Final Report
Impact of Dredging the Lower Narrow River on Circulation and Flushing in the Narrow River

Prepared for: Rhode Island Coastal Resources Management Council

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Date: 25 August 2016

Executive Summary

The Narrow River is a long, narrow and shallow estuary bordered by three towns, Narragansett, South Kingstown and North Kingstown, in southern Rhode Island, just west of the West Passage of Narragansett Bay. The estuary is primarily aligned on a north-south axis and extends approximately 10 km (6.2 mi), varies from 30 to 700 m (100 to 2,300 ft) in width and is generally less than 2 m (6.5 ft) deep. The Upper and Lower Ponds are kettlehole ponds created after the last glacial retreat and are 12 and 20 m (39 and 66 ft) deep, respectively. Mettatuxett is the narrow and shallow portion of the river downstream of the ponds. Pettaquamscutt Cove is located to the southwest and the Narrows is the lower reach from south of the cove to the mouth. The Narrows is the lower reach of the Narrow River with its lower half containing flood and ebb channels, and a flood tide delta system. This portion of the river is dynamic with shifting channels and shoals. A connection to Rhode Island Sound allows salt water to enter the system at northern end of Narragansett Beach.

The U. S. Fish and Wildlife Service (USFWS) and The Nature Conservancy (TNC), in collaboration with the New England Division of the U. S. Army Corps of Engineers (USACE) and the R. I. Coastal Resources Management Council (RICRMC) have undertaken a habitat restoration study to investigate the impact of dredging the lower reaches of the river and applying the dredged material to raise the level of the saltmarsh system in the southwest portion of the Narrow River (Pettaquamscutt Cove). The USFWS/TNC project dredging is unrelated to the present study and is being conducted solely as a habitat restoration effort to create eelgrass habitat and applying the dredged sediment to low-lying marsh areas to create elevation in an effort to add marsh resiliency to the existing tidal regime in the presence of sea level rise.

In addition, local and state representatives from the Town of Narragansett have expressed interest that dredging the Narrows be considered to increase the tidal flushing of the cove and hence reduce levels of pathogens and nutrients that degrade the river and is not focused on habitat restoration. Some portion of the sand removed from this dredging could be used to nourish Narragansett Beach, just west of the Narrow River mouth. It is important to note that federal funding for any dredging project within the Narrow River conducted as part of any future USFWS project efforts must be used strictly for habitat restoration, not beach nourishment, and meet federal cost/benefit ratios. In order to determine what the impact of dredging, and hence increasing the cross sectional area, might be on the circulation, flushing, and general water quality in the river the USFWS, USACE, and RICRMC recommended that a numerical circulation modeling study be undertaken to address this question.

The first objective of this study was to determine the impact of dredging in the lower reach (the Narrows) on circulation and tidal flushing in the river. A computer model that simulates the circulation in the Narrow River was used to evaluate the impact of various dredging options that increase the water depth in the Narrows. The second objective was to use the circulation model to determine the improvement in tidal flushing that occurs by increasing the tidal prism (volume of water entering and leaving the river on each tide. The increase of the tidal prism is accomplished by increasing the tide range that results from removing constrictions to the tidal flow (increasing water depth) in the Narrows.

The technical approach consisted of four major tasks:

- Review past river studies to determine historical variation in tidal range from mouth to head of estuary to gain a better understanding of the causes of this variation.

- Apply and calibrate ADCIRC, the Advanced CIRCulation model, a vertically averaged, finite element hydrodynamic model to the river. Model forcing focused on water levels in Rhode Island Sound that control the water levels in the river.
- Use the model to predict the change in tidal range (attenuation vs distance upriver) and flushing for different scenarios of dredging in the Narrows.
- Prepare a report documenting the results of the first three tasks and make recommendations on using the model results to evaluate pollutant transport in the river.

Previous studies over the last 45 years have shown a significant variation in tide range with distance from the mouth of the river, likely due to sediment dynamics (shoaling and channeling) in the Narrows reach located from the river mouth upstream to Sprague Bridge. The attenuation in tidal range at Sprague Bridge varies from 40% to almost 70% of the tide range at the river mouth. The attenuation in the Upper Pond varies from 10% to 25% of the tide range at the river mouth. The duration of the measurements did not appear to be a factor in affecting attenuation as much as the variation in tidal range during the experiment period.

The ADCIRC hydrodynamic model was used to evaluate the circulation in the river under historical, present and future bathymetric conditions which required synoptic information on the present bathymetry and the variation in the tides along the river. Using recently collected (April 2016) bathymetric data by URI/Graduate School of Oceanography (GSO) and tidal elevation data by USFWS and NOAA, the ADCIRC model used in the analysis to predict water elevations and current velocities was successfully calibrated. The model predicted tidal attenuation to be ~40% at Sprague Bridge, consistent with prior measurements.

The model predicted that highest maximum tidal flood currents occurred near the eastern shore looking upstream at and south of the Sprague Bridge at 0.45 m/s (1.5 ft/s). Highest maximum ebb currents occurred at the mouth reaching 0.36 m/s (1.18 ft). The currents are higher in the Narrows because of the constrictions in that reach, as well as the largest volume of water passing through the area on each tide. The sediment resuspension threshold is ~ 0.20 m/s (0.66 ft/s) so sediment transport occurs during each tidal cycle, particularly near the mouth and Sprague Bridge. Currents offshore from the river mouth were predicted to be ~10% of the currents in the Narrows.

The effects of Hurricane Bob were also investigated to determine whether the water elevation in the river responded similarly to both a storm surge and the tides. Data from the NOAA Newport tide station was used as a boundary condition for the model. The model showed that the water level attenuation at Sprague Bridge was ~50% of the offshore water level compared to ~40% for the April 2016 attenuation. The attenuation further up the river at Middlebridge was ~33% and ~30% and ~17% and ~10% in the Upper Pond, for Hurricane Bob and April 2016 (tidal), respectively. The maximum flooded area for Hurricane Bob was 3.21 km^2 (1.24 mi^2), 31% greater than the 2.22 km^2 (0.86 mi^2) for April 2016.

A series of four hypothetical dredging scenarios were chosen from -1 m MSL to -3 m MSL, which removed between 1.5 m (4.9 ft) and 3.5 m (11.5 ft) or between 21,500 m^3 (28,100 yds^3) and 184,000 m^3 (241,000 yds^3). The larger dredging scenario is likely unrealistic, but chosen to test the sensitivity of the analysis. Simulations were performed for the April 2016 measurement period. The attenuation values at Sprague Bridge increased from 0.42 to 0.84 (a factor of 2) with increasing dredging depth indicating that dredging reduced restriction to the flow. The values in the Upper Pond only increased from 0.18 to 0.25 (a factor of 1.5) indicating that for the mid and upper reaches of the river flow was more restrictive than near the mouth.

The tidal prism is a calculation using the variation of tide range along the river to determine the difference between the low tide and high tide volumes. Dividing the high tide volume by the tidal prism and multiplying by the primary tidal period (12.42 hrs) gives the tidal flushing time. The tidal flushing time for the present bathymetry was 3.8 days compared to the range of 3.5 to 2.3 days for the dredging scenarios, with decreasing times with increasing dredging depths. The limiting assumption in this calculation is that the flushing time is the average for all the reaches in the river. In reality the reaches closest to the mouth would have shorter times while the reaches distant from the mouth would have longer times. It does however provide a straightforward method to compare the relative effect of the dredging alternatives.

A sensitivity study to different tide ranges for the April 2016 period was conducted for a subset of dredging alternatives (-1 m MSL and -2 m MSL) to assess the importance of how the spring/neap cycle may affect flushing. The minimum tide range was 36-39% lower than the mean at Sprague Bridge for both the -1.4 and -2 m MSL scenarios and the maximum tide range was 57-64% higher than the mean. Similarly the minimum tide range was 27-29% lower than the mean at the Upper Pond for both the -1.4 and -2 m MSL scenarios and the maximum range was 60-63% higher than the mean. Ultimately the tidal flushing based on the minimum range in the river (5.0 to 5.7 days) was 69-72% larger than the tidal flushing based on the mean range (2.9 to 3.4 days) while the tidal flushing based on the maximum range in the river (2.3 to 2.5 days) was 22-25% smaller than the tidal flushing based on the mean range. Thus the influence of the tide range is a significant factor in determining the tidal flushing time.

The other important result of dredging and thus increasing the tide range (decreasing the attenuation) is the effect on Mean High Water (MWH) levels in the area of the USFWS habitat restoration project. The decrease in attenuation will likely have some negative effects on the sensitivity of existing saltmarsh to increasing water elevations and could impact future saltmarsh restoration efforts in the Narrow River. Thus the benefits of increased flushing must be weighed against the negative impacts saltmarsh restoration.

A comparison of predictions using the USACE HEC-RAS model applied to the study area by USACE and the ADCIRC model used in this study show generally consistent results, although the estimates from HEC-RAS application to 2007 indicated that the constriction in the mouth and Narrows was less influential on the tide range attenuation in the river at that time.

Finally the dredged volumes used in this analysis were compared with re-nourishment volumes determined for the adjacent beaches in Narragansett by Woods Hole Group (WHG) (2011). Two scenarios of re-nourishing different lengths of beach using five options were evaluated. It was found that the -1.4 m MSL dredging alternative could supply enough material for two of the five options under scenario 1 (just Narragansett town beach) and that the -2 m MSL alternative could supply enough material for a third option of scenario 1 and an option under scenario 2 (the town beach plus the private beaches closer to the Narrow River mouth). However the beaches would likely have to be re-nourished after four years for scenario 1 and after eight years for scenario 2.

This study has provided estimates of tidal flushing times which are a useful metric in understanding the length of time that pollutants will remain in a tidally dominated water body. Since the Narrow River, by its name, is a relatively long and narrow water body, the head waters will not flush as quickly and therefore pollutants would likely accumulate there more than near the mouth. To assess the pollutant transport through the Narrow River from their sources to Rhode Island Sound a further model calculation is recommended. To ensure that the model results are accurate that type of model is usually calibrated against field data collected in the river. A typical approach is to use a non-toxic dye whose concentration can be automatically measured by boat-mounted or statically deployed instruments. A plan to conduct a dye study in and apply a pollutant model to the Narrow River is recommended.

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1 Introduction

1.1 Study Area

The Narrow River, shown in Figure 1-1, is a long, narrow and shallow estuary bordered by three towns, Narragansett, South Kingstown and North Kingstown, in southern Rhode Island, just west of the West Passage of Narragansett Bay. The estuary is primarily aligned on a north-south axis and extends approximately 10 km (6.2 mi), varies in width from 30 to 700 m (100 to 2,300 ft) and is generally less than 2 m (6.5 ft) deep. The Upper and Lower Ponds are kettle hole ponds created after the last glacial retreat and are 12 and 20 m (39 and 66 ft) deep, respectively. Mettatuxett is the narrow and shallow portion of the river downstream of the ponds. Pettaquamscutt Cove is located to the southwest and the Narrows is the lower reach from south of the cove to the river mouth. A connection to Rhode Island Sound allows salt water to enter the system at northeastern end of Narragansett Beach. There is little freshwater flow into the river as the watershed is only 36 km^2 (14 mi^2).

Figure 1-1. The entire Narrow River study area showing the major features and the three bridges.

The Narrow River is crossed by three bridges: the Bridgetown (Lacey) Bridge (Bridgetown Road), downstream of the Lower Pond, the Middlebridge Road Bridge crossing a relatively wide and shallow section of the river 3.5 km (2.2 mi) south of Bridgetown Bridge, and the Sprague Bridge (Boston Neck Road) crossing the tidal inlet about 1.3 km (0.8 mi) northwest of the river mouth at Narragansett Beach. These bridges area shown in Figure 1-1 highlighted with yellow text. Both the Bridgetown Bridge and the Sprague Bridge cross the Narrow River at locations with relatively narrow widths but do not appreciably constrict the flow. The Middlebridge Road Bridge, although located in a relatively wide section of the River consists of causeways extending from each shore but is constructed with an opening sufficiently wide as to not constrict the flow.

The Narrows is the lower reach of the river from Sprague Bridge to Rhode Island Sound. Its lower half contains flood and ebb channels, and a flood tide delta system. This portion is dynamic with shifting channels and shoals. Deeper areas, greater than 2 m (6.5 ft), are located near the mouth and around Sprague Bridge.

Figure 1-2. The Narrows study area, defined as the lower reach of the river from Sprague Bridge downstream to the mouth.

1.2 Previous Studies

Previous studies of the Narrow River extend back to at least 1970. They have included academic research studies under University of Rhode Island auspices (Gaines, 1975; Carr, 1995). Federal government agencies including the U. S. Army Corps of Engineers (USACE) (1971, 1993, 2009, and 2010) and the U. S. Fish and Wildlife Service (USFWS) (2014). State agencies included the R. I. Coastal Resources Management Council (RICRMC) (1987, 1999) and the R. I. Department of Environmental Management (RIDEM) (2001). Also active were private firms under contract to government agencies including Applied Science Associates (Turner, C. et al., 1989; Applied Science Associates, URI Watershed Watch, SAIC Engineering, Inc. and UWR [Urish, Wright and Runge], 1995a; and Swanson, J.C. and H. Rines, 1995b), Apogee Research (1990), and Woods Hole Group (2011). Some of these studies included direct measurements of the tide range to be discussed below.

1.3 Study Background

The USFWS, in collaboration with the New England Division of the USACE and RICRMC, has undertaken a study to investigate the impact of dredging and applying the dredged material to raise the level of the marsh system in the southwest portion of the Narrow River (Pettaquamscutt Cove). This plan is designed to restore and enhance the long term viability and ecological health of the marsh in the presence of sea level rise.

In addition, local and state representatives from the Town of Narragansett have expressed interest that dredging the lower Narrow River (the Narrows) be considered to increase the tidal flushing of the cove and hence reduce high concentrations of nutrients that may lead to degradation of the salt marsh and its benthic habitats. The sand removed from this dredging could be used to nourish Narragansett Beach, just southwest of the Narrow River mouth.

In order to determine what the impact of dredging, and hence increasing the cross sectional area, might be on the circulation, flushing, and water quality in the river the USFWS, USACE, and RICRMC recommended that a numerical circulation modeling study be undertaken to address this question.

1.4 Project Objectives

The first objective of this project was to determine the impact of dredging in the lower reach (the Narrows) on circulation and tidal flushing in the river. A computer model that simulates the circulation in the Narrow River was used to address this objective by evaluating various dredging options that increase the water depths in the Narrows.

The second objective was to use the circulation model to determine the improvement in tidal flushing that occurs by increasing the tidal prism (volume of water entering and leaving the river on each tide). The increase of the tidal prism is accomplished by increasing the tide range that results from removing restrictions to the tidal flow (increasing water depth) in the Narrows.

1.5 Technical Approach

The technical approach consisted of four major tasks:

- Review past river studies to determine historical variation in tidal range from the mouth to the head of estuary to gain a better understanding of the causes of this variation.

- Apply and calibrate ADCIRC, the Advanced CIRCulation model, a vertically averaged, finite element hydrodynamic model, to the river. Model forcing will be from the water levels in Rhode Island Sound that control the water levels in the river.
- Use the model to predict the change in tidal range (attenuation) with distance upstream and flushing for different scenarios of dredging in The Narrows.
- Prepare a report documenting the results of the first three tasks and make recommendations on using the model results to evaluate pollutant transport in the river.

This report documents the results of the technical tasks performed. Specifically, Section 1 provides an introduction that includes a description of the study area, the previous studies of the river; the study objective and the technical approach. Section 2 provides a review of the previous historical measurements of the tide range along the length of the river. Section 3 summarizes the bathymetric and water level surveys conducted for this project. Section 4 presents a description of the hydrodynamic model, ADCIRC, and its application to the Narrow River, while Section 5 presents ADCIRC model results. Section 6 presents the dredging alternatives and the results of the associated model simulations. Section 7 provides conclusions from the study and recommendations for future work and Section 8 contains a list of references.

2 Water Level Attenuation in the Narrow River

Water level (tidal) attenuation is defined as the ratio of the tide range at any location in the Narrow River to the tide range at the river mouth. The tide range is simply the difference between low tide elevation and high tide elevation. Since the tide range at the mouth is approximately 1.0 m (3.3 ft) the attenuation can also be interpreted as the local tidal range in meters.

2.1 Historical Field Studies

Five historical studies have reported field activities including measurements of water elevation in the river with the use of self-recording instruments. A summary of the studies are given in Table 2-1, while Figure 2-1 shows the locations of water level (tide) gauges along the Narrow River. Additional details on the five studies are provided below.

Table 2-1. Summary of the five historical water level measurement studies.

Reference	Start Date	End Date	No. of Surveys	Survey Duration (days)	No. of Stations
Gaines (1975)	4 Jun 1970	24 Jun 1970	1	20	3
Carr (1995)	6 Aug 1993	1 Nov 1993	4	3, 15, 27, 63	4*
Swanson and Rines (1995)	25 Sep 1994	30 Nov 1994	6	7, 11, 13, 17, 54, 65	4*
USACE (2009)	12 June 2007	12 Jun 2007	1	0.4	3**
USFWS (Spreadsheet)	3 June 2014	18 Jun 2015	5	73, 49, 77, 49, 77	1 to 4**

* One station per overlapping survey.

**Stations within Pettaquamscutt Cove not included

Figure 2-1. Locations of tide gauges along Narrow River for the five historical field studies.

Gaines (1975) - Data collected in 1970

An extensive set of field studies was performed and reported in a dissertation by Gaines (1975) with the URI, Graduate School of Oceanography. The overall purpose of the research was to assess the geomorphology, hydrography and geochemistry of the Narrow River Estuary (described as the

Pettaquamscutt River Estuary). A tidal survey was conducted from December 1969 through September 1970, with gauges at Sprague Bridge, Bridgetown (Lacey) Bridge, and the Upper Pond. The period 4 through 24 June 1970 was specifically analyzed for attenuation of the tidal range with values of 0.47, 0.13, and 0.11 at Sprague Bridge, Bridgetown Bridge, and the Upper Pond, respectively.

Carr (1995) - Data collected in 1993

A field program and modeling study was conducted by Carr (1995) as part of a dissertation with the URI Department of Civil and Environmental Engineering, whose purpose was to develop a model that would determine the distribution and concentrations of fecal coliform throughout the Narrow River Estuary. Data from four tide gauge stations in the Narrow River during the August through September 1993 period were collected. Measurements at Sprague Bridge were made between 6 and 21 August 1993, Mettatuxet (30 August through 1 November), Bridgetown Bridge (5, 11, and 12 September) and the north end of the Upper Pond (13 August through 9 September) to provide attenuations of the tidal range of 0.46, 0.36, 0.33 and 0.24, respectively.

Swanson and Rines (1995): Data collected in 1994

Applied Science Associates, Inc. (Swanson and Rines, 1995) performed a study to assess the effects of the Middlebridge Bridge on circulation in the Narrow River as part of a plan to renovate the bridge by the RI Department of Transportation and to minimize its effects on flushing of the river. Both a field program and modeling study were conducted. On 25 September 1994, tide gauges were installed upstream and downstream of the Middlebridge Road Bridge. The downstream (south) gauge was removed on 18 November 1994 and reinstalled immediately at a station in the Lower Pond to acquire information on attenuation upstream of Middlebridge. Both gauges were removed on 19 November 1994. Additional unpublished water level data at a point just east of Sprague Bridge were acquired during the same time period from the University of Rhode Island (URI) Department of Ocean Engineering (OE).

