US Army Corps
of Engineers®
St. Louis District

Sedimentation and Channel Capacity Assessment - Rio Puerto Nuevo (RPN) Flood Mitigation Project

A 2-dimensional analysis using Adaptive Hydraulics (AdH)

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1 Executive Summary

Investigation and studies conducted on the Rio Puerto Nuevo hydrologic basin started in the late 1970s and progressed into the early 1980s. The conclusion to this study was a recommendation to move forward with a flood reduction project as it was shown to be beneficial to the public and the local communities. The recommended plan included approximately 11.2 miles of channel improvement to the following rivers and tributaries:

- Rio Puerto Nuevo (6.46mi, locally known as Rio Piedras)
- Margarita Channel (1.70mi)
- Josefina Channel (1.46mi)
- Dona Ana Channel (0.62mi)
- Buena Vista Diversion Channel (0.80mi)
- Guaracanal Channel (0.16mi)

Recent precipitation events, particularly the 2017 hurricanes Irma and Maria, garnered enough attention of the public to get more Federal funding to expedite the implementation of the project as recommended in the General Design Memorandum (GDM) released on December 20th, 1991. While the design and modeling of the different improvements play a key role in the development of the entire project, additional considerations such as sedimentation patterns along the design channel are essential for the project. For Rio Puerto Nuevo, control of sedimentation has a direct correlation to real performance, long-term functionality, and cost efficiency (including maintenance costs).

Over the last several years, the USACE St. Louis District (CEMVS) has been developing a 2D Adaptive Hydraulics (AdH) Hydraulics and Sediment model to identify and analyze sedimentation patterns along the to be improved reaches within the Rio Puerto Nuevo. This model has allowed engineers to identify potential channel capacity concerns, locate and quantify depositional areas, and analyze a variety of aggradation scenarios to include the channel response to frequency storms after depositional periods ranging from 1 to 6 years.

Understanding the uncertainties associated with sediment transport modeling as well as other natural phenomena should set the tone for the development of a thorough adaptive management (AM) plan. Considering the lack of observed project data, active monitoring and surveillance of the system will be essential in the success of these efforts. This study is aimed to inform on the initial operation and maintenance efforts of the project. Observed data -in combination with the system response to the project implementation- must be incorporated into the initial O&M suggestions included in this document to better accommodate for site-specific needs.

2 Introduction

2.1 *Study reach*

The total area of improvement covers an approximated linear distance of 11.2 miles which includes 6.46 miles of the Rio Puerto Nuevo main channel and 4.74 miles distributed along other tributaries mainly serving as urban drainage channels. Although the model covers an extensive area of the watershed, it was developed to focus on the 6.46 river miles of the main stem.

Throughout this reach of the main stem, tidal influence controls depositional patterns as both velocity and energy dissipate, allowing sediment particles to settle. Such environment limits the amount of sediment transported out of the channel during base flow conditions, resulting in a channel volume capacity reduction. RPN tributaries -as well as the upstream section of the main stem- have greater slopes and consequently higher velocities that decrease sedimentation issues along those reaches. Figure 1 shows the area of the proposed flood mitigation project being studied.

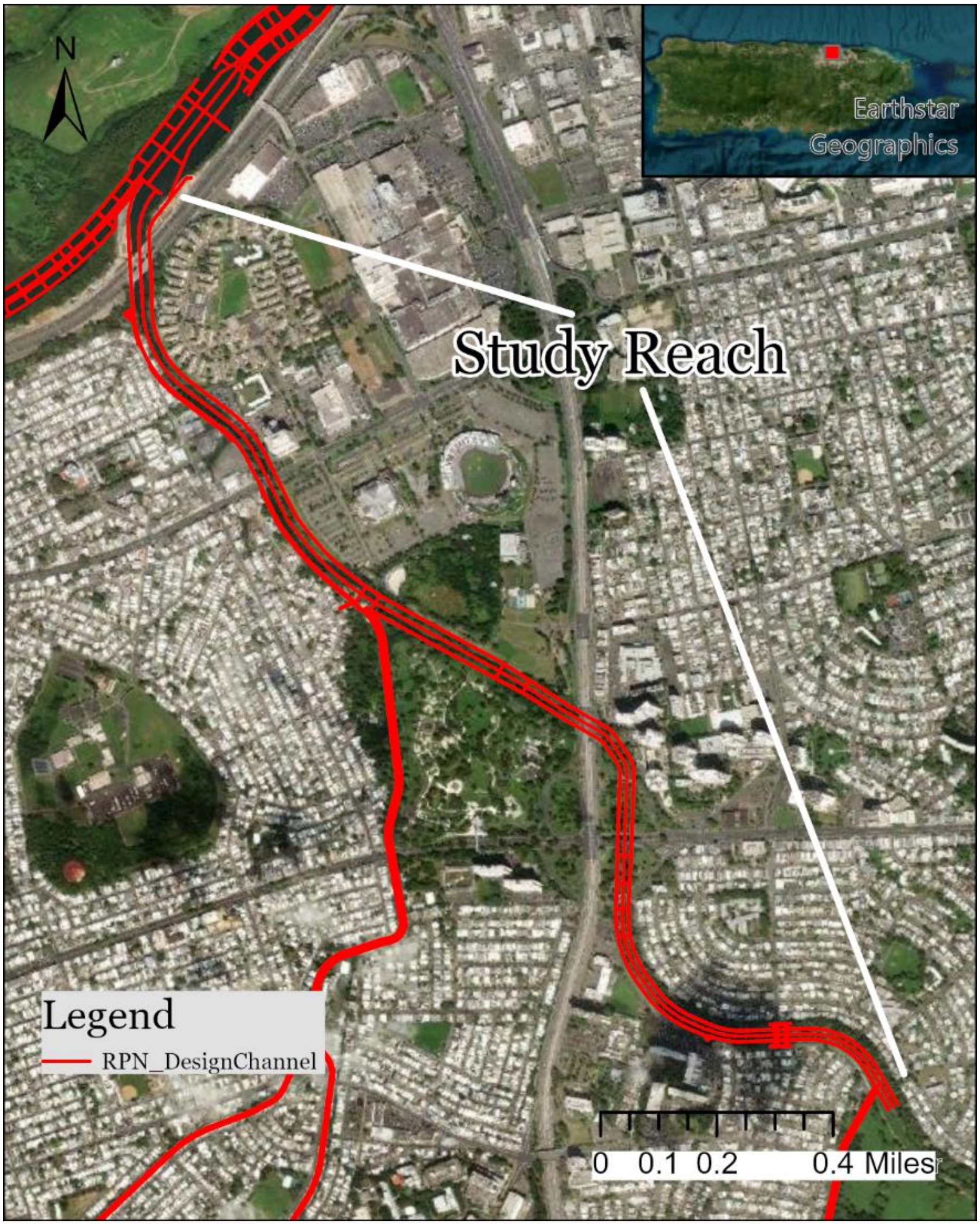


Figure 1. Master alignment of the Rio Puerto Nuevo Flood Mitigation Project highlighting the area of interest for the sedimentation model.

2.2 *Rio Puerto Nuevo Watershed Background*

The Rio Puerto Nuevo basin is a densely urbanized and highly developed watershed in the San Juan Metropolitan Area. It has a drainage area of approximately 20 square miles (sq. mi.) and an average basin slope of 13.4%. The longest flow path (Rio Piedras) covers approximately 11 miles from its headwaters down to sea level in the San Juan Bay. In Figure 2 the scale of the watershed in comparison to the metropolitan area can be observed along with the sub-basins and main tributaries.

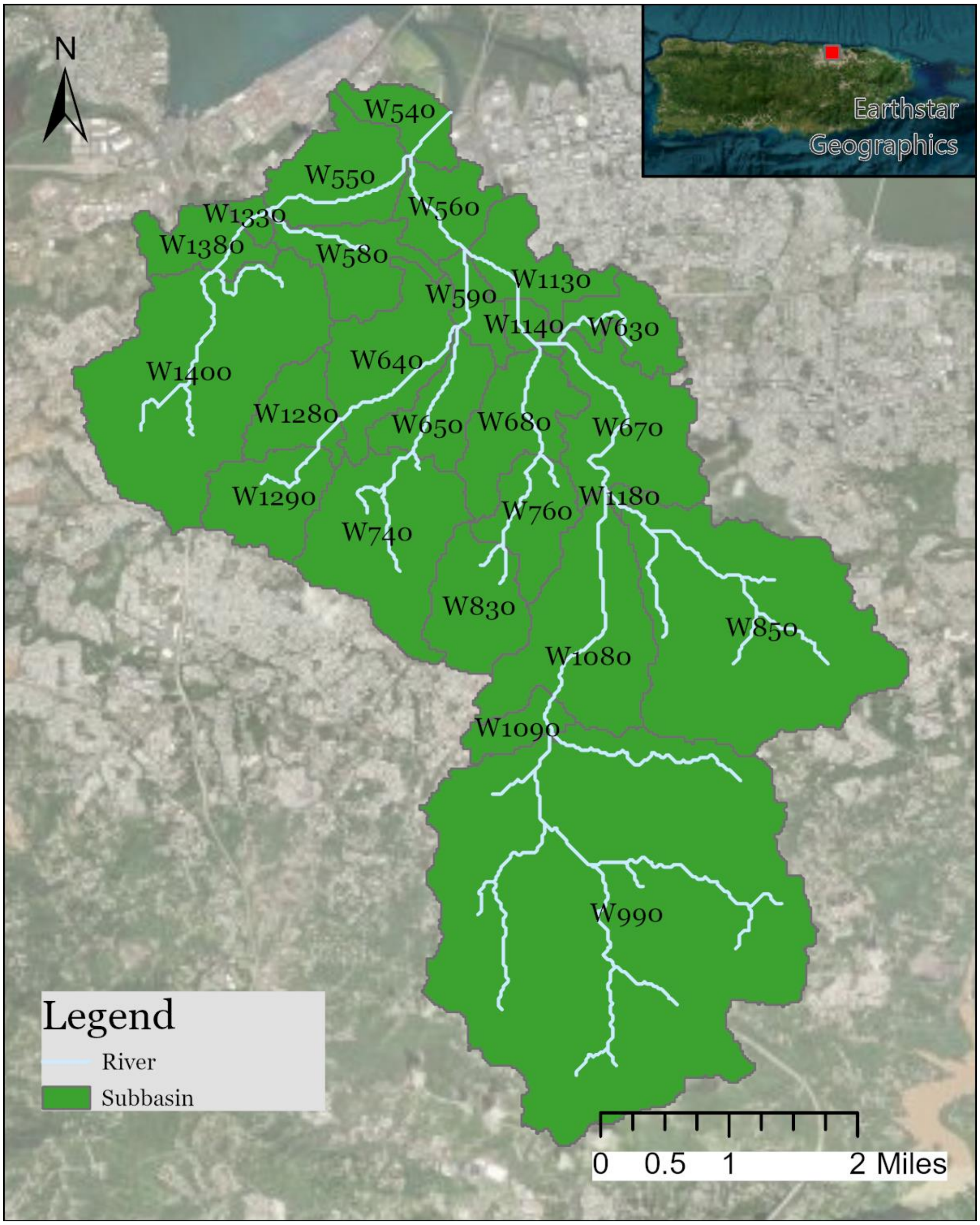


Figure 2. Sub-basins and channels within the Rio Puerto Nuevo watershed.

The watershed in general has experienced tremendous amounts of developed infrastructure, residential projects, and changes in land use in the last several decades. This has driven up the amount of impervious surfaces which correlate to greater watershed runoff. Because of budgetary cuts, monitoring and surveillance of the riverine system has fluctuated greatly, causing significant gaps in historical river gage data on this system. Currently, two USGS gages ramain active in this watershed (USGS 50049100 and USGS 50049310), while two other gages were removed from operations in 1993 (USGS 50049000) and 2015 (USGS 50048770). These four locations were utilized to monitor suspended sediment to identify sediment sources and potential locations for sediment basins. Figure 3 shows the location of the four monitoring gages.

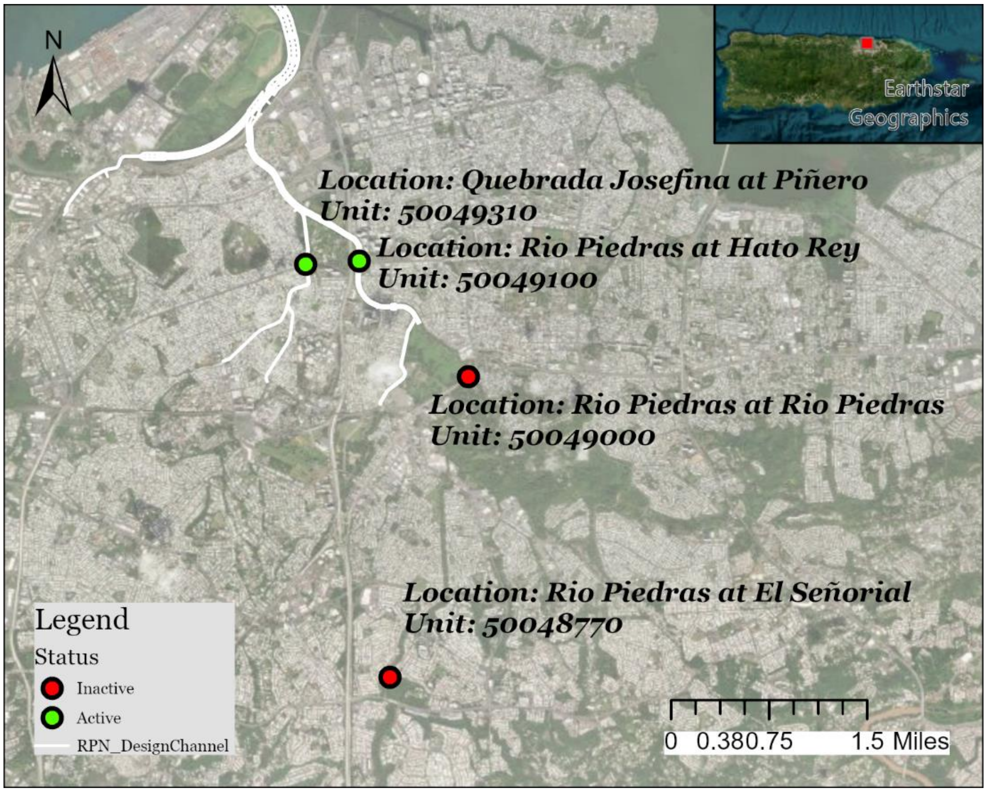


Figure 3. Original suspended sediment monitoring stations and status.

2.3 *Project Purpose/Need*

Recent atmospheric events (specifically hurricanes Irma and Maria in 2017) caused devastating damage to the entire Island of Puerto Rico. The damages and adverse impacts could be seen in the aftermath of the storms throughout the San Juan Metropolitan Area, especially along tributaries and the main stem of Rio Puerto Nuevo. Historical floods impacted the watershed and significant amounts of sediment were transported through the system. Both sediment and flow amounts produced localized damaging effects on residential and commercial areas as well as critical infrastructure throughout the watershed. Figure 4 shows the intensity of Hurricane Maria and Figure 5 depicts an example of the aftermath.

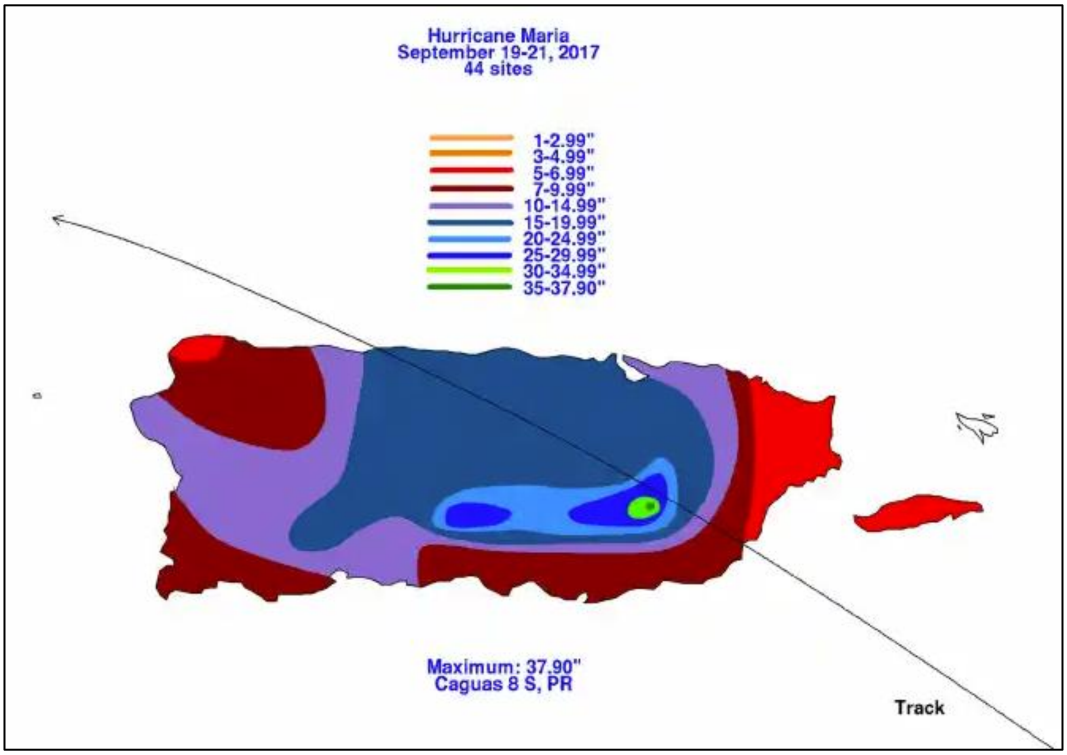


Figure 4. Storm total rainfall (inches) from Hurricane Maria (Source: NOAA - AL 152017).

Figure 5. Residential area under water and inaccessible after Hurricane Maria stroke Puerto Rico on September 20, 2017. (Source: The New York Times).

As part of the feasibility study, it was determined that sediment control structures would be needed to maximize the benefits of the project. However, due to land acquisition and access challenges, this design feature has been temporarily postponed. To understand the effects of eliminating such feature, the St. Louis District was tasked to develop a 2D adaptive hydraulics model laced with sediment.

The overarching goal of the model was to identify, quantify, and analyze depositional patterns along the design channel. This would ultimately allow the team to develop an Operation & Maintenance (O&M) manual to help the sponsor understand the importance of maintaining channel capacity to maximize the benefits of the project as well as the expected long-term cost of maintenance.

With the need to understand long-term sedimentation patterns, the team developed a suite of studies to identify long-term sedimentation impacts to the project: to enhance the understanding of the need of identifying long term sedimentation issues:

- Long-term Sedimentation Forecasting: Model simulated up to a maximum of six years with a predetermined hydrograph to understand impacts.
- Channel Conveyance and Volume Capacity: Multiple frequency storms were used to verify channel capacity and overall effectiveness of cleansing the system of unwanted sedimentation aggradation.
- Sediment Volumes: Determined quantities of sediment moving through the system and required dredging needs for cost estimating purposes.
- Depositional Distribution: Determined longitudinal profiles and spatial distribution of the sediment particles throughout the design engineered channel.

3 AdH Modeling – Existing Conditions

3.1 *Geometry*

Multiple datasets were combined for the development of the base mesh utilized in this study. The datasets consisted of LiDAR, bathymetric, and cross-sectional survey data to encapsulate overbanks and general channel geometry. Interpolation was used to delineate topographic cross sections and sparse bathymetric data. Though standard practice, interpolation may introduce error into the model. The bathymetric characteristics in the San Juan Bay represent a specific snapshot in time and is only included in the model for consistent exit conditions. Table 1 indicates the various datasets utilized for model terrain development.

Table 1. Elevation sources for merged mesh surface.

Survey	Survey Type	Vertical Datum	Year	Units of Measurement
2018 USGS Lidar DEM: Post Hurricane Maria - Puerto Rico - 1	LiDAR	(PRVD02)	2018	meters
2019 NOAA NGS Topobathy Lidar DEM: Puerto Rico - 1	LiDAR	(PRVD02)	2019	meters
2021 San Juan Harbor (SAH) SAJ Hydrographic Survey	Hydrographic	(PRVD02)	2021	meters
Channel Cross Sections	Topo Transects	(PRVD02)	2022	meters

This terrain served as the existing condition for the hydrodynamic and sediment calibration efforts and will be referred to as either pre-project or existing conditions going forward. Figure 6 depicts the model extents and a reference for topography.

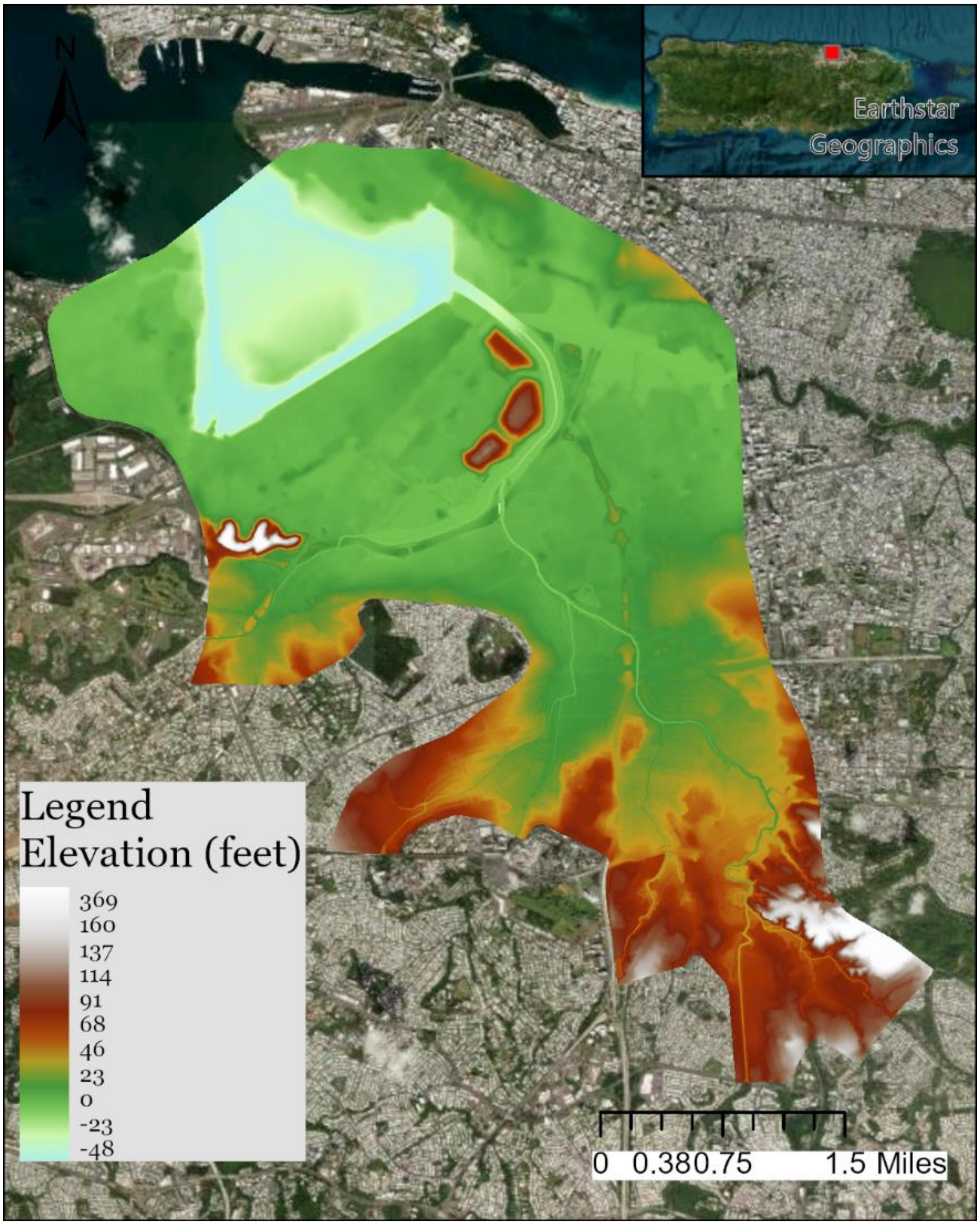


Figure 6. Digital elevation model (DEM) depicting model mesh domain. This DEM was utilized for hydrodynamic and sediment calibration of the existing condition. Units: feet.

3.2 *Calibration*

To develop and calibrate an AdH model, multiple items are necessary. These items include the following:

- Boundary Conditions
- 3D Mesh File

- Hot Start File
- Computational Environment

Information pertaining to flow data as well as material description and sediment characteristics is included in the boundary conditions file. Initial conditions include water depth and flow velocity vectors (for hydrodynamic runs) as well as initialized bed conditions (for sediment runs). These conditions are included on the hot start file.

The AdH model was calibrated by making small adjustments to the roughness values to achieve water surface elevations that closely matched the depth results obtained in the HEC-RAS model developed by SAJ and used as the base for MVS modeling efforts.

3.2.1 *Boundary Conditions: Discharge and Water Surface Elevation Data*

3.2.1.1 Discharge

In an AdH model, the boundary conditions file (BC) is where modeling parameters are stored for analytical purposes. Several of the variables assigned in the BC file either require historical river gage discharges and stages or synthetic hydrographs. In this case, due to lack of historical data and un-reliable gage data, modelers turned to synthetic hydrographs. All hydrologic routing information was obtained from a HEC-HMS model that was built by the Jacksonville District (SAJ) prior to initiating this study. From this HMS model, various synthetic frequency storms were generated to simulate hydrologic events of different magnitudes and are shown in Figure 7. The 24-hour duration of the storms is characterized by the intense rainfall with large volumes of runoff the basin undergoes within a few hours. RPN may reach or exceed bankfull conditions and return to pre-event flows within this 24-hour period.

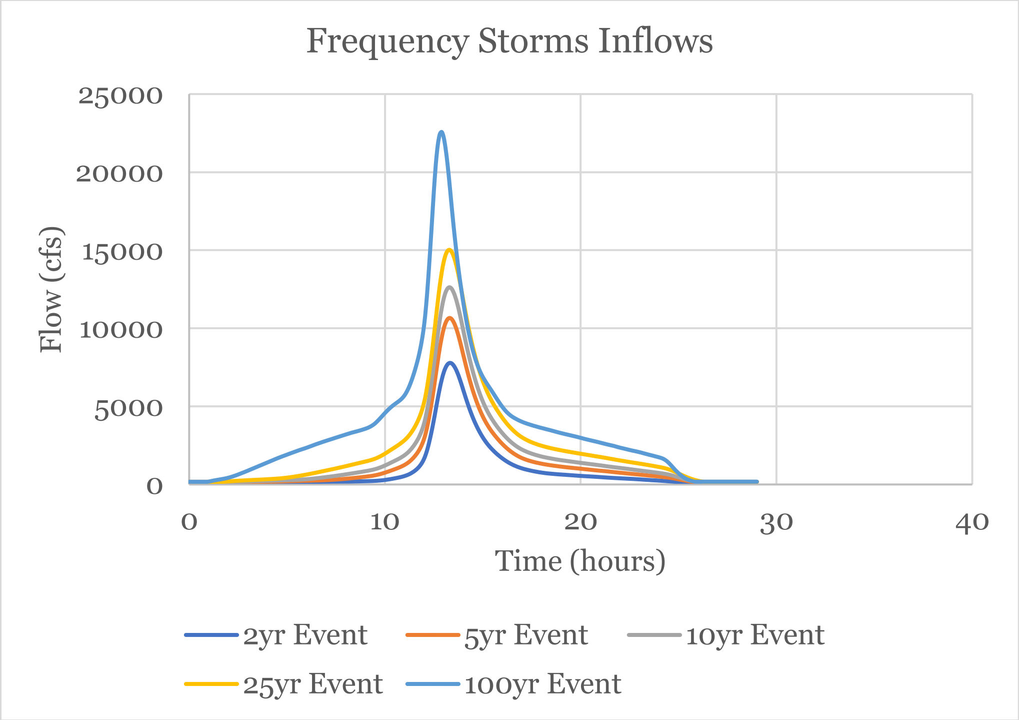


Figure 7. Synthetic frequency storms developed in HEC-HMS for the RPN basin. Units: cubic feet-per-second (cfs).

These hydrographs were built by adding the corresponding sub-basins according to the model inflow locations. River reaches and sub-basins were organized and assigned as described in Table 2. This information represents the total inflow for the entire basin and is not specific to any location within the domain. Both the main stem and the tributaries were included for the development of this plot.

Table 2. Flow data sources for frequency storms routing.

