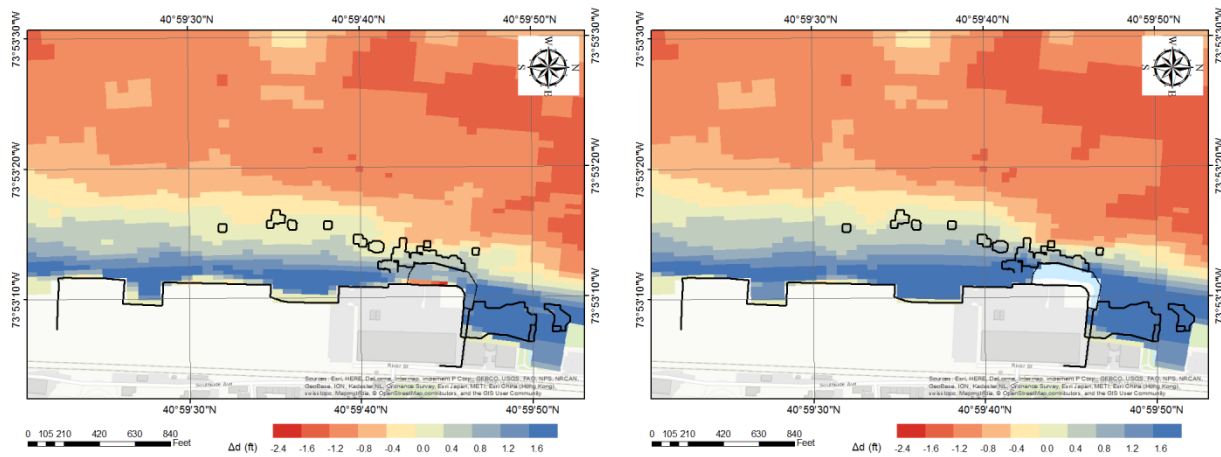
**Figure 11. Erosion and deposition patterns under the existing (left) and design (right)
conditions**
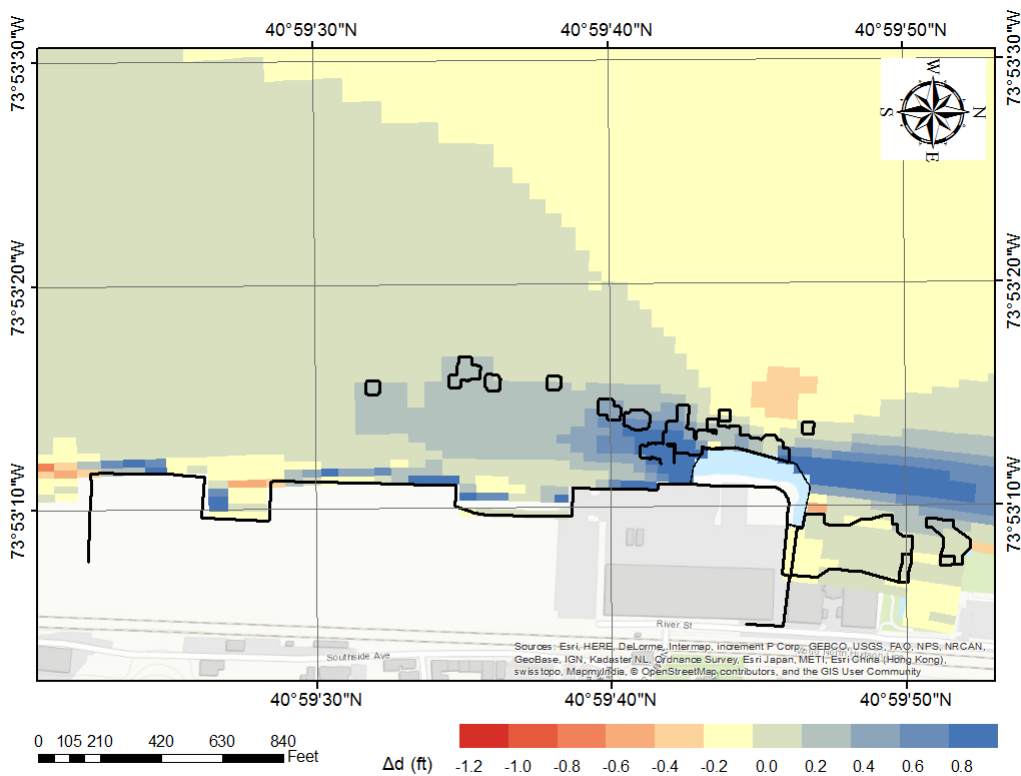
**Figure 12. Difference in erosion and deposition patterns between the existing and design
conditions**

Table 3: Deposition Rate and the Estimated Time for 1-foot Deposition in Remediation Dredging Areas

