Stantec

Memo

To: Atlantic Richfield Company (a BP affiliated company)

From: Stantec Consulting Services Inc.
30 Park Drive
Topsham, ME 04086

Date: February 17, 2016

Reference: Hydrologic and hydraulic computer model development

MODEL DEVELOPMENT

The overall purpose of this study is to develop a hydrologic and hydraulic (H&H) computer model that simulates baseline hydrodynamics in the Hudson River that are associated with the remediation design alternatives being consideration for a 28-acre site (Site) located in Hastings on Hudson, New York. The Site is situated along the eastern bank of the Hudson River, approximately 50 kilometers (km) (30 mi) upstream of its confluence with Upper New York Bay.

After a thorough review of available data and meetings with the client, it was determined that two models will be needed in order to capture the level of detail needed to evaluate the remediation designs under consideration for the Site. These include a coarse resolution regional hydrodynamic model of the Lower Hudson River (LHR Model) and a fine resolution local hydrodynamic model focused at the Site (HOH Model). The LHR model is required to ensure that hydrodynamics along the entire region are captured while the HOH model is required to assess detailed water levels, currents, shear stress, and other morphodynamic factors along the Site for various design alternatives.

The LHR Model extends from Green Island in the north to the Battery in the south, which are 200 km and 50 km downstream of the site, respectively. This extent was selected because the Battery contains a long record (since 1926) of measured water levels that include all hydrodynamic influence from the Atlantic Ocean and Upper and Lower Bays, whereas Green Island has a similarly long record of river discharge (since 1946) and is the approximate limit of tidal influence in the Hudson River. Not only does this extent allow for inclusion of the two primary forcing consideration of water levels and current velocities at the site (tidal elevations and river discharge), but it also allows for model calibration to measurements made at various locations within the Lower Hudson River. For more information about available data for model boundary conditions and available data for model calibration and validation, see sections 2 and 3 of Hastings on Hudson – Hydrodynamic Study Part 1 – Model Setup & Calibration dated February 2, 2016 (Report).

The boundary of the LHR Model follows the general banks of the Hudson River and includes boundaries for Pollepel Island, Iona Island, Round Island, and Con Hook. A combination of the NOAA, USGS and bathymetry contour lines were used to create a seamless topographic/bathymetric dataset, which was applied to the mesh. The model grid resolution varies along the model extent where the highest resolution occurs in the section of the River where the Site is located as well as locations of the river with complex bathymetry and channel geometry. This ensures model results can be seamlessly transferred to the higher resolution HOH model and capture the complex hydrodynamics that occur along the entire Lower Hudson River. Various grids with different resolutions were developed to assess the model sensitivity to this resolution. The aim was to identify the resolution at which modeled results converge as grid size reduces. This resulted in selecting the most efficient modeling grid for the Lower Hudson River (Figure 1).