Inflow Data

SMS Inflows	Sub-basin	HMS Input
Combined Inflows	W990	W990
	W1080	W1080
	W1090	W1090
W1180+R1190	W1180	W1180
	W850	R1190 OUT
W670-1	W670*0.5043	W670*0.5043
W670-2	W670*0.4957	W670*0.4957
W680+R170	W680	W680
	W760	R170 OUT

	W830	
W630+W1130+W1140	W630	W630
	W1130	W1130
	W1140	W1140
Contract 4 (W560+W590+R70)	W590	W590
	W560	W560
	W640	
	W650	
	W740	R70 OUT
	W1280	
	W1290	

3.2.1.2 Water Surface Elevation

Model tailwater conditions were set to zero feet or Mean Sea Level (MSL) to represent a slack water condition in leu of simulating tidal effects. This parameter setting was vetted by both SAJ & MVS hydraulic engineers. The setting was chosen because tidal actions have marginal effects on sedimentation trends on sedimentation trends in this case. This allows for a steady state boundary and higher model efficiency.

Because historical data lacked significance in this project, reference WSE for calibration metrics were provided by initial HEC-RAS modeling efforts. The stage curve provided is the best estimate of water surface elevations at the Piñero gage (USGS 50049100) location. The event corresponded to roughly a 100-year hydrologic event and the resulting stage is presented in Figure 8.

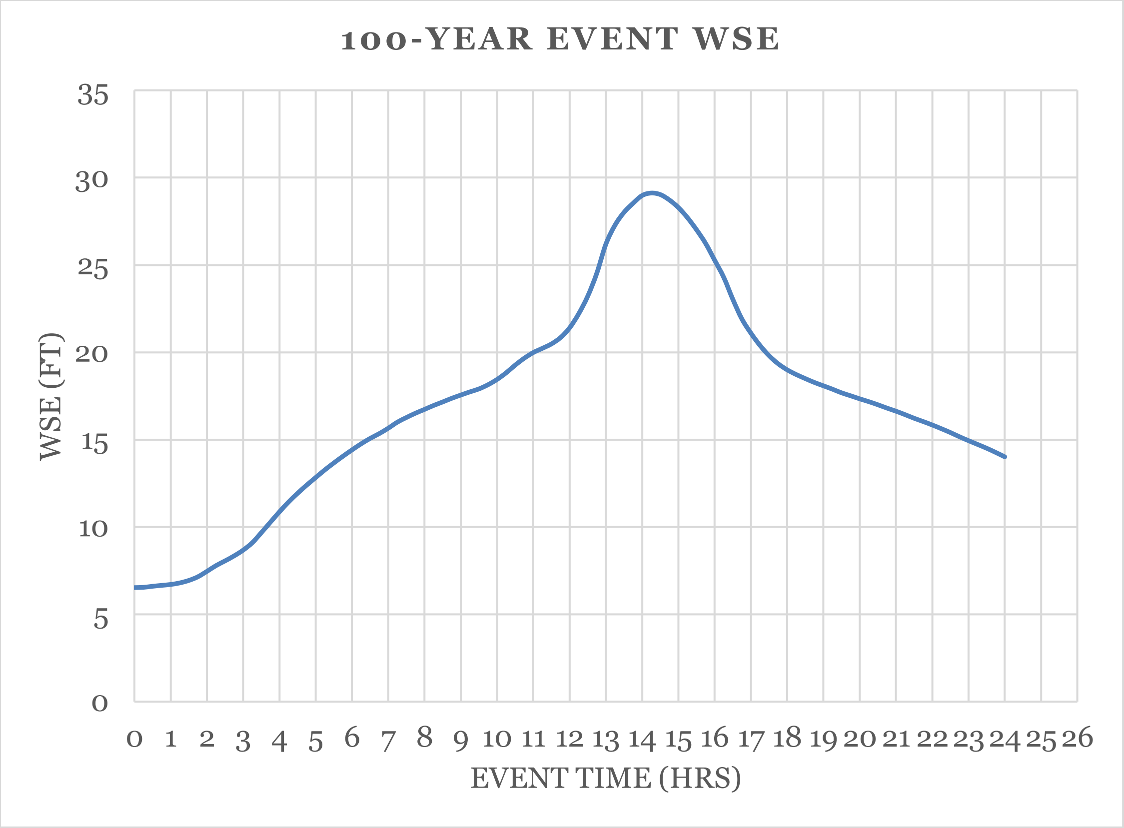


Figure 8. Water surface elevation at the reference location (Piñero Gage – USGS 50049100). Units: feet.

3.2.2 *Mesh Development*

The mesh file defines the finite element computational grid by assigning coordinates and elevations to the nodes. These nodes are located at the vertices of the various elements that define the computational mesh. The mesh is then generated by using triangular elements and nodes at various spacing which are then draped onto an elevation dataset to create a 2D surface mesh. The mesh for this study was constructed from scratch and underwent numerous rounds of mesh refinement to capture the desired level of detail.

To better represent the flow patterns along the model, different meshing methods were applied to include 'patching' along the main and secondary channels and 'paving' in areas outside of the channels. These methods along with the spacing/resolution of the final mesh were selected after performing multiple sensitivity tests. Initial efforts considered a very fine mesh (1 meter in-channel cells) which produced appropriate results according to the calibration standard. However, additional testing produced the same quality results with coarser (variable spacing) cell sizes. Following this result, the coarser mesh was selected for further modeling purposes to reduce run time.

3.2.3 *Hot Start File*

The hot start file is used to specify initial conditions or restart conditions for any given model. This file establishes an initial depth of water and velocity when available. Due to the proximity of the study reach to the ocean and the backwater effects it presents on the downstream portion of the RPN channel, the hot start file used for this study considered an initial water surface elevation set to mean sea level. This was combined with "pooled" inflow areas to prevent these areas from running dry due to the high gradient observed in the upper portions of this basin. Multiple mesh initialization efforts were conducted while getting the model to stabilize, leading to increased minimum inflows compared to the values utilized when creating and running the HEC-RAS model used as reference. These values were carried over throughout the many simulations conducted to calibrate the AdH model. To create the inflow hydrograph, engineers extrapolated the 100-year frequency event data from the HEC-HMS model and assigned it as the "total discharge" corresponding to the inflow areas respectively.

3.2.4 *Roughness Values*

Following the creation of the numerical model mesh file, roughness values were assigned to all elements based on the element's corresponding material type. The material boundaries were based on aerial imagery and LiDAR elevation data. The initial Manning's n-values were obtained from Open-Channel Hydraulics, (Chow 1959), and were adjusted within acceptable ranges to achieve model calibration. The roughness values used within this model study can be seen in the table below and graphically in the material assignment included in Figure 9 and in further detail along the main channel in Figure 10.

Table 3. Manning's n-values.

Number	Name	Roughness n
Mat 1	Ocean	0.035
Mat 2	Middle Channel (US)	0.045
Mat 3	Heavy Vegetated Area	0.064
Mat 4	Residential	0.065
Mat 5	Roads	0.030
Mat 6	Industrial	0.160
Mat 7	Combined Inflow	0.030
Mat 8	Medium Vegetated Area	0.050
Mat 9	Road Bridge	0.045
Mat 10	W680	0.030
Mat 11	Contract 4 and Margarita	0.030
Mat 12	Vegetated Sandbar	0.050
Mat 13	Secondary Channel	0.040
Mat 14	Margarita Channel	0.040
Mat 15	W6702	0.030
Mat 16	Upper River	0.050
Mat 17	Sandbar	0.050
Mat 18	W6701	0.030
Mat 19	W630	0.030
Mat 20	W1180	0.030
Mat 21	Middle Channel (DS)	0.045
Mat 22	Material available	0.030
Mat 23	Material available	0.030
Mat 24	Material available	0.030

*Materials with roughness coefficients of 0.30 do not have an influence on the results of the study. These materials are either inflow areas, available materials, or areas outside the inundation boundary.

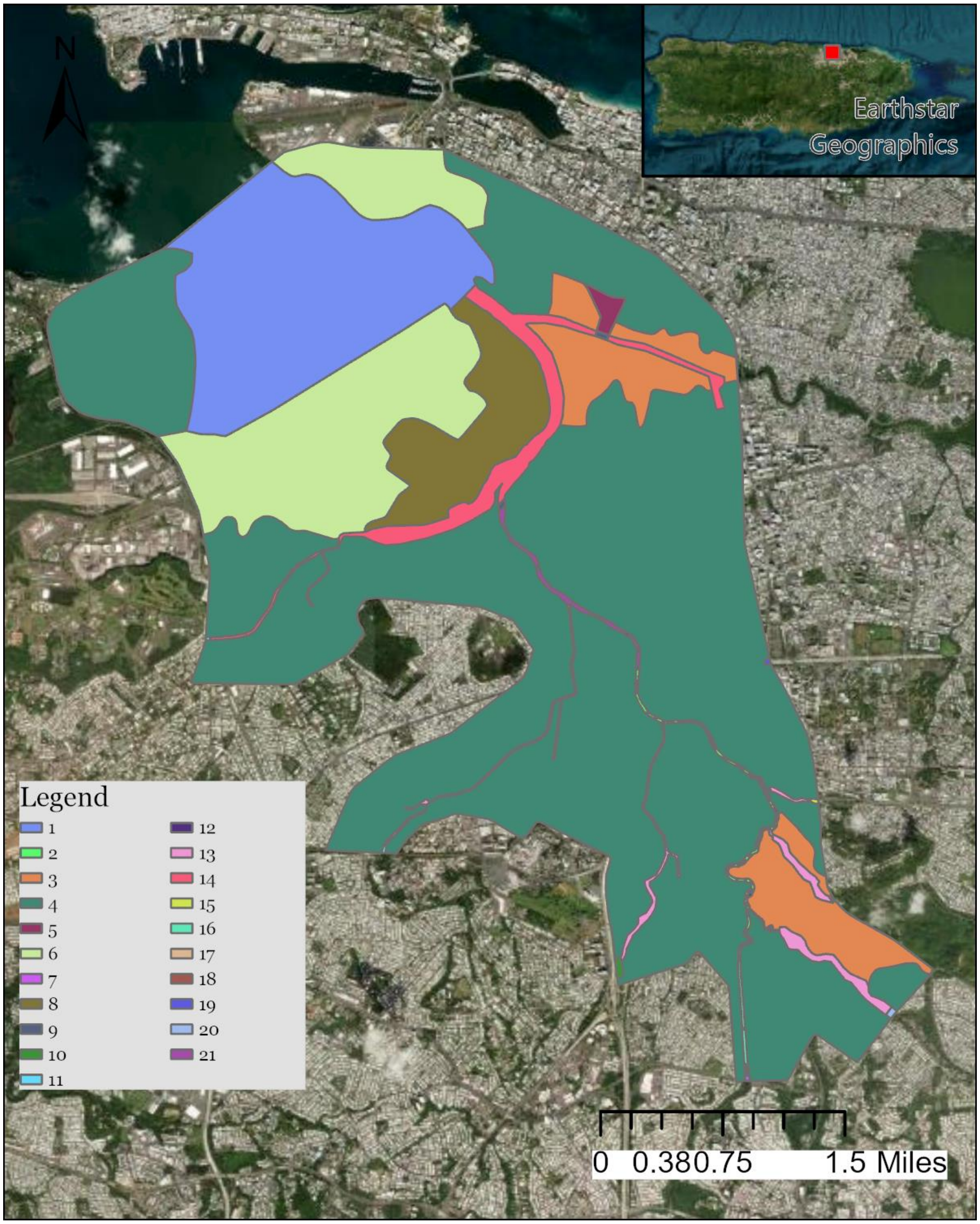


Figure 9. Mesh Material Assignment.

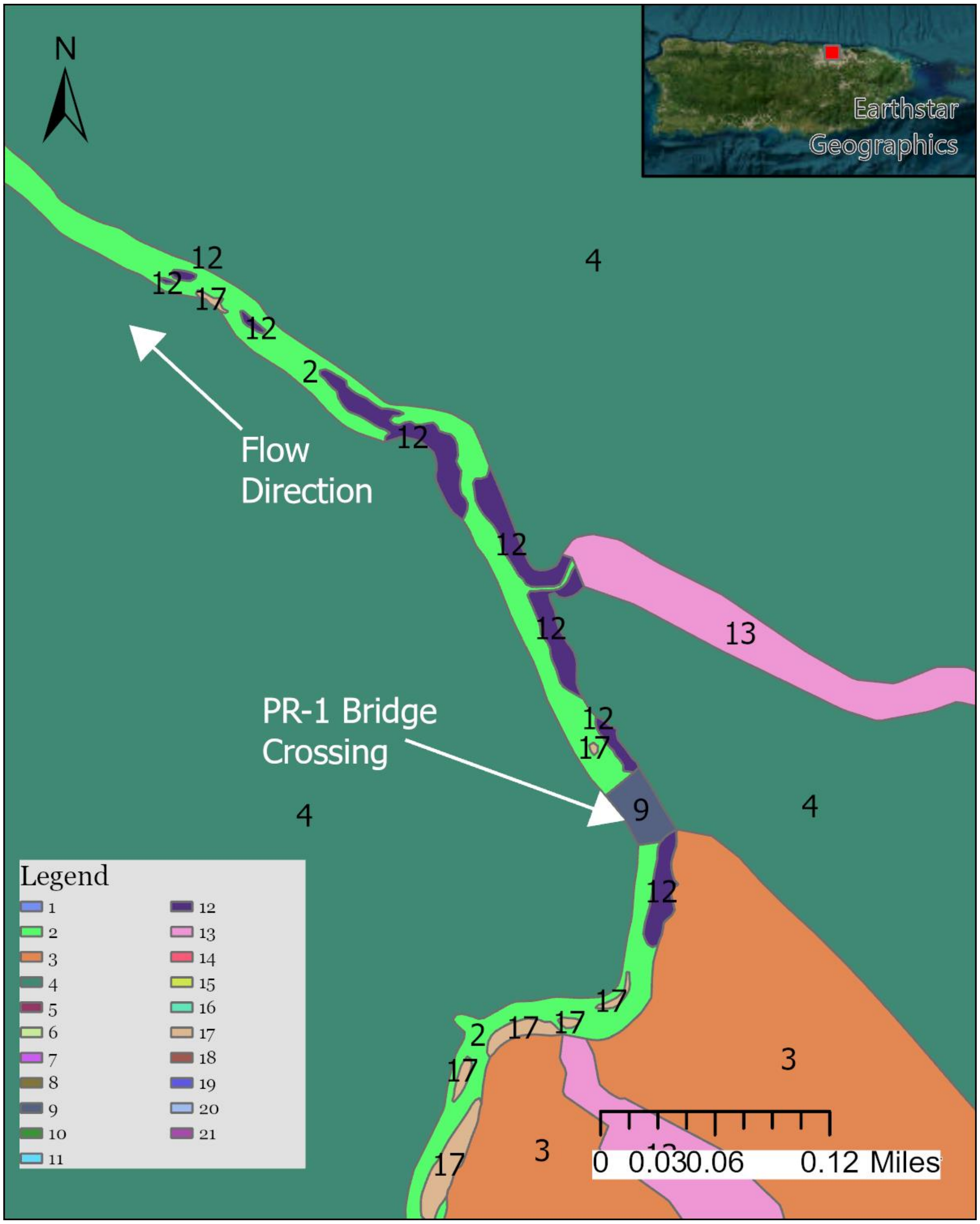


Figure 10. Channel Material Assignment.

During early stages of modeling and calibration efforts, engineers used Manning's roughness values ranging from 0.030 to 0.055 along the main channel. The channel was initially modeled using one material, but additional roughness sensitivity testing demonstrated that multiple roughness coefficients distributed by different reaches provided a better representation of the water surface elevation recorded at the reference location (Piñero gage location) as well as inundation coverage for the 100-year frequency event. Although there were multiple iterations in terms of number/consolidation of inflows, material/roughness coefficient assignment along the main channel, inflow type (total discharge 'NB DIS' versus flow 'NB OVL'), and meshing type, Table 4 presents some of the sensitivity analysis results for main channel roughness coefficient determination. Both the reference WSE and reference timing were obtained from the SAJ HEC-RAS model provided for calibration purposes.

Table 4. Sensitivity testing for main channel roughness coefficients.

Main Channel Material Roughness			WSE at Reference Location		
Upper	Middle Upper	Middle Lower	WSE (ft)	Difference	Timing (hrs)
0.031	0.031	0.031	24.31	-4.81	14.50
0.033	0.033	0.033	24.48	-4.63	14.50
0.037	0.037	0.037	24.54	-4.58	14.50
0.050	0.040	0.030	28.89	-0.23	16.00
0.055	0.045	0.035	26.19	-2.92	15.50
0.030	0.037	0.035	27.43	-1.69	15.00
0.050	**0.045**	**0.045**	27.47	-1.65	15.00

Selected values

Reference WSE	29.12	feet at Piñero
Reference timing	14.25	hours at Piñero

After an intensive period of trial-and-error evaluation of multiple roughness values, statistics corresponding to the root mean square error were calculated (RMSE) and it was determined that the 100-year event conditions (both timing and inundation coverage) were better represented by subdividing the main channel into three separate reaches: Upper, Middle Upper, and Middle Lower. The reaches are subdivided according to the following reference locations included below and presented in Figure 11.

- Upper (n = 0.05): Model Inflow (US) – Ana G. Mendez Ave. bridge
- Middle Upper (n = 0.045): Ana G. Mendez Ave. bridge – Piñero Ave. bridge (approximately at the reference gage location)

- Middle Lower (n = 0.045): Piñero Ave. bridge – Margarita Channel confluence

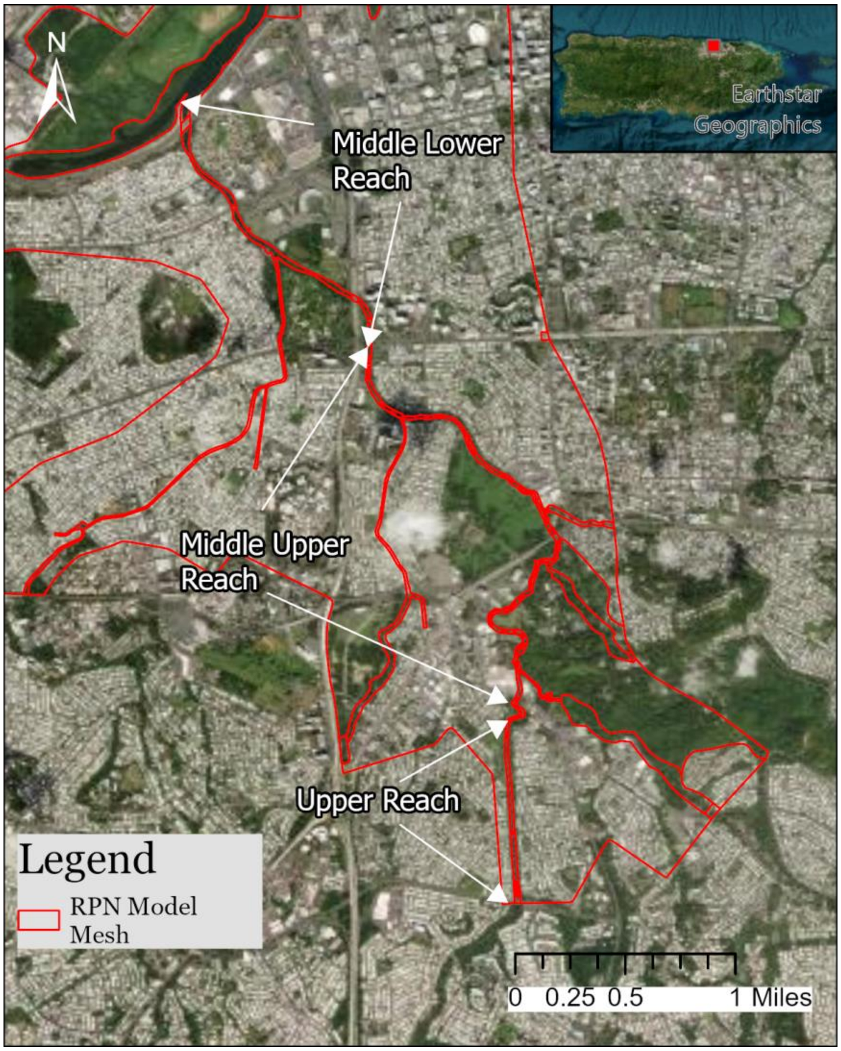


Figure 11. Main channel reach subdivisions for roughness assignments.

The roughness coefficients assigned to overbank areas were also adjusted throughout the calibration process to better match reference conditions. The inundation boundaries along with depth results obtained from the HEC-RAS model served as the key factors for determining the final n-values.

3.2.5 *Computational Environment*

Numerical modeling was executed and compiled by the U.S. Army Corps of Engineer Research and Development Center’s (ERDC) Coastal Hydraulics Lab private High-Performance Computing (HPC), named Jim as an ID.

3.2.6 *Calibration Results*

3.2.6.1 Water Surface Elevation and Depth

Water surface elevation is often utilized as a calibration parameter as it establishes a relationship between the water depth, flow conveyance, geometry, and channel invert. Due to a lack of appropriate monitoring and insufficient historic data, engineers relied on previous modeling efforts as their best source of metrics. After determining the best parameters for the model (including, but not limited to type of inflow, roughness coefficients, and minimum flows), a final calibration run was made to finalize and consolidate the model development efforts and move forward with long-term simulations.

The final calibration run provided a total RMSE of 0.44 for WSE and 0.46 for depth with average error values of 0.21m (0.69ft) and 0.26m (0.85ft) respectively. Table 5 provides additional information regarding the statistical analysis performed.

Table 5. RMSE for the calibration run. Units: feet.

Parameters	WSE	Depth
Total sample size (n)	64	64
Total Model RMSE	1.45	1.52
Average error	0.70	0.86
Average abs error	1.12	1.22

Although the AdH model was based on previous modeling efforts, it did incorporate more recent terrain data. This led MVS engineers to perform the analysis for both parameters (WSE and depth) in an effort of validating the accuracy of the model.

Model water surfaces were evaluated using stage curves from previous RAS modeling efforts and located at the Piñero Ave. interchange area. Figure 12 presents the WSE produced from the calibration run plotted against the reference WSE from Figure 8.

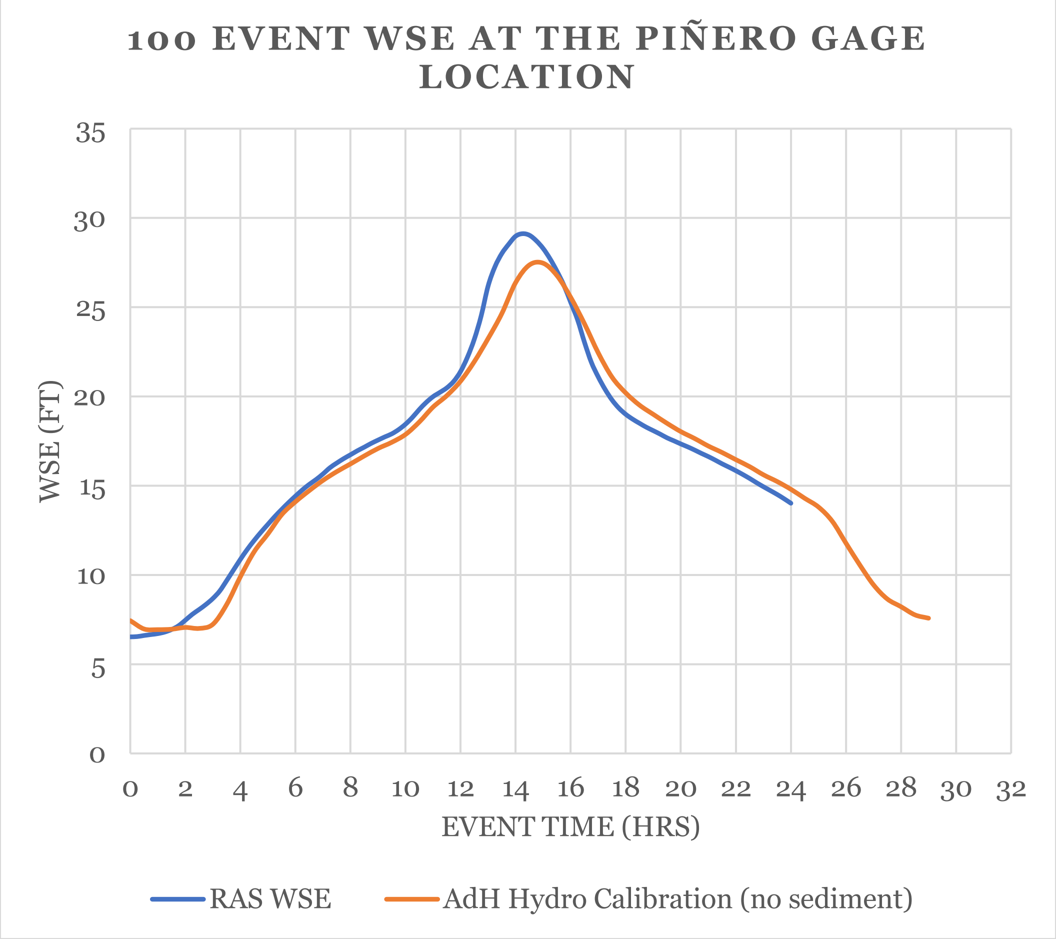


Figure 12. Water surface elevation comparison. Unit: feet.

In general, the RMSE analysis demonstrated fluctuations in orders of less than a foot in the 64 locations tested along the main channel and some overbank areas. At the gage location, however, the deviation increased to 1.6ft, with a peaking time 45 minutes after the peak recorded from the HEC-RAS model results. These results were determined to be within a reasonable range due to the numerous inflow locations, the complexity of the system (including its high gradient), and lack of better calibration/validation data.

Figure 13 through Figure 16 presents the numerical difference between the depths observed in the AdH calibration run and the HEC-RAS reference results.

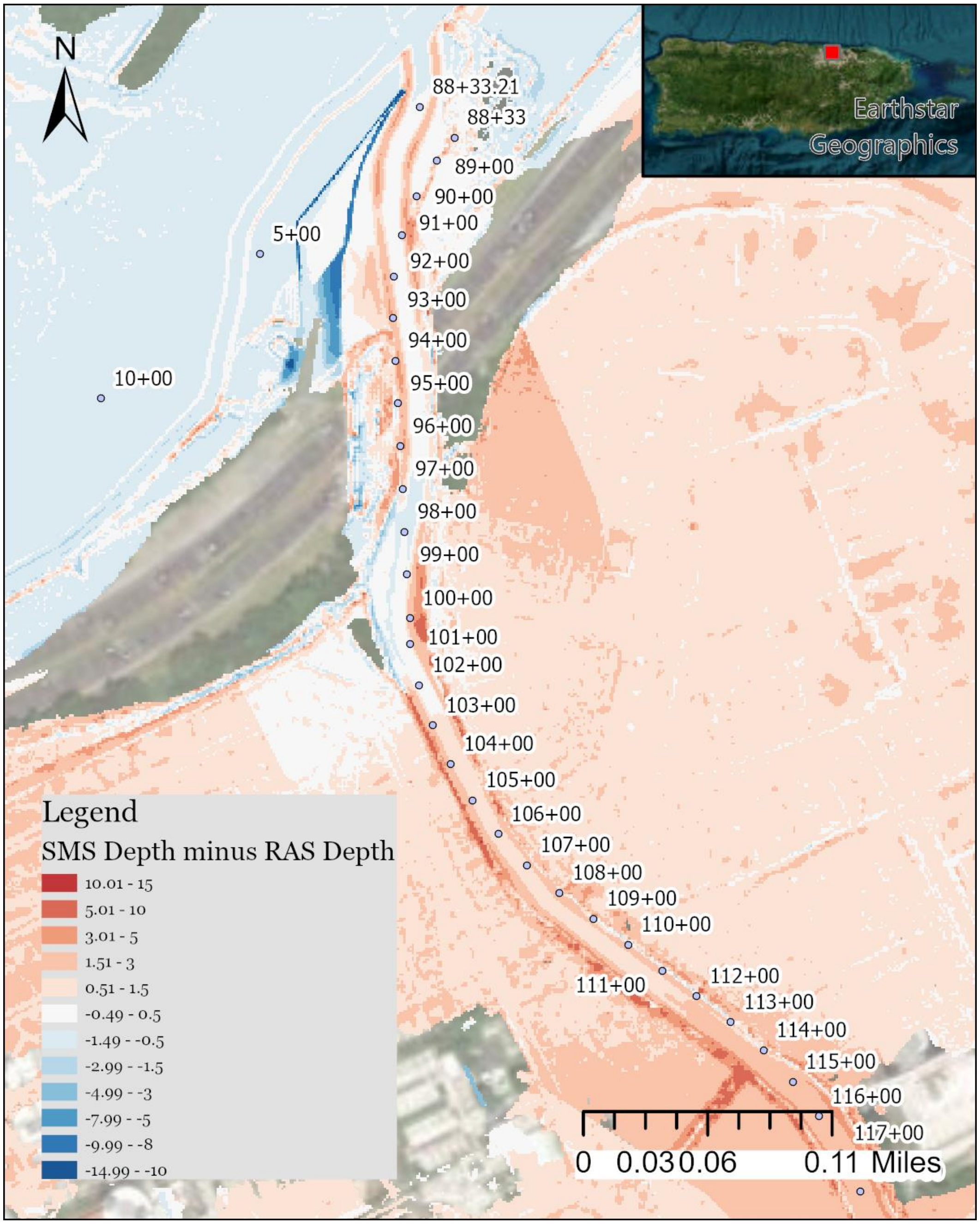


Figure 13. Depth differences between the HEC-RAS model and the AdH (SMS) model between stations 88+33.21 and 118+00. Unit: feet.

