2016 Post-Construction Monitoring of the Muddy Creek Restoration Project
Harwich and Chatham, Massachusetts

by **Trey Ruthven,**
Sean Kelley

Applied Coastal Research and Engineering, Inc.
766 Falmouth Road, Suite A-1
Mashpee, MA 02649

January 10, 2017

Prepared for: Towns of Harwich and Chatham, MA

Table of Contents

Section **Page**

List of Figures

List of Tables

1. Background

As part of the Muddy Creek Marsh Restoration Project, The Towns of Chatham and Harwich replaced the two tidally restrictive stone box culverts that connected Muddy Creek with Pleasant Bay with a larger single span bridge in the Spring of 2016. The stone box culverts were approximately 2.5-feet wide, 3.75-feet in height, and 100-feet in length, and the post restoration hydraulic opening is a trapezoidal channel with a 22-foot wide base and 1.7: side slope. The expanded tidal channel through the Route 28 roadway embankment will improve water quality and potentially restore salt marsh habitat. The increased hydraulic opening will also intensify tidal flow in and out of the Muddy Creek. The physical changes to the system and associated changes in tidal flow have raised questions regarding the potential evolution of the outer channel relative to the pre-restoration configuration and how those changes could possibly alter the functionality of the adjacent beach parking area and access road.

To monitor the influence the larger bridge opening has on the tidal channel, the Massachusetts Division of Ecological Restoration (DER) developed a pre-construction monitoring program to measure baseline channel bathymetry and alignment of the tidal channel (specifically the top edge of the marsh bank). A pre-construction monitoring survey was completed by DER in the Fall of 2015. The topographic survey captured nine channel cross-section transects, four upstream of Route 28 and five downstream within Muddy Creek. The survey also measured the top edge of the marsh bank along the channel.

This report presents and discusses post-construction monitoring. Four channel and bank surveys were conducted in 2016: June, July, September, and November. In addition, tide data records were collected at two stations: 1) offshore of Muddy Creek in Pleasant Bay, and 2) west of the Route 28 bridge, in the main body of Muddy Creek.

2. Top of Bank Surveys

The top of marsh bank, immediately adjacent to the channel, was measured to examine if the distinct set of meanders that define the channel into Muddy Creek remained relatively stable or shifted due to the increase in tidal flow associated with the new bridge opening. Individual top of bank locations and elevations were surveyed at approximately 25-foot intervals. The surveyed data was collected in Massachusetts State Plane Coordinates Horizontal Datum and North American Vertical Datum of 1988 (NAVD88) using a Leica Viva GS08 GNSS receiver RTK network rover coupled with a Leica Viva CS15 3.5G Data Collector system. The bank surveys were conducted on June 22, July 26, September 20, and November 17, 2016. The results from the top of bank surveys are shown in Figures 1 through 4.

Figure 1 shows the channel banks in the Fall of 2015 (pre-construction) and June of 2016 (post-construction). The top of bank position remained relative stable over the winter, as well as after the restoration of tidal flow through one half of the channel on February 11, 2016 and the full channel on April 1, 2016. Subsequent to the construction of the new bridge and restoration of full tidal flow, there has been some minor shifting in the channel entrance adjacent to Pleasant Bay. These shifts were expected due to the seasonal changes in wave climate on western Pleasant Bay and resulting changes in littoral transport along the coastline and inlet mouth. The inner and outer tidal channels remained in approximately the same positions over the 8-month period. Figure 2 shows the channel banks in the Fall of 2015 (pre-construction) and November of 2016 (post-construction). A comparison of the post-construction movement, June to November, is shown in Figure 3 and a composite of all the bank surveys is presented in Figure 4. Overall the bank position remained relatively stable with no pronounced movements in the meanders or channel, except for the mouth of the inlet along the Pleasant Bay shoreline.

Figures 1 through 4 do not illustrate specific areas where the marsh bank is slowly being undercut and shifting the channel landward as a result of the increased tidal flow scouring the outside of the channel bends. Figure 5 shows evidence of site-specific bank erosion where thin areas (1-4 feet in thickness) of marsh bank were observed cleaving away from the marsh surface and slowly settling into the channel as tidal currents eroded the material. The areas where the bank is being undercut are highlighted in red in Figure 6. The erosional areas are predominately located at channel bends, where the complex nature of the tidal flows caused by curvature effects generate secondary currents. The secondary currents occur in the plane normal (across channel towards the marsh banks) to the primary flow direction (along channel the axis). The secondary currents appear at bends due to skewing of a portion of the cross-stream vorticity into the along-stream direction. The main, skew-induced secondary cell drives fast, near-surface water outwards at a bend, and carries slow, near-bed water inwards. The high intensity outward flow scours sediment along the face of the channel bank, while the near-bed return flow carries sediment to the inside of the bend where it is deposited as the flow velocities decrease. The changes in channel geometry resulting from the secondary flows can be clearly observed in the cross-sectional plots presented in Section 3. The areas highlighted in blue in Figure 6 were lower in elevation than the surrounding marsh plain prior to the opening of the bridge. These areas remain low and have experienced minor bank erosion along the channel face, but have remained stable over the monitoring period.