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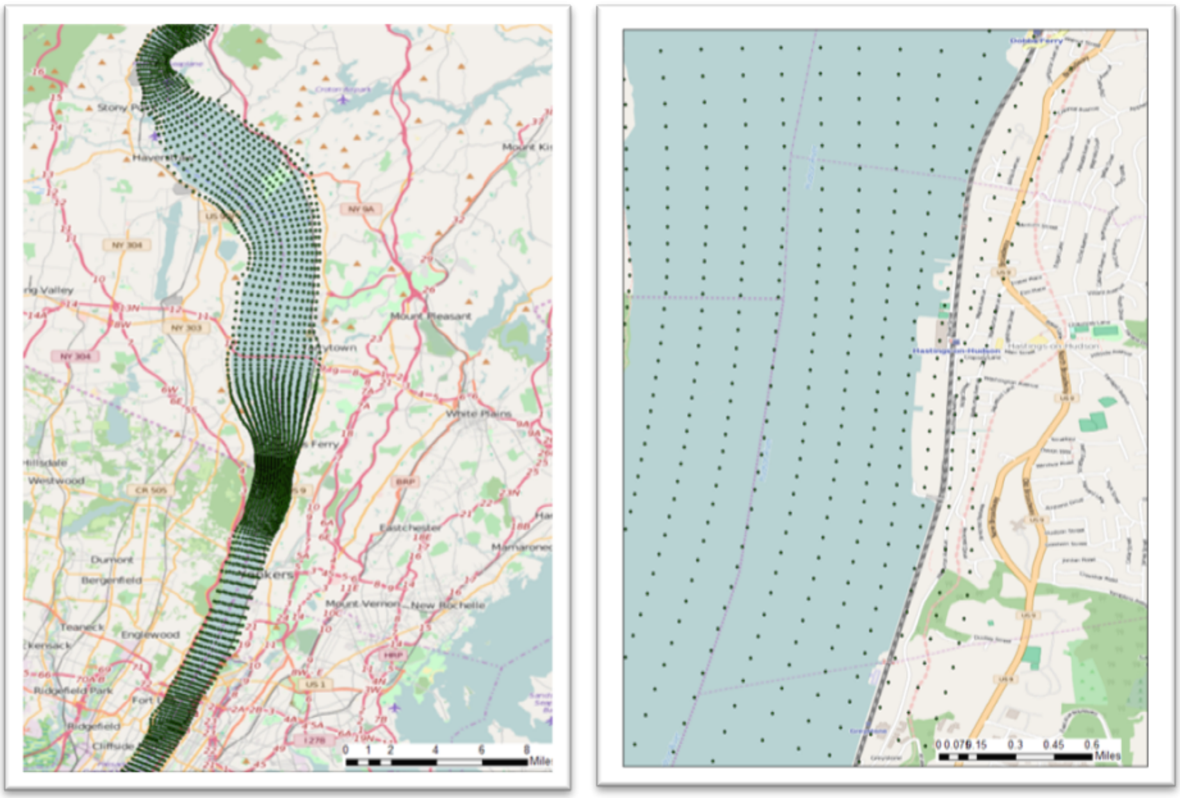

Figure 1 LHR Modeling Mesh Nodes from Poughkeepsie to the just North of the Southern Extent (left) and in the Vicinity of the Site (right).

The smaller and more refined HOH Model was created to resolve the geometry with higher resolution specifically around the Site as compared to the larger LHR Model (Figure 2). This HOH Model is such that there are approximately 29 grid cells along the Site. This allows for approximating shear stresses along the bed near the Site in the area of interest. Further, this HOH Model can be used to generate boundary conditions for very fine/highly resolved models at specific locations along the site to address more detailed design questions for different Site alternatives (i.e. comparing impacts of small scale design variations).

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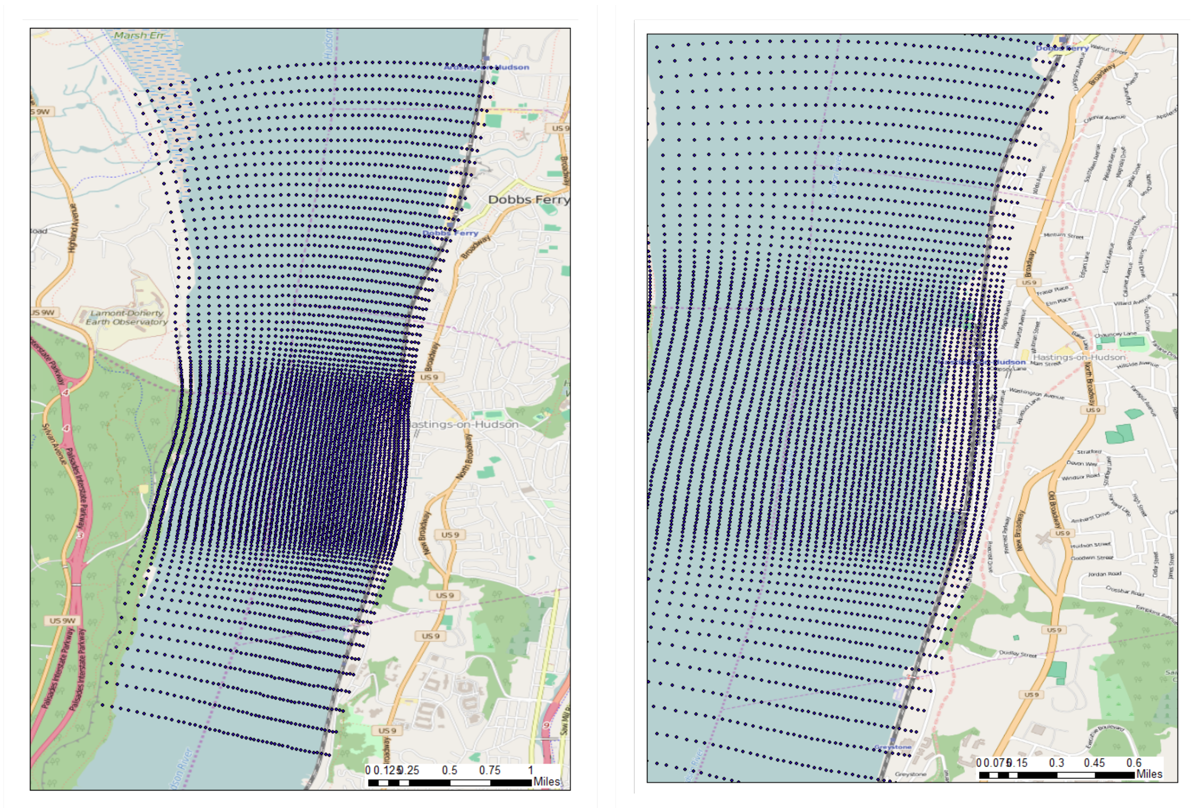