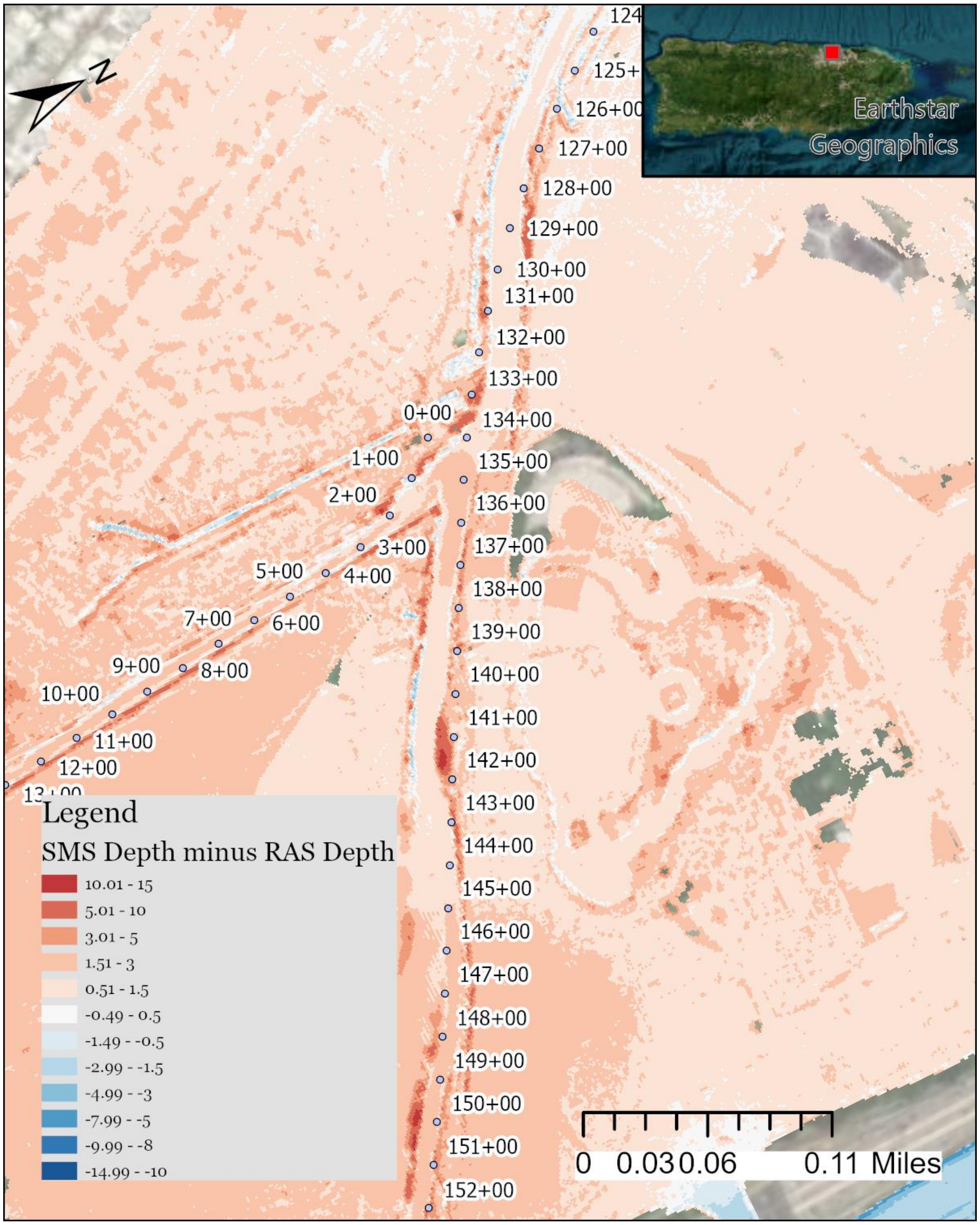


Figure 14. Depth differences between the HEC-RAS model and the AdH (SMS) model between stations 124+00 and 152+00. Unit: feet.

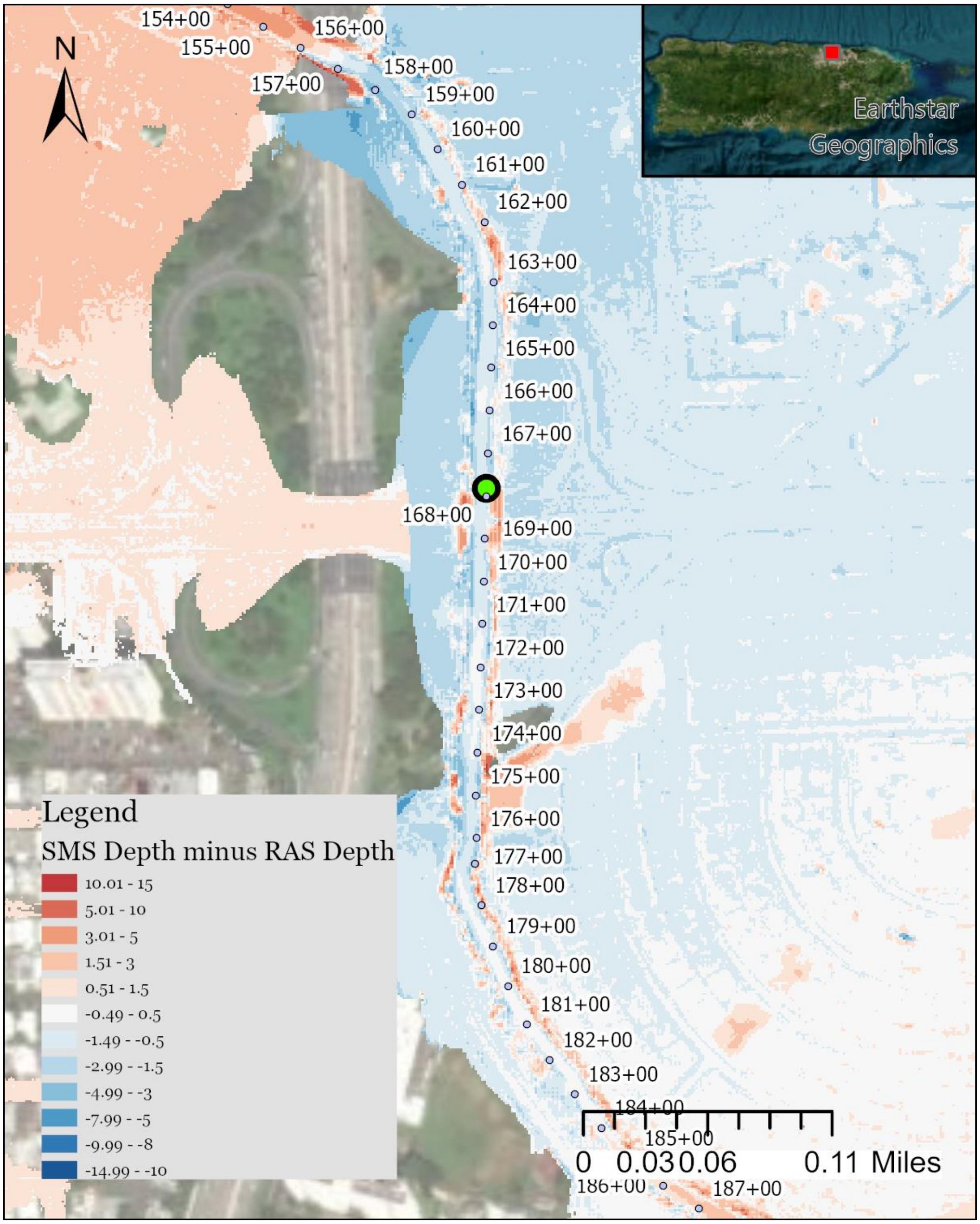


Figure 15. Depth differences between the HEC-RAS model and the AdH (SMS) model between stations 154+00 and 187+00. Unit: feet.

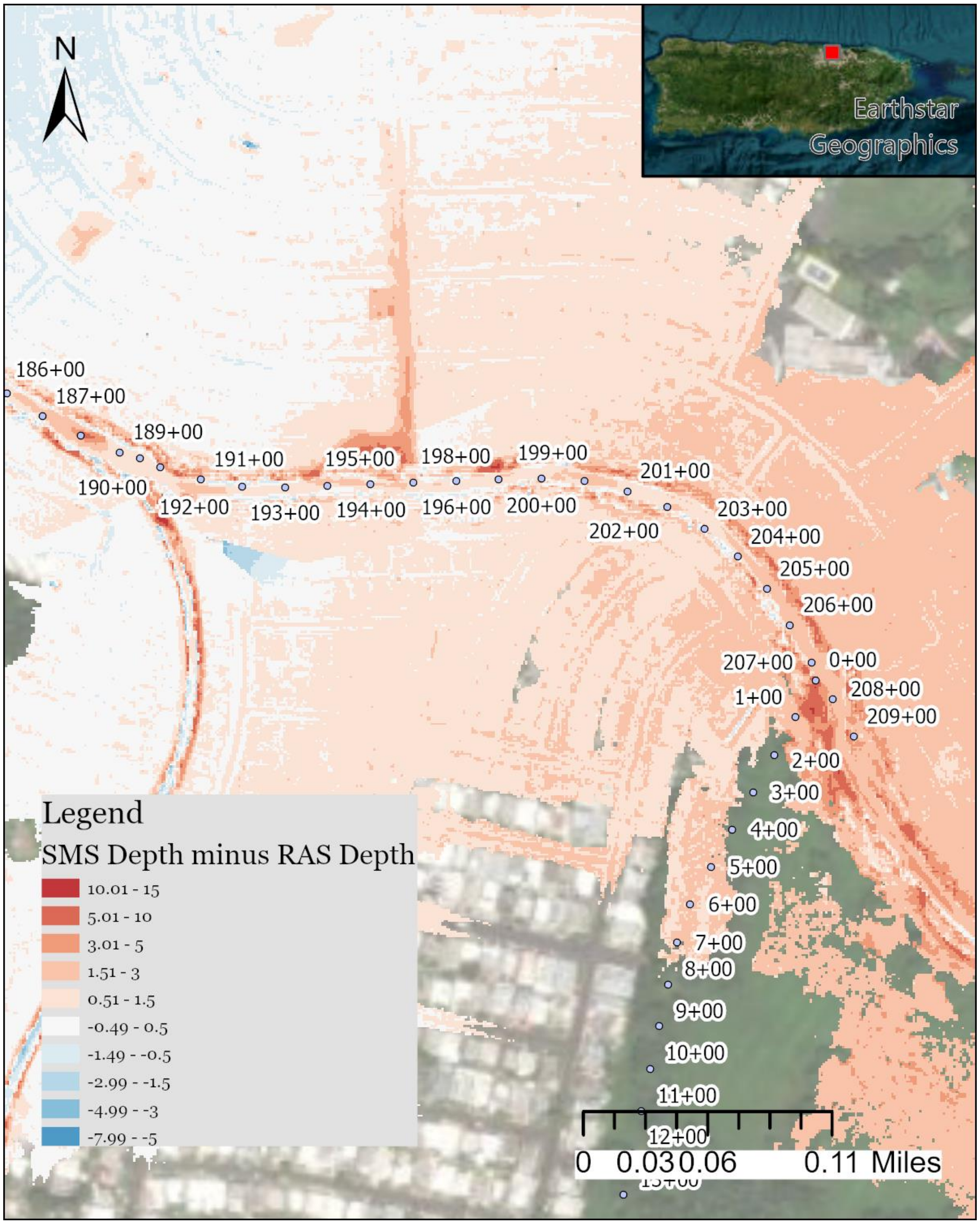


Figure 16. Depth differences between the HEC-RAS model and the AdH (SMS) model between stations 186+00 and 209+00. Unit: feet.

These differences were obtained by comparing depth values from both modeling platforms. Positive values in this case represent higher modeled WSE while negative values imply lowered WSE values when compared to RAS results. It should be noted that areas with higher observed error were located in overbank and inflow areas. Larger error in the overbanks can be attributed to lower mesh resolution in those areas as well as the various mechanisms for routing flow. The errors observed at and immediately downstream of the inflow areas are attributed to inflow boundary dynamics. These areas serve as stabilization zones, producing WSE values that do not necessarily match the reference dataset.

Another factor possibly influencing the flow development and its interaction with the computational elements along the main channel is the time lag for each individual inflow location. Since the suite of frequency events for this system is synthetic in nature, there are some trade-offs regarding the timing for volume routing and the actual flow paths.

3.2.6.2 Inundation Zone

Another parameter MVS engineers relied on while calibrating the AdH model was the inundation area. Using inundation results from the HEC-RAS modeling effort, engineers were able to validate the accuracy of the model as the inundation coverage presented similar extents when compared to the base conditions. Figure 17 and Figure 18 present the base reference for inundation coverage as well as the inundation coverage replicated by the new AdH model, respectively.

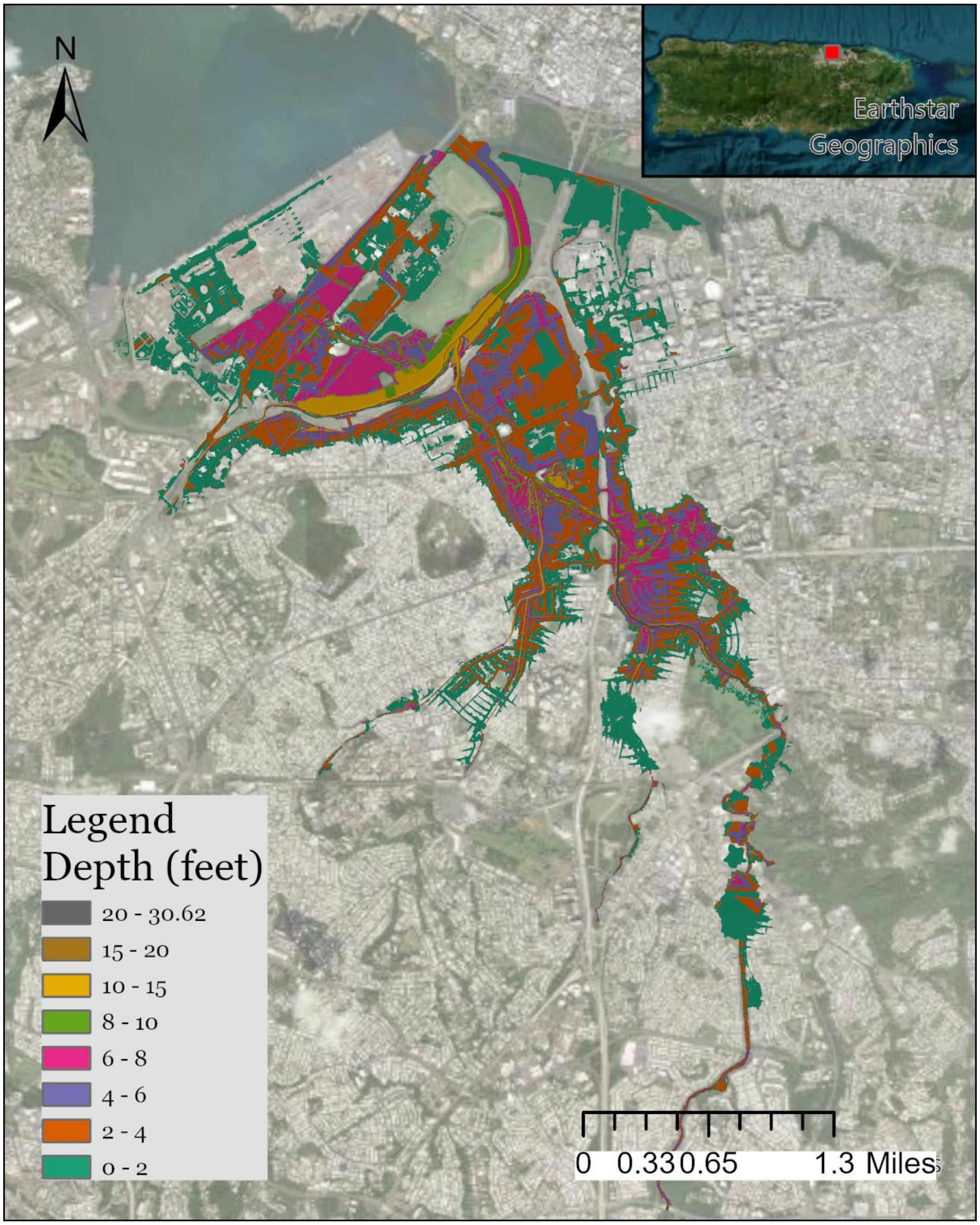


Figure 17. HEC-RAS results showing maximum depth for the 100yr event. This was utilized as the calibration dataset.

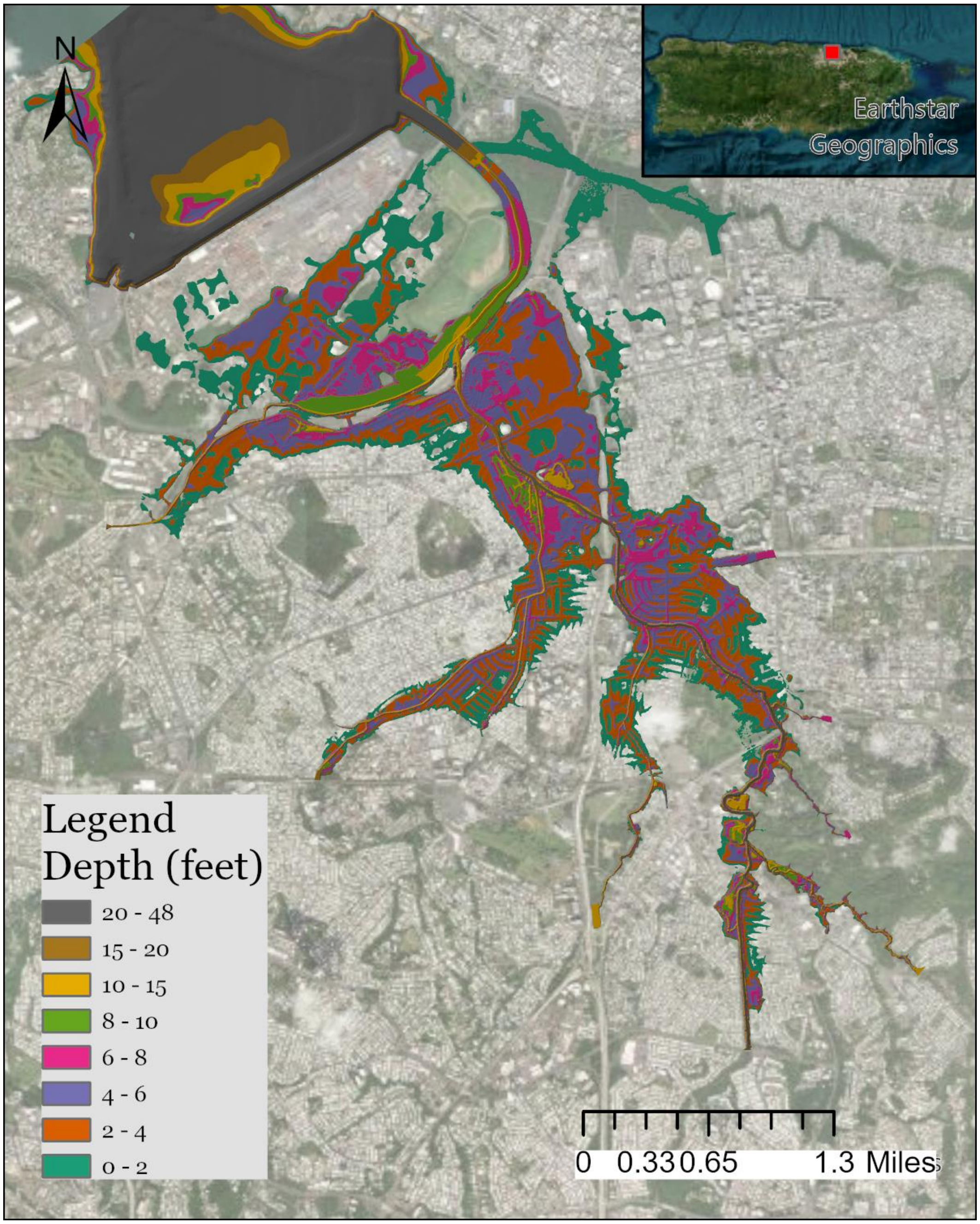


Figure 18. AdH hydrodynamic calibration run showing inundation coverage for the 100yr event.

3.2.6.3 Modeling Error

As the figures above indicate, there are areas within the AdH model that differ from the HEC-RAS results. The following factors could be attributed to those differences:

- Flow routing and inflow type variations from one modeling software to the other.
- Sand bar elevations and geometries are constantly changing and vary greatly in size and geometry in historical aerial imagery.
- Topographic data varied slightly from the HEC-RAS model and AdH due to different collection years on LiDAR being used.
- Roughness coefficient assignments and mesh material designations varied between models due to modeler judgement.

3.3 *Sediment Composition*

3.3.1 *Sediment Modeling Constraints*

Appropriate and complete sediment information is crucial when developing numerical models to replicate in-situ conditions and general riverine behaviors. Recognizing that sediment dynamics are extremely variable and unique to every system, it is essential to consider the levels of uncertainty implicit to any model when incorporating sediment components. The lack of current sediment data due to the absence of a monitoring station adds to the inherent risks associated with systematic sediment dynamics. However, sediment models utilize the best available information to forecast systematic trends and serve as an effective initial tool. Both the reliability and accuracy of the model could be improved by adjusting/updating it over time as information and data becomes available.

3.3.2 *Bed Gradation*

As with any AdH sediment model, modelers rely on accurate sediment gradation counts from the system being modeled for increased confidence in model results. In June 2021, St. Louis District engineers collected bed sediment samples in different locations throughout the Rio Piedras main channel to better understand the sediment classes transported through the system in the form of suspended load and mobile bed during high flow events. Laboratory reports resulting from these samples are included in the Appendix. The locations of the samples collected in this effort are included in Figure 19.

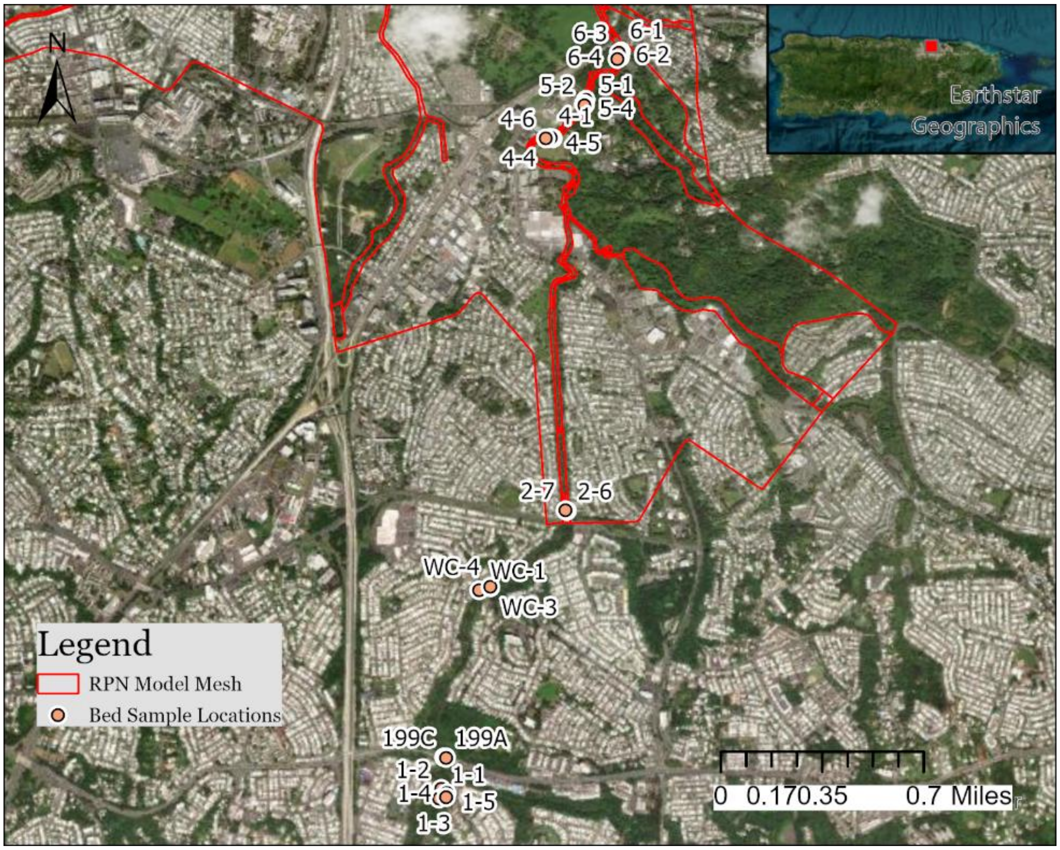


Figure 19. Sediment sample collection locations.

The samples collected were grouped based on their location on the channel. Average distribution information obtained from laboratory testing is included in the figure below for every grouped location as well as the global average for all 27 samples.

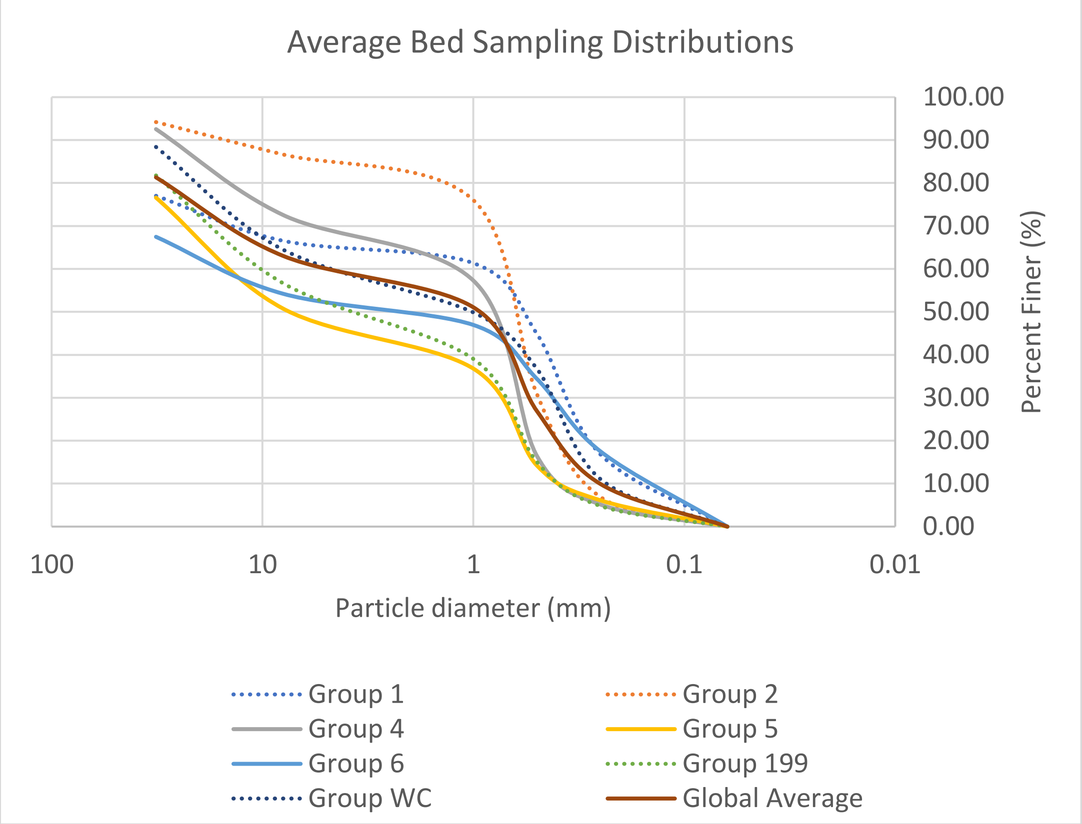


Figure 20. Collected samples gradation distribution per group. Groups 4, 5, and 6 are located within the final model domain.

After analyzing multiple bed gradations and compositions, engineers concurred on using an overall arithmetic average to assign initial bed distributions to the model. Laboratory results showed similar grain classes that make up the mobile bed portion of the main channel. A gradation curve and the random distribution of the initial bed conditions are illustrated in Figure 21. Table 6 presents the grain classes utilized for this modeling effort along with their initial compositions.