USACE (2009): Data collected in 2007

In order to calibrate a one-dimensional time-varying model (HEC-RAS) of the river the USACE (2009) collected tide level data using tide boards on 12 June 2007 during the flood tide from approximately 11:00 to 20:15. A series of four stations were occupied during this time: the Narrows, south and north of Middlebridge, and in Pettaquamscutt Cove (shown in Figure 1-1). The tide board location in the cove is not shown in Figure 2-1 as it is outside the focus of the present project.

USFWS (undated): Data collected in 2014-2015

As part of an extensive set of field studies to support the restoration of the marshes in Pettaquamscutt Cove, the USFWS conducted water elevation studies with up to six instruments over a significant fraction of the time between 3 June 2014 and 18 June 2015. Seven of the 21 stations over 5 deployments focused on Pettaquamscutt Cove (Figure 1-1) and were not included for analysis. Two other stations appeared to have recording problems and were also eliminated leaving 12 individual data sets. Table 2-2 provides details on these data sets.

Table 2-2. Summary of USFWS 2014-2015 field information.

Deployment	Location	Start Date	End Date	Duration (days)	Attenuation
1	Sprague Bridge Middlebridge	3 Jun 2014	15 Aug 2014	73	0.52 0.46
2	Sprague Bridge Middlebridge Sedge – East Channel Sedge – West Channel	19 Aug2014	7 Oct 2014	49	0.54 0.47 0.53 0.53
3	Sprague Bridge Middlebridge Sedge – West Channel	15 Oct 2014	31 Dec 2014	77 77 77	0.53 0.47 0.53
4	Sprague Bridge Middlebridge	6 Jan 2015	24 Feb 2015	49	0.48 0.41
5	Sprague Bridge	2 Apr 2015	18 Jun 2015	77	0.34

2.2 Attenuation Comparison

To visually compare the results of the field measurements described above, the water level attenuation as a function of upriver distance is shown in Figure 2-1. The value denoted Mouth is included to show that the attenuation value is 1.0 at the mouth (the reference location). A large number of measurement were taken at the Sprague Bridge, approximately 1.2 km (0.75 mi) upstream from the mouth. This reach is known as the Narrows where there is active sediment movement causing constrictions, particularly in the lower half nearer the mouth and generates a large drop in tidal range. This large attenuation varies from 0.47 to 0.67 at Sprague Bridge. The rate of drop in attenuation with distance is largest in this area. There is a further reduction to between 0.34 and 0.52 at Middlebridge, located approximately 2.5 km (1.6 mi) from the mouth. The reduction continues in the vicinity of Bridgetown Bridge with a range of 0.13 to 0.33 and finally an attenuation range of 0.11 to 0.25 in the Upper Pond.

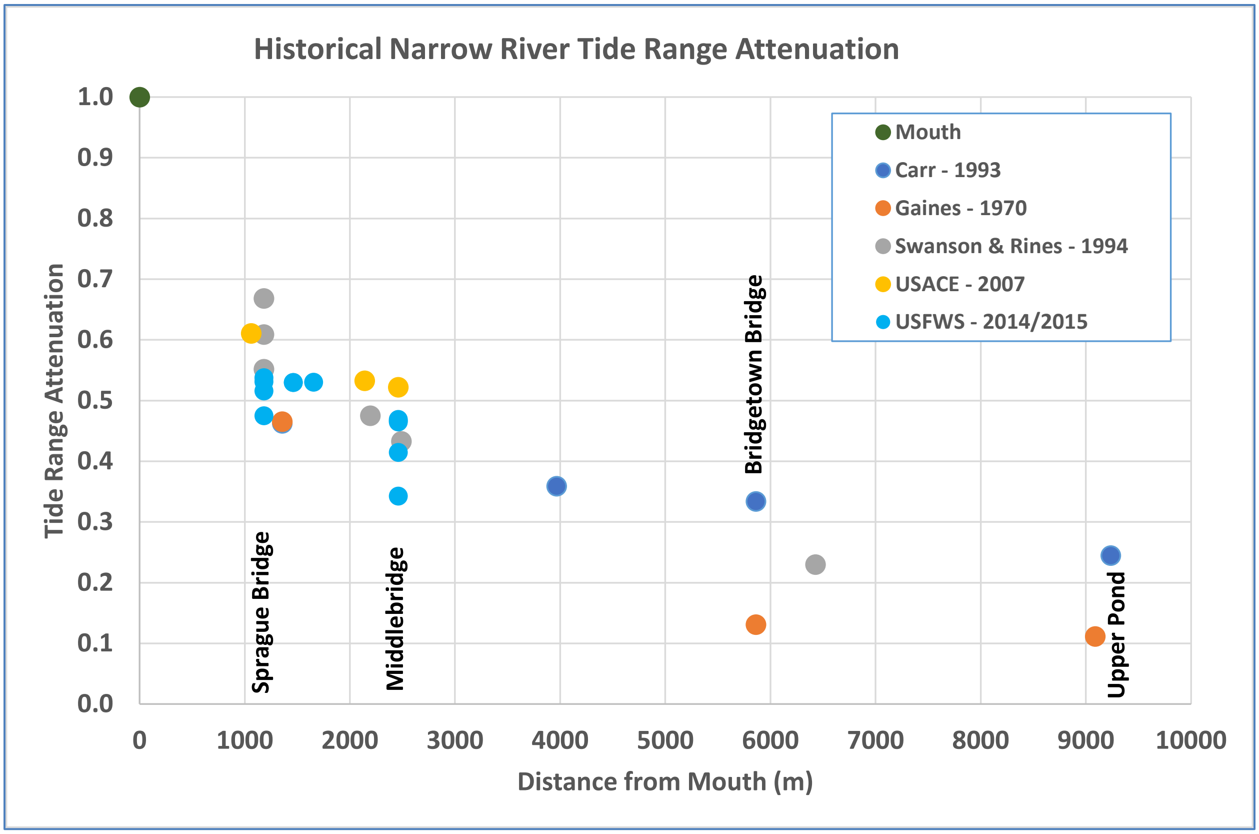


Figure 2-2. Historical field studies showing variation in water level attenuation in the Narrow River as a function of distance from the mouth.

As seen from Figure 2-2 there are significant variations among the studies which raise the question as to causation. If it is assumed that all the data are of good quality, then clearly there have been changes in the Narrow River system affecting tide range. This is particularly evident at Sprague Bridge but also in the Lower and Upper Ponds where the tidal range doubles from the Gaines (1975) data, from April 1970, to the Carr (1995) 1993 and Swanson and Rines (1995) studies.

Another possible explanation for the variation at each site is that the duration of the measurements may have played a role. The durations for each data set were attached as callouts to the markers and redisplayed in Figure 2-3. Larger callouts displayed multiple durations for the same attenuation. In general the shorter durations showed higher attenuations (USACE duration of 0.4 days; Swanson and Rines reporting durations of 7 and 13 days; and Carr data set at Bridgetown Bridge with a duration of 3 days) relative to the other studies with longer durations. The USFWS data, with longer durations ranging from 49 to 77 days, typically showed lower attenuations at its stations which spanned the river from Sprague Bridge to Middlebridge.

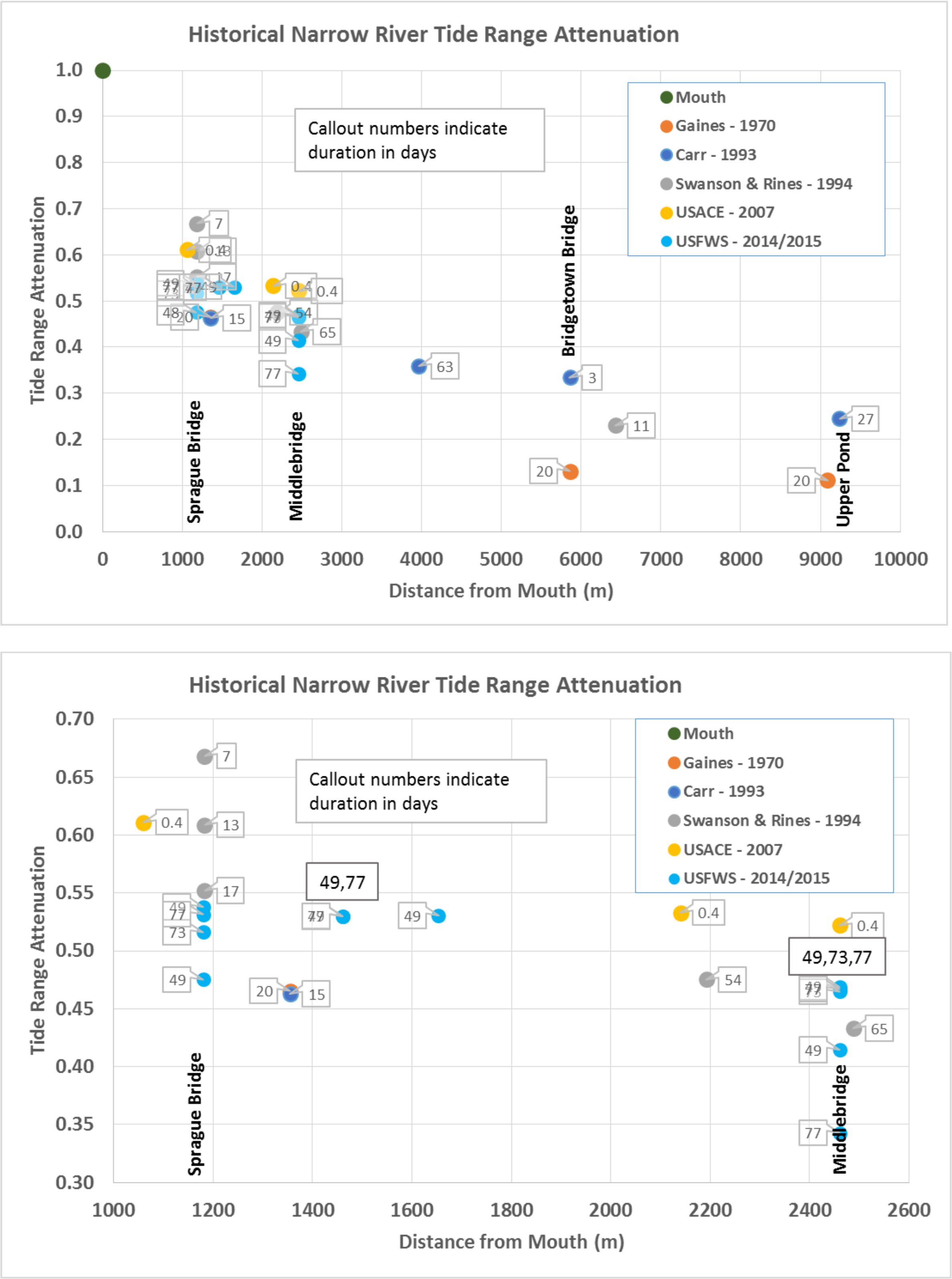


Figure 2-3. Variation in duration of water level measurement as shown in the callouts. Upper panel shows all measurements, while lower panel shows only measurements from Sprague Bridge to Middlebridge for clarity.

3 Project Field Studies

USACE (2009) reported difficulty in calibrating their model of the Narrow River with previous bathymetric and tidal information because the data were not synoptic. To address this problem they conducted a water level survey in 2007 with URI performing a bathymetric survey in similar time frame so the dates of the two surveys overlapped. USACE successfully calibrated its model with these data.

Due to the large variation in attenuation, probably significantly due to the bathymetric changes that occurred in the lower portion of the Narrows between 2007 and present, the present project followed USACE’s approach and commissioned a bathymetric survey by URI/GSO in the Narrows along with water elevation measurements by USFWS at Sprague Bridge to provide a synoptic view of the effects of bathymetric constrictions on tide range along the river. The water level data was used to benchmark the bathymetric survey data.

3.1 Bathymetric Survey

Bathymetric data collected by URI/GSO on 15 April 2016 in the Narrows used a shallow draft (0.3 m [1 ft]) 8.5 m (28 ft) long pontoon boat to access shallow areas of the river. They found it was not possible to follow the planned survey lines due to strong currents, sand bars, and boulders.

Data was collected with EdgeTech 6205, a Multi-Phase Echo Sounder system, using GeoDas software. Data was converted to a 0.5-m (1.6 ft) horizontal grid resolution in the surveyed area. Applanix POS MV system was used to ensure positional accuracy and correct for vessel motion. Data records were processed using OIC CleanSweep software correcting for tide, sound velocity and vessel motion and filtered to remove outlier soundings. Horizontal coordinate system was set to UTM Zone 19M and vertical datum to NAVD88. Vertical resolution was typically within 5-10 cm (0.16-0.32 ft).

Figure 3-1 shows the results of the bathymetric survey as color coded areas representing different depths. Light blue indicates depths above 0.1 m (0.32 ft) and magenta indicates depths below 4.41 m (14.5 ft).

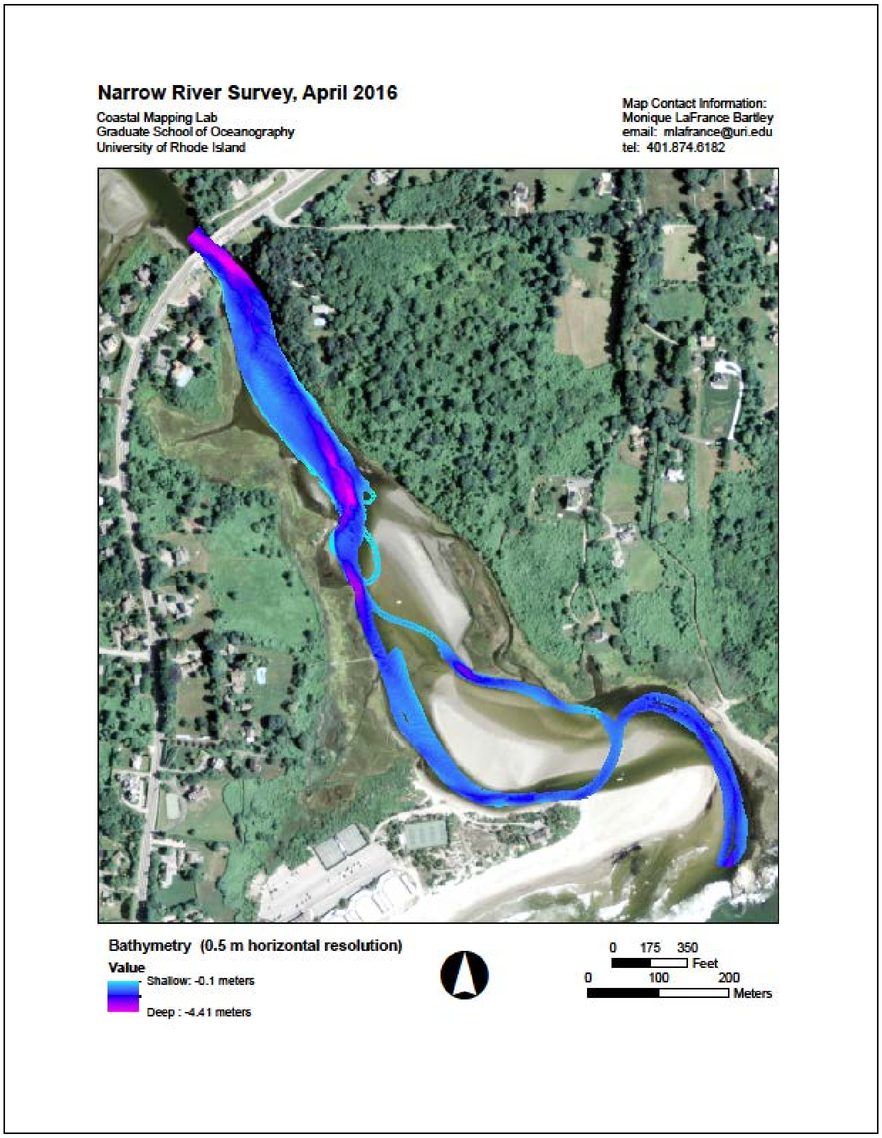
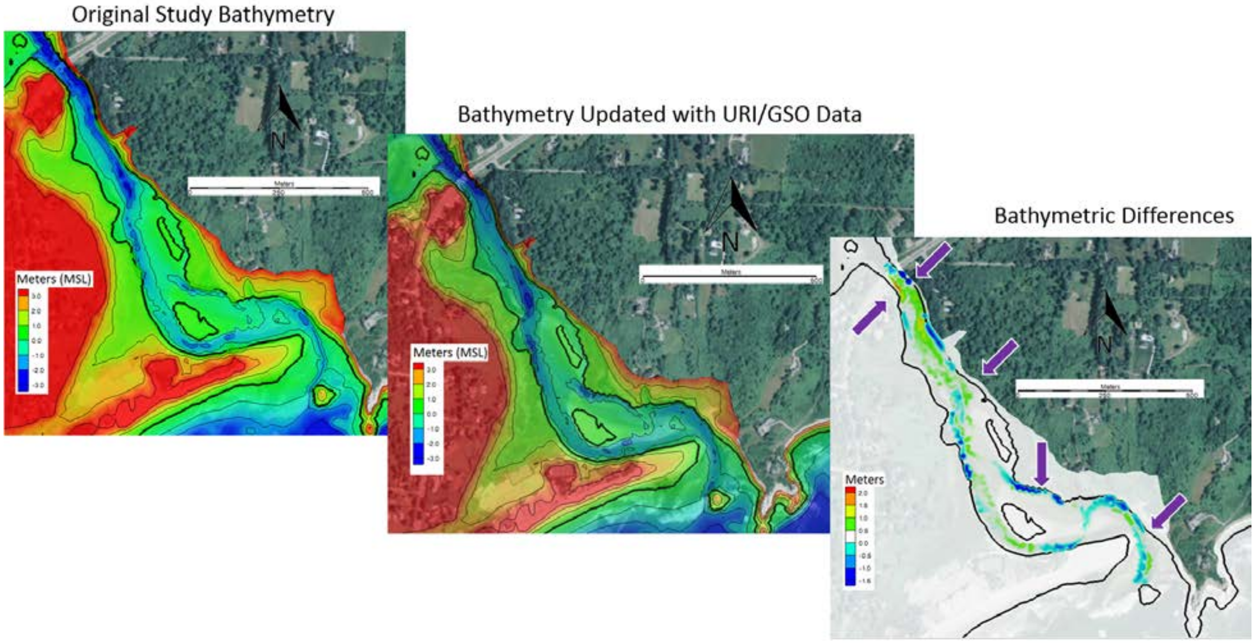


Figure 3-1. Contours of bathymetry in the Narrows from data collected by URI/GSO on 15 April 2016.

Figure 3-2 shows how the bathymetry changes from the original bathymetry developed from a variety of sources (USACE, 2009). The upper left panel shows color contours of the original bathymetry and the center panel shows the bathymetry updated with the URI/GSO results using the same color contours. The lower right panel shows the bathymetry differences (updated – original). The areas highlighted by arrows indicate the following:

- Portion of flood channel now deeper north of flood delta shoal by 2 m (6.6 ft)
- Western portion of channel at Sprague Bridge shallower (1 m [3.3 ft]) while eastern portion deeper by 2 m (6.6 ft)
- Areas south of Sprague Bridge and south of flood delta shoal shallower (0.5 to 1.5 m [1.6 to 4.9 ft])

The net bathymetric differences were equivalent to 6,990 m^3 (9,140 yd^3) more sediment with (16,180 m^3 [21,160 yd^3] added and 9,190 m^3 [12,220 yd^3] removed).