Figure 2 HOH Modeling Mesh Nodes from its full extent (left) and in the Vicinity of the Site (right)

MODEL CALIBRATION/VALIDATION

Model validation simulations and analyses were performed on the LHR model. The extent of this model covers many locations of water levels, currents, and salinity that are lacking in the extent of the local HOH model. So long as the LHR model is validated, it is ensured that accurate hydrodynamic conditions are being fed into the HOH model for more refinement. Also, a model to model comparison was made between the LHR model and HOH model to ensure the models made consistent predictions of water level and current velocity.

In order to calibrate and validate the LHR model, hindcast simulations were performed for June and July of 2005. This period was selected because during this 2-month period, NOAA collected current velocity profiles at various locations throughout the Lower Hudson River and water levels were recorded by the USGS near the Site. In other words, this time period contained the best quality measured data over the broadest stretch of the model's spatial extent.

To measure the performance of the calibrated model (validation), the Nash–Sutcliffe model efficiency coefficient (N-S), which is used to assess the predictive power of hydrological models, was used. Over this 2-month validation/calibration period, the N-S scores for the 4 current velocity measurement locations ranged from 0.91 – 0.96, which indicates 'excellent' agreement at all locations, where 1.00 represents perfect agreement, with the best agreement at the George Washington Bridge. The N-S score for the water level at the location of the USGS gage near the south end of the Site was 0.97; this was the only observation of water levels in the Lower Hudson River during this time period (Figure 3). To ensure calibration efforts were not biasing the model to obtain the best agreement for an otherwise arbitrary two month period in time, additional model predictions were made for a period from January to late July 2011. While observations of current velocities were unavailable during this time period, there were two different stations of water level data: a USGS gage at Piermont Pier and a buoy deployed by Stevens Institute of Technology at Castle Point. The N-S score for this simulation at these stations were 0.97 and 0.98. The near-perfect N-S scores for the hindcast simulations at locations where observations exist provide confidence in the model's ability to forecast water levels and current velocities (shear stresses) for design conditions. For more information about model calibration and validation see section 4.4 of the Report.