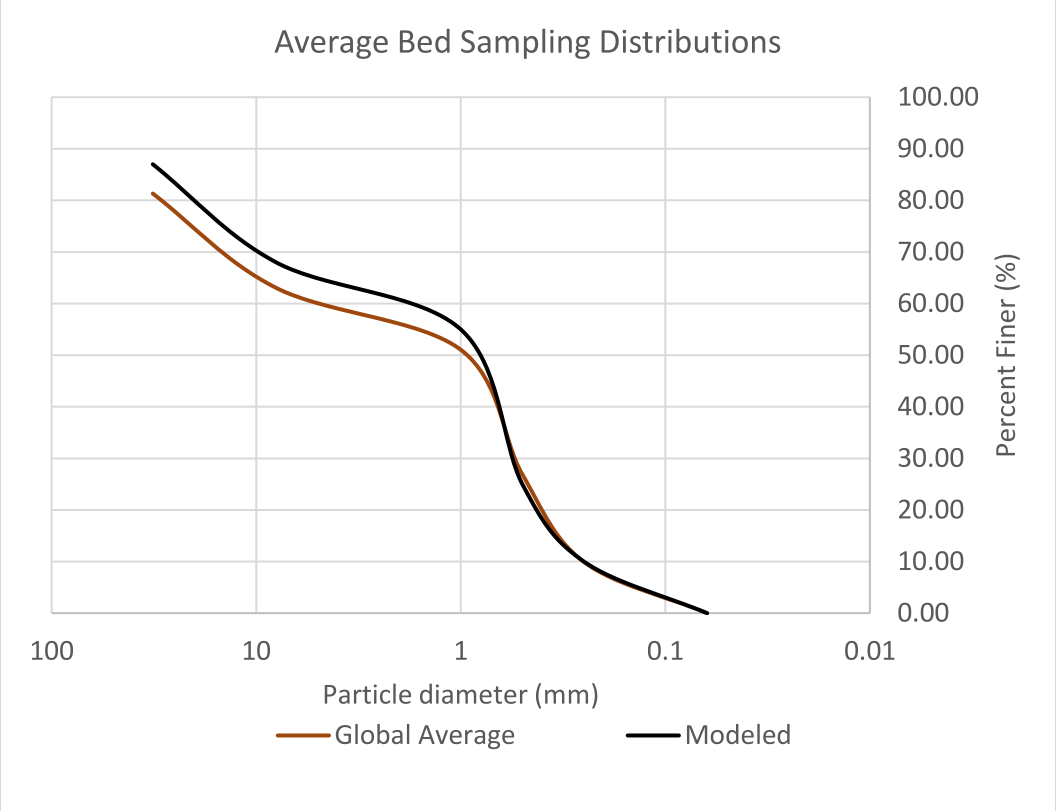


Figure 21. Sample Averaged Gradation curve.

Table 6. Sediment grain classes and initial bed composition.

Grain Class	Particle diameter (mm)	Fixed Bed Composition
Fine Sand	0.25	15%
Medium Sand	0.5	30%
Coarse Sand	1.0	13%
Fine Gravel	8.0	19%
Coarse Gravel	32.0	13%
Silt	0.0625	10%

The composition shown above as “Modeled” was utilized to initialize the model bed. Early sediment calibration efforts demonstrated that using a uniform sediment distribution across all the materials in the mesh produced more consistent results by replicating some of the riverine behaviors and natural sorting recorded through the collection samples. The values corresponding to the “Modeled” curve do show slight variations from the “Global Average” (arithmetic average) due to trying to replicate the in-situ conditions of the bed. Initial results showed an exponential increase in grain sizes at most of the sampled locations, which was countered with an increased amount of finer material in the “Modeled” distribution.

3.3.3 *Bedload sediment entrainment*

AdH provides multiple ways to re-insert bed material into the model domain, to include an equilibrium transport function (EQ TRN) that allows for the conservation of mass. Since manual inputs require extensive sources and amounts of data, modelers often utilize the built-in capabilities by allowing the model to sort out its own equilibrium based on the stream power and the corresponding concentration necessary to maintain equilibrium. Although this equilibrium card could be applied to both cohesive and non-cohesive sediment particles, it was only utilized for the non-cohesive portion of the grain classes (sands and gravels) given the conditions previously established.

3.3.4 *Suspended sediment entrainment*

The suspended portion of the sediment component was determined using pre-existing relationships between flow and concentration. As part of the data collection efforts dating back to the feasibility phase of the project (1980s), sediment load was measured at the formerly active Rio Piedras at El Señorial gage (USGS 50048770). Figure 22 shows the rating curve derived at this location.

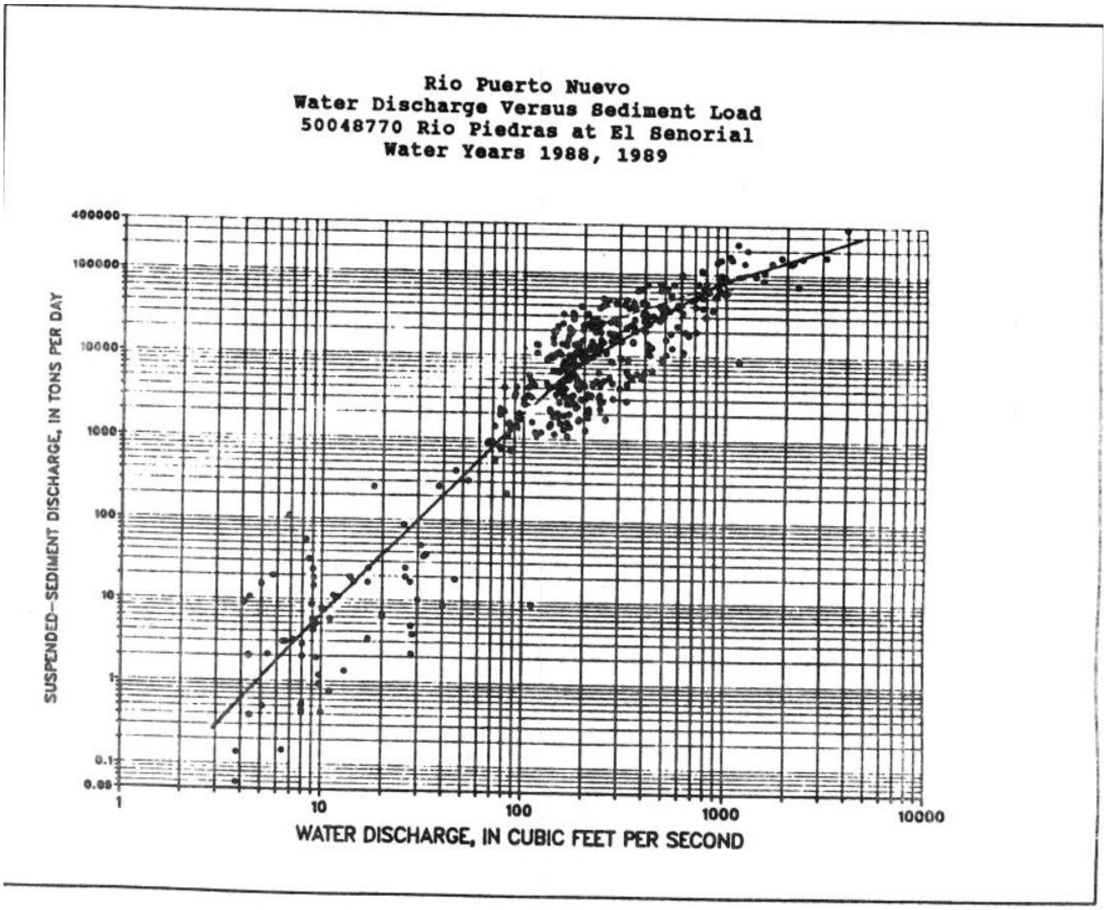


Figure 22. Sediment Load curve at El Señorial gage (USGS 50048770) (Source: GDM).

This rating curve, developed by the USGS, had to be estimated for computational purposes due to the original data being unavailable. Engineers identified pivoting points along the original curve and used linear functions to describe the resulting segment. The piecewise curve derived from it was utilized to estimate the sediment load at any given discharge value as presented in Figure 23.

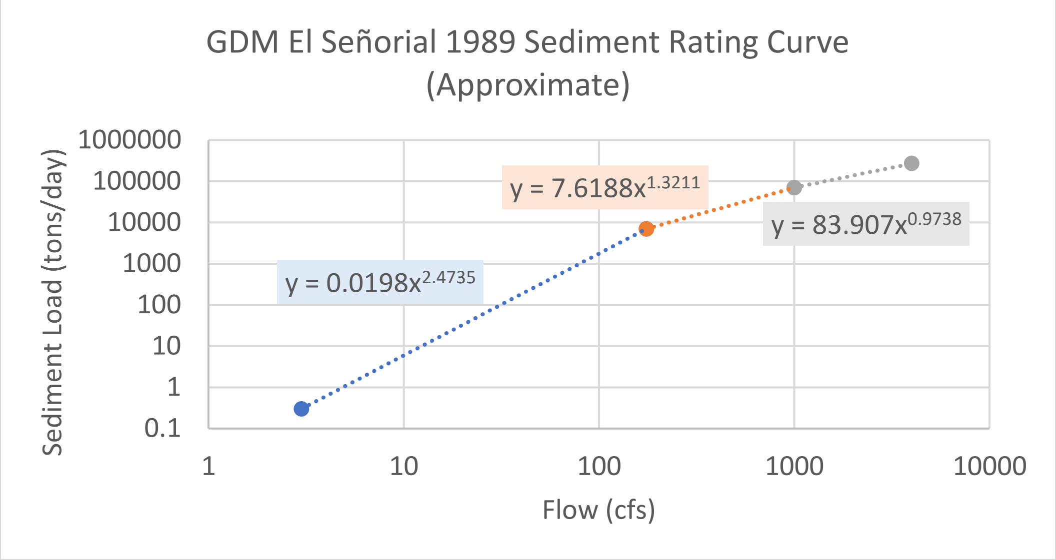


Figure 23. Sediment rating curve re-interpretation.

The silt portion corresponding to every sediment load value was obtained from relationships established while developing the HEC-RAS model. Since rating curves cannot be included within AdH models, all concentration values were calculated using MS Excel using the concentration equation and then incorporated as time series for every inflow area respectively. The equation for concentration (C) implemented considered both sediment load (Qs in units of tons/day) as well as water discharge (Qw in cubic feet/second) and is included below for reference. The 0.0027 coefficient (in inch-pound units) is based on the unit of measurement of the water discharge and assumes a specific weight of 2.65 for sediment particles (Gray & Simões, 2008).

$$C = \frac{Qs}{0.0027 * Qw}$$

Using this equation along with the long-term hydrograph, the concentrations for the sedimentation analysis were calculated. These concentrations were distributed throughout the simulation years as presented in Table 7.

Table 7. Annual suspended sediment concentration inflow.

Year	Annual concentration (ppm/yr)
Y1	1579399
Y2	1588816
Y3	1608403
Y4	1757211
Y5	1606543
Y6	1615874

3.4 *Model Sensitivity Testing*

Several parameters were altered to determine the model sensitivity. These parameters include but are not limited to:

- Mesh refinement
- Initial bed gradation
- Wetting and drying tolerance
- Gravel re-insertion disabled

3.4.1 *Mesh Refinement*

As with any modeling software, tradeoffs associated with the level of resolution and its effects in the computational time are also present in AdH modeling. To address this, engineers waited until sufficient information was obtained from the initial mesh and tested out multiple meshes with variations in spatial resolution. These additional tests demonstrated that changes to the original mesh resolution would not have significant impacts in the accuracy of the results obtained. However, due to the small scale of the system when running baseflow conditions, this parameter resulted to be the most sensitive. The original mesh used elements with 2m (6.5ft) edges, while the final mesh used cells with 5m (16.4ft) edges. With the change in cell size, WSE values at the reference location (USGS Piñero Gage) WSE observed values increased by approximately 0.3ft and flow conveyance increased by 0.15%. At the same time, run time was significantly reduced, resulting in more stable and efficient model runs.

Tests were performed for both hydrodynamic calibration and sediment calibration processes to ensure the new cell size did not influence sediment dynamics negatively.

3.4.2 *Initial Bed Gradation*

Selecting an initial gradation was a challenging yet crucial step for engineers to have confidence in the results obtained and the conclusions derived from this modeling effort.

Multiple alternatives were tested to include (1) assigning specific bed gradations per material (i.e.: differentiating sand bars from the main channel), (2) using an averaged gradation based on all the samples collected within the model domain (in other words: not differentiating between materials), and (3) using the gradations as developed for the HEC-RAS model during initial sediment modeling efforts. Table 8 presents the gradation variations between alternatives.

Table 8. Initial bed gradations tested during calibration phase.

Test	Fine Sand	Medium Sand	Coarse Sand	Fine Gravel	Medium Gravel	Coarse Gravel	Silt
1	24.0%	45.0%	11.0%	5.0%	0.0%	4.0%	11.0%
2	15.0%	30.0%	13.0%	19.0%	0.0%	13.0%	10.0%
3	15.0%	25.0%	15.0%	35.0%	5.0%	5.0%	0.0%

After an extensive calibration phase, engineers opted for using alternative/test 2 (an averaged gradation) to move forward with additional modeling efforts. Since WSE differences between the results of the alternatives were minimal (ranged in the order of 1/10 foot) and time conveyance was not compromised, the team decided to use a universal (or averaged) gradation for every material class uniformly. By doing this, added complexity was removed from the model as this alternative replicated what the model was predicting to happen (coarsening of the bed throughout the domain). Regardless of the bed gradation conditions initially established, the grain distributions throughout the waterway are bounded to change rapidly as flow exerts and dissipates energy during the long-term run.

Once the gradation trial period was completed, a 2-year storm event was routed through the system to redistribute the various grain classes throughout the domain. This ‘warm-up’ process is utilized at the initial stages of sediment modeling to allow the system to gain stability by self-adjusting in function of its energy and sediment-water interactions.

3.4.3 *Wetting and Drying tolerance*

The wetting and drying card in AdH allows the user to define the maximum drawdown or node submersion from one timestep to the next. This simple yet important parameter dictates how the model reacts and is especially important when modeling high-grade systems. RPN did present singularity issues (another term for 'inconclusive solution') directly associated with the variation of this parameter. Due to the flashiness of the system and the intensity of the events being tested, this parameter had to be set to 1m (3.28ft) for the model to be stable and run through completion when testing the scenarios. The wetting and drying tolerance is an adjustment parameter applied to a stabilization term within the model to conserve energy at wet-dry boundaries. Good modeling practices adopt small wetting/drying tolerances to ensure energy is preserved, but the actual value will be dictated by the system's gradient and hydrograph shape (with flashier systems requiring larger values than usual).

3.4.4 *Gravel re-insertion*

Since this card resolves equations pertaining to mass balance, the re-insertion of material through the upstream boundaries is based off the stream power and the different incipient motion thresholds for every grain size individually. In a high-grade system like Rio Piedras, stream power plays a big role in the type of sediment it is capable of mobilizing. Throughout the calibration phase, trends indicated a general increase in grain size across the model domain; specifically in grain sizes corresponding to fine gravels. This is a direct response from the model to stream power and bed shear as the bed distribution readjusts and armors to compensate for the energy exerted on the system.

Multiple sediment parameters were adjusted to reduce the coarsening of the bed. One of the sensitivity tests performed involved turning off the fine gravel reinsertion by eliminating the equilibrium card corresponding to this grain class. This did not resolve the coarsening of the bed Engineers determined the coarsening of the bed would have minimal impact on future sedimentation analyses as the erosional and depositional patterns followed the expected behavior. The long-term consequence of not allowing re-insertion of finer gravels could have incremented bed armoring, which would have altered the system's capacity to move finer materials in unrealistic amounts due to a lack of bed mixing.

4 Long-Term Sedimentation Simulations

The post-project condition (or with project condition) incorporates the changes corresponding to the implementation of the design channel in the lower reach of the system. This section presents the development of the base mesh for the long-term simulations as well as the built-in conditions utilized to perform the assessment. These modeling conditions were utilized to assess sedimentation as a consequence of not having a sediment basin or any other sediment control feature upstream of the natural-designed channel transition.

4.1 *Design Channel*

Once the team had a calibrated sediment model, the design channel section was embedded into the topography and simulated. SAJ personnel from the Geomatics Section combined the geometry features from the various contracts and stitched them together to create a new terrain for evaluation. The newly developed raster file, which combined the existing conditions with these geometric features, created the proposed project surface as indicted in Table 9.

Table 9. Elevation source for post-project mesh surface.

Survey	Survey Type	Vertical Datum	Year
RPNwSurvey_Model_NAD83_2011_PRVD02 _Meters_20221031	CADD	(PRVD02)	2022

This new mesh served for testing long-term sedimentation patterns along the design channel. It was also used to determine the efficiency of various frequency events on the ability to maintain channel capacity and remove unwanted sedimentation. In the figure below, we can see a sample of the design channel.

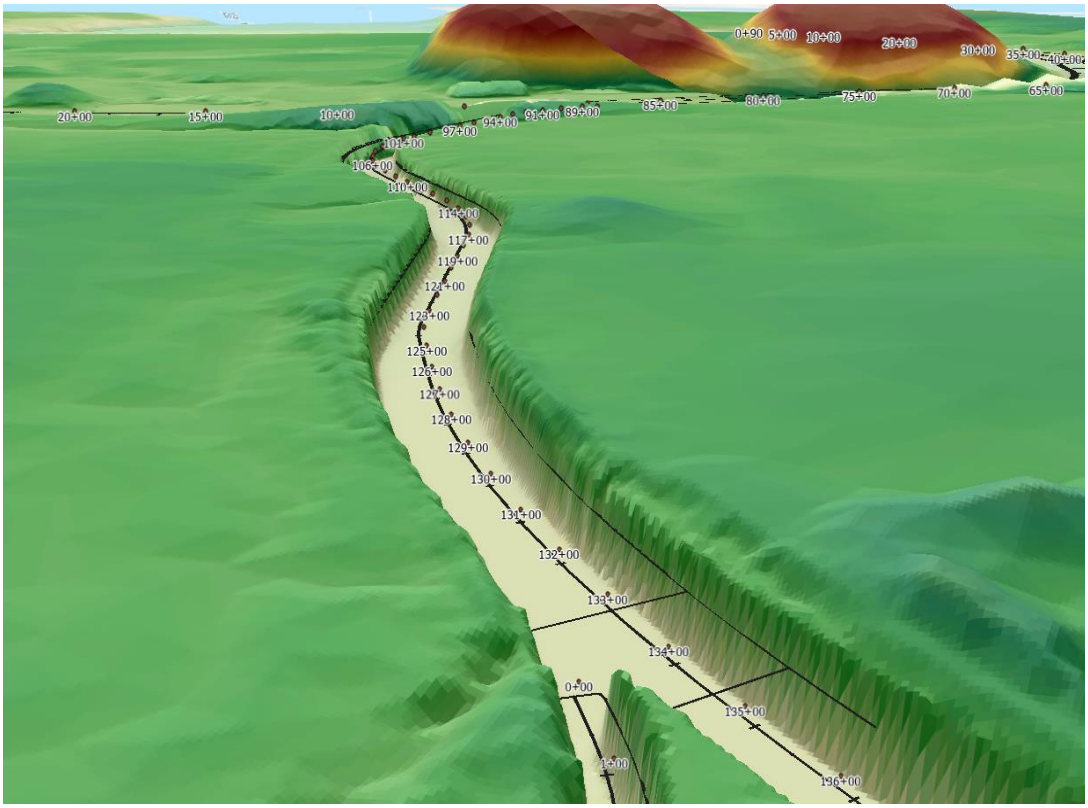


Figure 24. 3D view of the design channel raster buried into the model. This mesh was utilized for long term simulations and channel capacity tests.

4.2 *Long-term simulations*

4.2.1 *Hydrograph*

The long-term hydrograph presents a series of “lulls and peaks” recorded while the Rio Puerto Nuevo Flood Mitigation project was undergoing feasibility design. It consists of six years of uninterrupted flow data ranging from base flows of 2 cfs to ramped up periods of 1,500 cfs. It should also be noted that this selected hydrograph does not contain a frequency event greater than or equal to a 2-year event. It considers average daily flows with durations of 24 hours per data point and could be seen as quasi steady state. Figure 25 presents the hydrograph that was used for long term simulations.

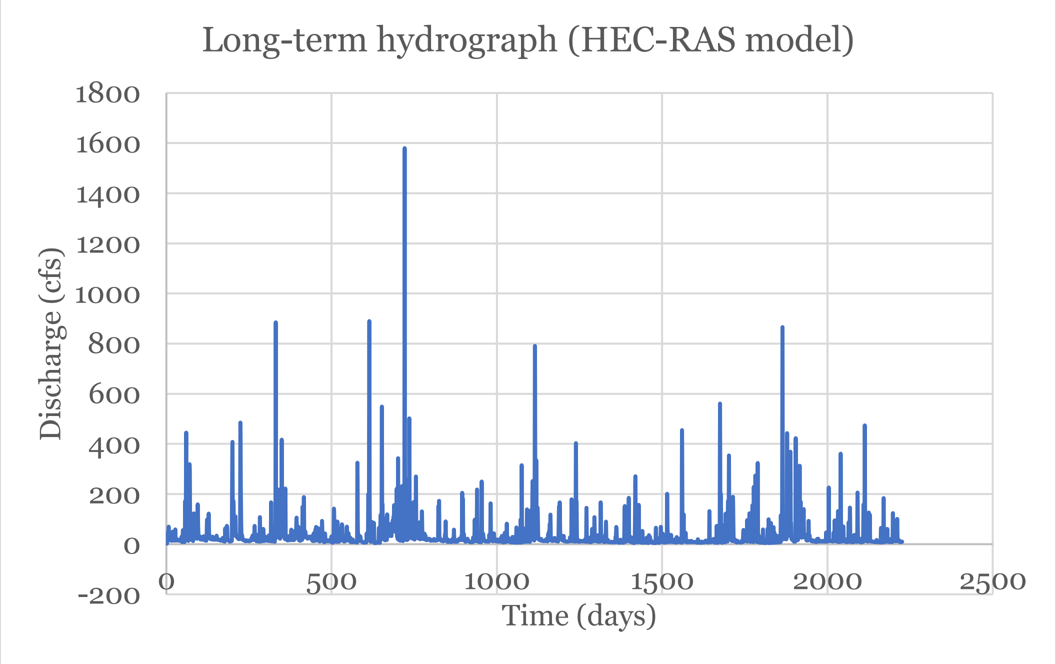


Figure 25. Long-term hydrograph from HEC-RAS quasi-steady simulation.

As detailed in the calibration section, the base flow was increased to improve model stability and solution conveyance. Along with this change, the hydrograph was slightly shifted to let low flows and scattered storms dictate the hydraulics and sediment dynamics for the first few years. This allowed sedimentation to occur along the design channel with limited transportability (or less scour potential) until the final year. This was viewed as a realistic approach and was vetted by hydraulic engineers from SAJ & MVS. Figure 26 illustrates the adjusted hydrograph and the computational breaks that were used for easier computational purposes. This also allowed engineers to test various frequency storms after every ramp up period and determine overall sedimentation impacts on the events.

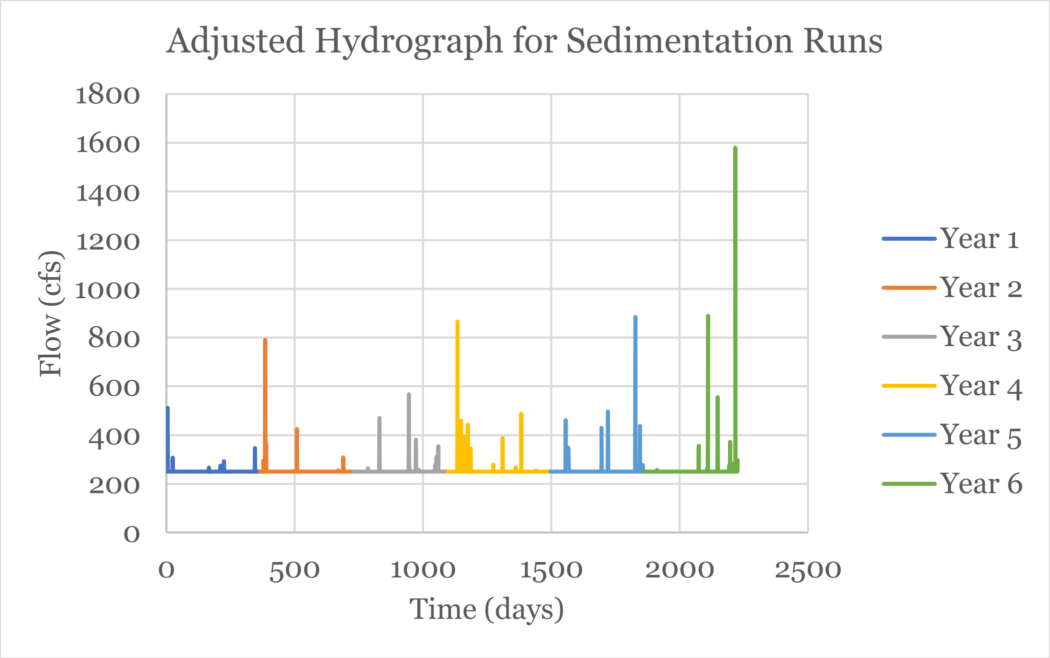


Figure 26. Long-term hydrograph adjusted for AdH sedimentation runs.

Even though the six years of data captured multiple scattered precipitation events, it is important to comment on their magnitude and characteristics when compared to frequency events. See Table 10 and

Table 11.

Table 10. Maximum Inflow at each long-term hydrograph subdivision.

Year	Maximum Inflow (cfs)
Y1	512
Y2	791
Y3	567
Y4	866
Y5	885
Y6	1580

Table 11. Maximum Inflow for frequency storm events.

Storm Event	Annual Exceedance Probability (AEP)	Maximum Inflow (cfs)
2-year	50%	7779
5-year	20%	10660
10-year	10%	12627
25-year	4%	15022
100-year	1%	22572

Understanding that none of the scattered rain events captured in the RPN watershed corresponds to a frequency storm is essential and implies that all sediment dynamics are guided by localized hydraulics rather than large scale transportation. Because this area is highly influenced by tidal effects, this results in sediment particle’s ability to settle out due to dissipation of stream power or energy.

5 Sedimentation Analysis and Results

Although the model covers the vast majority of the RPN watershed, sedimentation analysis efforts focused on the proposed design channel reach (see section 4.1). The channelized section extends upstream approximately 6.46 miles along the main channel of Rio Piedras from its confluence with the Margarita channel. Modeling efforts were geared towards understanding long term sedimentation and its effects on maintaining channel capacity. Ultimately, these results will be made available to the non-Federal sponsor in the Operation and Maintenance (O&M) plan.

5.1 *Sedimentation Analysis*

The analysis implemented to quantify and describe sedimentation along the engineered channel portion of the river consisted of a spatial analysis and a cross-sectional analysis. The spatial analysis focused on the horizontal distribution of the depositional material (plan view) while the cross-section tool focused on evaluating channel capacity (profile view). Because the Margarita channel was of concern due to potential dredging going forward, engineers also included this area to evaluate long-term sedimentation concerns.

5.1.1 *Spatial analysis*

The spatial analysis produced a qualitative assessment of the sediment distribution across the physical limits of the design channel. In this analysis, we see large swaths of either sediment aggradation or degradation and how the hydrodynamics generated by local conditions can have an impact on spatial distribution.

5.1.2 *RPN cross-section tool*

The RPN cross-sectional tool was developed specifically for this riverine system. This tool analyzes, quantitively, the channel capacity based on the cross-sectional area differences between the base condition and any given point in time during the long-term simulations. The tool functions by calculating the cross-sectional data and then calculating differences between base conditions and graphically plotting results. From these cross sections, we then estimate volume capacity by interpolating consecutive cross-sections to obtain volumes.

Additional details on the geoprocessing tools and other code specifics are included in the appendix.

5.2 *Sedimentation Results*

The tools and processes previously described were applied after the completion of every simulation year. In general, consistent results were generated in this study along with high confidence in aggradation and degradational trends. As expected, higher concentrations of silt settlement were recorded downstream of STA 181+00 due to tidal influence. Spatial distributions and estimated aggradation quantities are included in Figure 27 through Figure 32.

Although changes in material displacement were recorded at the Margarita Channel confluence area since the first year of simulations, quantifiable and significant depositions were not observed until after the third simulation year. Most of the material deposited in this area remained in place throughout the six years and was only significantly displaced after routing any of the five frequency storms through the system. Estimating depositional volumes in this area was identified as a need due to potential dredging concerns.

5.2.1 *In-channel sedimentation*

The following set of figures depict the spatial distribution of the aggraded material in the lower portion of the engineered channel after yearly simulations. Although results are reported in elevation units, results should be viewed as qualitative.