Original Study Bathymetry

Bathymetry Updated with URI/GSO Data

Bathymetric Differences

Figure 3-2. The upper left panel shows color contours of the original bathymetry and the center panel shows contours of the bathymetry updated with the URI/GSO results, using the same color contours. The lower right panel shows the bathymetry differences (updated – original).

3.2 Water Level Measurements

The USFWS deployed a water level gauge during 1-19 April 2016 just below Sprague Bridge (Figure 3-3). A Trimble R10 with Real Time Kinematic (RTK) satellite navigation was used taking five measurements on the gauge resulting in an average elevation of 0.601 m (1.972 ft) NAVD88. Elevation data was processed relative to NAVD88 with 15 min sampling frequency.

In addition two NOAA stations were used in the project: 8452660 Newport and 8454658 Narragansett Pier shown in Figure 3-3. Verified observations at 6-min intervals from the Newport station were https://tidesandcurrents.noaa.gov/waterlevels.html?id=8452660). The subordinate NOAA Narragansett Pier Station offsets to Newport (averaging 92% amplitude and zero phase shift) were also downloaded from the NOAA website (https://tidesandcurrents.noaa.gov/noaatidepredictions/NOAATidesFacade.jsp?Stationid=8454658) and applied for use in model forcing.

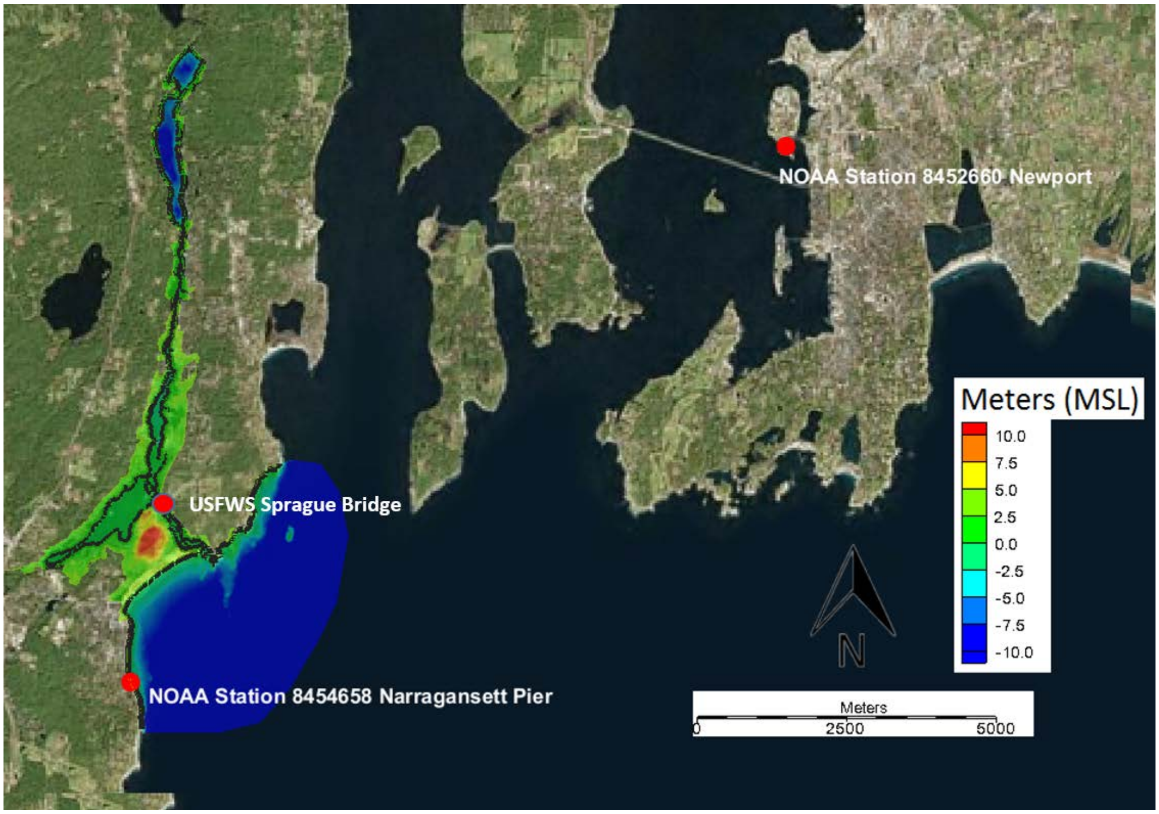


Figure 3-3. The location of water elevation measurements at Newport, Narragansett Pier and Sprague Bridge. Water depths relative to MSL are also provided for the study area.

Time series of the three stations are shown in Figure 3-4 all relative to MSL for the measurement period. The differences between Newport and Narragansett Pier are in amplitude only as discussed above. The data from the USFWS-deployed tide gauge at Sprague Bridge showed significant reduction in amplitude and an approximate 1-hr phase lag relative to high tide. The asymmetry in the tidal cycle (steeper rise rate during flood, lower fall rate during ebb) is also evident.

All the records showed events (non-tidal variations) seen on 3, 7, 9 April. The mean of the Sprague Bridge elevations were higher (~0.2 m [~0.66 ft]) than Narragansett Pier and Newport elevations indicating superelevation in the Narrow River. This condition is a buildup of water during a flood tide which cannot be sufficiently released during the following ebb due to frictional effects. It is dependent on the tidal amplitude, the major tidal period, and the duration of the flooding tide as described in the USACE Coastal Engineering Manual (USACE, 2008).

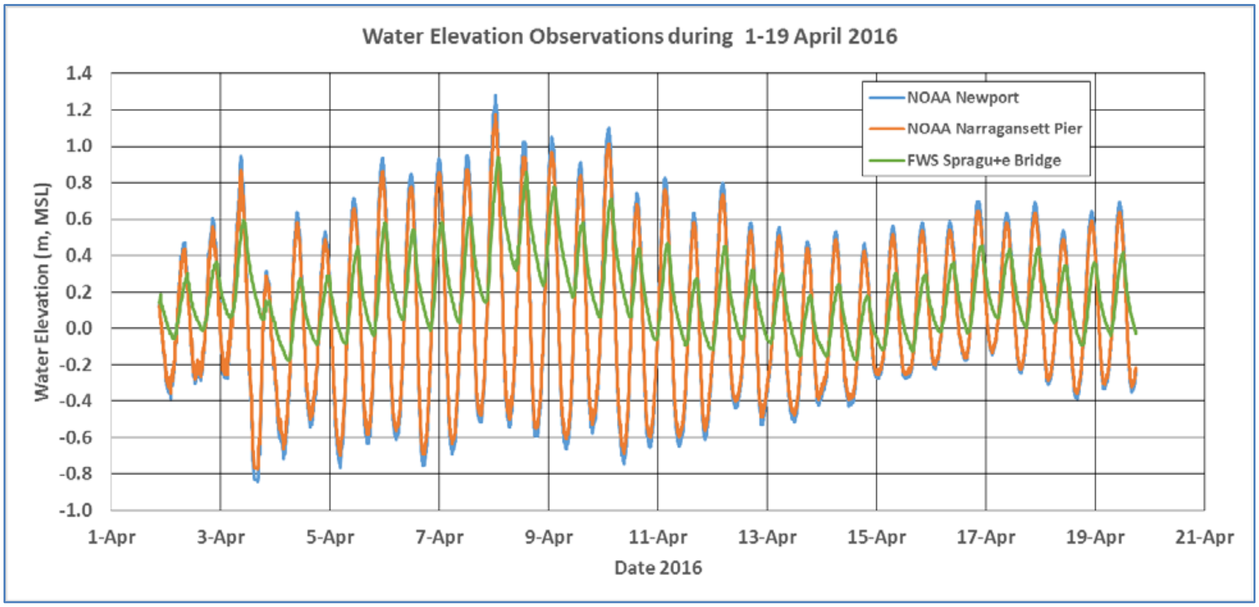


Figure 3-4. Time series of water levels for Newport, Narragansett Pier, and Sprague Bridge for the period 1 through 19 April 2016.

3.3 Sprague Bridge Attenuation Variability- April 2016

The Sprague Bridge and Narragansett Pier time series were analyzed for attenuation (the reduction in tide range) for each tide cycle. There were 34 complete tidal cycles (TCs) during the period from 1 April 2016 19:00 to 19 April 6:44. The Narragansett Pier and Sprague tide ranges, as well as the range attenuation, are shown in Figure 3-5. The fourth tidal cycle for both locations, which occurred between 8:48 and 18:14 on 3 April, showed an anomaly due to the meteorological event seen in Figure 3-4. The spring/neap cycle, defined here as spring constituting that portion of the tidal record when the range is above the mean and neap that below, is clearly seen in the Narragansett Pier tidal ranges and to a lesser degree in the Sprague Bridge ranges. The entire spring/neap cycle lasts approximately 29.5 days and included 28 tidal cycles with 14 spring tidal cycles (shown as red markers) and 14 neap tidal cycles (shown as green markers) overlain on the Narragansett Pier tidal ranges. The start of the spring/neap tidal cycle was chosen to exclude the outlier on 3 April. The attenuation showed smaller values during the larger spring tide ranges and larger values during the smaller neap tide ranges.

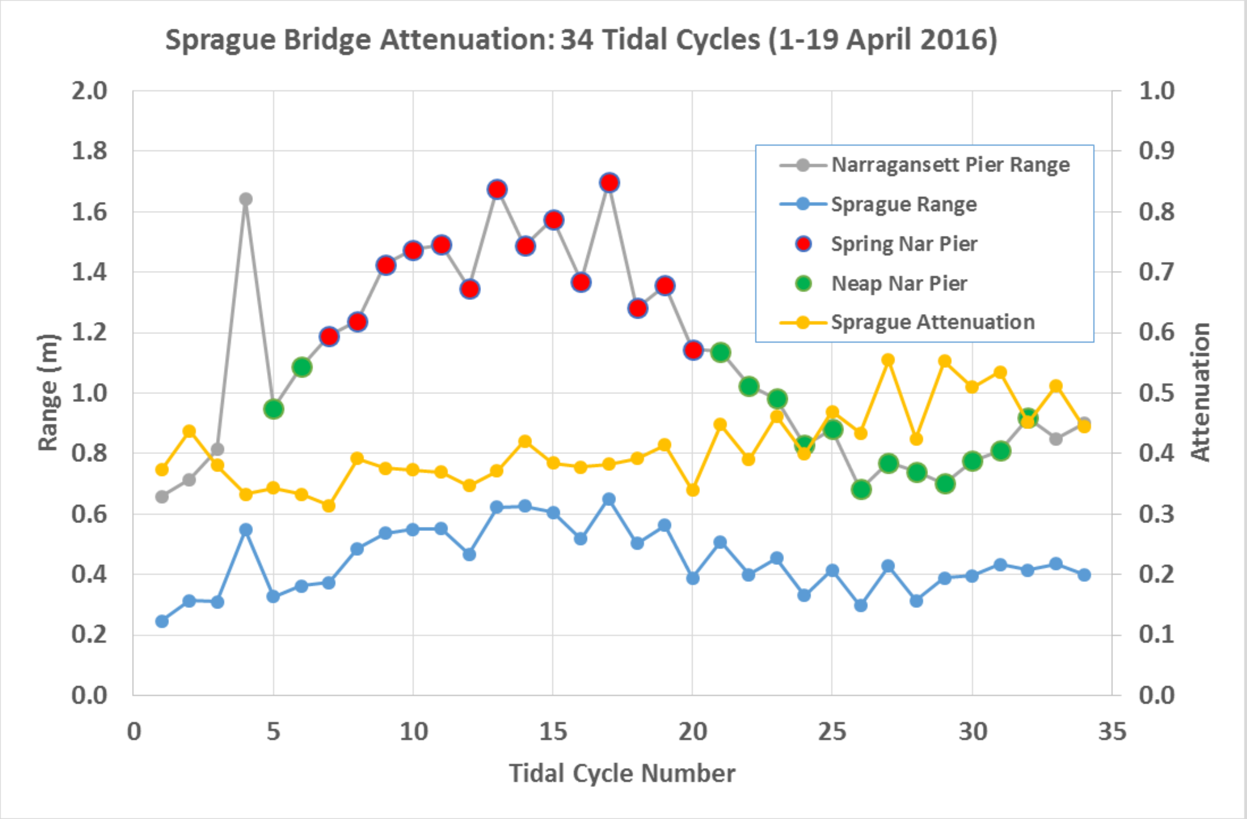


Figure 3-5. Sprague Bridge range and attenuation variability for the April 2016 study period.

A statistical summary of the Sprague Bridge and Narragansett Pier ranges and the attenuation is shown in Table 3-1 for all 34 tidal cycles in the record, the 28 spring/neap tidal cycles, the 14 spring tidal cycles and the 14 neap tidal cycles.

For all 34 tidal cycles the Sprague Bridge range varied from 0.25 to 0.65 m (0.81 to 2.1 ft) and the Narragansett Pier range varied from 0.66 to 1.70 m (2.16 to 5.57 ft), which resulted in a range attenuation variation of 0.31 to 0.56. The results for the 28 spring/neap tidal cycles was similar with slightly larger values seen in the means and minima at Sprague Bridge and Narragansett Pier only.

The 14 spring tidal cycles showed significantly larger Narragansett Pier and Sprague Bridge tidal ranges than the 14 neap tidal cycles as expected. The range attenuation did not show much variation, however, between the spring and neap tidal cycles.

Table 3-1. Summary statistics for various durations.

Statistic	Sprague Range (m) *[ft]*	Narragansett Pier Range (m) *[ft]*	Sprague Attenuation
All 34 Tidal Cycles			
Mean	0.45 *1.46*	1.11 *3.63*	0.41
Min	0.25 *0.81*	0.66 *2.16*	0.31
Max	0.65 *2.13*	1.70 *5.57*	0.56
28 Spring/Neap Tidal Cycles			
Mean	0.46…*1.51*	1.14…*3.76*	0.41
Min	0.30…*0.97*	0.68…*2.24*	0.31
Max	0.65…*2.13*	1.70…*5.57*	0.56
14 Spring Tidal Cycles			
Mean	0.53…*1.74*	1.41…*4.63*	0.38
Min	0.37…*1.23*	1.14…*3.75*	0.31
Max	0.65…*2.13*	1.70…*5.57*	0.42
14 Neap Tidal Cycles			
Mean	0.39…*1.28*	0.88…*2.88*	0.45
Min	0.30…*0.97*	0.68…*2.24*	0.33
Max	0.51…*1.67*	1.14…*3.73*	0.56

3.4 NOAA Newport Observations and Tidal Predictions- April 2016

Comparison of the NOAA Newport Station (8452660) observations and tidal predictions for the 1 – 19 April 2016 period are shown in Figure 3-6 along with their difference (observation – prediction). The observed and predicted time series generally tracked well with both showing the significant spring / neap tide range variation (1.7 m / 0.9 m [5.6 ft / 3.0 ft]). However, as shown by the difference time series, the observed and predicted significantly diverged during the meteorological event on 3 April: the high tide observation (0.94 m [3.1 ft]) was 0.46 m (1.5 ft) higher than the prediction (0.48 m [1.6 ft]) at 5:00 and the low tide observation (-0.84 m [2.8 ft]) was 0.42 m (1.3 ft) lower than the prediction (-0.42 m [1.3 ft]) at 12:18. The observed and predicted values also diverged during the event on 7-9 April: low tide observations were consistently smaller (-0.13 to -0.30 m [-0.43 to -0.98 ft]) than predictions throughout the period. Non-tidal variations are also evident in the difference calculation during a non-tidal event of 15-18 April. The high frequency oscillations seen in the observations were removed using a 40-min time-averaging filter before use in modeling.

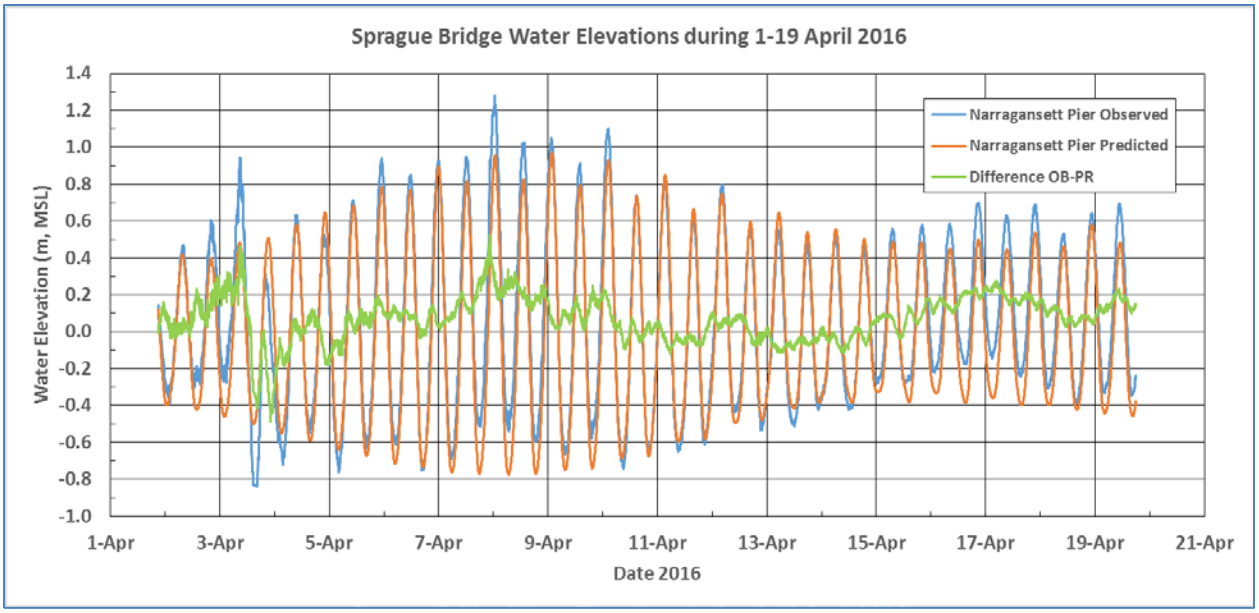


Figure 3-6. Comparison of NOAA Newport observations and predictions for April 2016 period

A comparison of tidal range attenuation at Sprague Bridge from the present field study to the historical tide range attenuation discussed above in Section 2 is shown in Figure 3-7. The mean value of 0.41 from the present study is shown as a green diamond marker in the figure. The relative smaller magnitude of this value indicates that the constriction in the Narrows is likely more severe at the present time than in the past. This is consistent with the change in bathymetry in this area as documented by comparison of the values in 2006 to the most recent bathymetric survey shown in Figure 3-2.