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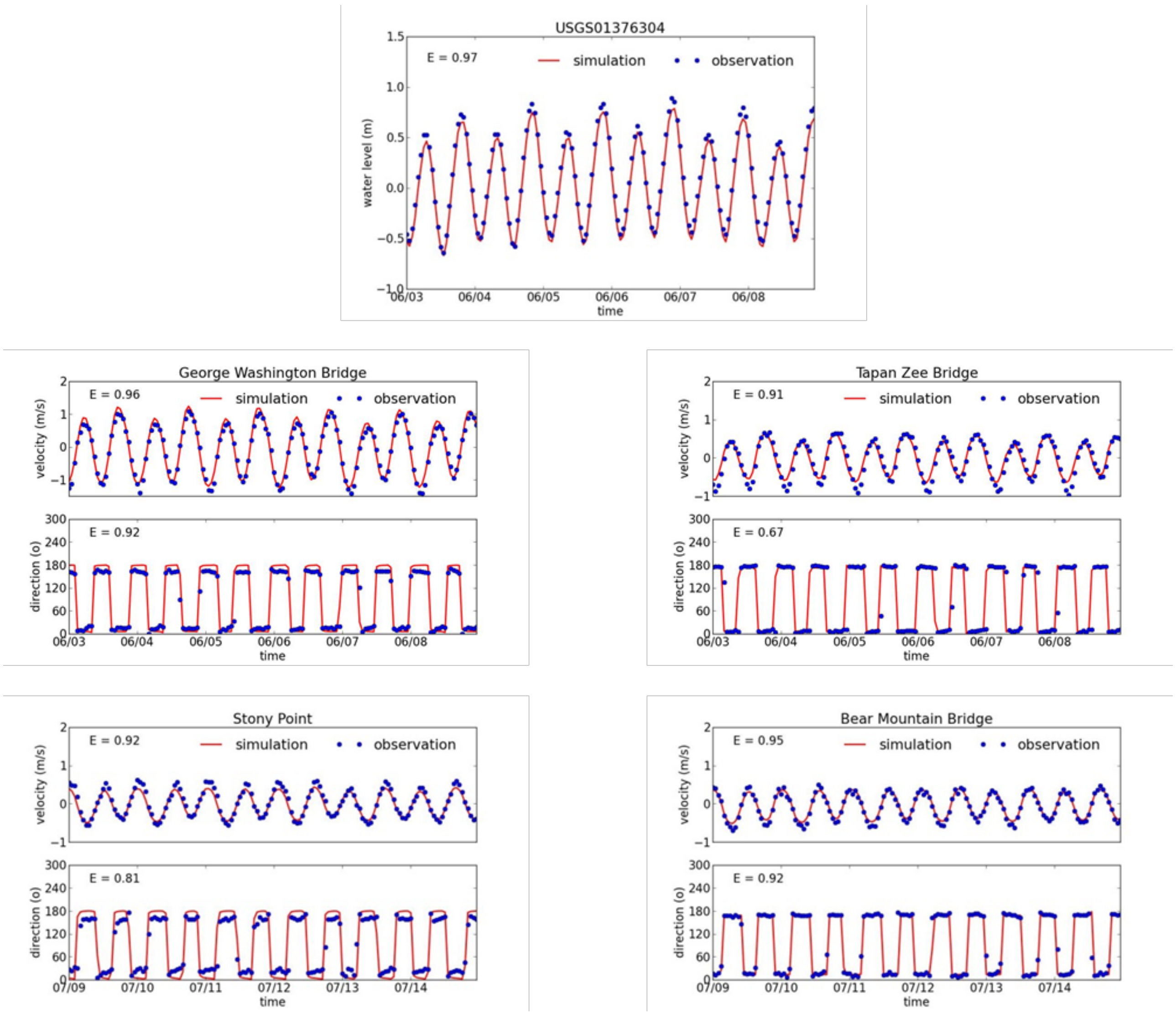

Figure 3 Comparison of Model Results and Observations for a Segment of the June–October 2005 Simulations. (top) Water Level at USGS 01376304 (bottom from left to right, top to bottom) Velocity at Various Locations

PROPOSED FORCING CONDITIONS FOR DESIGN CONSIDERATIONS

At this time, a general range of prescriptive short-term extreme forcing conditions have been defined for design conditions. A range of possible circumstances have been provided because forcing and design conditions depend on the particular design questions that are to be addressed in the near future (or in later phases of the project). For example, if the design question relates to the shear stress or wave forces a coastal structure (i.e. bulkhead, toe protection) must withstand, the return period against which the structure must protect should be defined by the design engineer. These critical forces for an assigned return period event can be simulated by simply modeling a single event with those water level, wind, and discharge conditions.

Table 1 NOAA's Predicted Extreme Water Levels at The Battery compared with Extreme Events in the Record

Percent Annual Chance	High Water Level (m, NAVD88)	Low Water Level (m, NAVD)
1%	2.44	-1.89
10%	1.86	-1.71
50%	1.49	-1.49
99%	1.22	-1.16
Recorded		
Sandy	*3.50*	---
September 1960	*2.33*	---
December 1992	*2.24*	---
August 2011	*2.15*	---

As shown in Table 1, the 100-Year event (1%-annual-chance) was well exceeded by Hurricane Sandy and has been closely reached over the past 50 years by the dates and months listed. Once design guidance is provided from the design engineers, storm events from historical observations or synthetic storms exceeding the strength of historic storms can be hindcast/simulated to obtain extreme shear stresses for structural design.