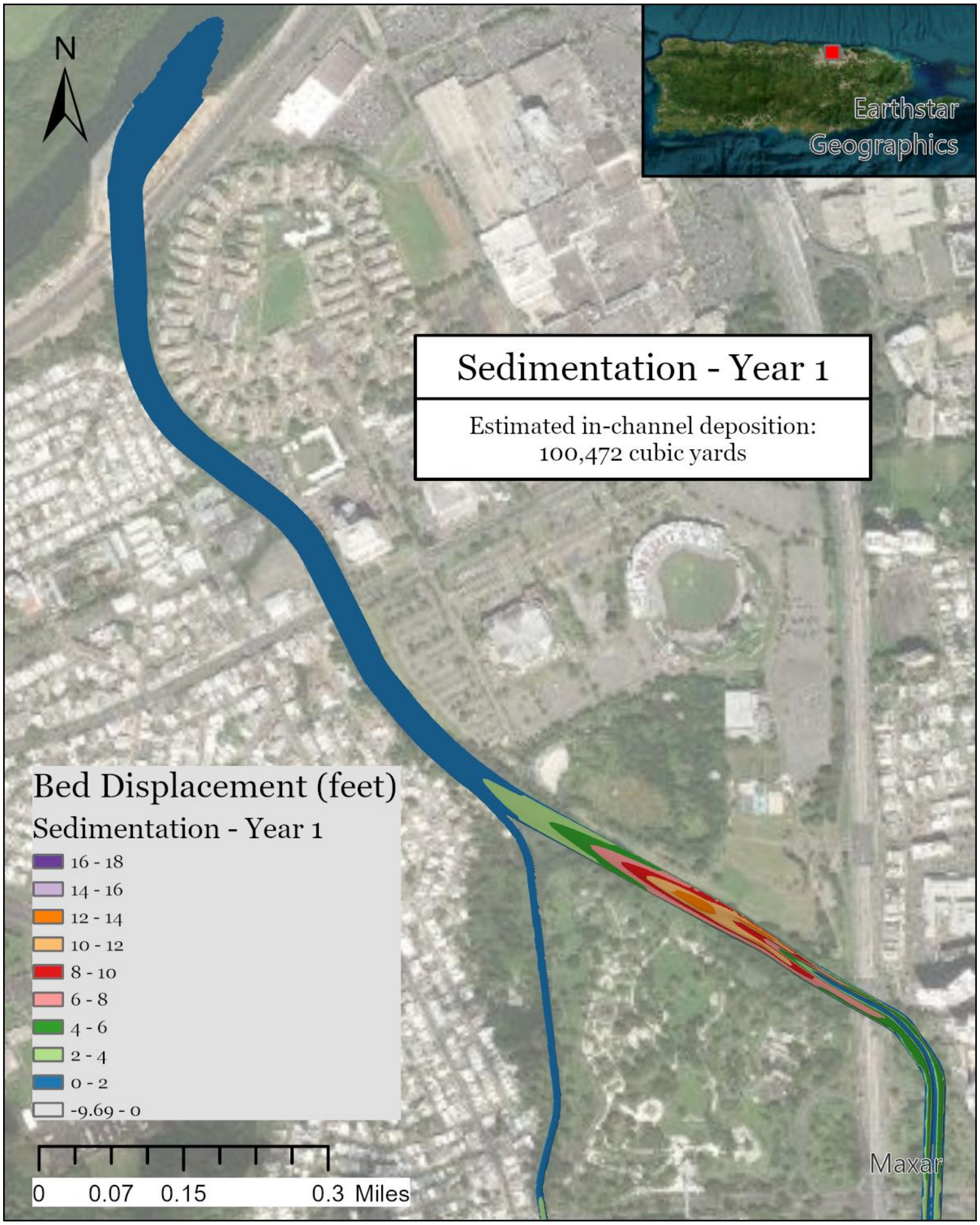


Figure 27. Sedimentation results after the first year of simulations.

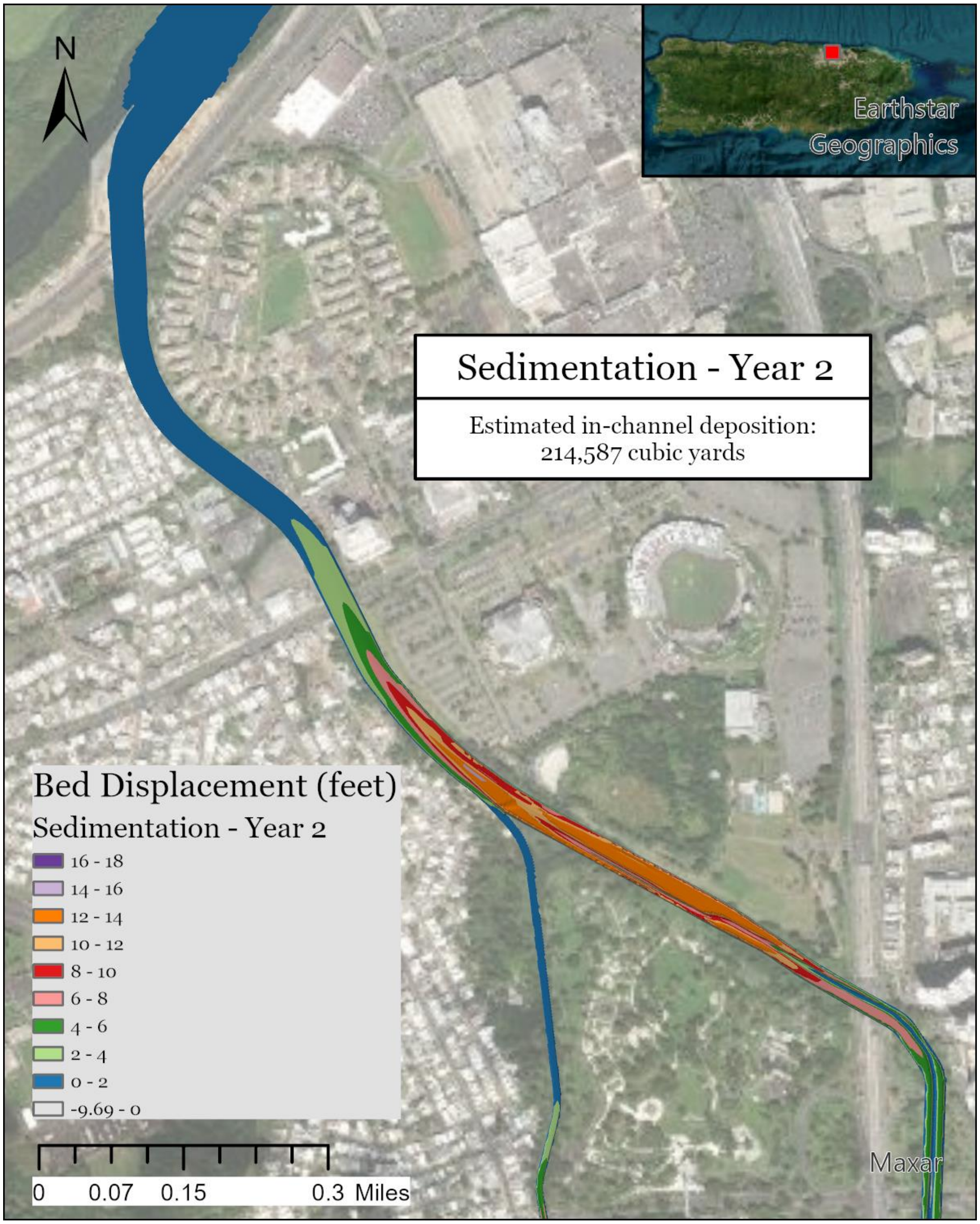


Figure 28. Sedimentation results after the second year of simulations.

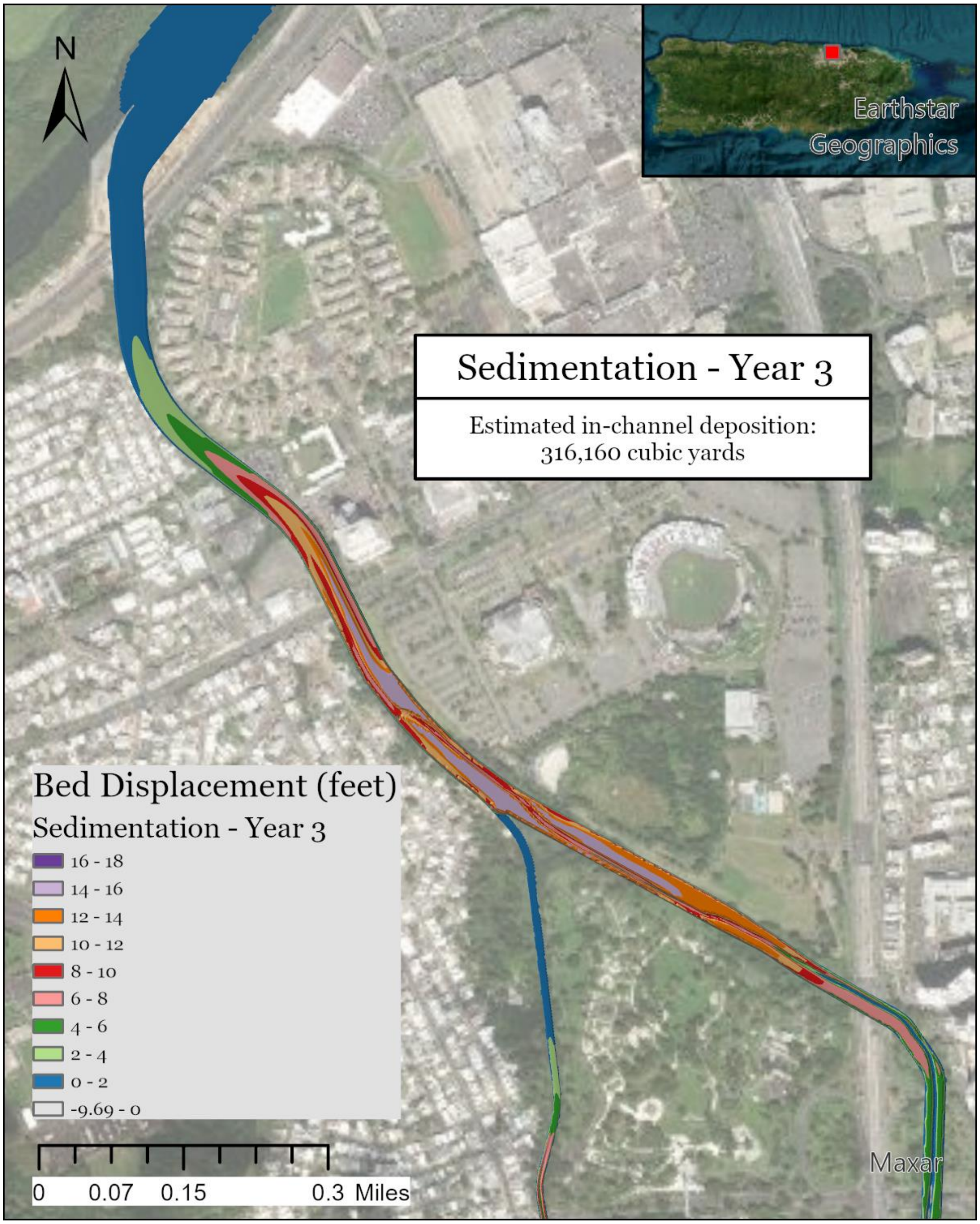


Figure 29. Sedimentation results after the third year of simulations.

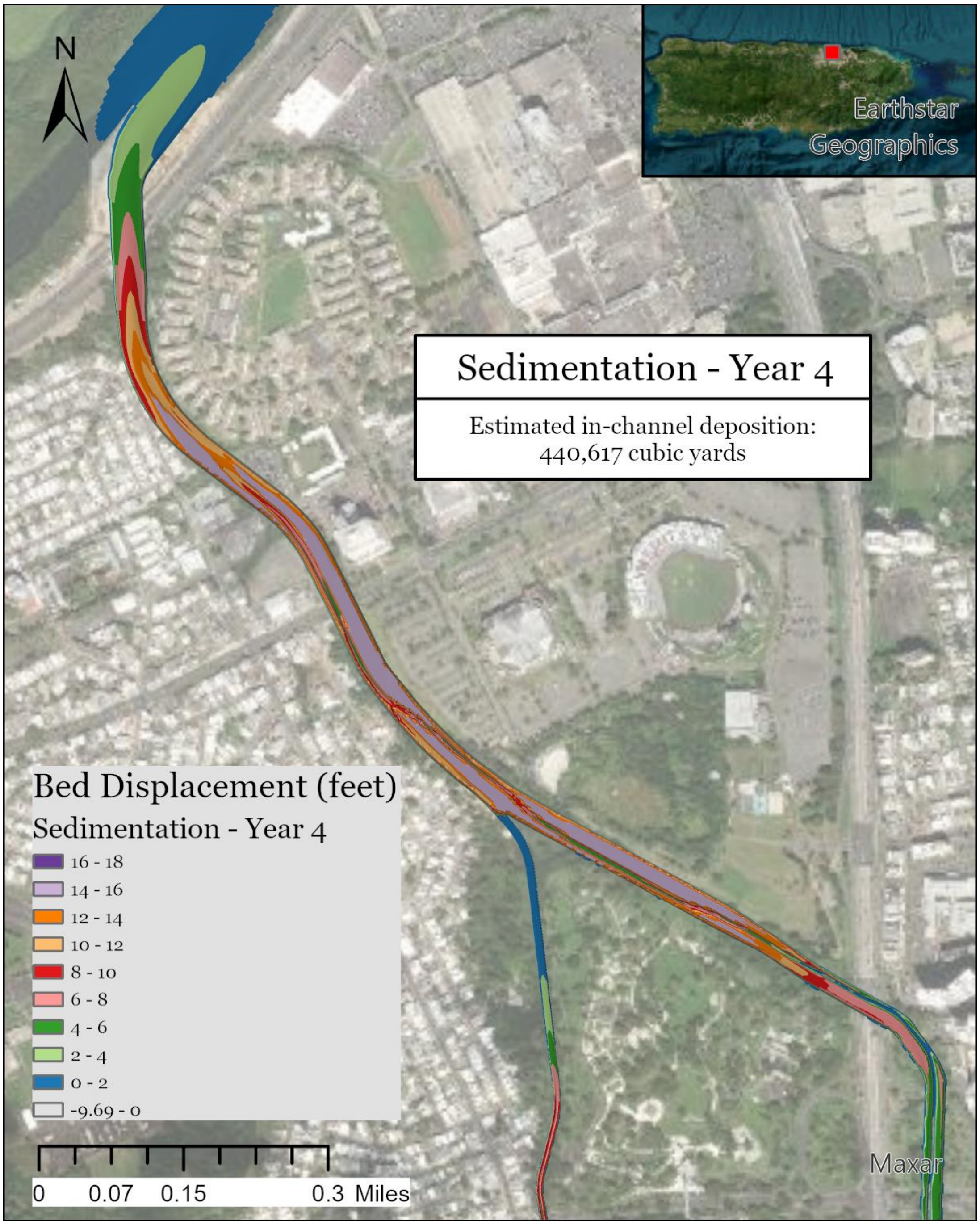


Figure 30. Sedimentation results after the fourth year of simulations.

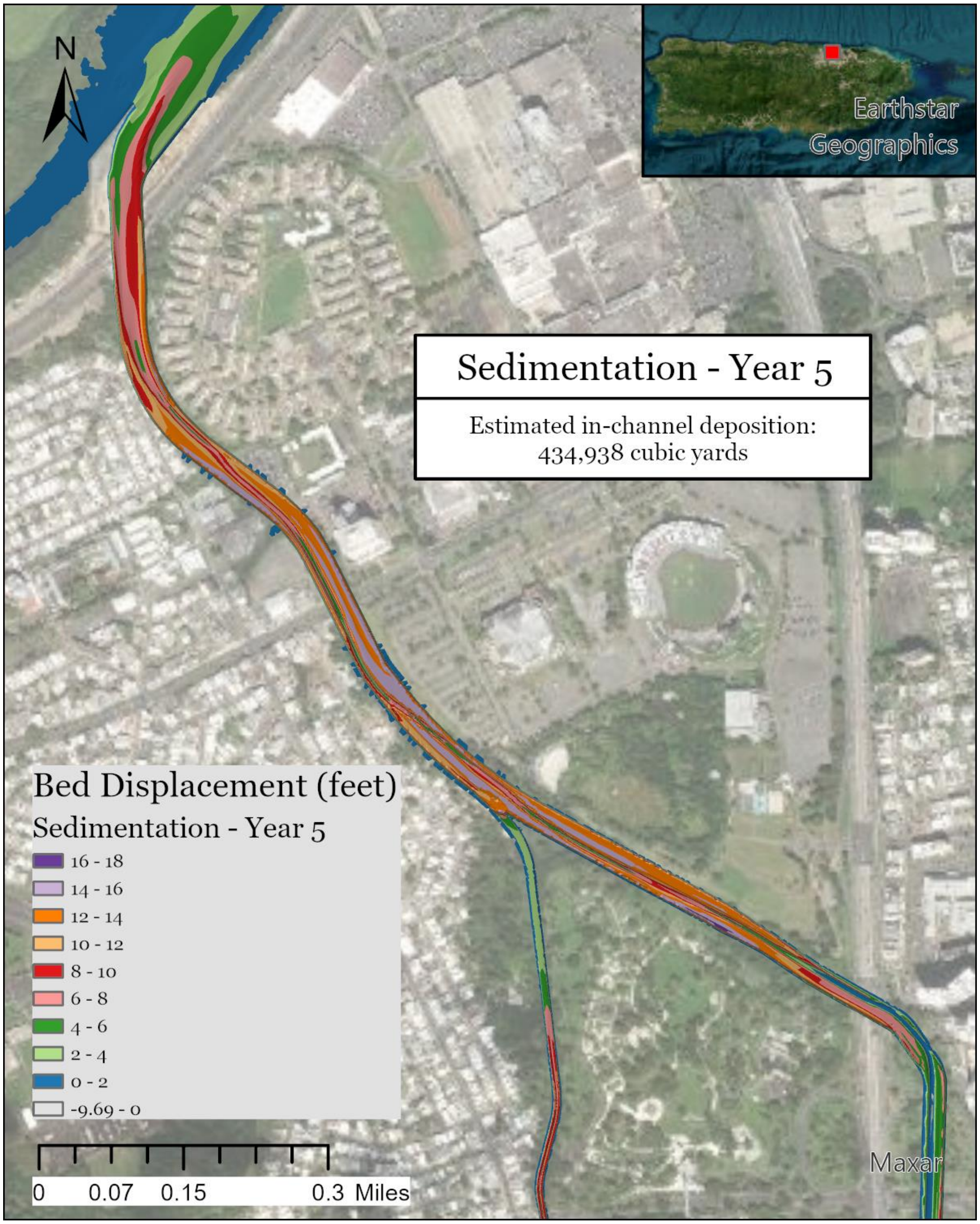


Figure 31. Sedimentation results after the fifth year of simulations.

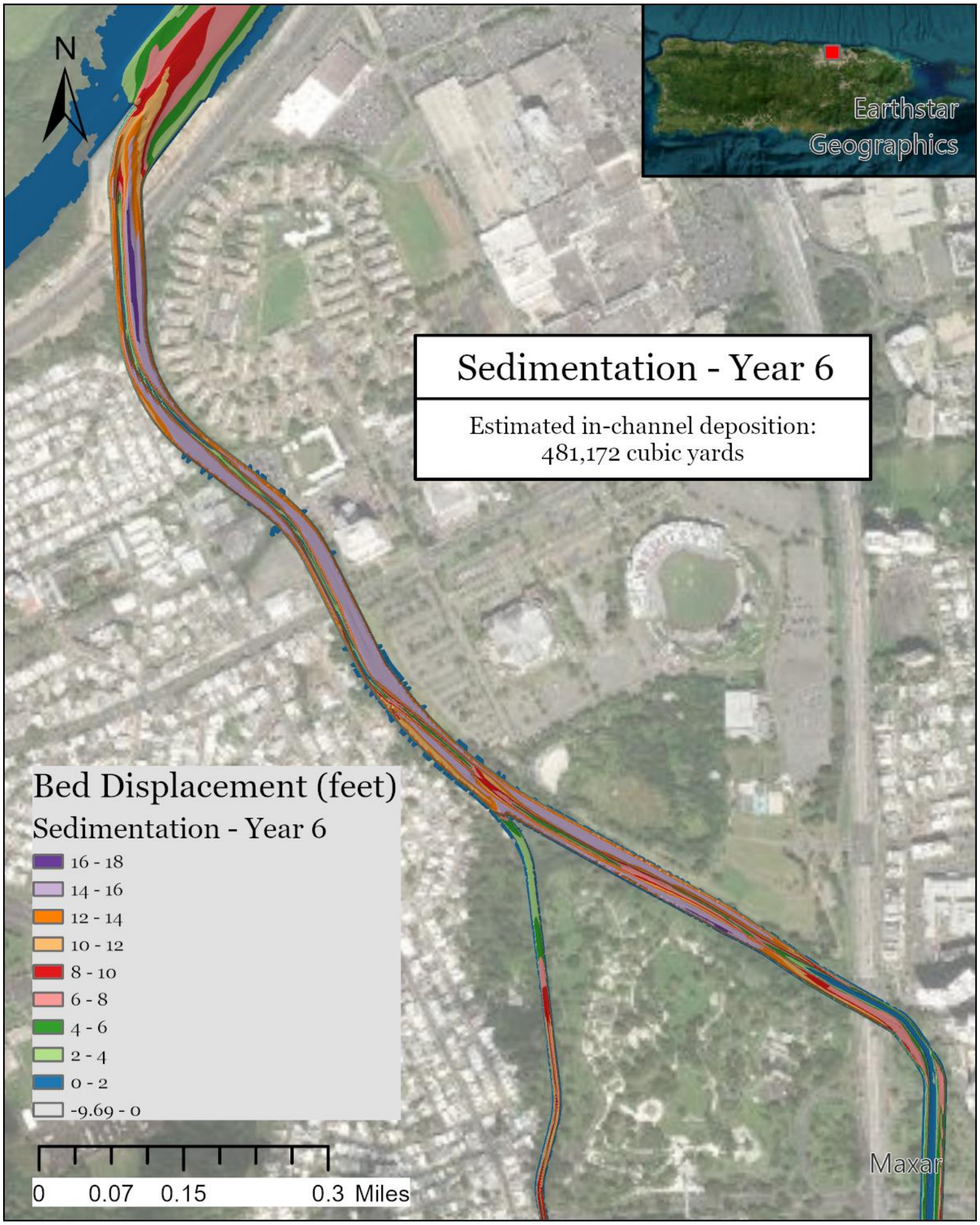


Figure 32. Sedimentation results after the sixth and final year of simulations.

Engineering judgement was applied to the sediment depositional distribution results to assess reasonableness. The sinuosity defining both the thalweg crossings and longitudinal propagation of the sediment mound exhibit common behaviors and can be compared to existing projects in watersheds with similar characteristics at other locations in the island.

The graphs included in Figure 34 through Figure 39 depict the riverine geomorphology trends along the centerline of the channel. The main component of the design channel spans from STA 88+33 to STA 209+00. The channel stationing is included in Figure 33 for reference as well.

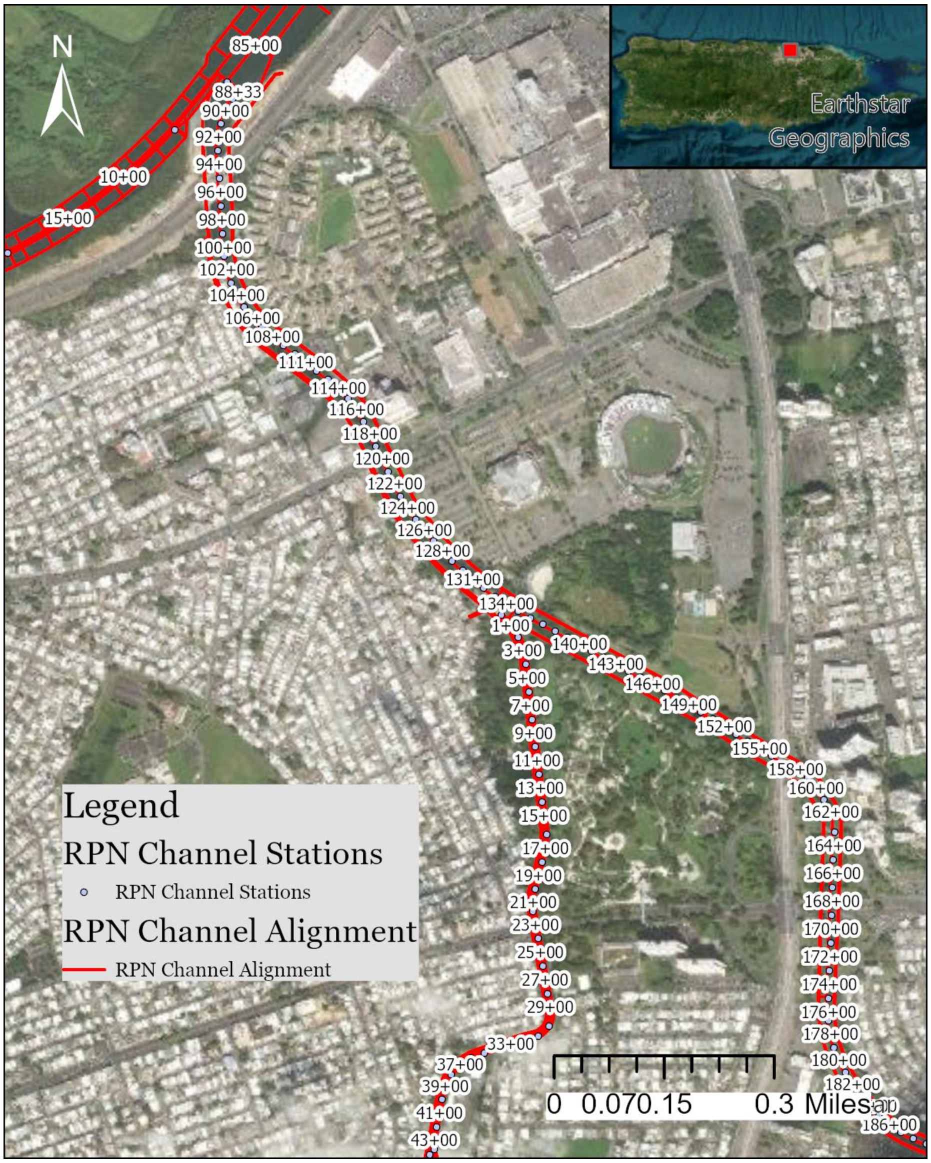


Figure 33. RPN design channel stationing.

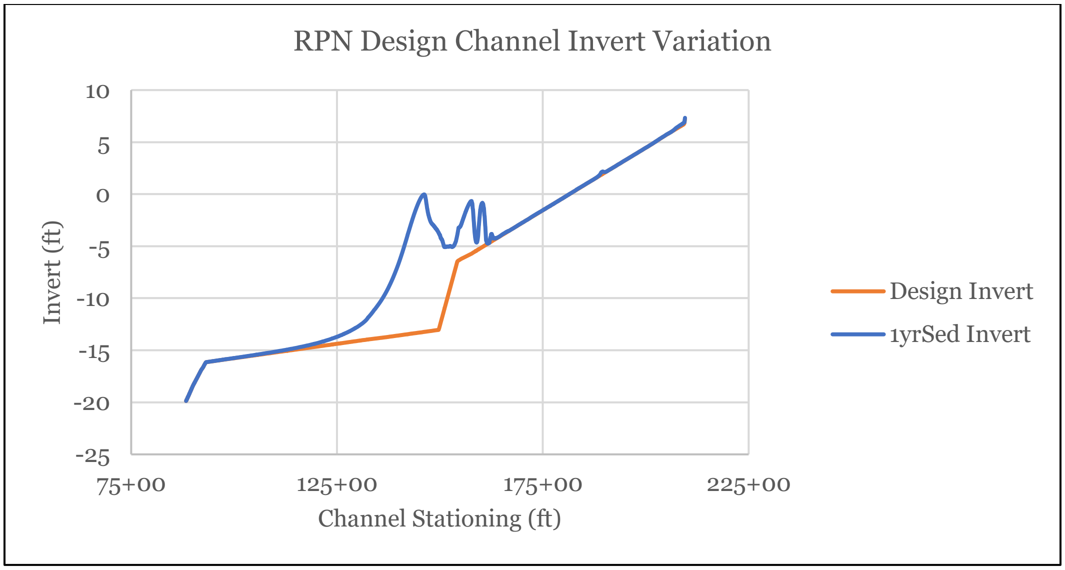


Figure 34. Channel invert change along the centerline after the first year of simulations.