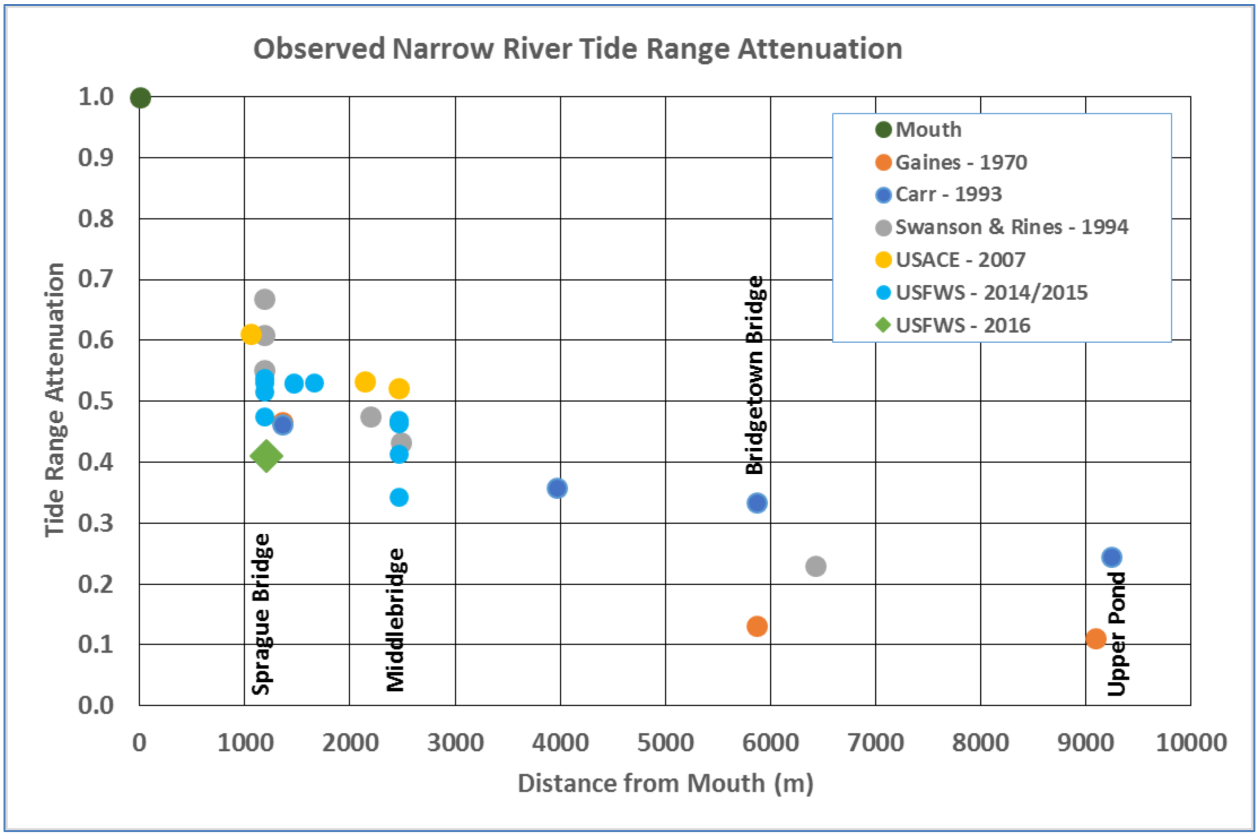


Figure 3-7. Historical field studies showing variation in water level attenuation in the Narrow River as a function of distance from the mouth with April 2016 observations (USFWS 2016) overlain (large green diamond marker).

4 ADCIRC Model Description and Application to the Narrow River

4.1 Model Description

ADCIRC v-52 is a computer model that solves the time dependent equations for water circulation in rivers, lakes, estuaries and oceans known as the conservation of water mass and momentum equations on a finite element mesh for both two and three dimensions depending on the application (Luettich Jr et al., 1992) (http://adcirc.org/home/documentation/users-manual-v50/introduction/). For this project the 2D version is used which predicts the free surface displacement and vertically averaged velocities. ADCIRC is generally forced along the open boundaries by water elevation/velocity. The finite (triangular) element method allows for a highly customizable mesh, with high resolution for areas of particular interest and lower resolution elsewhere, which allows for shorter computation times.

4.2 Application to the Narrow River

The Narrow River grid was generated with an upper limit of 3 m (9.8 ft) elevation above MSL. This limit was chosen to ensure that the model could predict flooding and drying that naturally occurred (including the effects of a storm) through the river without constraints of a limited domain. The mesh consists of 38,765 nodes that combine to create 75,792 elements. The resolution of the mesh varies with the width of the river. The wider ponds have a 30 m (100 ft) resolution, while most of the river has a resolution of 10 m (33 ft) and specific narrow areas have 5 m (16 ft) resolution. The domain offshore from the river mouth has coarser resolution increasing from 5 m (16 ft) at the mouth to 200 m (660 ft) at the open boundary in Rhode Island Sound. Figure 4-1 shows the entire grid from the Upper Pond at the north end to the open boundary, while Figure 4-2 shows the Narrows reach with its variable mesh resolution.

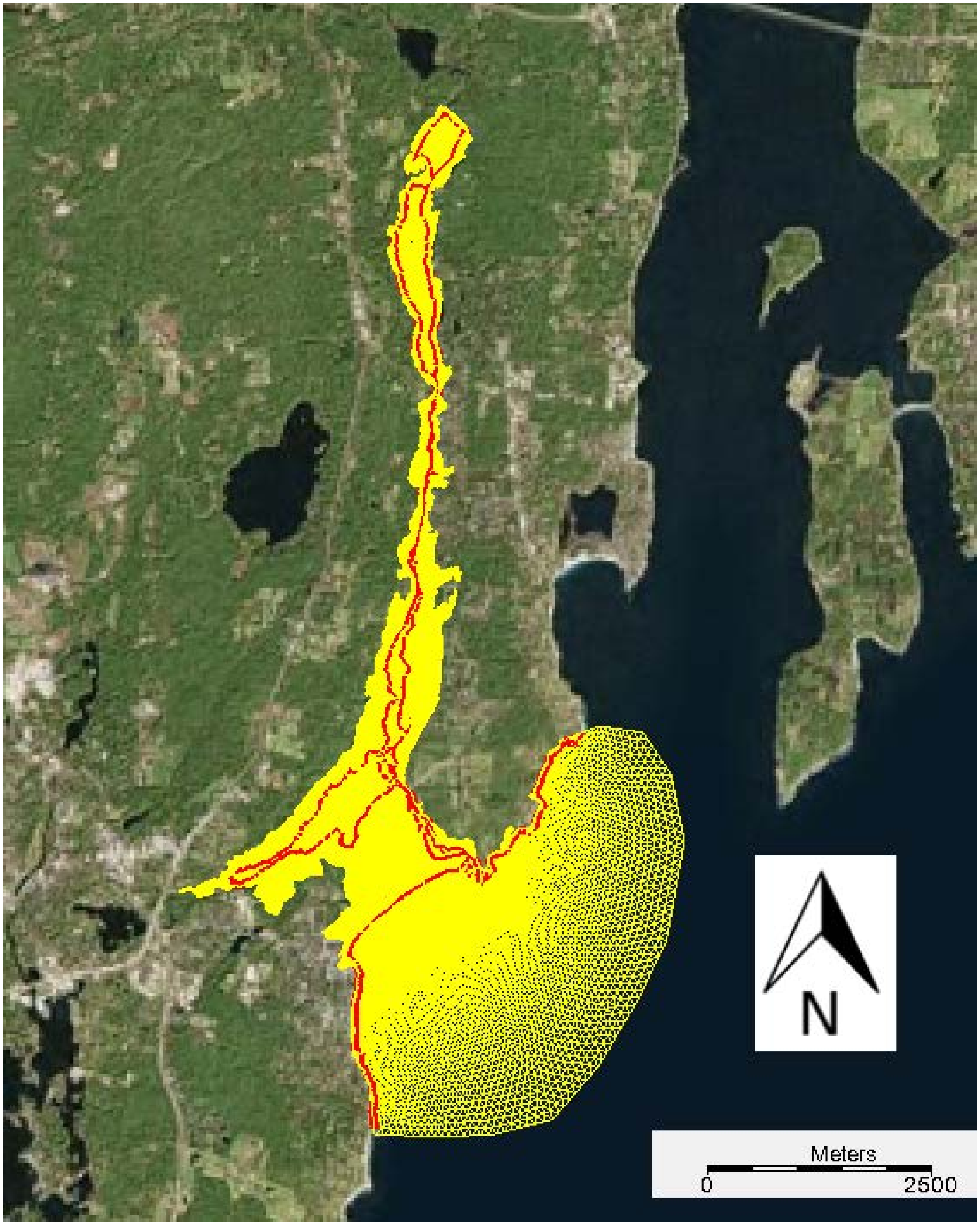


Figure 4-1. Entire ADCIRC model grid for Narrow River. Red outline indicates shoreline at MSL.

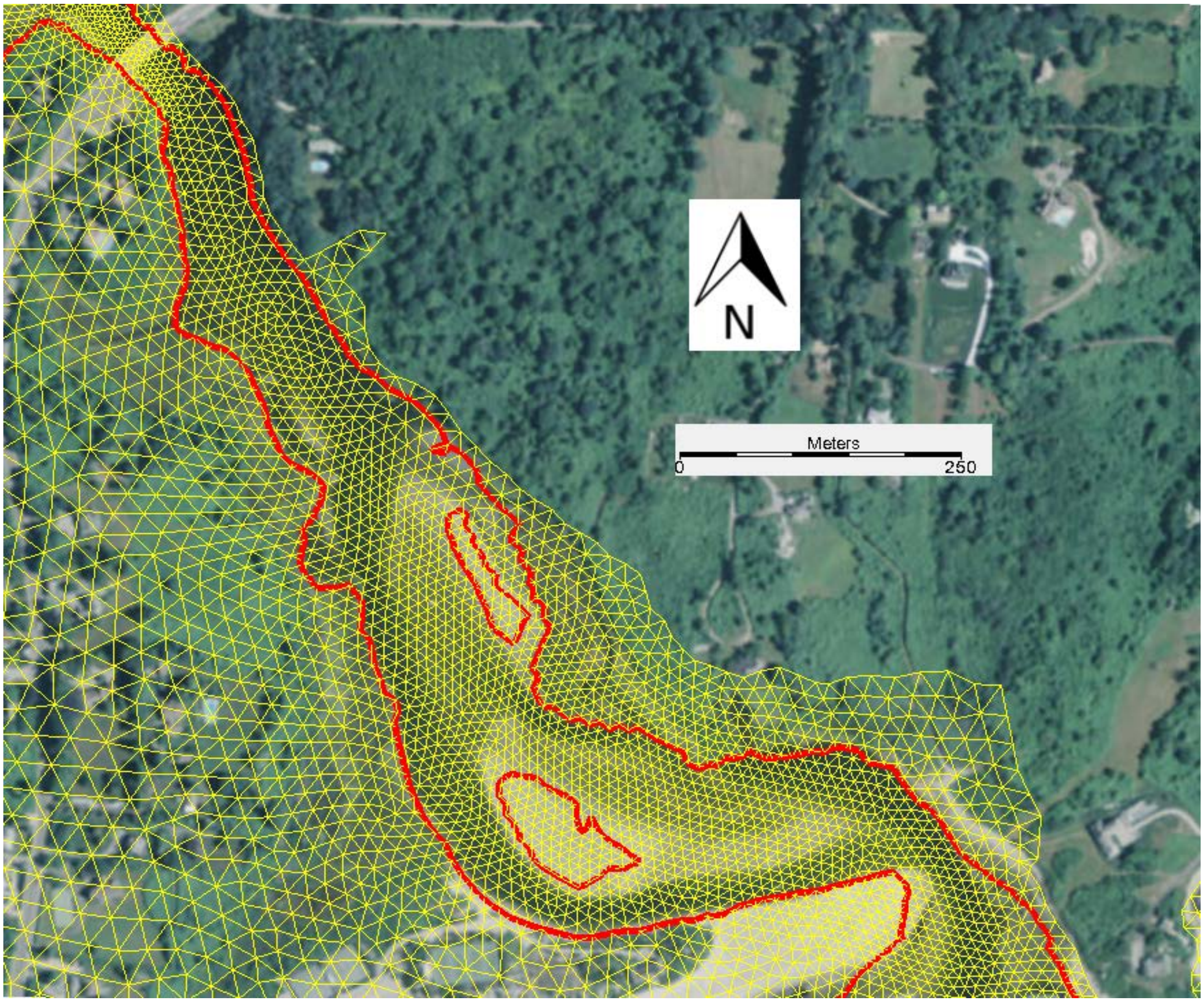


Figure 4-2. Expanded view of the ADCIRC model grid for the lower reach of the Narrow River. Red outline indicates shoreline at MSL.

The topography for the study area (elevations above MSL) were provided from a Digital Elevation Model (DEM) of the state of Rhode Island available from RI GIS based on 2011 LIDAR measurements (1m [3.3 ft] horizontal resolution, 15 cm [0.49 ft] RMSE vertical). The DEM is known to be inaccurate for water depths in coastal ponds and hence the river bathymetry was thus taken from multiple sources. From the Upper Pond to Middle Bridge a bathymetric grid generated by RPSASA for a previous study was used (D. Crowley, personal communication, 16 February 2016). The area between Middle Bridge and Sprague Bridge was surveyed by John Winkelman of the USACE in support of his Narrow River modeling effort (USACE, 2009). The area from the Sprague Bridge to the mouth was surveyed for this project by URI/GSO led by John King and was discussed in Section 3.1. The combination of these datasets provided an accurate representation of the topography and bathymetry of the Narrow River. The final elevation dataset for the mesh has a maximum water depth of 26 m (85 ft) below MSL offshore in Rhode Island Sound and a maximum topographic elevation of 3 m (9.8 ft) above MSL.

The ADCIRC model for this area was forced with water elevations taken from the NOAA tidal station at Newport, with a mean range of 1.05 m (3.44 ft). There was also a subordinate station at Narragansett

Pier, closer to the Narrow River mouth, that was monitored for four months in 1987, which showed the averaged observed water elevation averaged 92% of the Newport elevation (91% of high tide amplitude and 93% of low) with no average time offset (-11 min for high tide and +11 min for low).

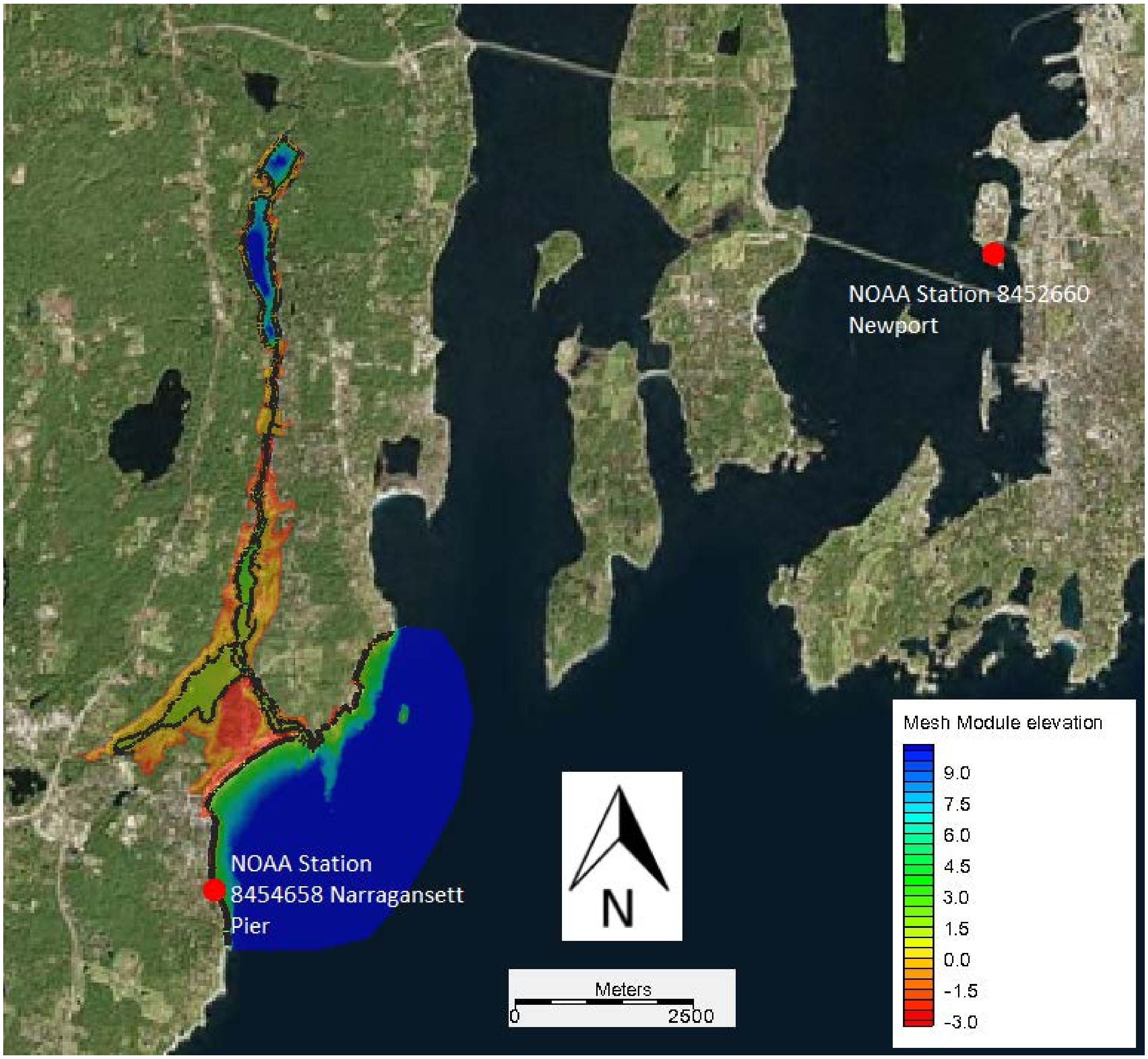


Figure 4-3. Open boundary forcing using NOAA Narragansett Pier tidal station data based on NOAA Newport tidal station. Elevations of the mesh nodes are provided in meters relative to MSL.

5 Model Results

The model was run for the 31 March - 19 April 2016 period using the Narragansett Pier water elevations as open boundary forcing (the earlier start time allowed for model spinup). Based on preliminary model runs friction was increased at different areas to improve stability of the model and allow for the attenuation to be correctly represented in the model. A Manning's roughness coefficient, n, of 0.018 was used for depths greater than 2 m (6.6 ft), with depths less than 2 m (6.6 ft) given a higher n value of 0.10.

5.1 Model – Data Comparison of Water Level at Sprague Bridge for 1-19 April Period

The ADCIRC model – USFWS data comparison for water level at Sprague Bridge is shown in Figure 5-1. Overall the Root Mean Square Error (RMSE) was 0.065 m (0.21 ft), generally a very good comparison. Model predictions and observations were close during the 3 April non-tidal event but diverged during the 7-9 April event seen in the Narragansett Pier forcing (modified from Newport data). Model predictions and observations showed the same slight tidal asymmetry and no phase difference.