	ID	Deposition in 1-Year (feet) Modeled (±30%)	Linear Extrapolated Time for 1-foot deposition (months) Modeled (±30%)
Kinnally	K1	1.88 (1.32—2.44)	6.4 (4.9—9.1)
	K2	1.88 (1.32—2.44)	6.4 (4.9—9.1)
	K3	1.61 (1.13—2.10)	7.5 (5.7—10.6)
OID Marina	O1	1.62 (1.13—2.11)	7.4 (5.7—10.6)
	O2	1.61 (1.13—2.10)	7.5 (5.7—10.6)
	O3	1.61 (1.13—2.10)	7.5 (5.7—10.6)
Northwest Deepwater	P3	0.75 (0.53—0.98)	16.0 (12.3—22.9)
	P4	0.60 (0.42—0.78)	20.0 (15.4—28.6)
	P5	1.00 (0.70—1.30)	12.0 (9.2—17.1)
	P27	0.91 (0.64—1.18)	13.2 (10.1—18.8)
	P29	0.11 (0.08—0.14)	109.1 (83.9—155.8)
	P30	-0.18 (-0.23 — -0.13)	—
Deepwater	P7	0.62 (0.43—0.81)	19.4 (14.9—27.6)
	P8	0.58 (0.41—0.75)	20.7 (15.9—29.6)
	P9	0.45 (0.32—0.59)	26.7 (20.5—38.1)
	P10	0.45 (0.32—0.59)	26.7 (20.5—38.1)
	P11	0.41 (0.29—0.53)	29.3 (22.5—41.8)
	P12	0.50 (0.34—0.64)	24.0 (18.8—35.0)
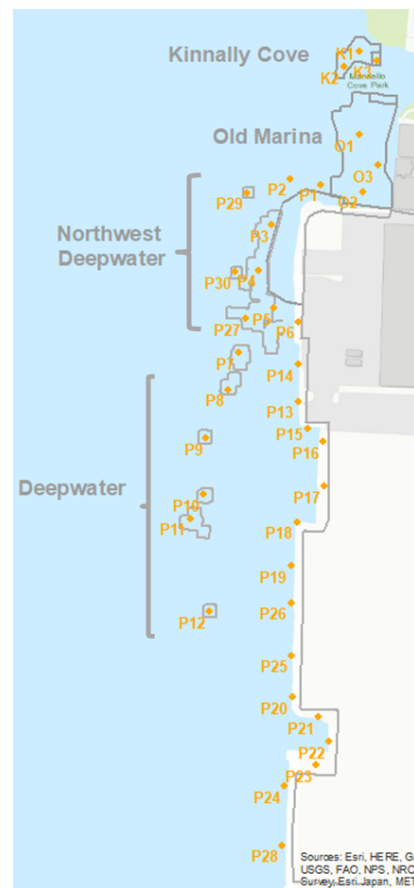
Highlighted: model predicts an average of less than 2-years for one foot of deposition

Proposed Mitigation

The ROD requires onsite mitigation for the fill that will be placed in the waters of the United States behind and as part of the proposed NEA bulkhead. This mitigation is likely to include creation of an onsite tidal wetland. Several onsite locations for this wetland have been evaluated, including on land along and adjacent to the shoreline south (downriver) of the proposed NEA bulkhead. Current riverine existing conditions in this area are depositional, and as discussed above, this model predicts that under design conditions deposition in this area will increase slightly, which would be favorable to the creation of a

properly designed wetland (Figure 11). The results of this model support the proposed area for mitigation just south of the NEA bulkhead.

## 4.3   DEFINING DEPOSITION ZONES

To facilitate development of the remedial design, it is helpful to identify those areas that are expected to experience natural deposition of one foot within a reasonable timeframe, defined herein as under three years. The identification of these areas as "1 ft Deposition Confidence Zone" and "1 ft Deposition Uncertainty Zone" is illustrated in Figure Figure 13 and is based on three criteria:

1. The general erosion and deposition patterns were examined relative to the dredge areas.

2. The transition zone between erosion and deposition areas where there is little predicted change in bathymetry were identified based on both model results and field observations.