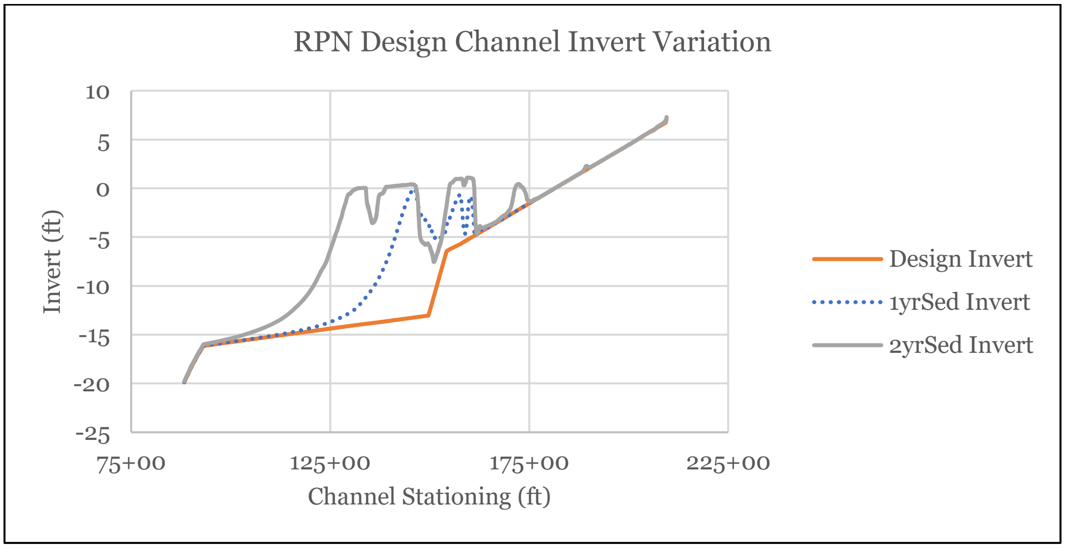


Figure 35. Channel invert change along the centerline after the second year of simulations.

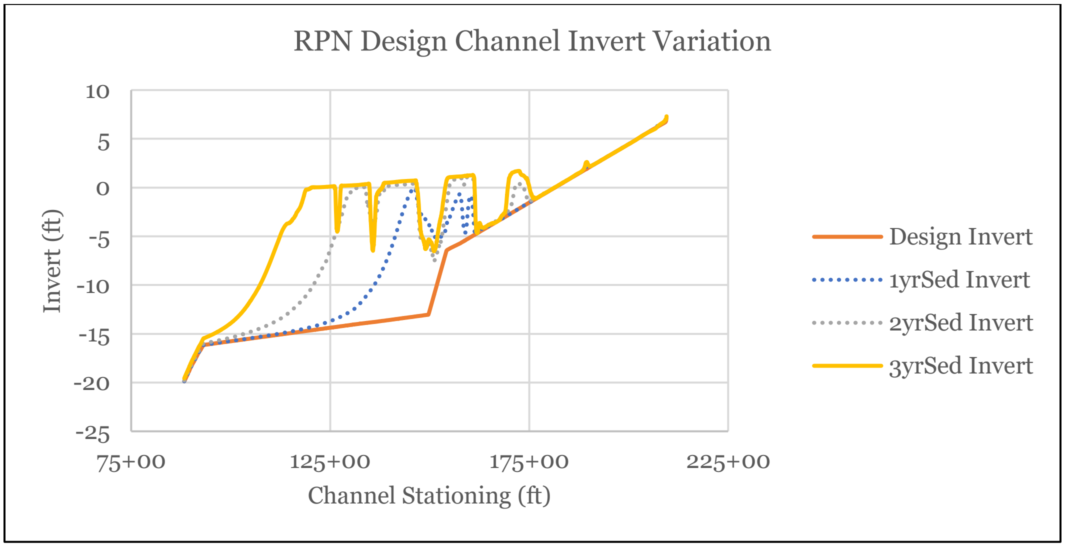


Figure 36. Channel invert change along the centerline after the third year of simulations.

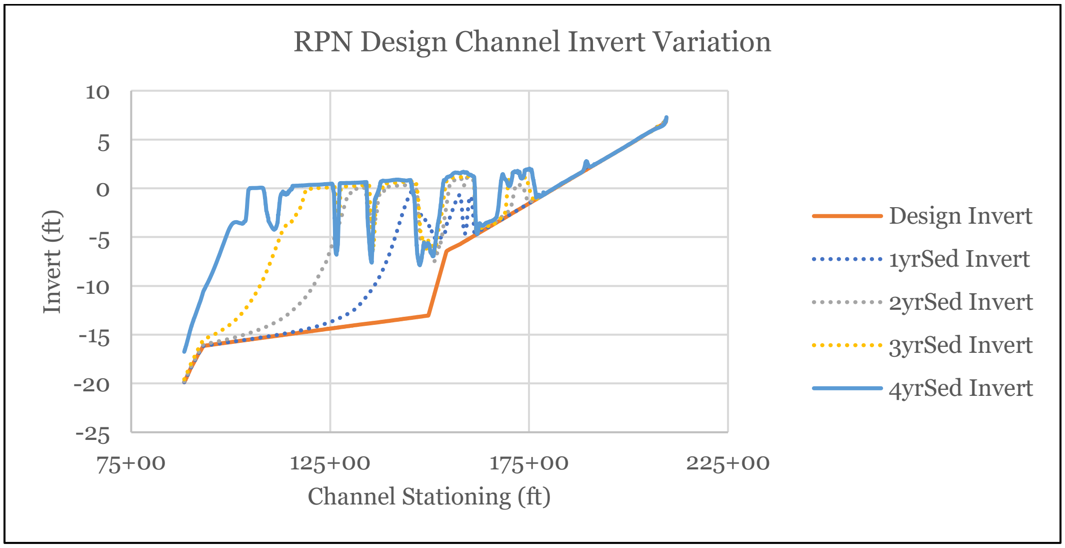


Figure 37. Channel invert change along the centerline after the fourth year of simulations.

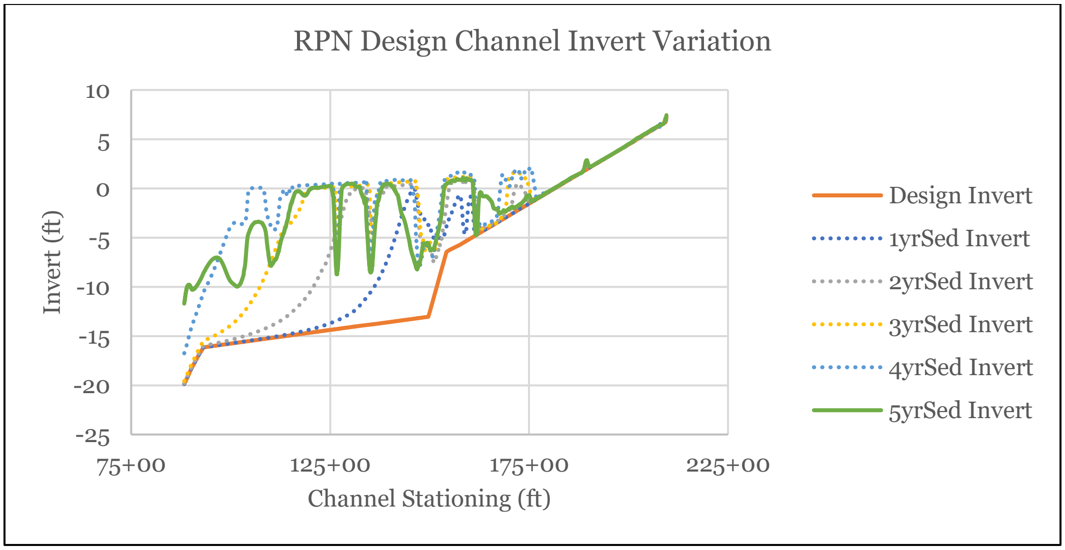


Figure 38. Channel invert change along the centerline after the fifth year of simulations.

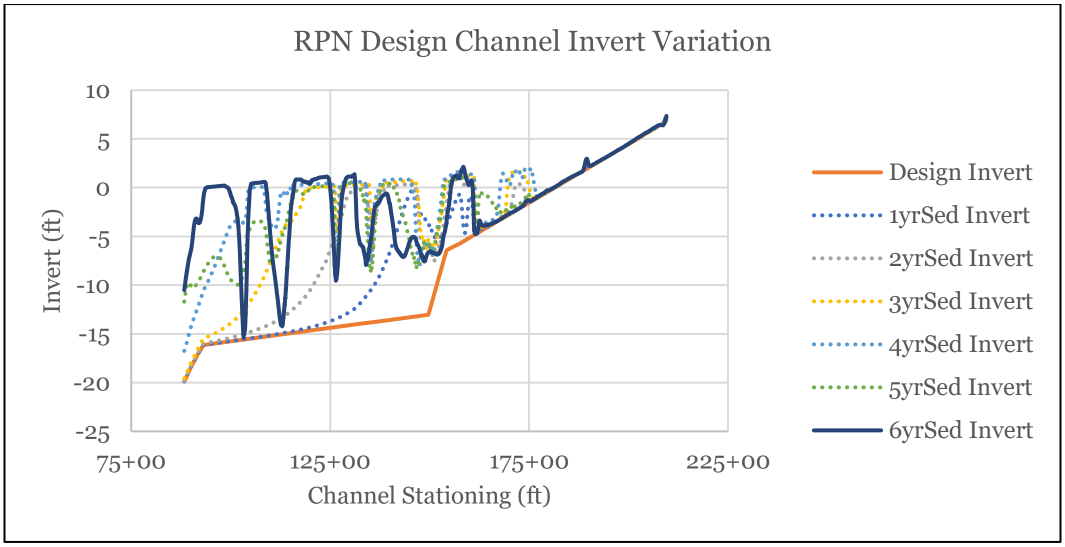


Figure 39. Channel invert change along the centerline after the sixth year of simulations.

The RPN cross-sectional tool was utilized to quantify the effective flow areas at various stations of the design channel after every sedimentation year. Examples of the cross-section outputs from the tool are included in the set of figures included below. Additional cross-sectional results can be found in the appendix.

Cross sections included in Figure 41 through Figure 46 correspond to STA 147+00 and the changes predicted by the model for every simulation year.

This station was selected due to its particular location along the design channel. Unique hydraulic and sedimentation patterns are observed in this area due to its location immediately downstream of the channel enlarging and ensizing section. An aerial view of STA147+00 in relation to the channel alignment is included for reference in Figure 40.

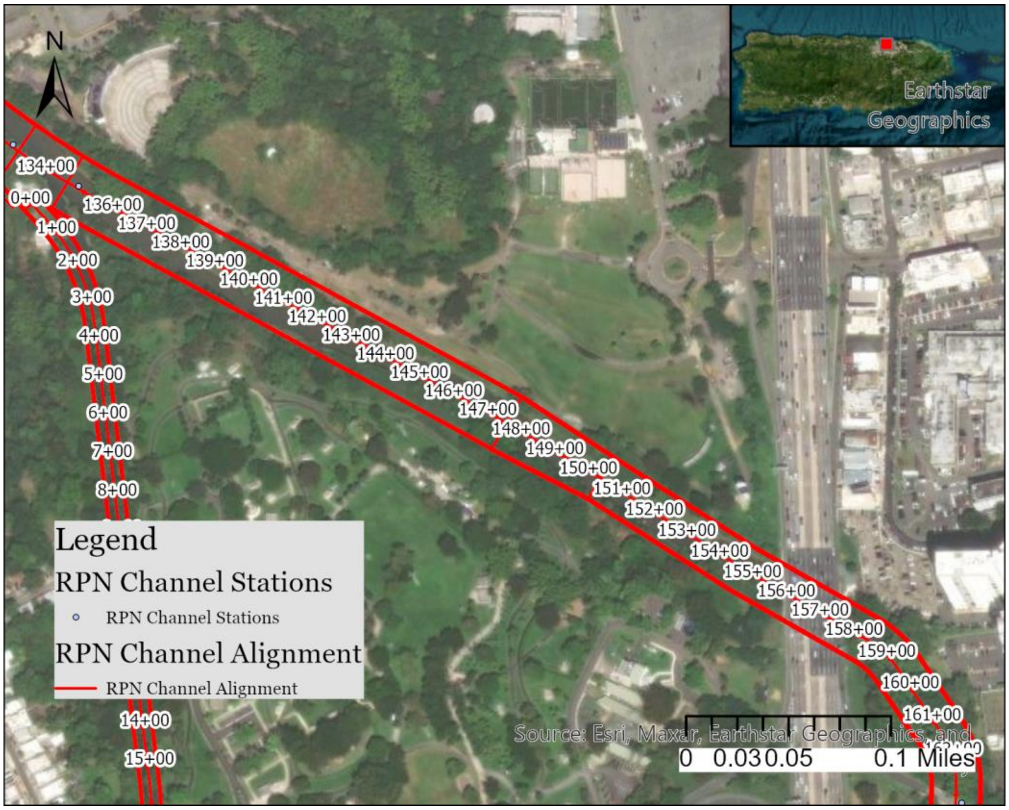


Figure 40. Channel stationing centered at STA147+00.

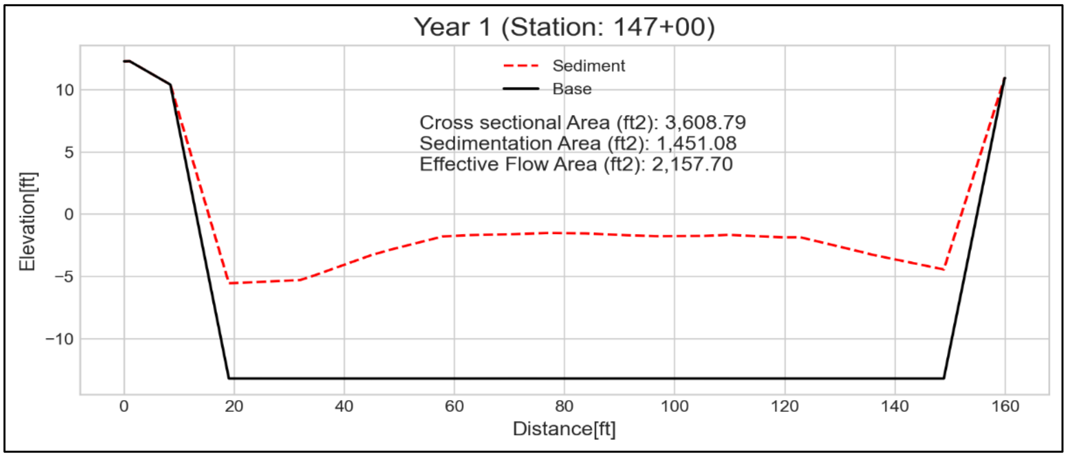


Figure 41. Cross-sectional area changes at station 147+00 after the first year of simulations.

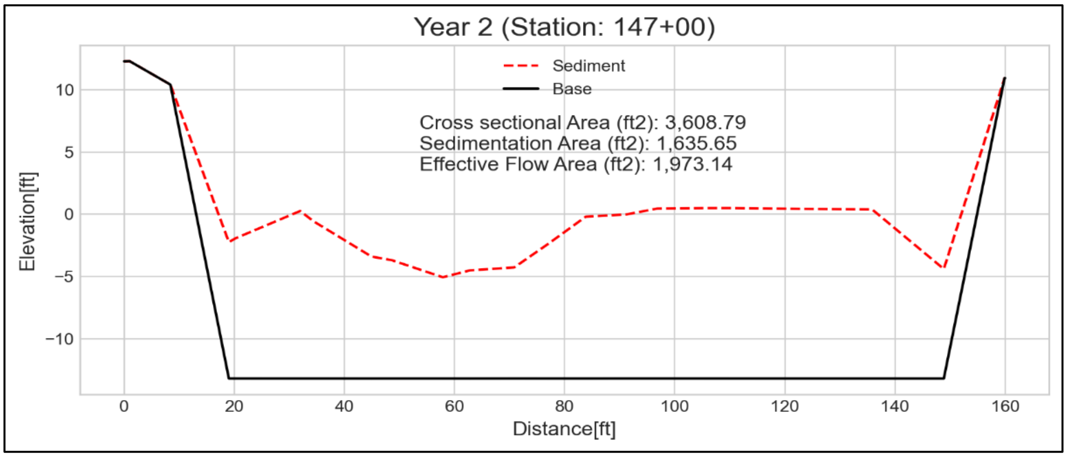


Figure 42. Cross-sectional area changes at station 147+00 after the second year of simulations.

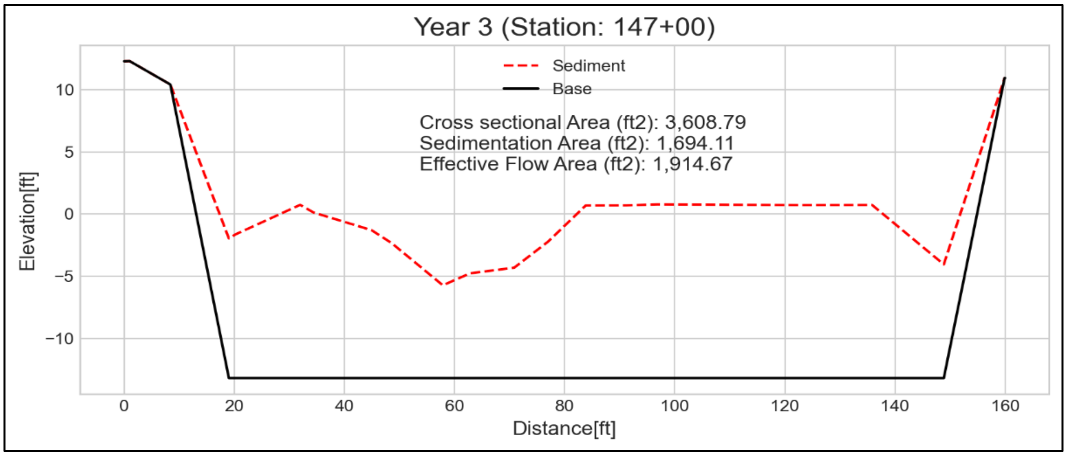


Figure 43. Cross-sectional area changes at station 147+00 after the third year of simulations.

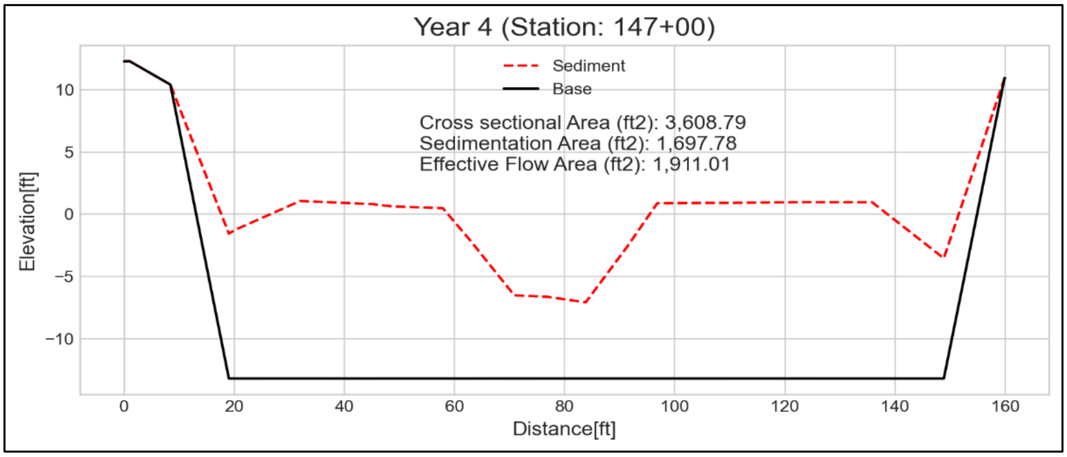


Figure 44. Cross-sectional area changes at station 147+00 after the fourth year of simulations.

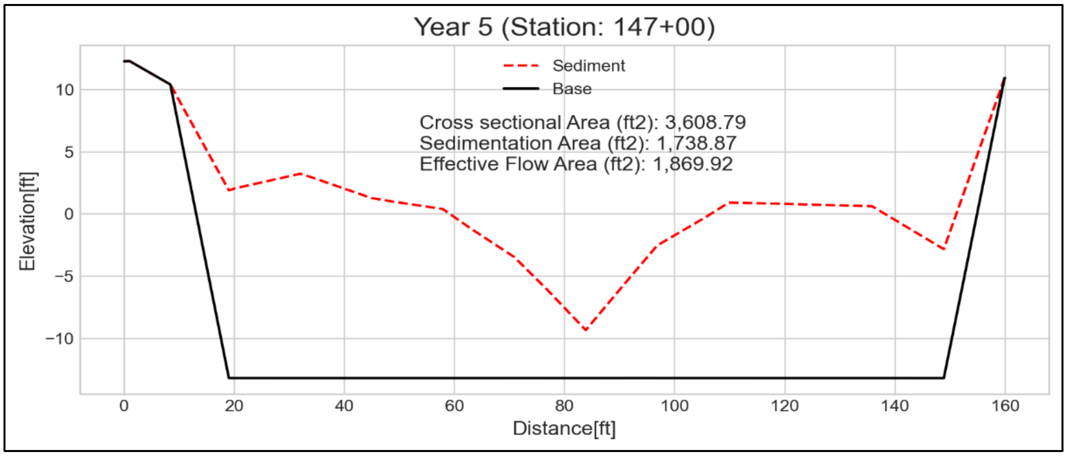


Figure 45. Cross-sectional area changes at station 147+00 after the fifth year of simulations.

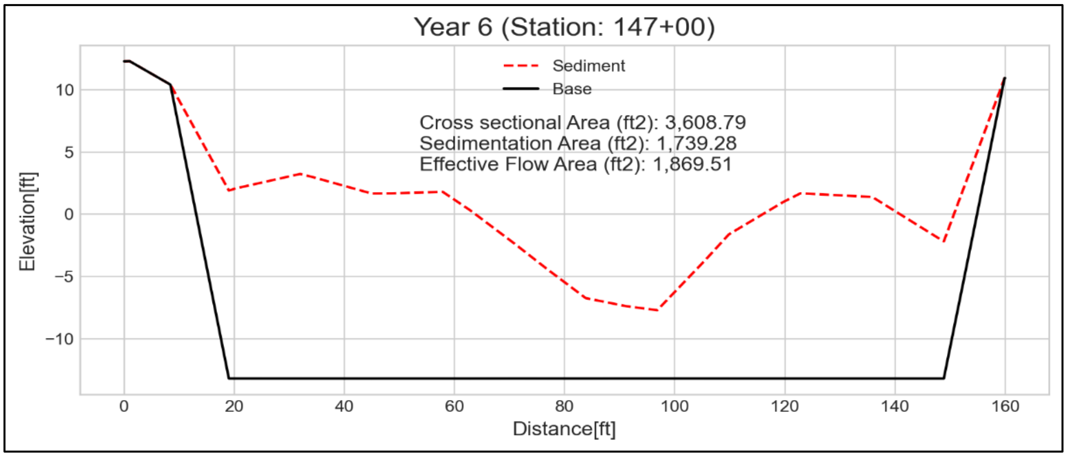


Figure 46. Cross-sectional area changes at station 147+00 after the sixth year of simulations.

In the process of determining the effective flow area, the portion occupied by sediment was calculated and eventually interpolated with its upstream consecutive cross section to estimate depositional volumes. These volumes were then compared to the total volume capacity of the channel, 35.5 million cubic feet (1.3 million cubic yards), to determine the percentage of volume capacity available after simulating every year. The model predicted that the channel would reduce its net volume capacity approximately by 35% after the completion of all six years. A flow conveyance capacity analysis is included in the next section.

Table 12. Channel volume capacity results.

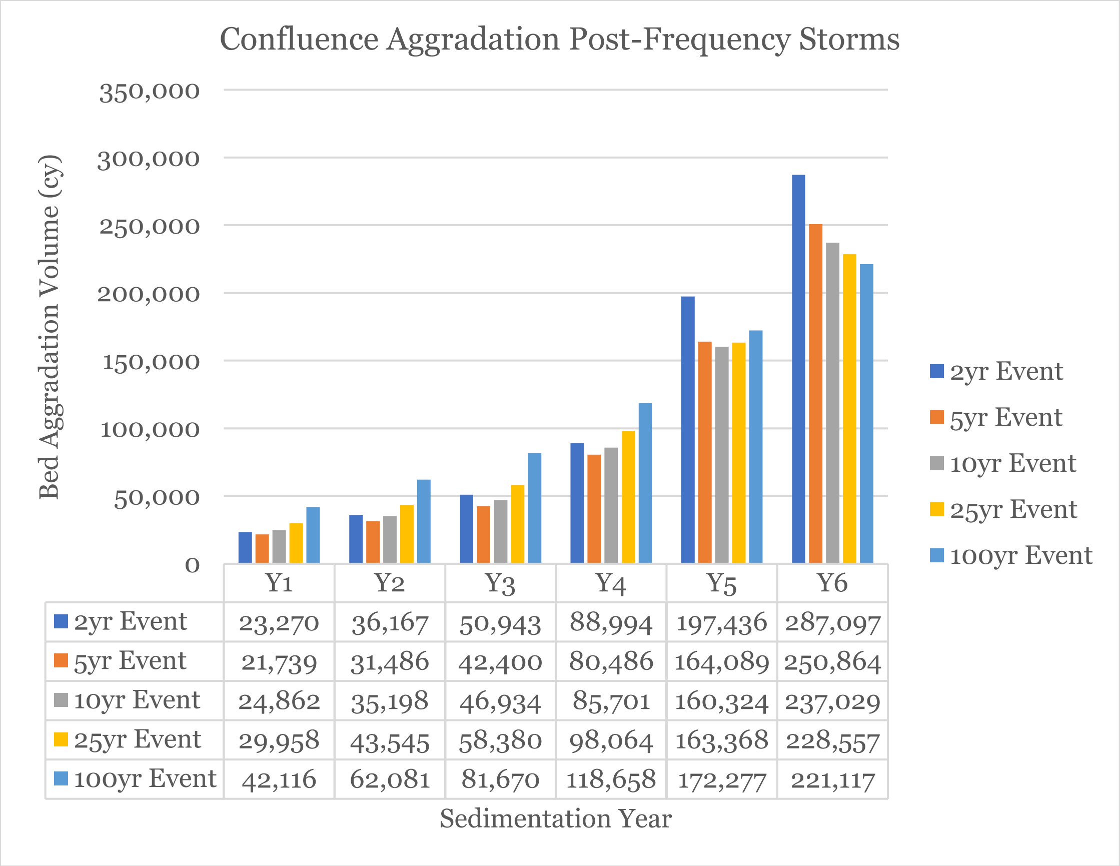
Year	Sedimentation (cy)	Channel Capacity (cy)	Estimated Remaining Channel Capacity (%)
1	100,472	1,352,189	92.6%
2	214,587	1,352,189	84.1%
3	316,160	1,352,189	76.6%
4	440,617	1,352,189	67.4%
5	434,938	1,352,189	67.8%
6	481,172	1,352,189	64.4%

5.2.2 *Confluence sedimentation*

Multiple factors other than volume and conveyance reduction due to in-channel sedimentation compromise channel capacity. In fact, obstructions downstream of the engineered channel could have considerable impacts on flow conveyance capacity if backwater effects prevent flow to be routed effectively. After analyzing the sedimentation dynamics along the design channel, the RPN - Margarita Channel confluence sedimentation was estimated. Sediment particles transported and deposited in this area could cause dredging concerns on a frequency basis. Figure 47 illustrates the confluence area identified as the area of interest for this analysis.

Figure 47. Confluence area delineated for bed aggradation estimate.

A specific analysis was conducted to estimate the consequences of the storm events in terms of material displacement. Figure 48 provides with the estimated quantities of material mobilized by every storm event and deposited in the confluence area. The volumes presented should not be viewed as finite values and rather higher or lower levels of confidence associated with dredging needs.



	Y1	Y2	Y3	Y4	Y5	Y6
2yr Event	23,270	36,167	50,943	88,994	197,436	287,097
5yr Event	21,739	31,486	42,400	80,486	164,089	250,864
10yr Event	24,862	35,198	46,934	85,701	160,324	237,029
25yr Event	29,958	43,545	58,380	98,064	163,368	228,557
100yr Event	42,116	62,081	81,670	118,658	172,277	221,117

Figure 48. Confluence aggradation summary. The figure presents the estimated aggradation volumes produced by the frequency storms.

These aggradation volumes at the confluence area represent between 23% and 60% of the deposited material throughout all six years of simulation (see Table 12 for total in-channel aggradation). Results show that even with the channel's capacity to clear/self-scour, there are still considerable amounts of material throughout the engineered portion. Keeping the remaining depositional areas (see O&M Recommended Plan) clear and the confluence open are key to increase the chances of project success.

6 Channel Conveyance Capacity Analysis and Results

The process for determining the impacts of sedimentation on channel capacity was based on the maximum simulated water surface elevation of all five frequency storms after being routed through the system. To perform this analysis, the final condition of each sedimentation year was used as the initial condition for each frequency storm. The maximum water levels recorded for each one of the frequency events were then compared to the channel wall elevations for channel capacity assessment. This methodology is intended to answer the following question:

"What happens -in terms of channel conveyance capacity- if a given frequency storm event (2yr, 5yr, 10yr, 25yr, 100yr) strikes the system after a given period (1 to 6 years) of continuous sedimentation?"