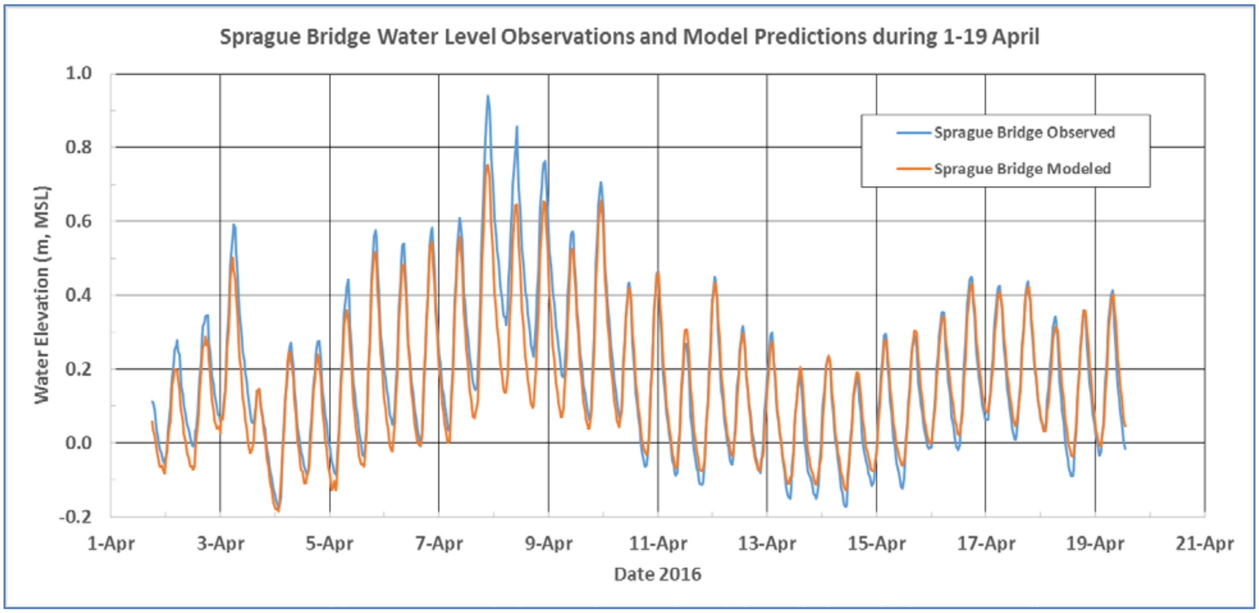


Figure 5-1. Comparison of model predictions to observations for 1 to 19 April 2016 period.

5.2 Velocity Predictions for the April 2016 Period

The maximum velocities in the Narrows during flood and ebb conditions are shown in Figure 5-2 during the first half of 11 April 2016. The speeds are color coded as shown in the legend for each condition although the scales are different. The black line indicates MSL. The highest maximum flood currents (left panel) occurred near the eastern shore looking upstream at and south of the Sprague Bridge at 0.45 m/s (1.5 ft/s). Significant speeds at or greater than 0.35 m/s (1.1 ft/s) extend some distance downstream, again offshore of the eastern shore. A small area near the western shore in the mid area of the Narrows and a larger are north northwest of Bass Rock above 0.35 m/s (1.5 ft/s) are also seen. Significant areas of the Narrows reach show maximum flood velocities of 0.15 and 0.25 m/s (0.49 and 0.82 ft/s).

Highest maximum ebb currents occurred west, northeast and north of Bass Rock reaching 0.36 m/s. Other areas offshore the eastern shore looking upstream reached 0.28 m/s and a small area off the western shore reached 0.32 m/s. Most areas saw maximum ebb currents of 0.08 to 0.24 m/s.

A study of the currents at Sprague Bridge was conducted by URI Ocean Engineering undergraduates on 3 May 2102. Measurements were made using an Aanderaa acoustic current meter at mid depth immediately east of the bridge for a period of approximately 10 hrs. They found peak currents of approximately 0.35 to 0.43 m/sec (1.14 to 1.41 ft/sec) consistent with the model results. The predicted levels are somewhat lower than unmeasured anecdotal observations by others, however.

The sediment resuspension threshold is ~ 0.20 m/s (0.66 ft/s) so sediment transport during the tidal cycle is likely, particularly near the mouth and Sprague Bridge.

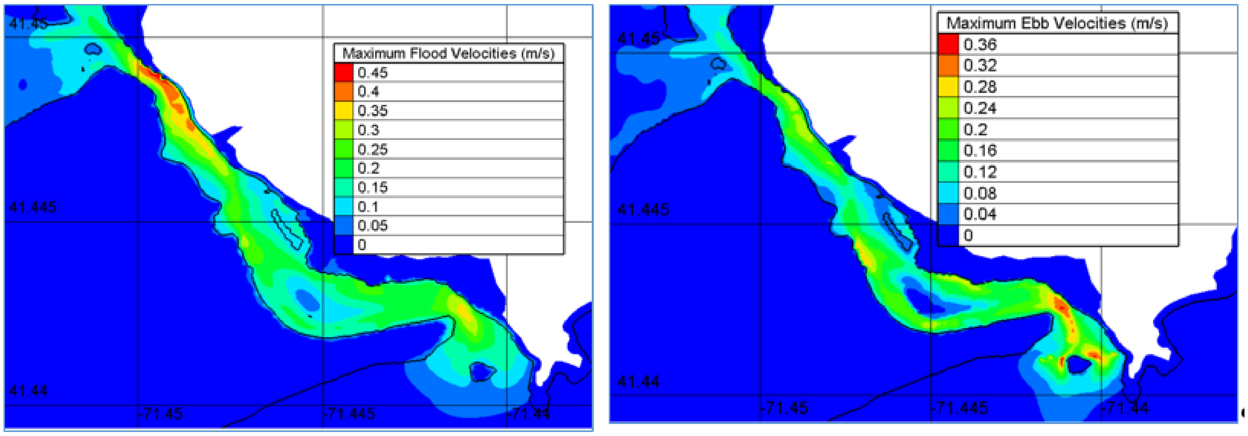


Figure 5-2. Contours of maximum speed (m/s) in the Narrows reach of the Narrow River during flood and ebb.

Tidal ellipses are a useful graphic representation to illustrate how tidal currents vary in time at specific locations. A time series of velocities are plotted at a distance from an origin corresponding to the magnitude and at the direction of the currents. The points can be connected in time which will form an ellipse whose major axis indicates the primary direction of the flow. If the minor axis is zero then the ellipse collapses to a line (rectilinear flow); if both minor and major axes are equal then the ellipse becomes a circle (circular flow). Figure 5-3 shows the tidal ellipses for four locations: Sprague Bridge, mid Narrows, near mouth and offshore.

The Sprague Bridge location shows that velocities were constrained by the narrowness of the river to be rectilinear pointing along the river thalweg. The major axis showed significantly stronger flood (0.37 m/s [1.21 ft/s]) than ebb (0.20 m/s [0.66 ft/s]). Velocities in the slightly wider mid Narrows location also showed rectilinearity with a somewhat stronger flood (0.18 m/s [0.59 ft/s]) than ebb (0.13 m/s [0.43 ft/s]) but less in magnitude than Sprague. Velocities near the mouth are again constrained by the narrowness of the river to be rectilinear. Flood (0.34 m/s [1.12 ft/s]) is slightly strong than ebb (0.31 [1.02 ft/s]) roughly equal to the Sprague Bridge location. The velocities southwest of the mouth offshore Narragansett Beach is elliptical with larger along shore component than cross shore component. Flow direction is northeast / southwest and the magnitude is much reduced (~10X) compared with the other locations with slightly stronger flood (0.025 m/s [0.082 ft/s]) than ebb (0.020 m/s [0.066 ft/s]).

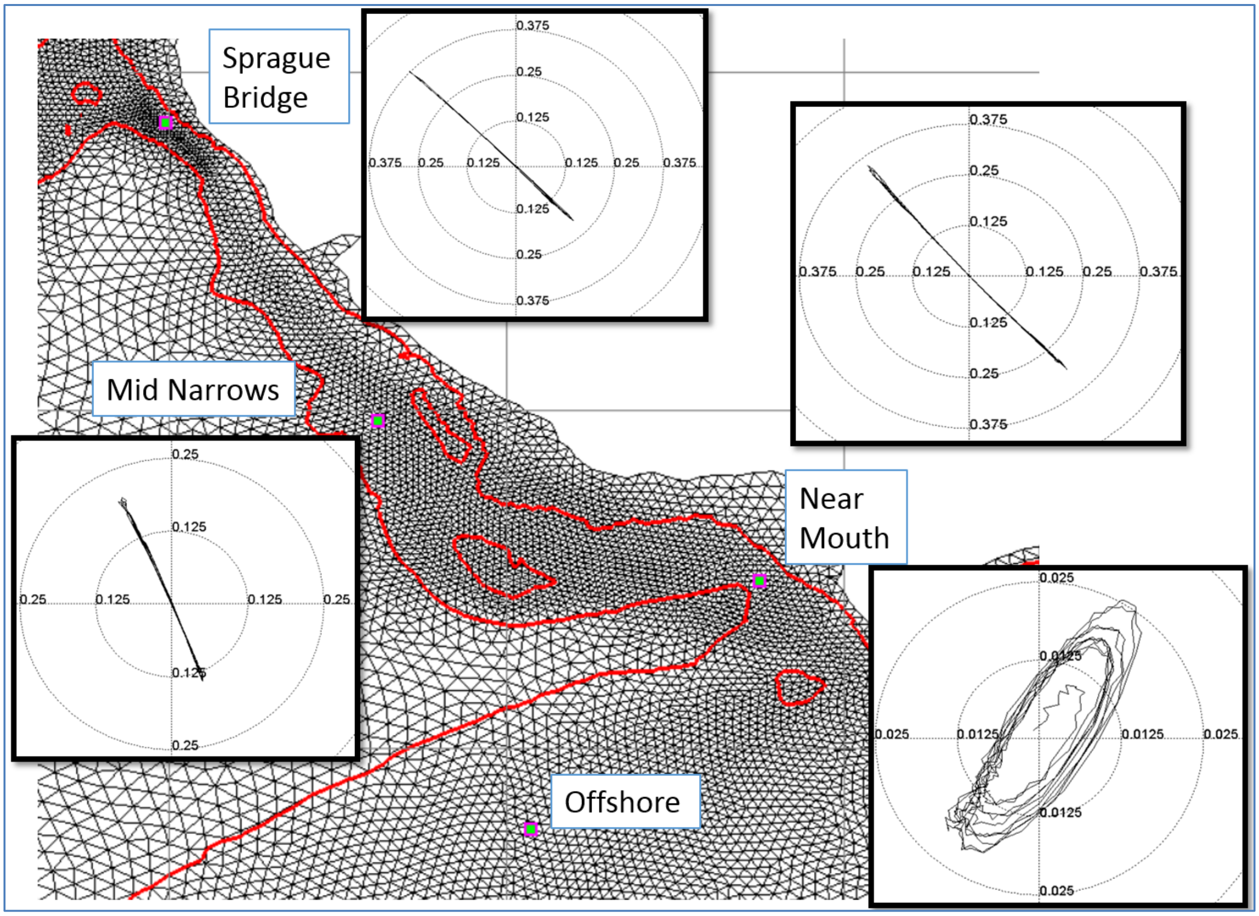


Figure 5-3. Tidal ellipses for selected stations, indicated by light blue markers bordered by red, in the Narrows region and offshore. Red outline indicates shoreline defined by MSL.

5.3 Model Results for Simulation of Hurricane Bob – 19 April 1991

To estimate the effects of an extreme offshore water level on the water level in the river a hurricane storm surge was modeled. Hurricane Bob was selected as a representative of a moderate storm impacting the area. Hurricane Bob developed from an area of low pressure near the Bahamas in August 1991 and reached Category 3 (major hurricane of maximum sustained winds of 185 km/hr [115 mi/hr) intensity as it traveled in a generally northern direction along and offshore of the U.S. east coast (Pasch and Livion, 1992). It weakened to a Category 2 (sustained maximum wind between 154-177 km/hr [96-110 mi/hr]) as it made landfall at Newport, RI at about 1400 EDT on 19 August 1991.

The ADCIRC model was run for Hurricane Bob using water level measurements from the NOAA Station Newport that is shown in Figure 5.4 along with the predicted tide level. Data available from NOAA was limited during this period to a 1-hr timestep. The storm surge is clearly evident in the record where its effect on water level began about 10:00 EDT and peaked at 1.78 m (5.84 ft) MSL at 14:00 EDT. A set-down was observed of -0.55 m (1.80 ft) MSL about midnight after the surge. The 0.92 amplitude reduction from Newport to Narragansett Pier, applied to the tidal signal for April 2016, was not used as forcing for this case assuming the likely storm surge amplitude at the model boundary offshore the mouth of the Narrow River was the same as Newport.

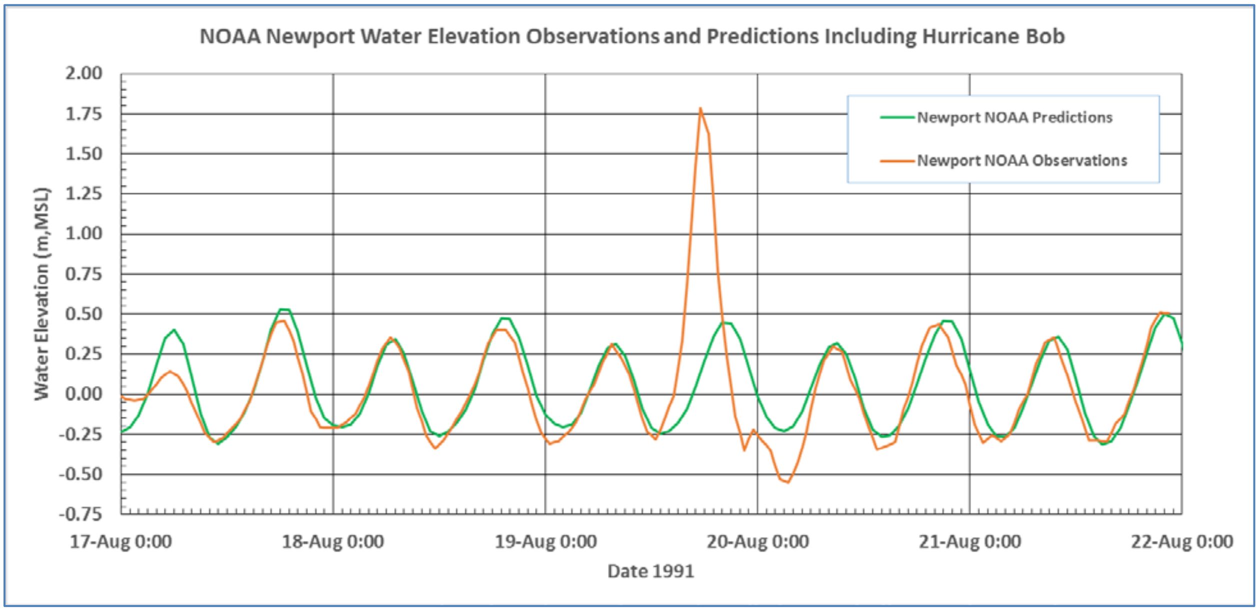


Figure 5-4. NOAA water level observations and tidal predictions at Newport for 17 through 21 August 1991 (EDT time zone) showing the storm surge from Hurricane Bob.

Model results are shown in Figure 5-5 at Sprague Bridge compared to the observed offshore forcing for the period 17 through 21 August 1991. The reduction in tide range at Sprague Bridge relative to the offshore forcing (at Newport) is evident. The effects of Hurricane Bob at Sprague Bridge were seen with a peak surge level of 0.87 m (2.85 ft) occurring approximately 1 hr after the surge offshore. No set down was seen at Sprague Bridge after the surge.

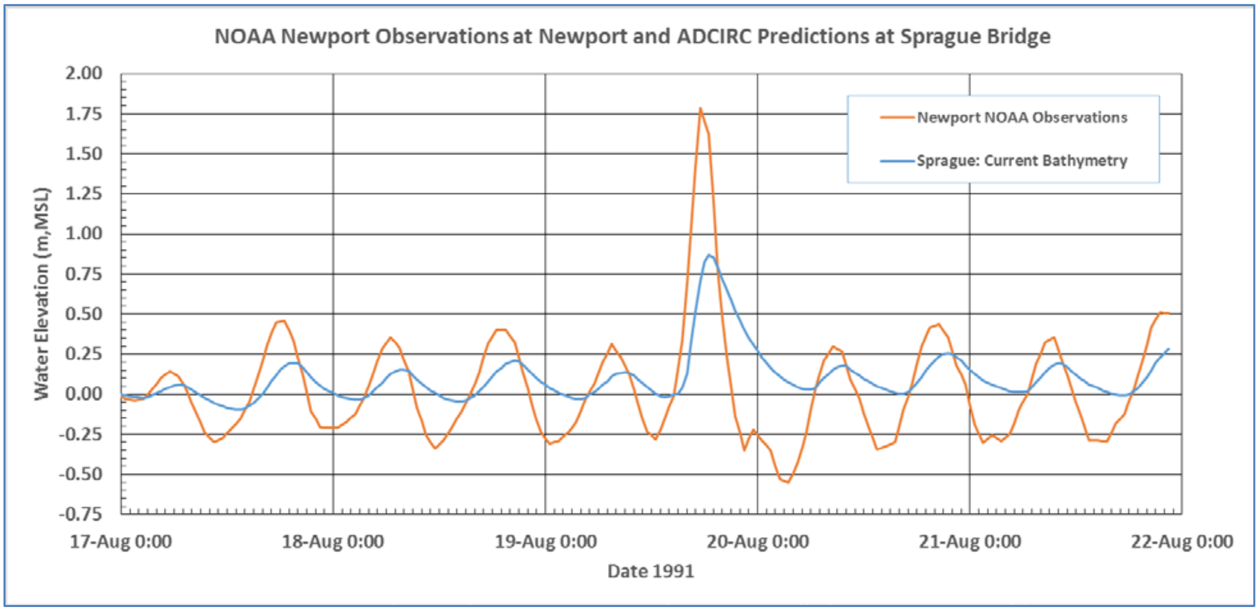


Figure 5-5. ADCIRC model predictions of water level at Sprague Bridge relative to NOAA offshore observations for the period 17 to 22 August 1991 during Hurricane Bob.

5.4 Comparisons of Flooding between April 2016 and Hurricane Bob Model Results

The flooded surface area was determined from ADCIRC model results by summing all element areas that showed water elevations above MSL during the two time periods (1-19 April 2016 and 17-22 August 1991). The flooded (high tide) surface area from April 2016 tides under current bathymetric conditions was 2.22 km^2 (0.86 mi^2). The flooded surface area from Hurricane Bob under current bathymetric conditions was 3.21 km^2 (1.24 mi^2) an increase of 31%. A comparison of these areas is shown in Figure 5-6. Most of the flooding occurred in the lowlands around Pettaquamscutt Cove in the southwest and in lowlands upstream of the Cove mostly along the eastern shore.

Figure 5-6. Comparison of maximum flooded areas between April 2016 tides and Hurricane Bob.

An interesting feature of the response of the Narrow River is its natural ability to reduce the amplitude of tidal and storm surge in the river from that occurring in the area offshore of its mouth. This is seen in

Figure 5-7 showing the maximum water elevation during April 2016 due to tides and Figure 5-8 showing the maximum elevation during the storm surge from Hurricane Bob. The figures show color contours of water elevation above MSL between 0 and 0.9 m (0 and 3 ft) and above in increments of 0.1 m (0.3 ft). Figure 5-7 (April 2016) shows the offshore area amplitude between 0.7 and 0.8 m (2.3 and 2.6 ft) and dropping at Sprague Bridge to between 0.4 and 0.5 m (1.3 and 1.6 ft). By Middlebridge the amplitude was reduced to between 0.3 and 0.4 m (1.0 and 1.3 ft) and between 0.2 and 0.3 m (0.7 and 1.0 ft) in the Lower and Upper Ponds. Figure 5-8 (Hurricane Bob) shows the offshore amplitude greater than 0.9 m (3 ft) (the actual peak was 1.8 m [5.9 ft]) and dropping to between 0.8 and 0.9 m (2.6 and 2.9 ft) at Sprague Bridge. By Middlebridge the amplitude was reduced to between 0.7 and 0.8 m (2.3 and 2.6 ft) and between 0.2 and 0.3 m (0.7 and 1.0 ft) in the Lower and Upper Ponds. Thus the flooding from Hurricane Bob was about 0.1 m (0.3 ft) (in the ponds) to 0.4 m (1.3 ft) (at Sprague Bridge) than that from the tides during April 2016.