3. Changes in erosion and deposition pattern under design conditions were also considered.

The line demarcating these zones is generally consistent with the transition region between erosional and depositional areas predicted by the model as well as with field observations, and its placement was guided by locations where deposition was predicted to be enhanced rather than reversed under design conditions. In general, the confidence zone extends from the design shoreline approximately 400 feet into the river. The possible exceptions to this are areas immediate in front of the bulkhead to the west as highlighted by green line in Figure Figure 13, where there is increased uncertainty related to predictions of erosion versus deposition. A model of finer mesh would be needed to evaluate local conditions in this part of the bulkhead. Instead, the design will likely conservatively assume that the dredge areas in front of the bulkhead to the west will not experience natural deposition of one foot within a reasonable timeframe. It should be noted that there is generally higher confidence in predictions related to those areas that are predicted to experience deposition, and lower confidence in those areas that are predicted to experience a decrease in deposition or an increase in erosion.
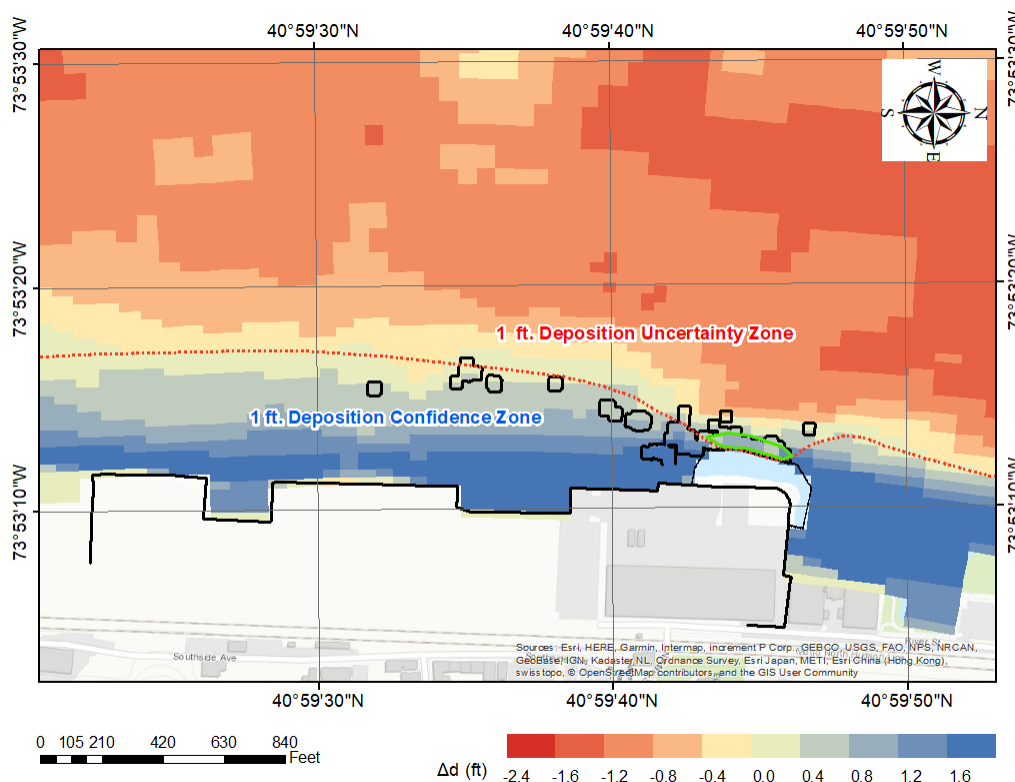
Figure 13. Zone boundary designation for 1-foot deposition

5.0   SUMMARY AND DISCUSSION

Stantec was asked to assist Atlantic Richfield with the evaluation of the potential hydrodynamic and morphodynamic responses to the remediation activities at the Site, particularly those associated with bulkhead installation, remediation dredging and backfill, and shoreline modifications. The project was carried out in two phases.

During Phase I, a coarse resolution and a fine resolution hydrodynamic model were developed for the entire LHR and the HOH Site, respectively. The hydrodynamic models were calibrated against the field observations of water levels and current velocities at different locations along the Hudson River. The Phase I results were reported in a document titled *Hastings on Hudson Hydrodynamic Study Part I – Model Setup & Calibration, Stantec, February 19, 2016*.

In this Phase II study, a morphodynamic HOH model was developed by extending the hydrodynamic HOH model presented in Phase I to include modeling capabilities for sediment transport and morphological changes. The morphodynamic HOH model predicts deposition occurring near the shallow areas along the river bank, within approximately 400 feet of the shoreline, with areas further from land will

experience erosion. These findings are consistent with the field observations by Nitsche et al. 2007 as well as a numerical study by Ralston et al. 2012.

To assess the hydrodynamic and morphodynamic responses to the remediation activities, the HOH model was applied to the design conditions, and the results were compared with those under existing conditions. The remediation design reduces flow immediately upstream and downstream of the bulkhead due to its physical obtrusion into the river. Changes in erosion and deposition patterns after 1-year simulation compared with the existing conditions are primarily close to the bulkhead alignment with a slight increase of deposition corresponding to the hydrodynamic changes (reduced flow). Areas immediately in front of the bulkhead to the west as highlighted by green line in Figure 13, where there is increased uncertainty related to predictions of erosion versus deposition. A model of finer mesh may be needed to evaluate local conditions in this part of the bulkhead. The other key objective was to assess the time required for one foot of natural deposition to occur in the project area, with particular focus on the remediation dredging areas. The model predicts that one foot of deposition will occur in under two years in most areas, and that one foot of deposition will occur in less than one year in Old Marina and Kinnally Cove. This time period is considered reasonable in the context of the OU-2 ROD, which allows for natural deposition of the last foot of sediment within dredging areas meeting this condition. Northwest areas near the bulkhead and areas in deeper water may require a longer time for one foot of deposition to occur and will generally be experiencing erosional forces, particularly those further away from the shoreline. For areas immediate in front of the bulkhead to the west, erosional forces currently exist and would be only increased slightly by the presence of the bulkhead. Based on the above described model results, zones were identified where it is relatively certain that one foot of deposition is likely to occur within a reasonable time frame (within 1 to 3 years). Additionally, the area being considered for location of an onsite tidal wetland is adjacent to an area of the river identified as depositional and would be expected to experience slightly increased deposition under design conditions, which would be favorable to the creation of a properly designed wetland.

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