Channel wall height information was obtained from various design documents corresponding to the different phases of the project. Plan drawings corresponding to contracts 2B, 3, and 4 were scrutinized for these purposes. Channel wall elevations past STA 175+90 were not available at the completion of these efforts as the final design for contract 6, which corresponds to that reach of the channel, is still ongoing.

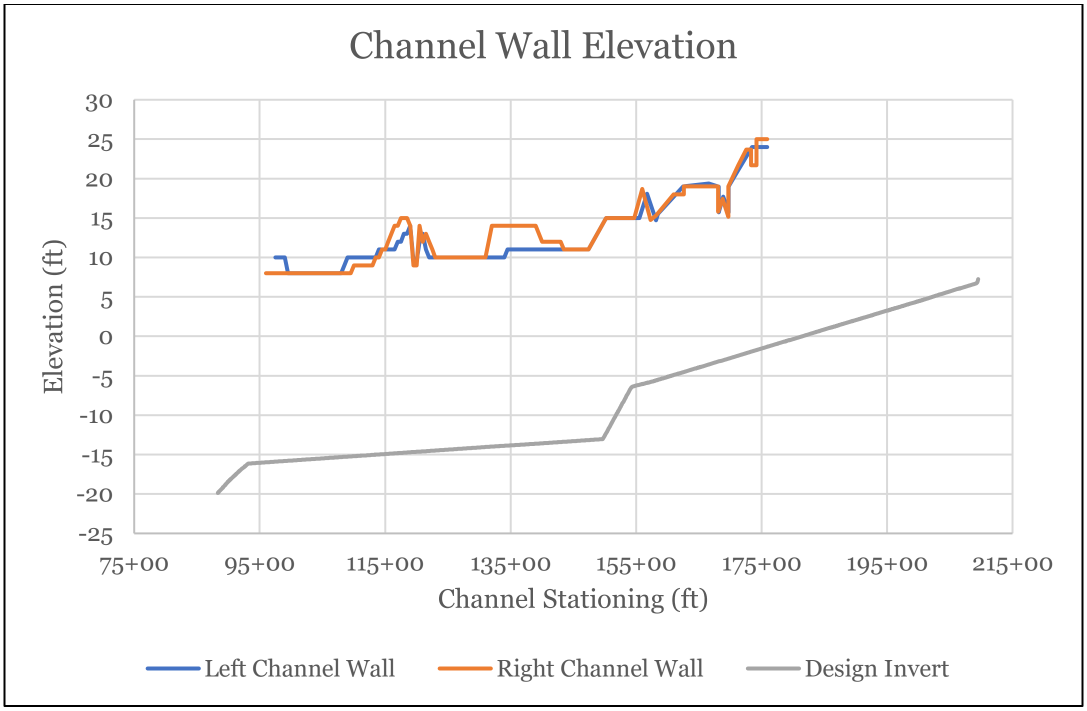


Figure 49. Channel wall elevation used for channel capacity assessment.

There were two possible scenarios proposed for assessing channel capacity using the methodology previously described. The first scenario considers erodible depositional material while the second scenario assumes the conservative approach of ‘non-erodibility’.

6.1 *Erodible condition*

‘Erodible material’ implies that no external factors or processes other than gravitational forces or the weight of over-stacking sediment particles are acting over the aggraded material. Consequently, if the stream reaches a point where incipient motion occurs, there is nothing preventing it from initiating motion.

In other words, the material was assumed to be non-cohesive or non-clay for simplification purposes. Since many clays lose much of their cohesive properties in presence of salt water, this assumption was considered fair as the critical reach (verified at the simulations) is tidal influenced. Also, with limited background data, it was deemed appropriate to make the non-cohesive assumption as it would not alter the use of the study results.

The maximum water surface elevations corresponding to the erodible condition scenario for the various sedimentation conditions are included in the set of figures below (Figure 50 through Figure 55).

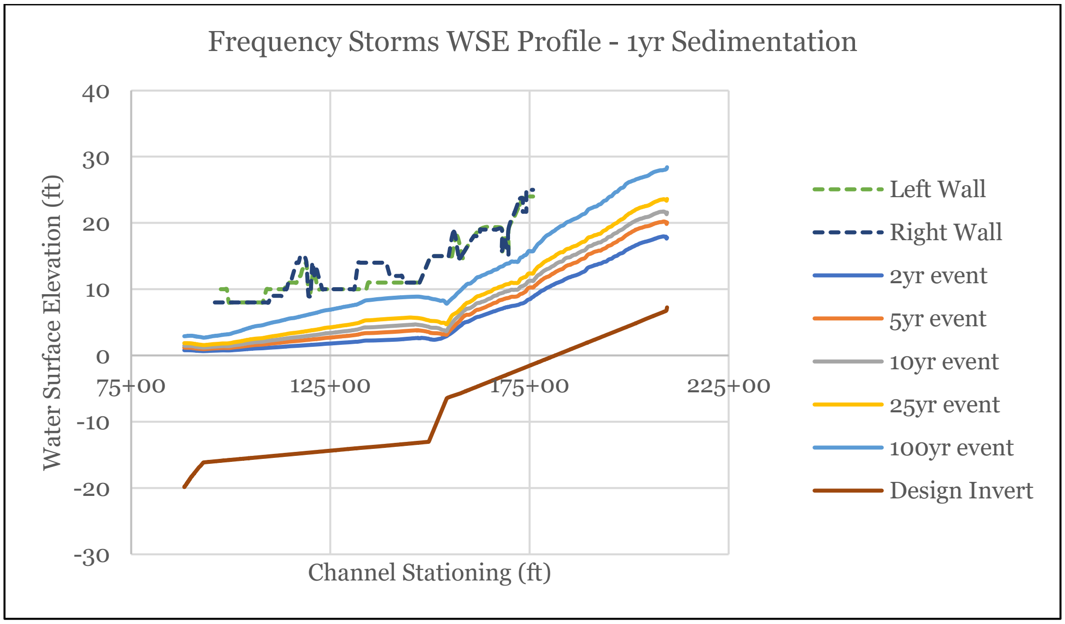


Figure 50. Maximum water surface elevation of frequency storms after the first sedimentation term (erodible condition).

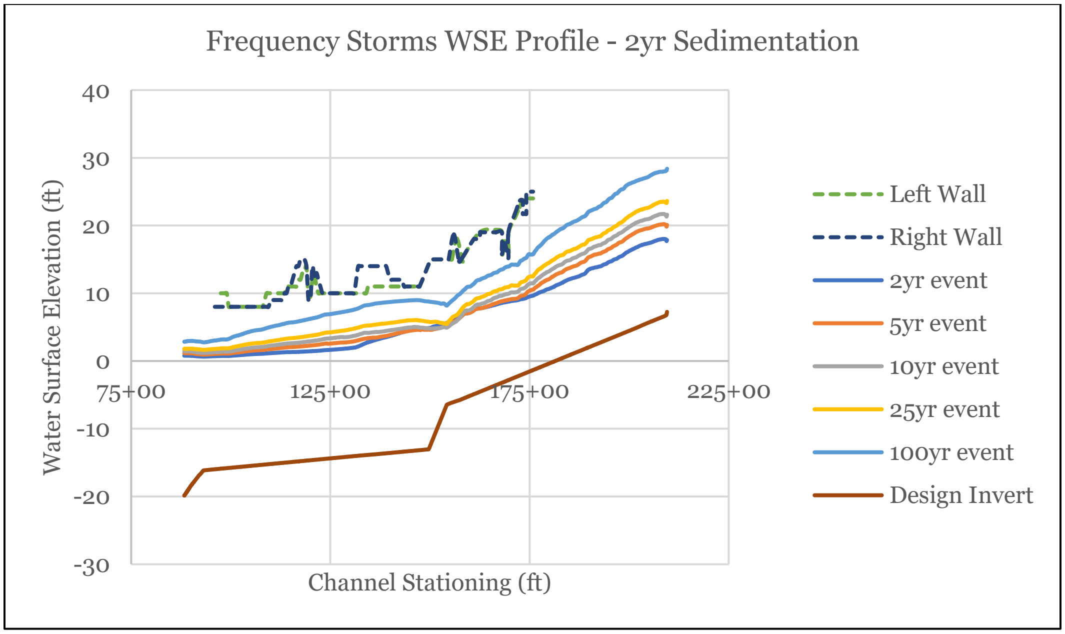


Figure 51. Maximum water surface elevation of frequency storms after the second sedimentation term (erodible condition).

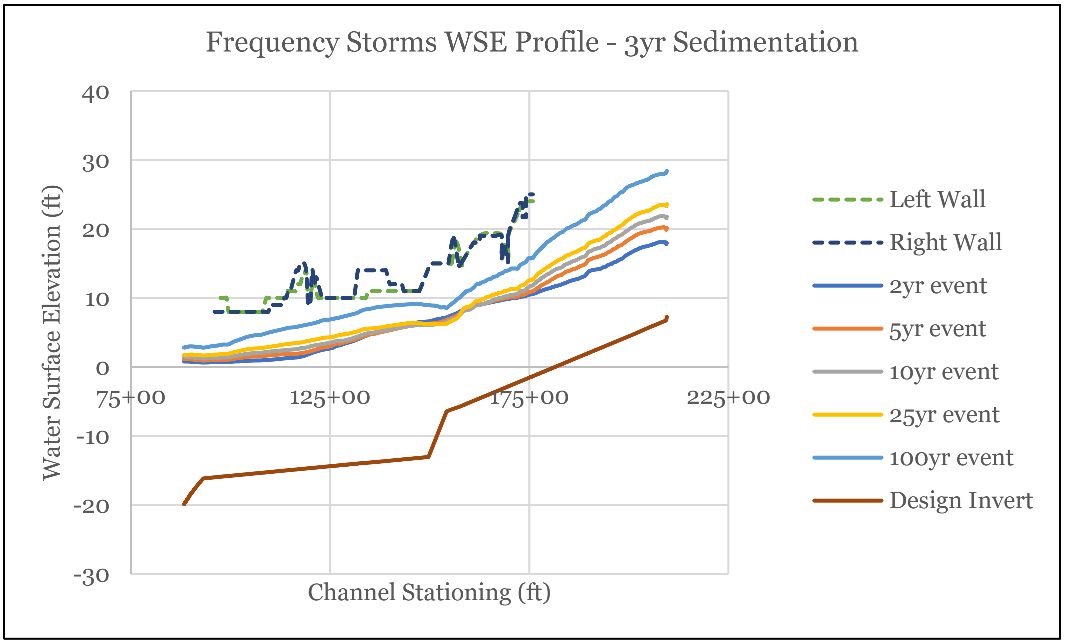


Figure 52. Maximum water surface elevation of frequency storms after the third sedimentation term (erodible condition).

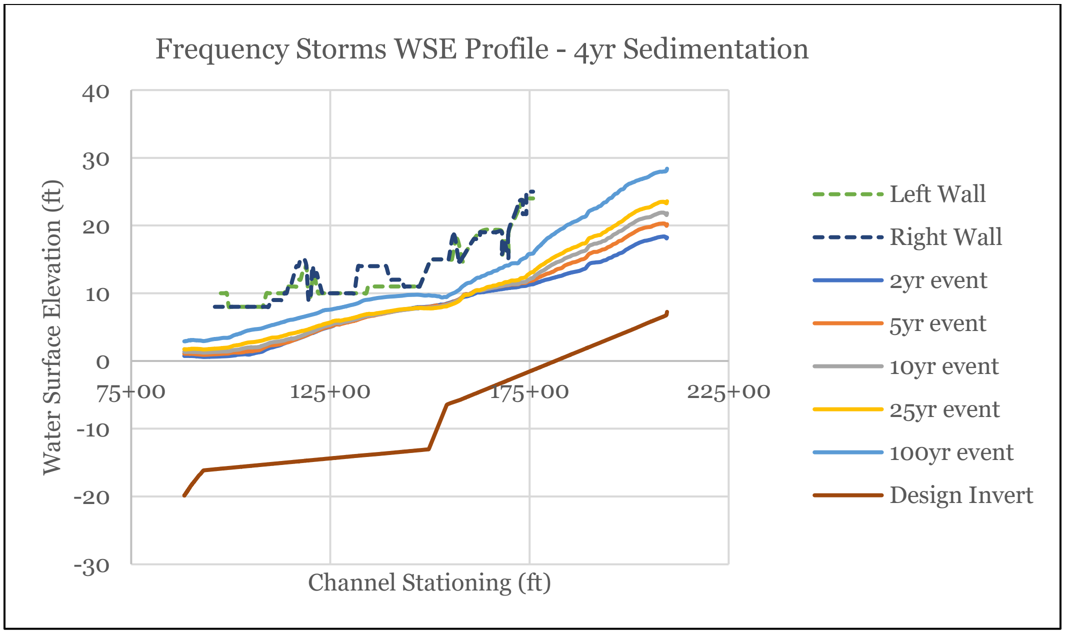


Figure 53. Maximum water surface elevation of frequency storms after the fourth sedimentation term (erodible condition).

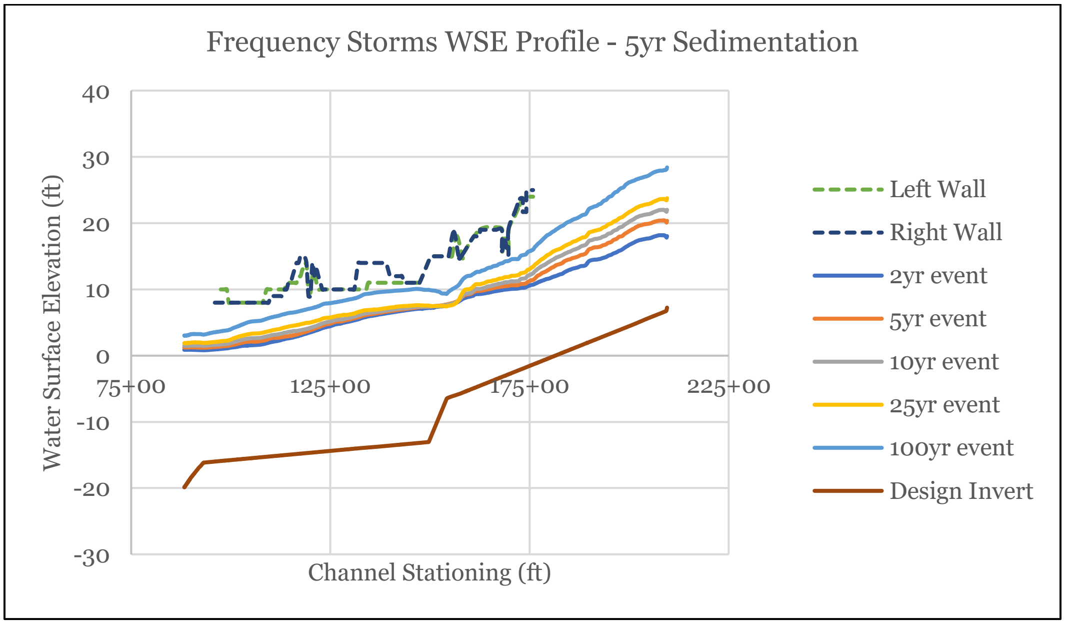


Figure 54. Maximum water surface elevation of frequency storms after the fifth sedimentation term (erodible condition).

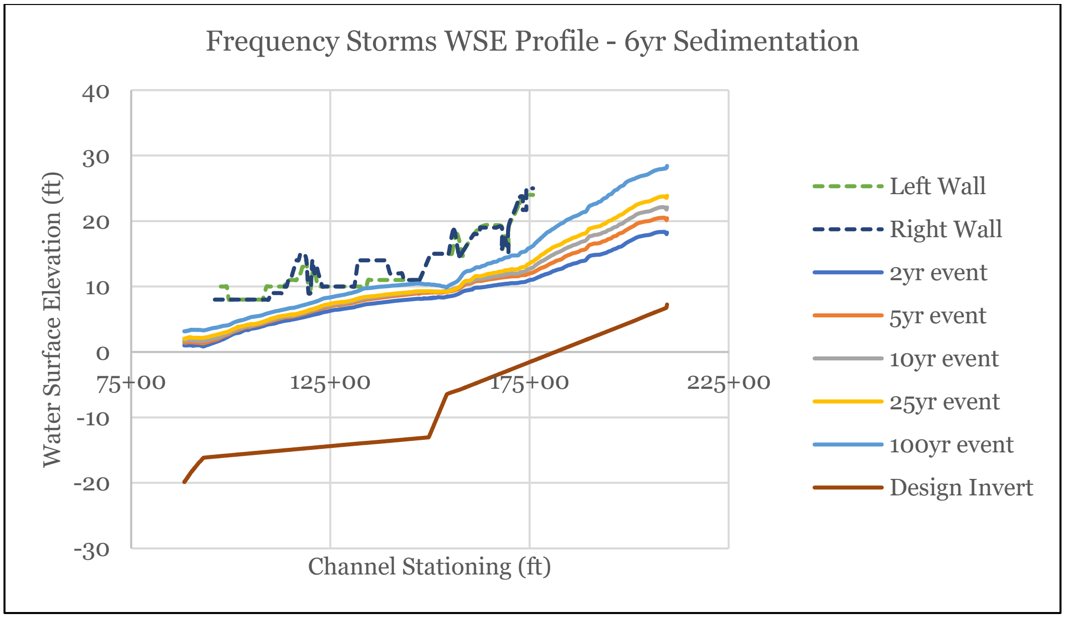


Figure 55. Maximum water surface elevation of frequency storms after the sixth sedimentation term (erodible condition).

After analyzing the maximum water levels recorded for every frequency storm throughout the simulations, it was found that most of the scenarios for the 2yr, 5yr, 10yr, 25yr were properly routed through the design channel and no wall overtopping was observed. The exception for these being the 10-yr and 25-yr events using the six-year sedimentation as the base. In this case, the events were properly routed but the maximum WSE encroached into the minimum 2-feet freeboard at STA 134+40.

The 100yr event compromised the channel conveyance capacity for all simulated year-increments. Water levels for the 100yr event at STA 134+40 were observed to be within the 2-feet required freeboard as well. At this station, the elevation of the left channel wall is set to be 10.00 feet. Table 13 presents the recorded WSE values at this location.

Table 13. Maximum WSE recorded at STA 134+00.00 for the 100-yr event.

Year	Maximum WSE (ft)
Y1	8.34
Y2	8.25
Y3	8.37
Y4	9.04
Y5	9.34
Y6	9.75

Similar measurements were recorded between STA 143+00.00 and STA 147+00.00 as well as STA 169+00.00. At this location, the freeboard available decreased to as little as 0.27 foot. Figure 56 presents the variations of the maximum WSE as modeled for the 100-yr storm event in this location.

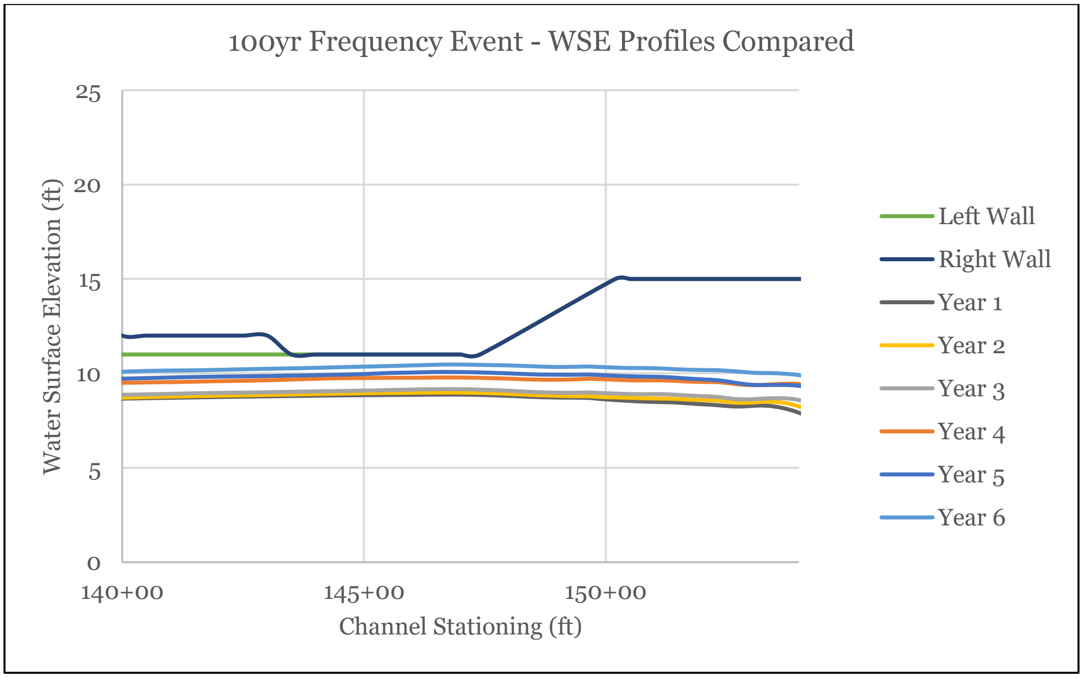


Figure 56. Maximum water surface elevation produced by the 100-yr frequency storms between STA 140+00 and STA 154+00.

Figure 57 summarizes the WSE produced by the 100-yr event after all the six sedimentation terms.

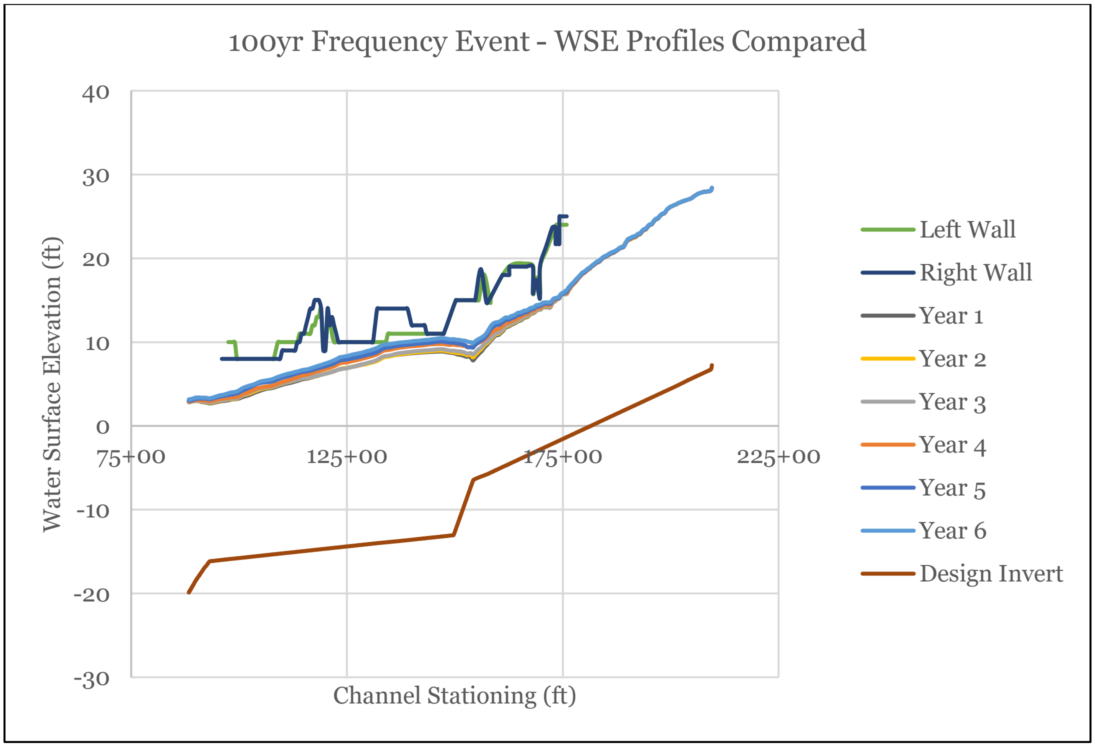


Figure 57. Maximum water surface elevation produced by the 100-yr event.

The overall impact produced by the long-term sedimentation runs in the incremental water levels is captured in Table 14. The base condition refers to the routing of all five frequency storm events with no sedimentation present in the design channel. This condition allows to quantify the incremental effects of sedimentation on channel flow conveyance capacity during potential flood events. The maximum WSE change included in the table corresponds to STA 154+22.21 in all instances. The average WSE change is not particular to any station, but the overall trend along the design channel reach.

Table 14. Water surface change summary for the 100-yr event.

Parameter	Base-Y1	Base-Y2	Base-Y3	Base-Y4	Base-Y5	Base-Y6
Max Change (ft)	0.16	0.52	0.87	1.79	1.70	2.23
Avg Change (ft)	0.02	0.07	0.12	0.42	0.64	0.87

Combining the results included in this section, the channel capacity assessment was performed. Table 15 summarizes the information presented here by answering the following question: *"Was the event contained within the design channel?"*

Table 15. Channel capacity assessment results for the suite of frequency storms (erodible condition).

Sedimentation Condition	Frequency Storm				
	2yr	**5yr**	**10yr**	**25yr**	**100yr**
1 year	Yes	Yes	Yes	Yes	Yes
2 years	Yes	Yes	Yes	Yes	Yes
3 years	Yes	Yes	Yes	Yes	Yes
4 years	Yes	Yes	Yes	Yes	Yes
5 years	Yes	Yes	Yes	Yes	Yes
6 years	Yes	Yes	Yes	Yes	No

The elements shaded green maintained the 2-feet freeboard at all locations throughout the design channel reach. The elements shaded yellow stayed within wall height but encroached into the 2-feet freeboard. Only one element, corresponding to the 100-yr event after 6 years of continuous sedimentation, met or exceeded wall height at multiple locations. The most critical stations being STA 134+00.00, STA 147+00.00, and STA 169+69.00.

Table 16 presents the minimum distances or freeboard available to the top of the walls (both left and right) as well as the corresponding stationing for the 100yr events. The number of locations where the WSE encroaches the 2-feet freeboard is included as well. The table in full is included in the appendix section.

Table 16. WSE encroachment distance to the top of the channel walls

Sedimentation Condition	**No. locations <2ft**	**To top left (ft)**	**To top right (ft)**	**Left wall STA**	**Right wall STA**
1 year	8	1.69	1.28	134+00.00	169+69.00
2 years	8	1.77	1.23	134+00.00	169+69.00
3 years	28	1.65	1.19	134+00.00	169+69.00
4 years	62	0.98	1.06	134+00.00	169+69.00
5 years	77	0.69	0.88	134+00.00	169+69.00
6 years	99	0.27	0.53	134+00.00	147+00.00

An additional flow conveyance capacity test was performed to analyze the system's ability to self-dredge. In nature, atmospheric events often defeat statistics by not following the expected trends. In 2017, hurricanes Irma and Maria (both being low frequency-high intensity events) stroke the watershed with only a few days in-between. Considering the possibility of having such events in a back-to-back scenario, the following test was performed.

These scenarios considered the final condition of 2-year storms routed through the system (after all six sedimentation years) as the initial condition for a 100-year event storm. With the 2-year event being the least intense of all the frequency events being tested, it provides with a solid lower bound to characterize self-scouring capabilities. Table 17 provides with the resulting WSE results for the 100-year event using the 2-year final displacement condition for each sedimentation year.

Table 17. WSE encroachment distance to the top of the channel walls for the 100-yr event using the 2-yr event final displacement.

Sedimentation Condition	No. locations <2ft	To top left (ft)	To top right (ft)	Left wall STA	Right wall STA
1 year	8	1.66	1.27	134+00.00	169+69.00
2 years	18	1.68	1.22	134+00.00	169+69.00
3 years	28	1.57	1.21	134+00.00	169+69.00
4 years	58	1.07	1.09	134+00.00	169+69.00
5 years	67	0.83	0.91	134+00.00	169+69.00
6 years	94	0.44	0.70	134+00.00	146+50.00

As mentioned in the Confluence sedimentation section, remaining depositional areas along the channel reduce both the storage and conveyance capacity of the project. Even though there was a reduction in the locations compromised freeboard (<2 feet), the actual encroachment did not vary much and only experienced increments from 0.1 feet to 0.2 feet overall. Stations 134+00.00, 169+69.00 and 147+00.00 remained as the worst/most problematic locations in terms of encroachments.

6.2 *Non-erodible condition*

The non-erodible condition implies that external factors or processes do not allow sediment particles to initiate motion by restricting their displacement and forcing them to stay in place. This scenario could be caused by rooted vegetation or by over-consolidation processes of wetting and drying cycles caused by incremental tides. In this scenario, engineers are being conservative in estimating minimal bed changes due to heavy vegetation.

Although it is unlikely that absolutely no sediment will be displaced in any given event, SAJ proposed this alternative test to be performed to better inform incremental consequences. This condition is not intended to argue against the establishment of fauna or any other valuable ecological and biodiverse habitat systems. It aims to inform on the potential consequences if the channel is not maintained adequately once constructed.

Figure 58 summarizes the changes to the channel bottom elevation through the yearly increments of sedimentation build-up. These inverts were used as the base condition in the channel conveyance capacity assessment of the non-erodible condition. The large dips observed in the inverts correspond to channelization through the aggraded sediment as captured along the centerline of the channel.