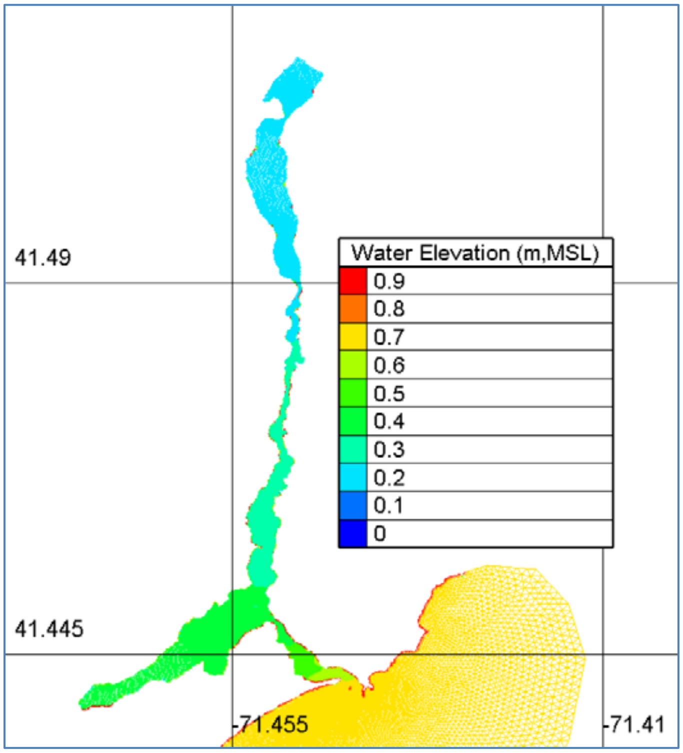


Figure 5-7. Spatial variation of maximum water levels for April 2016 tides.

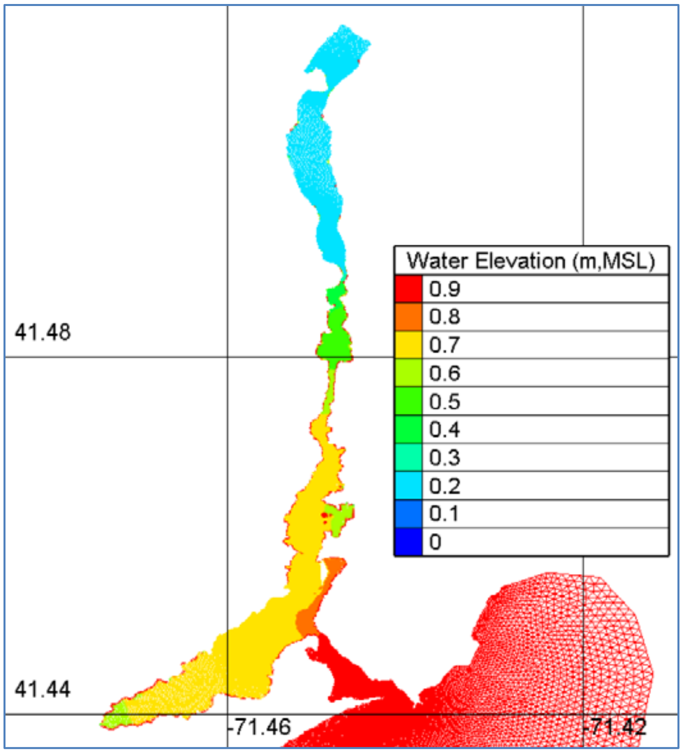


Figure 5-8. Spatial variation of maximum water levels for Hurricane Bob. The offshore water level is 1.8 m (5.9 ft).

The attenuation in the Narrow River from both the April 2016 tides and Hurricane Bob revealed that it is less affected than flooding amplitudes. Figure 5-9 show the attenuation as a function of distance up the river both model runs. The figure shows that the values for Hurricane Bob are somewhat greater than the April 2016 tides for most of the river but then less for the Lower and Upper Ponds at the head of the river. The similarity in response between tidal and Hurricane Bob forcing, as measured in terms of attenuation vs distance upstream, is consistent with the fact that the time scale for the events are very similar (about 6 hrs) and the known dependence of filtering characteristics of tidal inlet systems on time variation of forcing (UASCE, 2008).

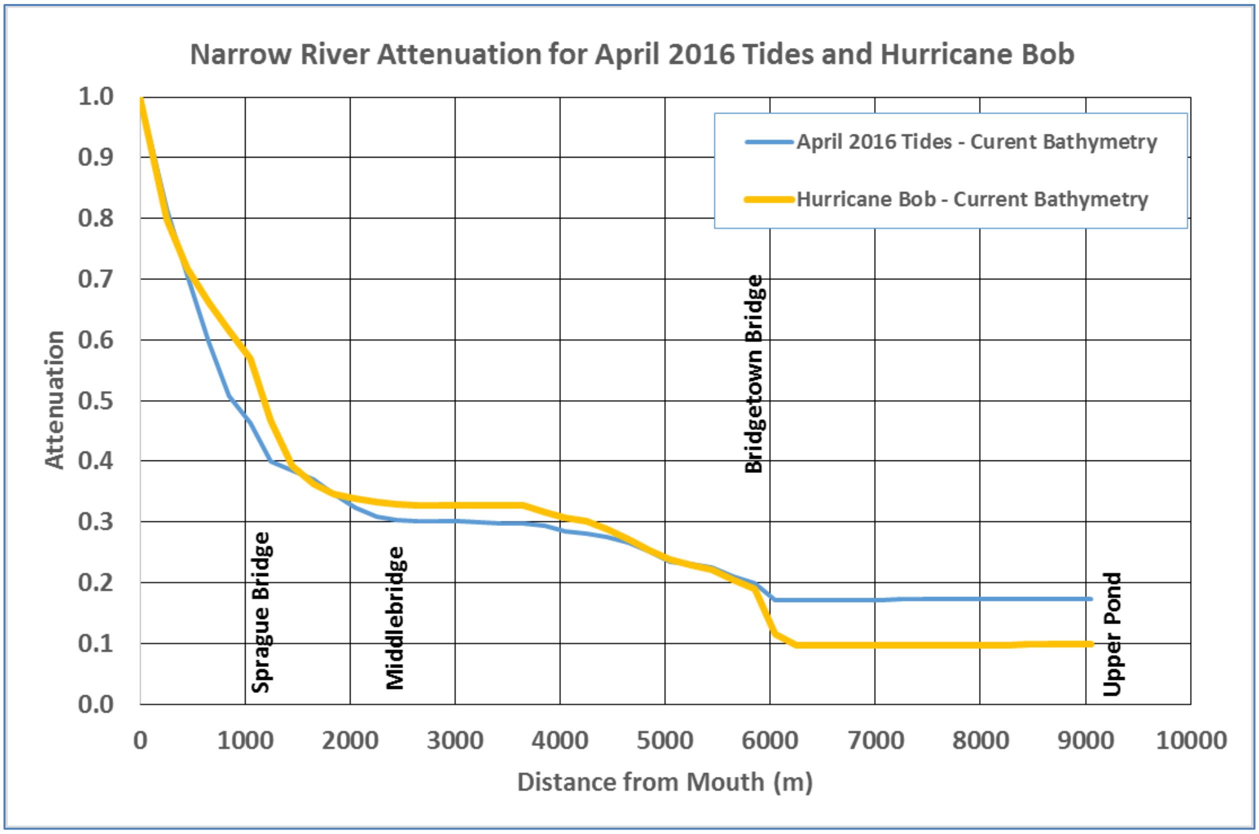


Figure 5-9. Attenuation comparison of model results for April 2016 rides and Hurricane Bob.

6 Dredging Alternatives

6.1 Dredging Scenarios

A set of dredging scenarios was selected to investigate the effects of dredging to different depths in the Narrows reach between Sprague Bridge and the mouth of the river. These scenarios were chosen to better understand the sensitivity of the tidal response (attenuation and flushing) in the river to a variety of dredging options. Four scenarios were selected, including one from the USACE (2009) study. Dredging depths are referenced to both MSL as well as NGVD (the vertical benchmark used in the USACE study).

- Dredging to -1 m MSL (-2.9 ft NGVD)
- Dredging to -1.4 m MSL (-4 ft NGVD) [USACE, 2009]
- Dredging to -2 m MSL (-5.7 ft NGVD)
- Dredging to -3 m MSL (-8.6 ft NGVD)

Each plan represents dredging to the specified depth for the area that is currently below MSL with water depths deeper than 50 cm (1.6 ft) near the mouth of the river. Plan views of the four scenarios are shown in Figure 6-1 via colored contours of the thickness of the removed material. It was assumed that all material was sand and that there would be no problems with bedrock outcrops or large boulders potentially requiring more complex removal techniques (e.g., blasting).

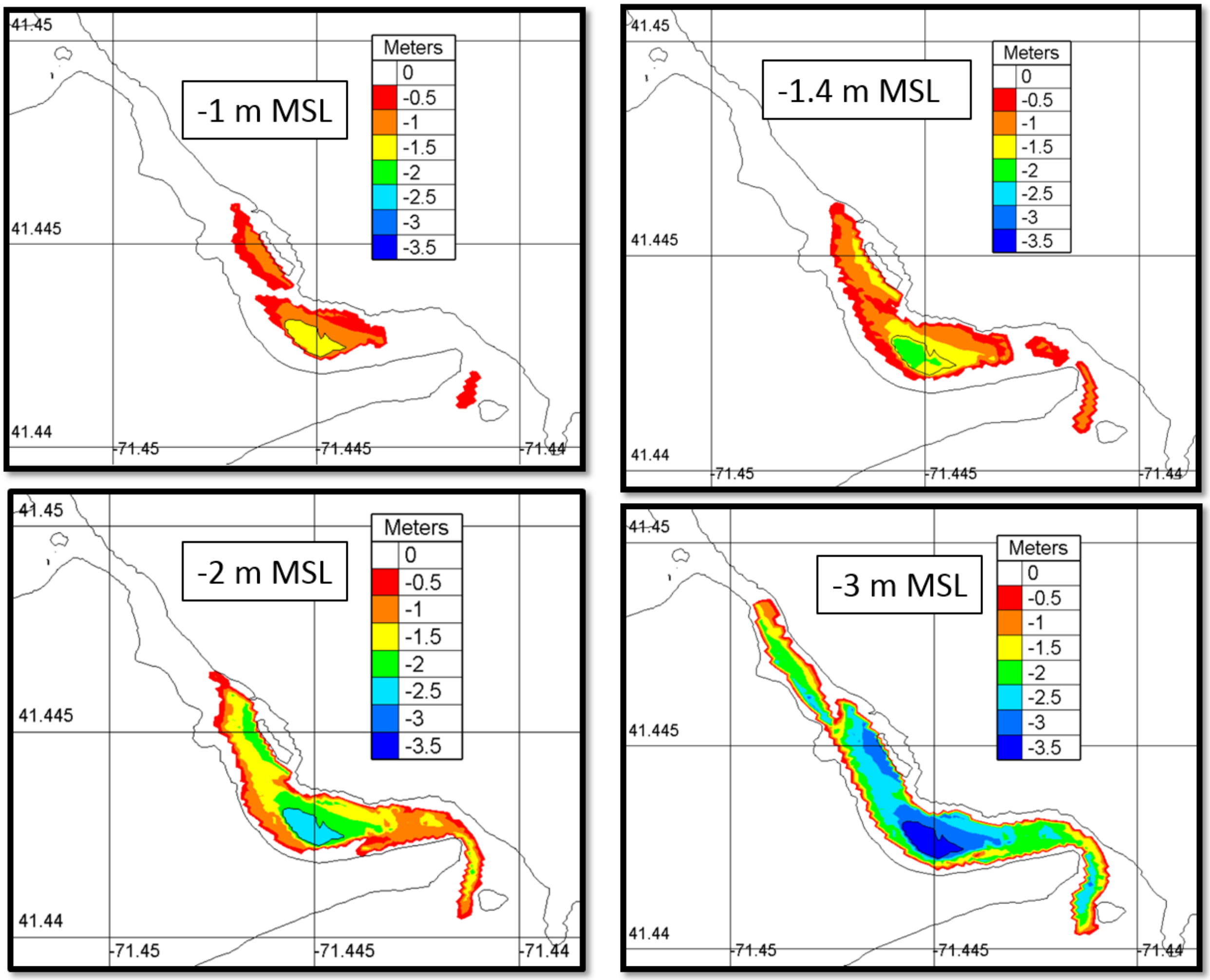


Figure 6-1. Plan views of the Narrows showing material removal thicknesses for the four dredging scenarios selected.

As seen in Figure 6-1 the shallowest areas are located in the shoal area at the bend in the river thalweg approximately one third the distance from Bass Rock (shown as the round coastline feature just south of the mouth of the river; see also Figure 1-2) to Sprague Bridge. Table 6-1 summarizes the maximum thickness removed and the total volume removed. The four dredging scenarios were modeled for the April 2016 (tides) period.

Table 6-1. Summary of maximum removal thickness and dredged volumes for various dredging scenarios.

Scenario	Maximum Removal Thickness (m) *(ft)*	Total Dredging Volume (m^3) *(yds^3)*
Dredging to -1 m MSL	1.5 *4.9*	21,500 *28,100*
Dredging to -1.4 m MSL (USACE)	2.0 *6.6*	43,000 *56,200*
Dredging to -2 m MSL	2.5 *8.2*	80,500 *105,000*
Dredging to -3 m MSL	3.5 *11.5*	184,000 *241,000*

6.2 Dredging Results for April 2016 Tides

Time series of water elevation at Sprague Bridge, attenuation along the Narrow River, and the calculation of tidal flushing times will be presented for each model forcing condition. Tidal flushing was calculated as (high tide volume) / (tidal prism)*(12.42 hr) / (24 hr/day).

6.2.1 Time Series of Water Elevation

The time series of water level for the period 10-14 April 2016 are shown in Figure 6-2. The model results showed an increase in tide range as dredged depth increased. The change was greater between the -2 to -3 m MSL dredging cases compared to those for -1 to -2 m MSL cases and most noticeable at low tide. The larger change for the deeper dredging depths may be caused by the increased footprint of the dredged area (Figure 6-1). In addition the tide cycle shape became more symmetrical between flood and ebb tide as well as a small reduction in high tide phase lag and a larger reduction in low tide phase lag as the dredged depth increased.

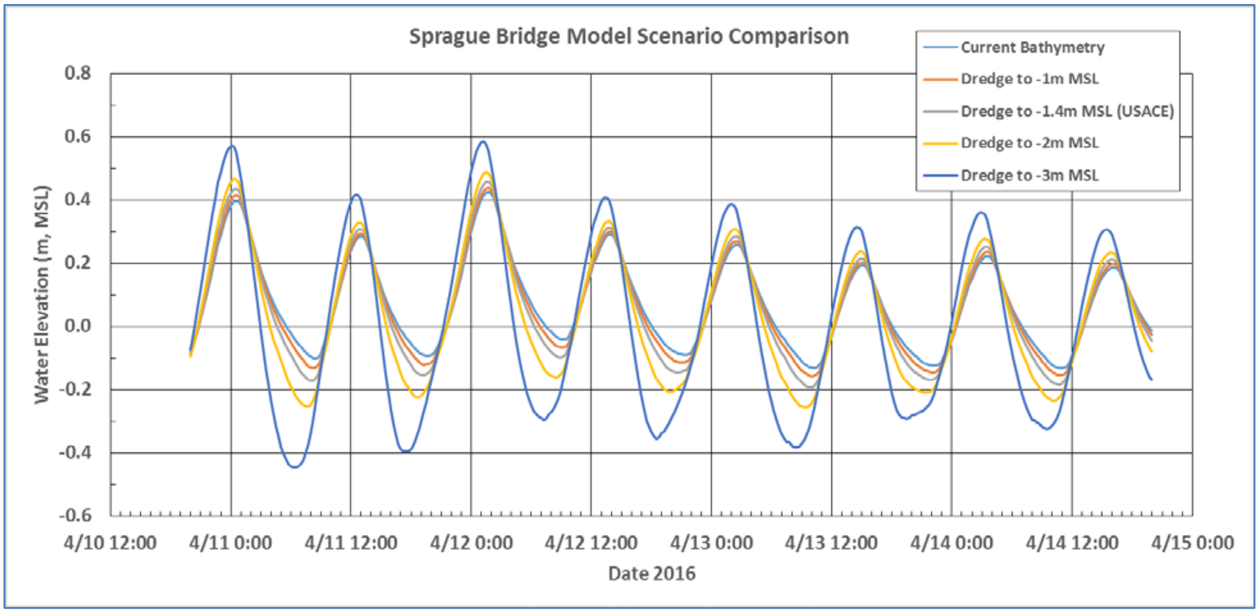


Figure 6-2. April 2016 time series of water elevation at Sprague Bridge for current bathymetry and the four dredging scenarios.

6.2.2 Attenuation

The tide range attenuation for the current bathymetry and the four dredging scenarios based on the tide cycle beginning 11 April at 0:00 are shown in Figure 6-3. All model runs showed relatively rapid drops in attenuation for approximately the first 1 to 2 km (0.6 to 1.2 mi) of the river, plateaus between 2 and 4 km (1.2 and 2.5 mi), then lower rates of attenuation until 6 km (3.7 mi), and then no changes in the attenuation thereafter. The flat response above Bridgetown Bridge is due to the depths of the Lower (20 m [66 ft]) and Upper (12 m [39 ft]) Ponds exerting no frictional losses so the ponds act solely as storage.

The current bathymetry scenario tide range attenuation compares well with USFWS - 2016 observed attenuation (0.41) at Sprague Bridge. This scenario predicts attenuation to be 0.17 in Upper Pond. As dredging depths increase the tide range attenuation value increases from 0.44 (Dredge -1 m scenario) to 0.81 (Dredge -3 m scenario) at Sprague Bridge. As dredging depths increase the tide range attenuation values only slightly increasing from 0.18 (Dredge -1 m scenario) to 0.25 (Dredge -4 m scenario) in the Lower and Upper Ponds.