Another consideration for assessing extreme forces for structural design is the potential for strong waves coincident with high water levels to impact the Site. The preliminary flood insurance study and associated modeling for Westchester County shows the presence of wave induced high hazard zones (VE-zones) along the Site with a 1%-annual-chance (100-Year) wave height and period of 1.16m and 3.82s, respectively. The return period water levels at the Site as computed in the preliminary flood insurance study as well as the water level measured at the USGS station near the Site in 2011 are presented in Table 2.

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Table 2 Water Level Recurrence Intervals at the Site from the Preliminary Flood Insurance Study Compared with Measured Data on August 2011.

Percent Annual Chance	Water Level (m, NAVD88)
0.2%	3.52
1%	2.56
2%	2.23
10%	1.56
August 2011	*2.25*

As previously mentioned, modeling extreme events can be performed rapidly since the modeling time frame is short (only hours or days). Therefore, simulations can be performed on demand to assess hydrodynamic conditions from historic observations or synthetic more extreme storms, and can include/exclude estimated wave forcing from historic or synthetic winds.

Modeling morphodynamic responses at the Site poses a more difficult challenge. Alterations can be thought of as perturbations to an otherwise quasi-steady system. Following this 'perturbation,' it may take years or decades to yield morphodynamic trends that are in quasi-equilibrium with prevailing forces. Since it is unlikely that a historical set of years will repeat in the future, an alternative to using a hindcast (a history of observation) to forecast long-term morphology has been developed. Unlike modeling short-term extreme events for structure consideration morphodynamic modeling must be more prescriptive owing to the time required for simulation.

In order to develop a 'calm' or 'normal' baseline year for water level boundary conditions applied at the Battery. The residuals of the water levels or surge (deviation from astronomical tides) were analyzed on a monthly basis for each year since 1926 at the Battery. Positive and negative residuals were analyzed separately. It should be noted negative residuals can result in abnormally low water levels, which can lead to strong currents and shear stresses flowing downstream. The average positive and negative residuals were computed from each month for all years. The average residual for each particular month and year was compared to that month's total average. Those years for which that particular month was closest to the average positive and negative residuals were selected. These months were combined and added to an annual astronomical tide record to develop a normal year of water levels at the downstream boundary (see Figure 3).

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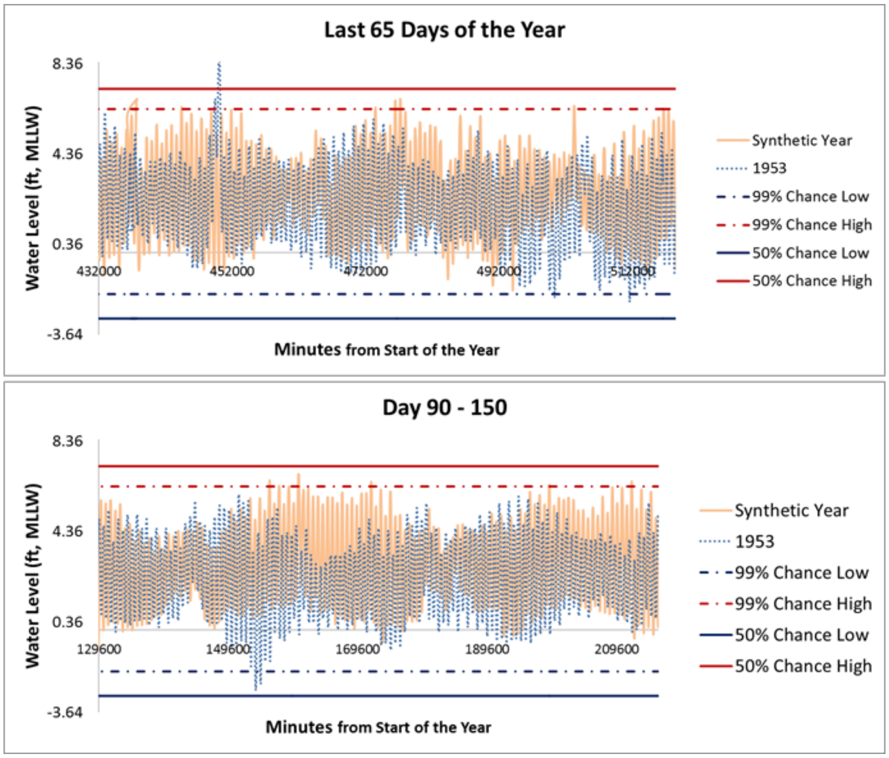