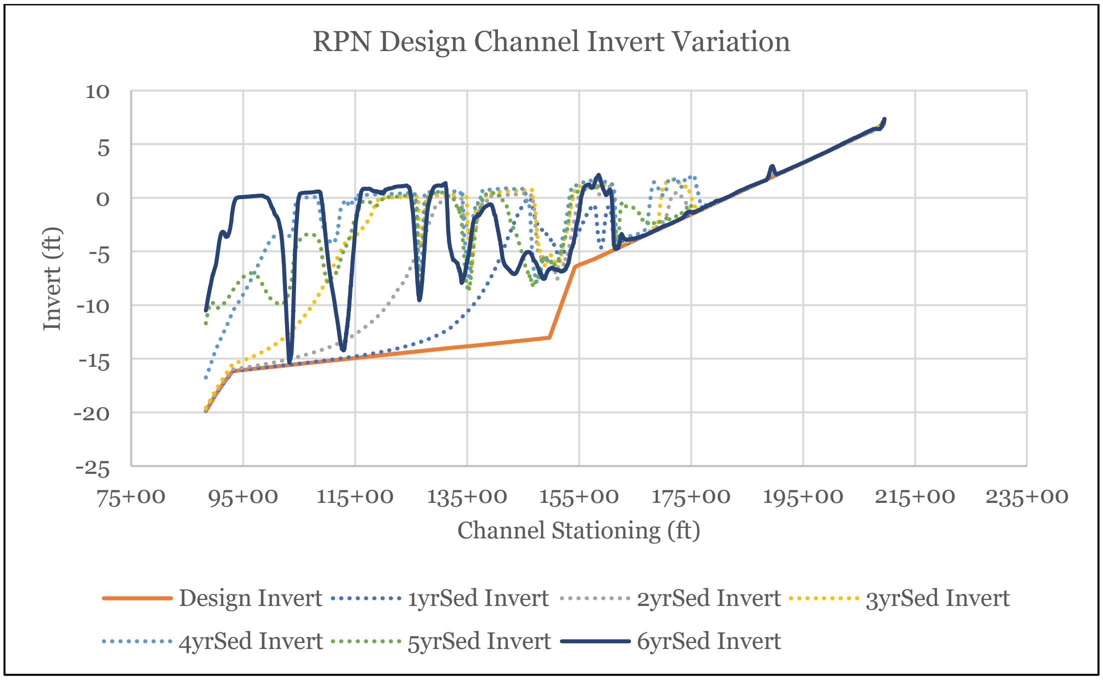


Figure 58. Channel invert variation summary.

Maximum water surface elevations corresponding to the non-erodible condition scenario are included in the set of figures below.

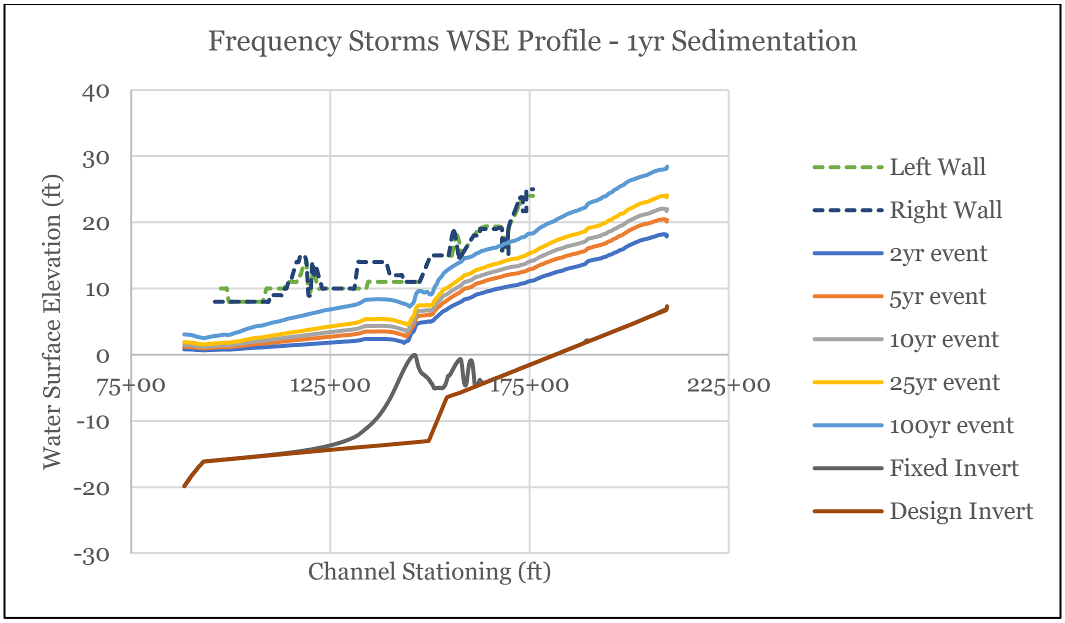


Figure 59. Maximum water surface elevation of frequency storms after the first sedimentation term (non-erodible condition).

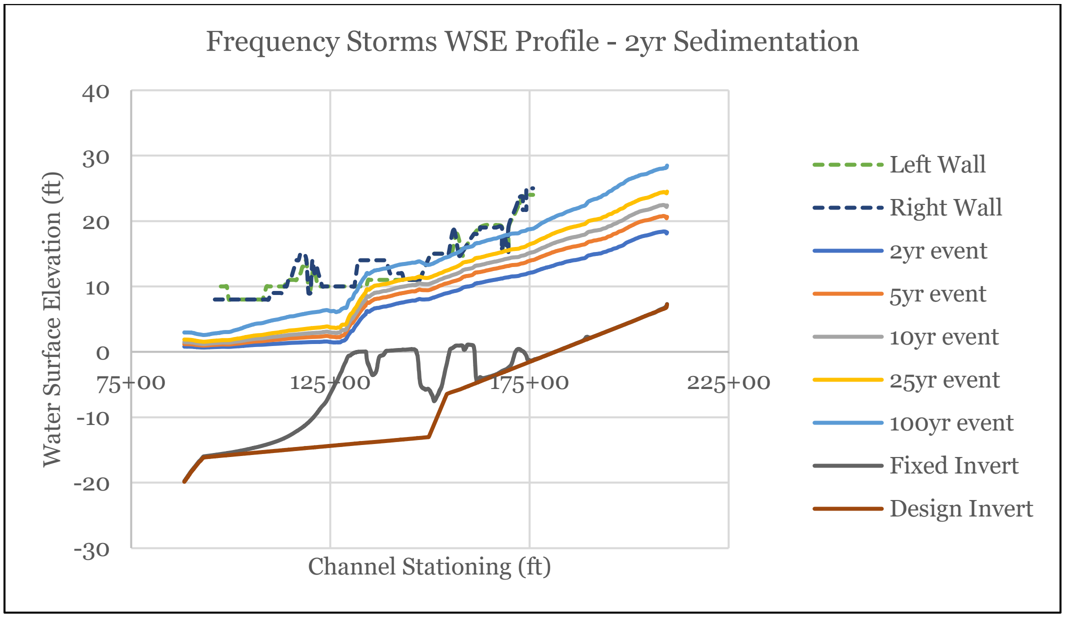


Figure 60. Maximum water surface elevation of frequency storms after the second sedimentation term (non-erodible condition).

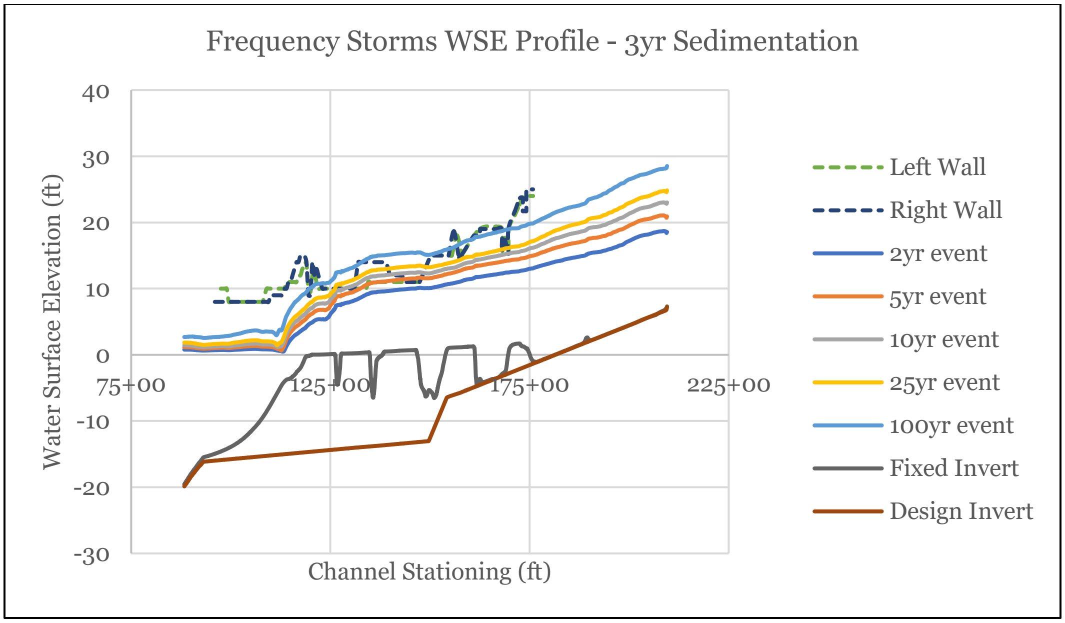


Figure 61. Maximum water surface elevation of frequency storms after the third sedimentation term (non-erodible condition).

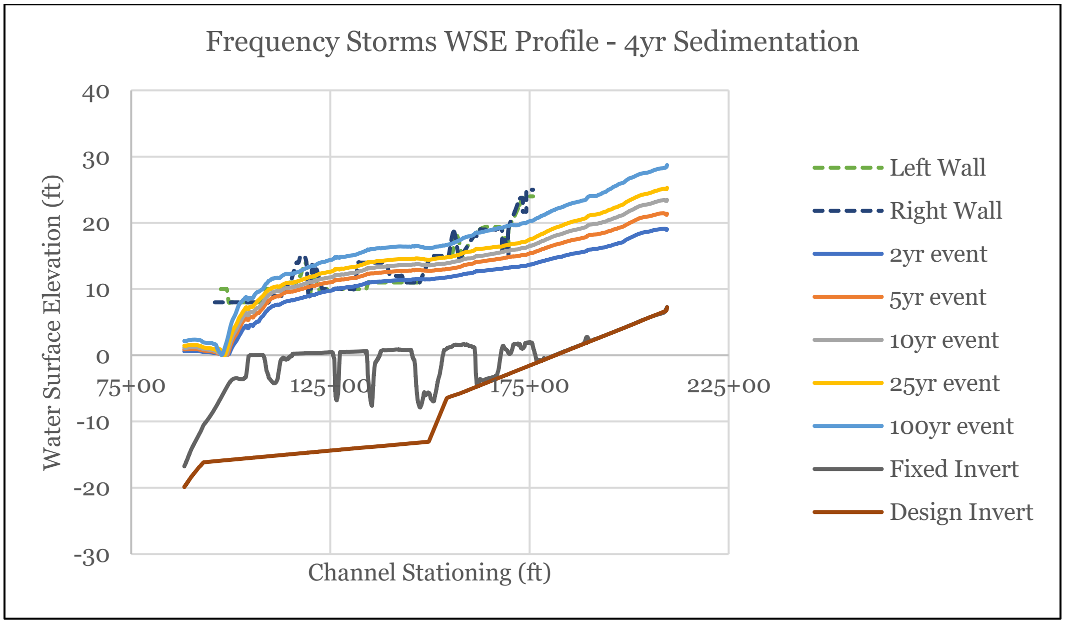


Figure 62. Maximum water surface elevation of frequency storms after the fourth sedimentation term (non-erodible condition).

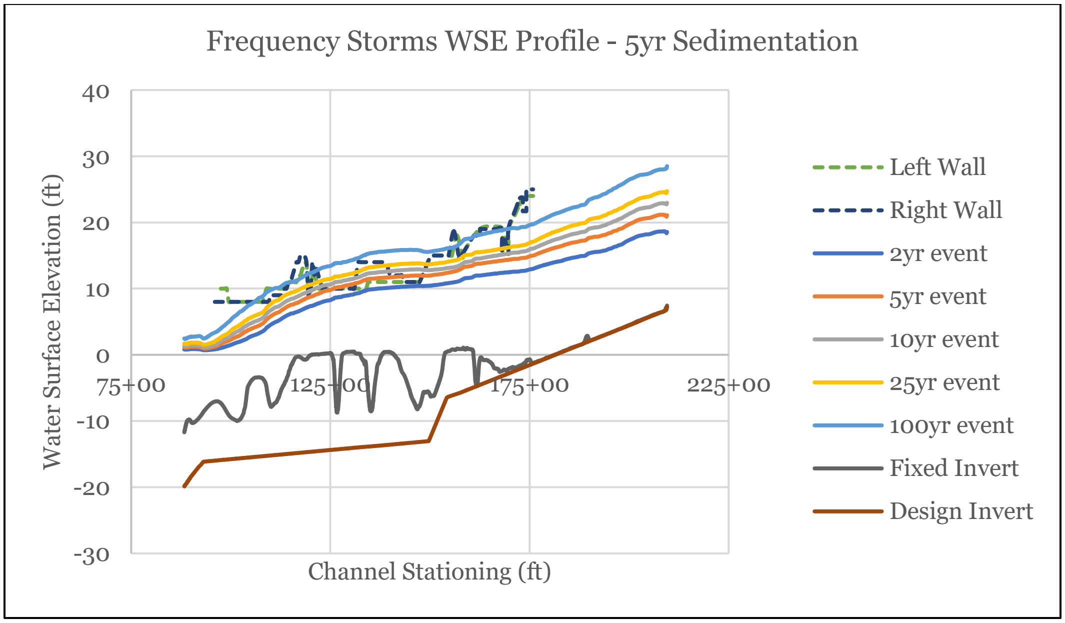


Figure 63. Maximum water surface elevation of frequency storms after the fifth sedimentation term (non-erodible condition).

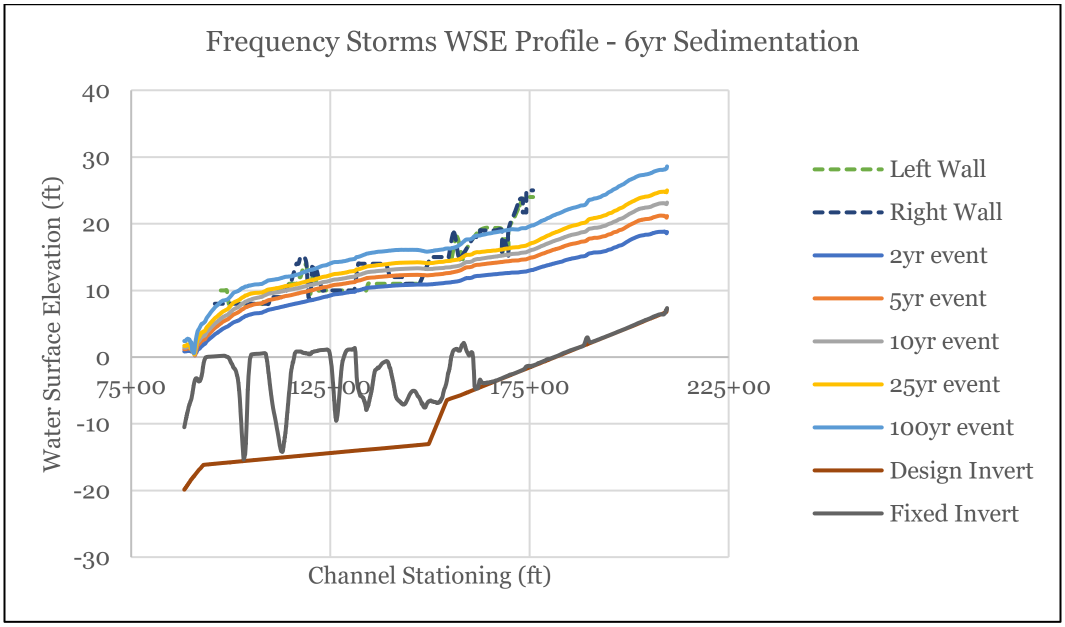


Figure 64. Maximum water surface elevation of frequency storms after the sixth sedimentation term (non-erodible condition).

Table 18 summarizes the information presented here by answering the following question: *"Was the event contained within the design channel?"*

Table 18. Channel capacity assessment results for the suite of frequency storms (non-erodible condition).

Sedimentation Condition	Frequency Storm				
	2yr	**5yr**	**10yr**	**25yr**	**100yr**
1 year	Yes	Yes	Yes	Yes	No
2 years	Yes	Yes	Yes	No	No
3 years	Yes	No	No	No	No
4 years	No	No	No	No	No
5 years	No	No	No	No	No
6 years	No	No	No	No	No

The elements shaded green maintained the 2-feet freeboard at all locations throughout the design channel reach. The elements shaded yellow stayed within wall height but encroached into the 2-feet freeboard. Elements shaded in red met or exceeded wall height at least at one location. The most critical stations being STA 134+00.00, STA 147+00.00, and STA 169+69.00.

The non-erodible condition shows that if vegetation is allowed to establish and take hold within the channel (particularly below STA 175+00) there would likely be significant adverse impacts on channel conveyance capacity. Not allowing the depositional material to erode represented an almost instantaneous loss in conveyance capacity that resulted in overbank flow from the first year of sedimentation. Although the conditions modeled for this scenario are extreme, they do show the incremental risks that poses a lack of monitoring and maintenance especially after the implementation of the project.

Table 19 presents the minimum distances or freeboard available to the top of the walls (both left and right) as well as the corresponding stationing for the 100yr events. The number of locations where the WSE encroaches the 2-feet freeboard is included as well. The table in full is included in the appendix section.

Table 19. WSE encroachment distance to the top of the channel walls

Sedimentation Condition	No. locations <2ft	To top left (ft)	To top right (ft)	Left wall STA	Right wall STA
1 year	44	-1.20	-1.75	169+75.00	169+69.00
2 years	170	-2.83	-2.83	147+40.00	147+40.00
3 years	248	-4.48	-4.48	147+40.00	147+40.00
4 years	329	-5.79	-5.52	134+00.00	146+50.00
5 years	318	-5.18	-4.86	134+00.00	145+00.00
6 years	342	-5.48	-5.09	134+00.00	144+00.00

*Note that positive values indicate WSE above the top of the channel walls.

After analyzing the inundation results corresponding to the non-erosive condition, it was determined that pre-project inundation levels would not be observed for the timeframe studied. As expected, the 100yr event simulation, which used the aggradation corresponding to sedimentation year 6, recorded the highest levels of inundation outside the channel walls. However, water depth in nearby communities was much lower compared to the pre-project condition.

Figure 65 presents a comparison of the maximum water depth corresponding to the 100yr event for both the pre-project (left) and post-project condition using the sedimentation corresponding to year 6 as the base.

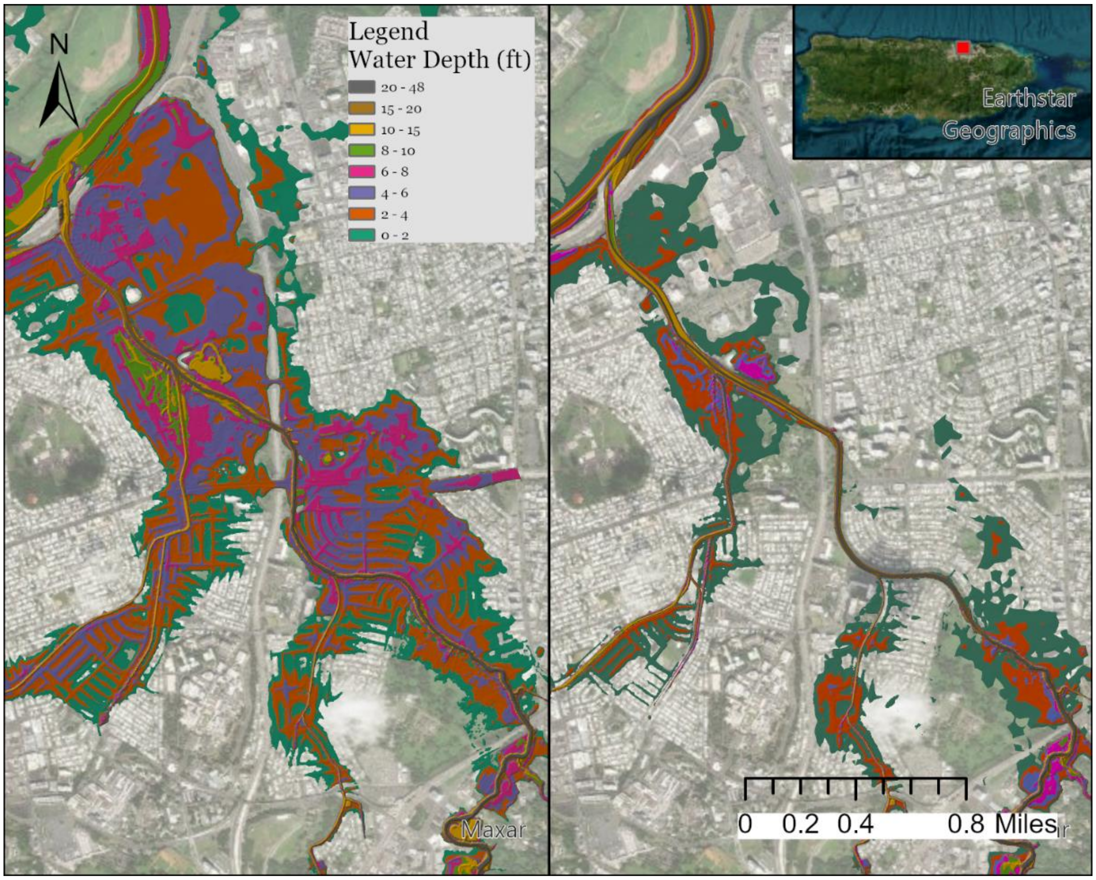


Figure 65. Pre-project (left) inundation depth VS. post-project (with fixed sixth year aggraded bed) inundation depth corresponding to the 100yr event.

7 O&M Recommended Plan

Continuous monitoring and appropriate maintenance efforts are key in the success of any project. This is particularly important and applicable to the Rio Puerto Nuevo Flood Mitigation project as some features of the original design --to include a sediment basin located upstream of the engineered channel-- are no longer being implemented. With this feature removed from the project there is a direct and uninterrupted flux of sediment being inputted into the channel. A combined monitoring-maintenance approach is recommended as the best plan to ensure project success. After analyzing the results of the sedimentation modeling efforts, the following plan is suggested.

7.1 *Monitoring plan*

The monitoring plan recommended focuses on tracking vegetation establishment in aggradation/depositional areas within the design channel limits and particularly downstream of STA 155+00. This station is an important inflection point in the project as tidal influence area, with its incremental depth, allows for particle settling during base flow conditions resulting in channel shoaling. Model results showed that not allowing the depositional material to scour under natural flow variations could result in catastrophic consequences such as the loss of channel conveyance capacity.

This plan should include preventive general assessments of the channel before and after significant storm events as well as the installation of remotely operated instruments to provide continuity of these efforts. Additional monitoring recommendations include:

- Installing an additional river gage on the downstream side of the WB De Diego bridge (near STA 93+70.00) to monitor both hydrologic and sediment conditions.
- Enhancing capabilities of the existing gage (USGS 50049100) to include sediment data collection.
- Conducting bathymetric surveys to monitor depositional areas and inform dredging activities. *Frequency*: at least one per year, after hurricane season.
- Performing sediment analyses using a mass balance approach incorporating data from the existing monitoring unit (USGS

50049100) and the newly proposed monitoring unit (near STA 93+70.00). These analyses are intended to estimate depositional conditions in-between bathymetric surveys. *Frequency*: quarterly.

- Performing specific gage analyses to identify changes in WSE and flow relationships as an additional measure to assess channel sedimentation in-between bathymetric surveys.
- Conducting sediment collections to characterize bed composition and determine transportability characteristics (incipient motion, erodibility, etc.). *Frequency*: one per year or after a significant storm event; whichever comes first.

7.2 *Preventive maintenance plan*

Although the model demonstrated that any of the five frequency storms would have sufficient energy to self-dredge the channel and still maintain its capacity, it is important to make an active maintenance program. Because of this, the following maintenance plan is recommended.

Table 20. Preventive Maintenance Plan.

Aggradation period (no significant storms)	Preventive Maintenance Plan
After 1 year	Monitor vegetation establishment. Complex and strong rooted systems could limit erodibility and reduce transport capacity.
After 2 years	In addition to the efforts described for the first year, consider dredging the channel at least partially. Expected depositional volume: 175,000-225,000 cubic yards.
After 3 years	Continue to monitor vegetation establishment. Consider dredging the channel at least partially. Expected additional depositional volume: 100,000-125,000 cubic yards.
After 4 years	Continue to monitor vegetation establishment. Consider dredging the channel at least partially. Expected additional depositional volume: 100,000-125,000 cubic yards.

After 5 years	Continue to monitor vegetation establishment. Consider dredging the channel completely. Expected additional depositional volume: 100,000-125,000 cubic yards.

Notice that one year of constant and uninterrupted aggradation yields approximately 100,000-125,000 cubic yards of deposited material. These are estimated amounts. The actual amount may vary significantly based on any number of parametric variations. This may include storm frequencies, storm intensities, and changes in the sediment supply due to alterations in the drainage basin among others. Appropriate monitoring and surveillance, such as bathymetric surveys, will better inform on dredging quantities.

Model results indicate that the remaining depositional areas after storm events will be located primarily along the channel wall. These areas were identified to be the low-energy portions of the channel due to their location relative to the flow approach angle. Although the extension of these remaining depositional pockets varies upon storm intensity, the general stationing and channel side of occurrence is included in Table 21.

Table 21. Remaining depositional areas

Descending Wall	Start STA	End STA
Left	158+00	134+00
Right	149+00	113+00
Left	114+00	104+00
Right	104+00	88+33

Figure 66 presents a comparison of remaining depositional areas (using conditions corresponding to 6 years of sedimentation as the base) for reference. The actual location of these depositional areas should be determined using field data.

Figure 66. Remining depositional areas compared (2yr event on the left and 100yr event on the right). Both using sedimentation results from year 6 as the base.

7.3 *Maintenance plan*

The maintenance plan focuses on the impacts of significant storm events. Regardless of their intensity, storm events also have the energy to mobilize the bed significantly. Storm events as frequent as a 2-yr event (50% AEP) have the stream power to re-shape the system and change local conditions along the channel. In the RPN system, such events will have quantifiable consequences. These could result in the mobilization of substantial amounts of depositional material from the channel into the confluence area. This could create backwater effects, reducing the conveyance capacity and potentially increasing the WSE, where upon secondary drainage is impacted. To address this issue, it is recommended to perform a bathymetric survey followed by dredging at the confluence area after significant storm events.

8 Conclusion

Hydraulic and sediment interactions may have significant and adverse impacts in terms of system stability, sediment particle transport and posterior sedimentation throughout the system. Although modeling tools and literature allow scientists and engineers to describe the phenomena associated with these systems, they only provide guidance on the general trends that could derive from them. It is understood within the sediment transport community of practice that model results should not be relied upon for absolute quantities. There are an almost infinite number of variables in the natural system that prevent guarantees. However, this study provides results as its best available data.

After completing the modeling and analysis efforts related to predicting, analyzing, and describing the sedimentation dynamics along the proposed engineered channel, the following items are concluded:

- The RPN AdH model was built and used to hindcast potential depositional patterns along the proposed engineered portion for a 6-year period.
- None of the flows recorded throughout this 6-year period correspond to any of the frequency storm events for this system. This implies an almost completely depositional period with little to no potential for massive displacement, resulting in channel clearing.
- Sediment data input for non-cohesive sediment particles to include sands and gravels relied on built-in capabilities while the suspended sediment inflow (cohesive) was determined using previously collected data and determined coefficients.
- After simulating 6 full years of data, the model estimated a deposition of approximately 481,172 cubic yards of sediment. This aggradation results in a reduction on the net capacity of the design channel by approximately 35.6%.
- Under the assumption that all deposited material can be carried downstream if sufficient energy is being exerted by the river, all the frequency storms are contained within the walls of the channel. However, channel capacity is predicted to be compromised for all simulations of the 100-yr event by water levels encroached within the 2 feet minimum freeboard at certain locations along the channel.

- On the other hand, if the deposited materials were fixed in place due to physical constraints (vegetation establishment, over consolidation, etc.) the channel capacity is potentially compromised, even after one year of consistent sedimentation only. Channel capacity was observed to be completely lost for all six frequency events after three years of consistent sedimentation.
- Comparing the resulting conditions after the 6-year modeling period to existing projects with similar watershed characteristics, it was determined that the depositional patterns predicted are appropriate.

9 References

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10 Appendix

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