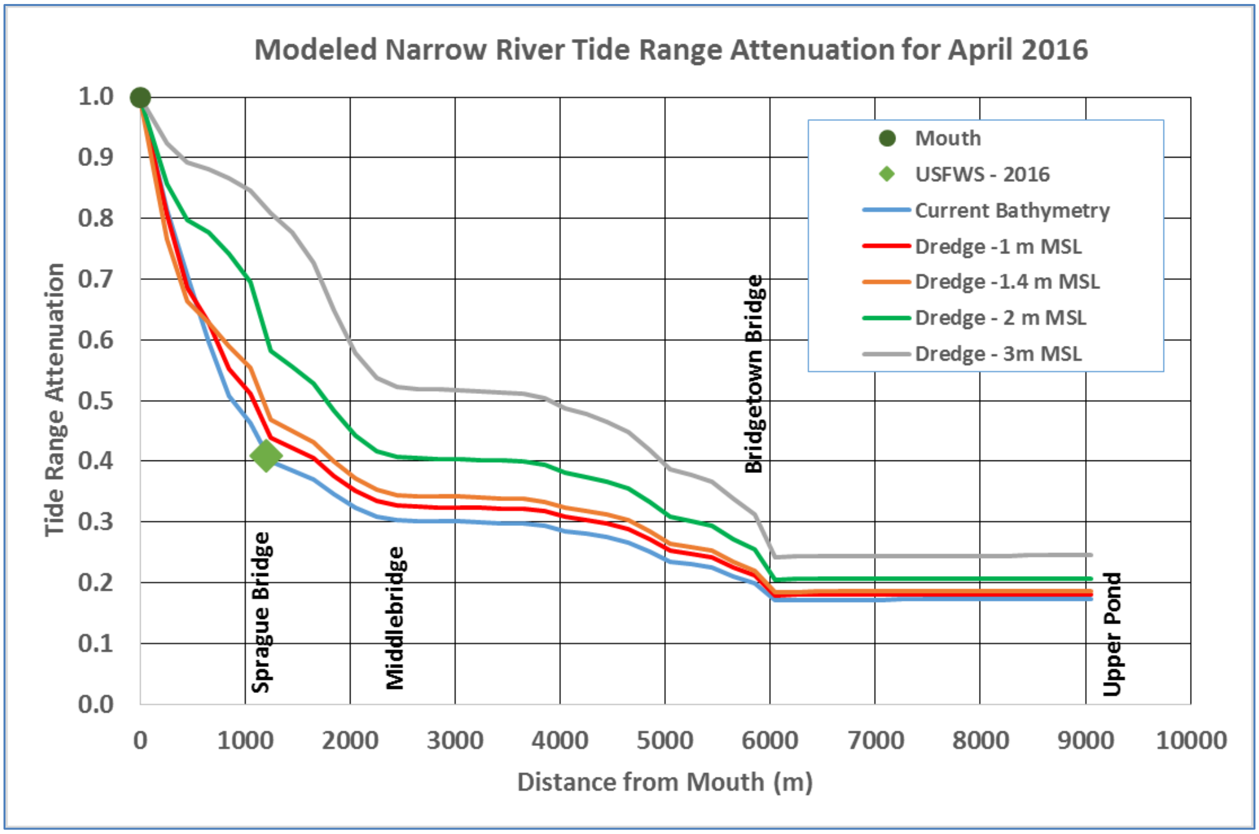


Figure 6-3. Model and data comparison of variation in water level attenuation in the Narrow River as a function of distance from the mouth for the April 2016 period for current bathymetry and various dredging options.

6.2.3 Summary of Specific Tide Range and Attenuation Results, Tidal Flushing Times and Tidal Datums

To facilitate a comparison among the April 2016 dredging scenarios a summary is provided in Table 6-2 consisting of the tide range and attenuation at both Sprague Bridge and the Upper Pond as well as the tidal prism, the high tide volume and the resulting tidal flushing. The tidal prism is defined as the high tide volume minus the low tide volume while the tidal flushing is calculated as (high tide volume) / (tidal prism)*(12.42 hr) / (24 hr/day).

As expected the tide range increased at Sprague Bridge with increasing dredged material volume removed (see Table 6-1) from 0.38 m (1.24 ft) for current bathymetry to 0.77 m (2.51 ft) for the dredging to -3 m MSL scenario where the attenuation followed this increase (0.41 to 0.84). The tide range increase at the Upper Pond showed a much smaller increase: from 0.17 m (0.57 ft) for current bathymetry to 0.24 m (0.80 ft) for the dredging to -3 m MSL scenario again with the attenuation following this increase (0.17 to 0.25). The tidal flushing in days decreased from 3.8 days for current bathymetry to 2.3 days for the dredging to -3 m MLS scenario. It should be remembered that the tidal flushing estimate is the optimum since it assumes that the entire tidal prism volume is replaced with ocean water on each tide and thus represents the case when there is complete change of water with the ocean.

Table 6-2. Summary of tide ranges, attenuations, and tidal flushing results for various dredging scenarios for the April 2016 period.

Scenario	Sprague Bridge Tide Range (m) *(ft)*	Sprague Bridge Attenuation	Upper Pond Tide Range (m) *(ft)*	Upper Pond Attenuation	Tidal Prism (m^3) *(ac-ft)*	High Tide Volume (m^3) *(ac-ft)*	Tidal Flushing (days)
Current Bathy	0.38 *1.24*	0.41	0.17 *0.57*	0.17	675,100 *550*	4,928,000 *4,000*	3.8
Dredging to -1 m MSL	*0.41* *1.35*	0.42	*0.18* *0.59*	0.18	731,670 *590*	4,971,800 *4,030*	3.5
Dredging to -1.4 m MSL (USACE)	0.44 *1.44*	0.48	0.19 *0.61*	0.19	771,630 *630*	5,010,800 *4,060*	3.4
Dredging to -2 m MSL	0.54 *1.78*	0.60	0.21 *0.68*	0.21	912,580 *740*	5,098,600 *4,130*	2.9
Dredging to -3 m MSL	0.77 *2.51*	0.84	0.24 *0.80*	0.25	1,185,400 *960*	5,357,000 *4,340*	2.3

The tidal datums for Mean Low Water (MLW), Mean High Water (MHW), and Mean Tide Level (MTL) are summarized in Table 6-3 for the current bathymetry plus the four dredging scenarios for three locations in the river: the mouth, Sprague Bridge and Middlebridge. As expected, dredging has no effect on the tidal datums at the mouth while upstream MHW increases and MLW decreases (tidal range increases) with increased depths (volumes dredged). At Sprague Bridge the MHW level increases by 0.01 m for the -1 m MSL dredging scenario and by 0.05 m for the -2 m MSL scenario when compared to the current (un-dredged) bathymetry. Similarly the MLW level decreases by 0.03 m for the -1 m MSL dredging scenario and 0.12 m for the -2 m dredging scenario, when compared to the current bathymetry. At Middlebridge the MHW level increases by 0.01 m for the -1 m MSL dredging scenario and by 0.04 m for the -3 m MSL scenario when compared to the current bathymetry. Similarly the MLW level decreases by 0.02 m for the -1 m MSL dredging scenario and 0.06 m for the -2 m dredging scenario when compared to the current bathymetry. The decrease in attenuation will likely have some negative effects on the sensitivity of the existing saltmarsh to increasing water elevations and could impact future saltmarsh restoration efforts in the Narrow River. Thus the benefits of increased flushing must be weighed against the potential negative impacts on saltmarsh restoration.

Table 6-3. Tidal datums (MLW, MHW, and MTL) from Narrow River ADCIRC model results for 8 tidal cycles (11 through 14 April 2016) expressed in meters relative to NAVD88 for the current bathymetry and various dredging options.

	Mouth			Sprague Bridge			Middlebridge		
Scenario	MLW	MHW	MTL	MLW	MHW	MTL	MLW	MHW	MTL
Current Bathymetry	-0.363	0.636	0.136	-0.010	0.375	0.183	0.034	0.336	0.185
Dredging to -1 m MSL	-0.363	0.636	0.136	-0.035	0.386	0.176	0.018	0.345	0.182
Dredging to -1.4 m MSL (USACE)	-0.363	0.636	0.136	-0.055	0.394	0.170	0.007	0.351	0.179
Dredging to -2 m MSL	-0.363	0.635	0.136	-0.128	0.427	0.149	-0.030	0.377	0.173
Dredging to -3 m MSL	-0.363	0.635	0.136	-0.263	0.511	0.124	-0.072	0.449	0.189

6.2.4 Results for Other Tide Cycles during April 2016

An evaluation of the sensitivity of the tidal flushing time to differences in tide range was also performed. Table 6-4 compares the model results for the mean tide range that occurred between 0:00 and 12:00 on 11 April to the minimum and maximum tide range conditions for the -1.4 m MSL and -2 m MSL dredging scenarios. The minimum tide range cycle occurred between 21:30 1 April and 3:30 on 2 April and the maximum tide range cycle occurred between 3:29 and 11:44 on 10 April. The minimum range was 36-39% lower than the mean at Sprague Bridge for both the -1.4 and -2 m MSL scenarios and the maximum range was 57-64% higher than the mean. Similarly the minimum range was 27-29% lower than the mean at the Upper Pond for both the -1.4 and -2 m MSL scenarios and the maximum range was 60-63% higher than the mean. The attenuation at Sprague Bridge based on the minimum range was 27-30% lower than the attenuation based on the mean range while the attenuation based on the maximum range was 17-20% also lower than that based on the mean range due to its definition of the ratio of the Sprague Bridge range to the range at the mouth. The attenuation based on both the minimum and maximum ranges at the Upper Pond were 10-11% lower than the attenuation based on the mean range while the maximum was also 10% lower than the mean range. Ultimately the tidal flushing based on the minimum range in the river was 69-72% larger than the tidal flushing based on the mean range while the tidal flushing based on the maximum range in the river was 22-25% smaller than the tidal flushing based on the mean range. It should be noted that attenuation is sensitive to tidal range and care should be exercised in comparing results from different analysis that use differing tidal time series.

Table 6-4. Summary of tide ranges, attenuations, and tidal flushing results for various dredging scenarios for the April 2016 period.

Scenario	Sprague Bridge Tide Range (cm) *(ft)*	Sprague Bridge Atten-uation	Upper Pond Tide Range (cm) *(ft)*	Upper Pond Atten-uation	Tidal Prism (m^3) *(ac-ft)*	High Tide Volume (m^3) *(ac-ft)*	Tidal Flushing (days)
Mean							
Dredge to -1.4 m MSL	0.44 1.44	0.48	0.19 0.61	0.19	771,630 *630*	5,010,800 *4,060*	3.4
Dredge to -2 m MSL	0.54 1.78	0.60	0.21 0.68	0.21	912,580 *740*	5,098,600 *4,130*	2.9
Min							
Dredge to -1.4 m MSL	0.28 *0.92*	0.35	0.14 *0.44*	0.17	428,540 *350*	4,710,700 *3,820*	5.7
Dredge to -2 m MSL	0.33 *1.09*	0.42	0.15 *0.49*	0.19	495,680 *400*	4,773,100 3,870	5.0
Max							
Dredge to -1.4 m MSL	0.72 *2.36*	0.40	0.30 *0.99*	0.17	1,137,700 *920*	5,513,100 *4,470*	2.5
Dredge to -2 m MSL	0.86 *2.81*	0.48	0.33 *1.09*	0.19	1,274,200 *1,030*	5,579,600 *4,520*	2.3

6.3 USACE Dredging Alternatives (USACE, 2009)

The purpose of this section is to compare the results of the USACE HEC-RAS modeling results with the ADCIRC model results for the Narrow River. The USACE applied HEC-RAS, a 1-D unsteady (time varying) hydrodynamic model, to the Narrow River. Model results were documented in their 2009 report where a series of dredging scenarios that consisted of three different dredging depths at the mouth and in the Narrows: -2, -3, and -4 ft NGVD plus existing conditions (2007) were evaluated. The tidal ranges for the four scenarios were determined from Figures 16 and Figure 17 in the USACE (2009) report by scaling the height of the bars for Transect 4.5 (west of Sprague Bridge) and Transect 10.9 (north of Bridgetown Bridge). The tidal prisms for the model scenarios were determined from Figure 20 and Figure 22 by measuring the height of the bars for each scenario: Existing, -2 ft NGVD, -3 ft NGVD, and -4 ft NGVD. A summary of model results are shown in Table 6-5.

Table 6-5. Summary of USACE modeling results for various dredging scenarios.

USACE Option	Dredging Volume (m^3) *(yds^3)*	Sprague Bridge Tide Range (m) *(ft)*	Sprague Bridge Attenuation	Upper Pond Tide Range (m) *(ft)*	Upper Pond Attenuation	Tidal Prism (m^3) *(ac-ft)*	Tidal Flushing (days)
Existing (2007)	n/a	0.74 *2.44*	0.57	0.38 *1.25*	0.29	1,284,000 *1,040*	1.6
Dredging to -0.7 m MSL (-2 ft NGVD)	21,400 *28,000*	0.86 *2.82*	0.66	0.41 *1.33*	0.31	1,482,000 *1,200*	1.4
Dredging to -1.1 m MSL (-3 ft NGVD)	35,900 *47,000*	0.98 *3.22*	0.75	0.43 *1.39*	0.33	1,608,000 *1,300*	1.3
Dredging to -1.4 m MSL (-4 ft NGVD)	Not reported	1.07 *3.51*	0.82	0.41 *1.35*	0.31	1,608,000 *1,300*	1.3

The USACE HEC-RAS modeling was based on information collected in 2007 while the ADCIRC modeling results presented here were based on information acquired in April 2016. The tides, using water level values at Narragansett Pier as a metric, were substantially different, 1.31 m (4.29 ft) tide range for USACE and 92 cm (3.02 ft) for ADCIRC. Based on the present analysis of April 2016 tidal measurements, the USACE tide is indicative of mean spring tide conditions (1.40 m [4.59 ft]) with an attenuation at Sprague Bridge of 0.39. Since the actual attenuation as shown in Table 6-3 was 0.57, it suggests than the constriction in the Narrows and mouth was significantly lower back in 2007. This is consistent with the sedimentation of the inlet shown in Figure 3-2.

In addition the USACE Sprague Bridge and Upper Pond tide ranges were 0.74 m (2.44 ft) and 0.38 m (1.25 ft), respectively, almost twice the ADCIRC April tide ranges of 0.38 m (1.24 ft) and 0.17 m (0.57 ft). This likely accounts for a USACE tidal prism of 1,284,000 m^3 (1,040 ac-ft) about 1.9 times the ADCIRC tidal prism of 675,100 m^3 (550 ac-ft). The USACE tidal flushing time is about 40% lower (1.6 days) than the ADCIRC based estimates (3.8 days).

A comparable scenario was evaluated for both models using the same dredging depth at the mouth and in the Narrows, -4 ft NGVD for USACE and -1.4 m MSL for ADCIRC. The USACE Sprague Bridge and Upper Pond tide ranges were 1.07 m (3.51 ft) and 0.41 m (1.35 ft), respectively, more than twice the ADCIRC tide ranges of 0.44 m (1.44 ft)and 0.19 m (0.61 ft) actually 2.44 times for Sprague Bridge and 2.20 times for the Upper Pond. This accounts for a USACE tidal prism of 1,608,000 m^3 (1,300 ac-ft) more than twice the ADCIRC prism of 771,630 m3 (630 ac-ft). The USACE tidal flushing is 1.3 days, about 37% of the ADCIRC flushing (3.4 days).

The HEC-RAS and ADCIRC model results are generally consistent considering the large difference in tide range used in each model and that the 2007 data used by the USACE indicated that the constriction in the mouth and Narrows was less influential on the tide range attenuation in the river at that time. The results that the USACE -3 ft NGVD and -4 ft NGVD scenarios had identical tidal prism volumes and flushing time results even though the tide ranges at Sprague Bridge were slightly different (0.98 m [3.22 ft] vs 1.07 m [3.51 ft]).

Given the sensitivity of model predictions of attenuation and flushing time it is very important to make sure the model simulation period covers a sufficient amount of time to capture the neap spring variations in tidal range that are characteristic of the area.

6.4 Narragansett Town Beach Replenishment (WHG, 2011)

One potential use of the material dredged from the Narrows from Sprague Bridge to the river mouth is to replenish Narragansett Beach west of the river mouth. Woods Hole Group (WHG 2011) was contracted by the Town of Narragansett to develop and assess beach replenishment alternatives or “templates”. A series of five beach re-nourishment templates defined by beach profiles: berm width, berm elevation and offshore slope were developed, plus four other templates that represented existing equilibrium or equilibrium adjustments of the re-nourishment templates after two years. Figure 6-4 shows the geometry used to define the five templates relevant to the present analysis.

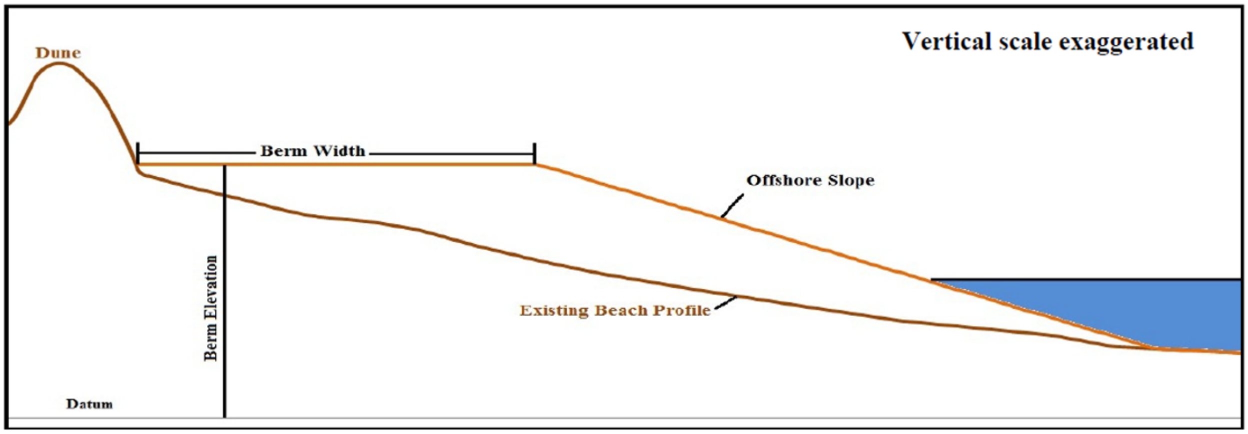


Figure 6-4. Beach profiles defined by berm width, berm elevation, and offshore slope (from WHG [2011]).

In addition to the templates, the beach was divided into two scenarios based on the project lengths: 863 m (2,465 ft) for Narragansett Town Beach along the western portion and 1,822 m (5,205 ft) for both the town beach plus the privately-owned beaches along the eastern portion. Three other scenarios that included structures (jetty, groin) were also developed. The two scenarios relevant to the present analysis are shown in Figure 6-5.

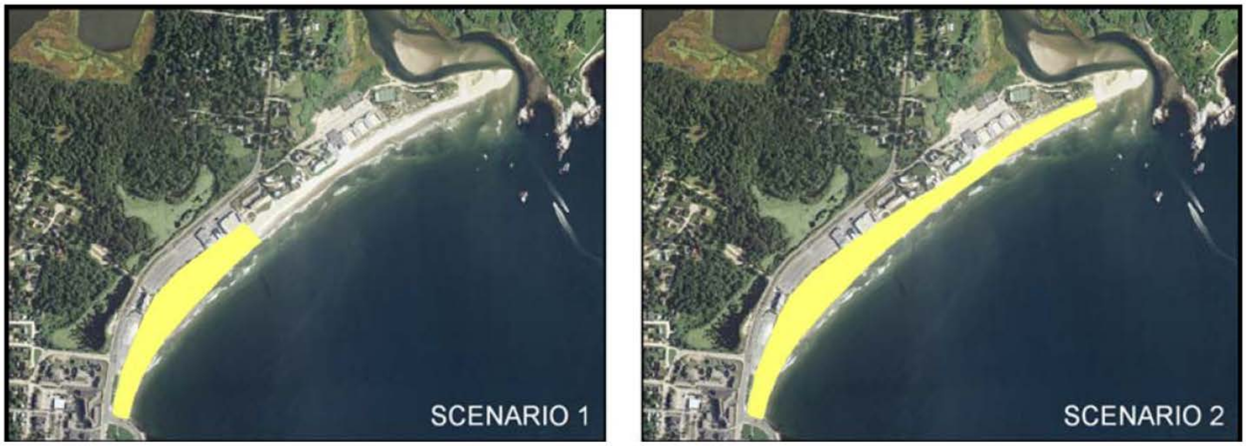


Figure 6-5. Beach scenarios relevant to the present analysis (from WHG [2011]).