Figure 4: Comparison between the synthetic water level and observations

Similar steps were taken to derive a normal year of discharge at Green Island using that gages entire recorded. As a first step, the base flow and storm flow were separated from the discharge record. The average base flow for each month over the entire record were computed and combined to yield a normal base flow discharge time series (see Figure 5, top). Storm flows were analyzed to select a year for each month that had relatively calm (excluding atypically calm years) flows by a process similar to that used in selecting residual water levels. To do so, the average peak flow and average storm runuoff volume over the entire observed record was computed for each month. The year whose peak flow and runoff volume were closest to the averages were identified for each month. An annual time series of storm flow was created by concatenating these monthly storm flow time series for these identified years. The base flow time series was summed with the concatenated monthly storm flow time series to yield a synthetic annual total flow time series (see Figure 5, bottom). See section 6.0 of the Report for more details on the creation of boundary conditions to assess morphodynamic factors under normal conditions.

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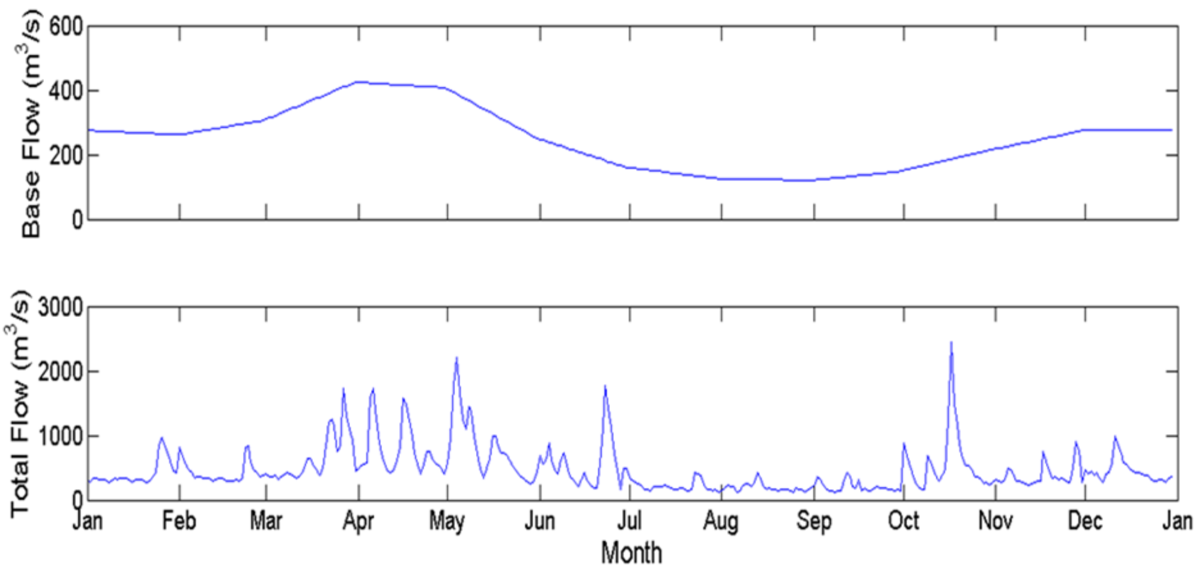

Figure 5: (top) Annual base flow derived from monthly averages (bottom) Annual total flow time series derived from average monthly base flow and storm flow from selected years

Morphodynamic responses can be modeled over this normal year to assess erosion and deposition patterns following proposed construction activities. At this time, it is proposed that scale factors be applied to project morphological responses further into the future (several years or decades) under normal conditions to yield long term projections. Historic storm events (such as Sandy or Irene) or synthetic 'storm' events (with both high and low water levels) will be superimposed on these normal conditions to assess how extreme events impact the normal morphological patterns.