A summary of the required re-nourishment volumes for the two scenarios, with five alternative options is shown in Table 6-6 (WHG, 2011).

Table 6-6. Re-nourishment volume requirements for two scenarios with five alternative options.

Renourishment Options	Scenario 1 –Narragansett Town Beach (863 m [2,465 ft]) Required Volume (m^3) *(yd^3)*	Scenario 2 - Narragansett Town Beach and private sections of barrier spit (1,822 m [5,205 ft]) Required Volume (m^3) *(yd^3)*
Option 2 Berm Width 30 m (100 ft) Berm Elevation 1.8 to 3.7 m (6 to 12 ft) Offshore Slope (12H:1V)	78,170 *102,240*	130,770 *171,040*
Option 3 Berm Width 30 m (100 ft) Berm Elevation 2.4 to 3.7 m (8 to 12 ft) Offshore Slope (12H:1V)	113,500 *148,450*	250,160 *327,200*
Option 5 Berm Width 15m (50 ft) Berm Elevation 1.8 to 3.7 m (6 to 12 ft) Offshore Slope (12H:1V)	46,000 *60,170*	115,200 150,670
Option 7 Berm Width 23 to 30 (75 to 100 ft) Berm Elevation 2.4 to 3.0 m (8 to 10 ft) Offshore Slope (15H:1V)	91,590 *119,800*	187,680 *245,470*
Option 9 Berm Width 9 to 15 m (30 to 50 ft) Berm Elevation 2.4 to 2.7 m (8 to 9 ft) Offshore Slope (15H:1V)	38,230 *50,000*	70,570 *92,300*

Comparing the required volumes from Table 6-6 with the total dredging volumes (Table 6-1):

- Dredging to -1.4 m MSL with a total dredging volume of 43,000 m^3 (56,200 yd^3) can supply enough volume for Option 9, Scenario 1 requiring 38,230 m^3 (50,000 yd^3) and almost enough for Option 5, Scenario 1 requiring 46,000 m^3 (60,170 yd^3).
- Dredging to -2 m MSL with a total dredging volume of 80,500 m^3 (105,000 yd^3) can supply enough volume for Option 2, Scenario 1 requiring 78,170 m^3 (102,240 yd^3) and Option 9, Scenario 2 requiring 70,570 m^3 (92,300 yd^3).
- Dredging to -3 m MSL with a total dredging volume of 184,000 m^3 (241,000 yd^3) is not a likely option to be pursued but can supply all cases for Scenario 1 and all cases for Scenarios, except for Option 7.

A major concern with any beach renourishment project is to determine the likely design life of the activity. Figure 6-6 is an image of Figure 22 in the WHG (2011) report which displays the percent of fill remaining over 20 years for some of the scenarios that were developed. The report states that the results should be considered conservative since the analysis did not consider limitations on sediment losses due to partial interruption of the longshore transport around rocky headlands at the site. Scenarios 1 and 2 are of relevance to the present project.

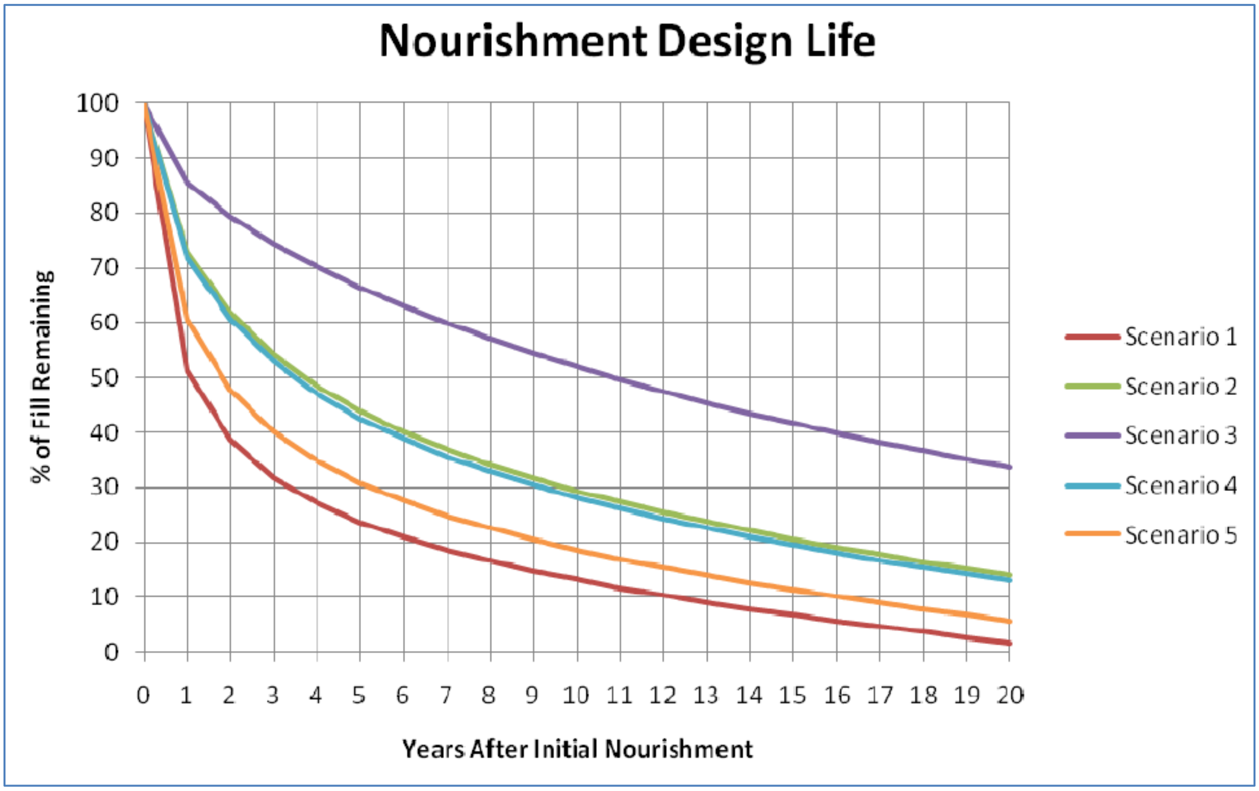


Figure 6-6. Beach nourishment design life. Scenarios 1 and 2 are relevant to the present analysis (from WHG [2011]).

Scenario 1 showed the shortest project lifetime with 27% of the initial fill remaining after four years and 16% after eight years. Scenario 2 showed that 49% of the initial fill remaining after four years and 34% after eight years. WHG (2011) states:

> *As a general rule of thumb, renourishment is generally considered appropriate when 30 to 40% of the fill is remaining in the original project area. Depending on the Scenario chosen for Narragansett Beach, replenishment could be considered between 3 and 10 years after initial construction. However, given the conservative nature of the design life estimates replenishment timelines closer to the 10 year interval are most likely.*

Without knowing the sedimentation rate in the Narrows reach of the river it is not possible to estimate how often that section could be dredged again in the future.

7 Conclusions and Recommendations

7.1 Conclusions

Previous studies over the last 45 years have shown a significant variation in tide range likely due to sediment dynamics (shoaling and channeling) in the Narrows reach located from Sprague Bridge downstream to the river mouth. The attenuation in tidal range at Sprague Bridge varies from 40% to almost 70% of the tide range at the river mouth. The attenuation in tidal range in the Upper Pond varies from 10% to 25% of the tide range at the river mouth. The geometry and bathymetry significantly constrain the tides entering and exiting the river. The duration of the measurements did not appear to be a factor in affecting attenuation as much as the variation in tidal range for the record period used to perform the analysis.

The ADCIRC hydrodynamic model was used to evaluate the circulation in the river under historical, present and future bathymetric conditions which required synoptic information on the present bathymetry and the variation in the tides along the river. Using recently collected (April 2016) bathymetric data by URI/GSO the ADCIRC model used in the analysis to predict water elevations and current velocities was successfully calibrated with water level data collected by USFWS and NOAA for the April 2016 period. The model predicted tidal attenuation to be ~40% at Sprague Bridge, in very good agreement with measurements.

The model predicted that highest maximum flood currents occurred near the eastern shore looking upstream at and south of the Sprague Bridge at 0.45 m/s (1.5 ft/s). Highest maximum ebb currents occurred at the mouth reaching 0.36 m/s (1.2 ft/s). The currents are higher in the Narrows both because of the constrictions in that reach, as well as the largest volume of water passing through the area on each tide. The sediment resuspension threshold is ~ 0.20 m/s (0.66 ft/s) so sediment transport occurs during each tidal cycle, particularly near the mouth and Sprague Bridge. Currents offshore from the river mouth were predicted to be much lower than the currents in the Narrows.

The effects of Hurricane Bob were also investigated to determine whether the water elevation in the river responded similarly to both a storm surge and the tides. Data from the NOAA Newport tide station was used as a boundary condition for the model. The model showed that the water level attenuation at Sprague Bridge was ~50% of the offshore water level compared to ~40% for the April 2016 attenuation. The attenuation further up the river at Middlebridge was ~33% and ~30% for Hurricane Bob and April 2016, respectively, and with similar values of ~17% and ~10% in the Upper Pond. The flooded area for Hurricane Bob was 3.21 km^2 (1.24 mi^2), 31% more than the 2.22 km^2 (0.86 mi^2) for April 2016. The attenuation for Hurricane Bob hence was comparable to that for normal tidal forcing. This is attributed to the duration of the peak surge being equivalent of that for normal tidal variations in water level and the importance of forcing period in the filtering characteristics of this inlet-basin system.

A series of four hypothetical dredging scenarios were chosen from -1 m MSL to -3 m MSL, which removed between 1.5 m (4.9 ft) and 3.5 m (11.5 ft) or between 21,500 m^3 (28,100 yds^3) and 184,000 m^3 (241,000 yds^3). The larger dredging scenario is likely unrealistic but chosen to test the sensitivity of the analysis and an upper bound value. Simulations were performed for the April 2016 study period. The attenuation values at Sprague Bridge increased from 0.42 to 0.84 indicating the larger dredging reduced restrictions to the flow. The values in the Upper Pond increased from 0.18 to 0.25 indicating that the mid and upper reaches of the river further continued to restrict the flows in the upper reaches of the river.

The tidal prism is a calculation using the variation of tide range along the river to determine the difference between the low tide and high tide volumes. Dividing the high tide volume by the tidal prism and multiplying by the primary tidal period (12.42 hrs) gives the tidal flushing time. The tidal flushing time for the present bathymetry was 3.8 days compared to the range of 3.5 to 2.3 days for the dredging scenarios. The limiting assumption in this calculation is that the flushing time is the average for all the reaches in the river and assumes a complete exchange of water with the ocean. In reality the reaches closest to the mouth would have shorter times while the reaches distant from the mouth would have longer times. In addition some portion of the water exiting the river on ebb will likely return on the next flood. It does however provide a straightforward method to compare the relative effect of the dredging alternatives.

A sensitivity study to different tide ranges for the April 2016 period was conducted for a subset of dredging alternatives (-1 m MSL and -2 m MSL) to assess the importance of how the spring / neap cycle may affect flushing. The minimum tide range was 36-39% lower than the mean at Sprague Bridge for both the -1.4 and -2 m MSL scenarios and the maximum tide range was 57-64% higher than the mean. Similarly the minimum tide range was 27-29% lower than the mean at the Upper Pond for both the -1.4 and -2 m MSL scenarios and the maximum range was 60-63% higher than the mean. Ultimately the tidal flushing based on the minimum range in the river (5.0 to 5.7 days) was 69-72% larger than the tidal flushing based on the mean range (2.9 to 3.4 days) while the tidal flushing based on the maximum range in the river (2.3 to 2.5 days) was 22-25% smaller than the tidal flushing based on the mean range. Thus the influence of the tide range is a significant factor in estimating on flushing estimates.

The dredging scenarios will result in increased elevation of MHW and thus potential impacts to saltmarsh habitat. This is particularly important because saltmarsh vegetation is already stressed from sea level rise in the Narrow River and increasing the tidal range and MHW elevation as a result of dredging may cause further negative impacts and potentially affect the ongoing USFWS/TNC saltmarsh restoration project.

A comparison between the USACE HEC-RAS model and the ADCIRC model used in this study show generally consistent results although the results from HEC-RAS application to 2007 indicated that the constriction in the mouth and Narrows was less influential on the tide range attenuation in the river at that time. The USACE results are representative of spring tidal ranges and reflect a time when there was less sediment in the Narrows.

Finally the dredged volumes used in this analysis were compared with renourishment volumes determined for the adjacent beaches in Narragansett by WHG (2011). Two scenarios of renourishing different lengths of beach using five options were evaluated. It was found that the -1.4 m MSL dredging alternative could supply enough material for two of the five options under scenario 1 (just Narragansett town beach) and that the -2 m MSL alternative could supply enough material for a third option of scenario 1 and an option under scenario 2 (the town beach plus the private beaches closer to the Narrow River mouth). However the beaches would likely have to be renourished after four years for scenario 1 and after eight years for scenario 2.

7.2 Recommendations

This study has provided estimates of tidal flushing times which are a useful metric in understanding the length of time that pollutants will remain in a tidally dominated water body. Its use is most appropriate where the assumption that water near the head of a water body will flush in approximately the same time as the water near the mouth. Since the Narrow River, by its name, is a relatively long and narrow water body, the head waters will not flush as quickly and therefore pollutants would likely accumulate there more than at the mouth.

To assess the pollutant transport through the Narrow River from their sources to Rhode Island Sound a further model is required. This type of model accounts for pollutant movement by the predicted current velocities from a hydrodynamic model (e.g., ADCIRC), physical diffusion, and the kinetics of the pollutant. To ensure that the model results are accurate this type of model is usually calibrated against field data collected in the river and then applied to investigate the influence of the issue of interest; impact of dredging in this case on river water quality.

Berounsky and Nixon (2007) have performed an in-depth review of the literature and field observations made by the Narrow River Preservation Association (NRPA) and others. The review shows that the water quality indicators of primary interest are nutrients and bacterial indicators and that non-point sources dominate. There are offsetting trends with implementation of sewering reducing contaminant levels while increasing development as a result of the installation of sewage collection increases contaminant levels from non-point sources. These contaminants are particularly challenging to use for model validation because the sources are not well characterized and the parameters are non-conservative. As an alternative, non-toxic dyes (e.g., rhodamine) can be released at known locations with specified rates and tracked by boat mounted or statically deployed fluorometric measurement devices. The dilution effects and long term transport of the conservative dye can be followed by this method and generate data sets for model calibration/validation. The method is also amenable to determining the exchange rate between the river and the ocean. In practice several releases are performed to characterize the behavior from key locations were non-point sources principally discharge to the river (e.g. Middlebridge and Mettatuxet).

Once calibrated the pollutant transport model can be used to assess accumulation and flushing for a variety of pollutants of concern. A plan to conduct a dye study in and apply a pollutant model to the Narrow River would be required. Ideally this would be coordinated with the NRPA sampling program.

It is also recommended that a further assessment of the impact of dredging the mouth of the Narrow River and resulting increased MHW elevations on saltmarsh habitat is warranted.

8 References

Apogee Research 1990. The stormwater management utility: a guide to planning for the Narrow River Watershed, Rhode Island report, Prepared for U.S.E.P.A and the Narragansett Bay Project.

ASA et al. (Applied Science Associates, URI Watershed Watch, SAIC Engineering, Inc. and Urish, Wright and Runge). 1995. Narrow River stormwater management study: Problem assessment and design feasibility & Appendices, 6 September 1995.

Berounsky, V. M. and S. W. Nixon, 2007. Historical and recent water quality conditions in the Narrow River (Pettaquamscutt River Estuary), Prepared for US ACOE New England District, Concord, MA.

Carr, V. E., 1995. Digital modeling of pollutants to the Narrow River Estuary. PhD dissertation in Civil and Environmental Engineering, University of Rhode Island.

Gaines, A. G., 1975. Papers on the geomorphology, hydrography and geochemistry of the Pettaquamscutt River Estuary. PhD dissertation in Oceanography, University of Rhode Island.

Luettich Jr, R. A., J. J. Westerink, and Norman W. Scheffner. ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries. Report 1. Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL. No. CERC-TR-DRP-92-6. Coastal Engineering Research Center, Vicksburg, MS, 1992.

Pasch, R.J., and A.A. Lixion, 1992. Annual summaries Atlantic hurricane season of 1991. Monthly Weather Review, Vol. 120, pp. 2671-2687.

RICRMC (Howard-Strobel, M. M., T.G. Simpson, and T.P. Dillingham), 1987. Narrow River special area management plan, adopted December 1986, Published May 1987.

RICRMC (Ernst, L.M., L.K. Miguel, and J. Willis), 1999. The Narrow River Special Area Management Plan for the watershed of the Narrow River in the Towns of North Kingstown, South Kingstown and Narragansett, April 12, 1999.

RIDEM (Rhode Island Department of Environmental Management), 2001. Fecal Coliform TMDL for the Pettaquamscutt (Narrow) River Watershed, Rhode Island Including: Narrow River Estuary, Gilbert Stuart Stream, Mumford Brook. Office of Water Resources, Rhode Island Department of USACE (U.S. Army Corps of Engineers), 2010. Narrow River Restoration Project, Narragansett and South Kingston, Rhode Island. Detailed Project Report and Environmental Assessment. Team Review Draft. U.S. Army Corps of Engineers New England District. January 2010.

Swanson, J.C. and H. Rines, 1995. Influence of the Middlebridge Road Bridge on circulation in the Narrow River. ASA Project 94-083, 17 February 1995.

Turner, C., K. Jayko, and S. Puckett, 1989. Flushing and exchange in the Narrow River Estuary (Pettaquamscutt River). Applied Science Associates, Inc., Narragansett, RI.

USACE (U.S. Army Corp of Engineers), 2008. Coastal Engineering Manual, Chapter 6, Hydrodynamics of Tidal Inlets, US Army Corp of Engineers, Manual Number: EM-1110-2-1100.

USACE (U.S. Army Corps of Engineers), 2009. NARROW RIVER, NARRAGANSETT, RHODE ISLAND Hydrodynamic Numerical Modeling and Data Collection Report. New England District - Water Management Section, 21 April 2009.

USACE (Hatfield, C.L., D. Wood, D. Acone, and H. Sullivan), 1993. Effect of Middle Bridge on flooding of the Pettaquamscutt River Narragansett and South Kingstown, Rhode Island. Final Report, U. S. Army Corps of Engineers, New England Division, Waltham MA.

USACE (U.S. Army Corps of Engineers), 1971. Narrow River, Narragansett, South Kingstown, and North Kingstown Rhode Island, review of reports. New England Division, Army Corps of Engineers, Department of the Army, Washington, D.C. 10pp.

USFWS (U.S. Fish and Wildlife Service), 2014. Draft Environmental Assessment, Narrow River Estuary Resiliency Restoration Program. U.S. Fish and Wildlife Service, Rhode Island National Wildlife Refuge Complex, October, 2014.

USFWS (U.S. Fish and Wildlife Service), undated. Spreadsheet of water elevation measurements taken during 2014-2015 throughout lower Narrow River and Pettaquamscutt Cove.

WHG (Woods Hole Group), 2011. Narragansett Town Beach Replenishment Feasibility Project. Woods Hole Group, Inc., East Falmouth, MA, September 2011.