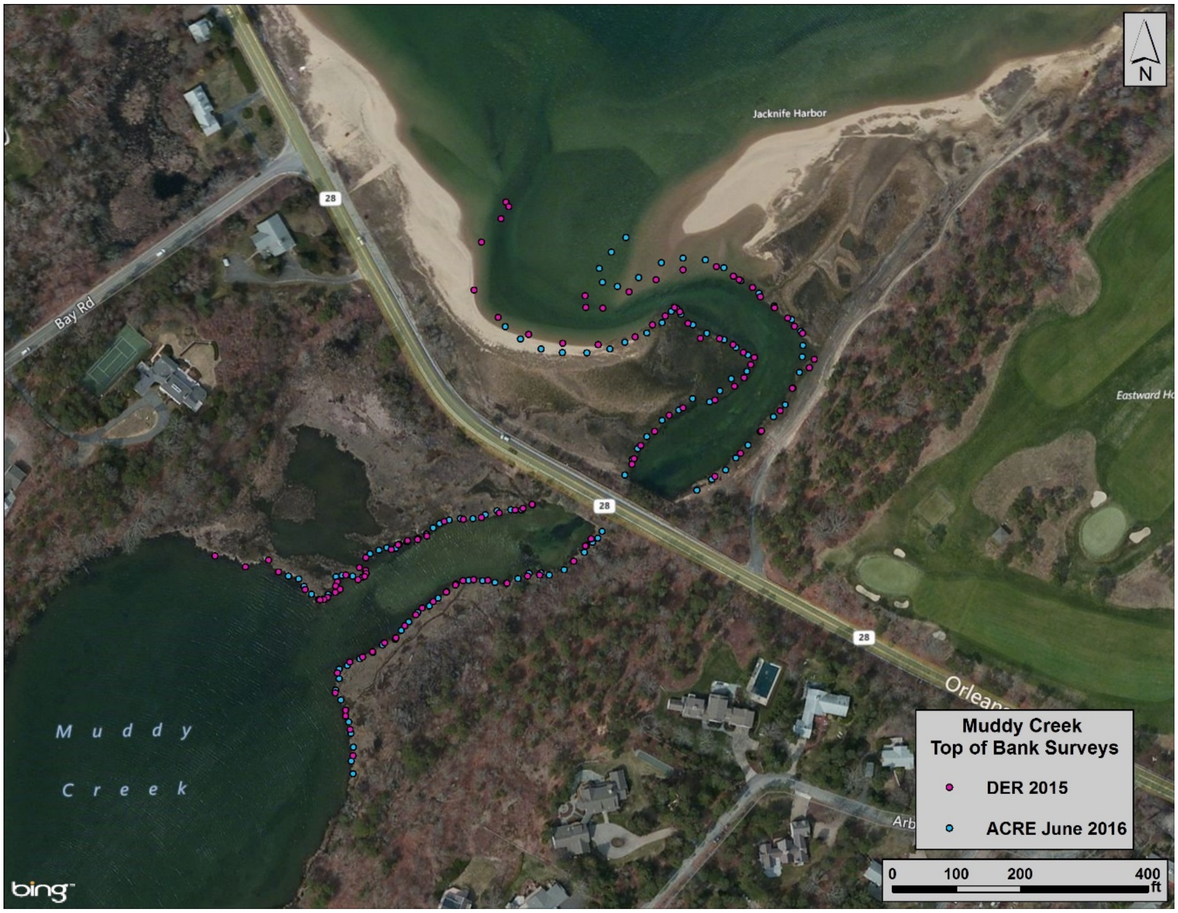

Figure 1. Fall of 2015 (pre-construction) and June of 2016 (post-construction) measured top of bank positions. The measurements are overlaid on a composite 2014 aerial photograph (Bing, 2014) of Muddy Creek. Pleasant Bay is seen in the upper portion of the photo.

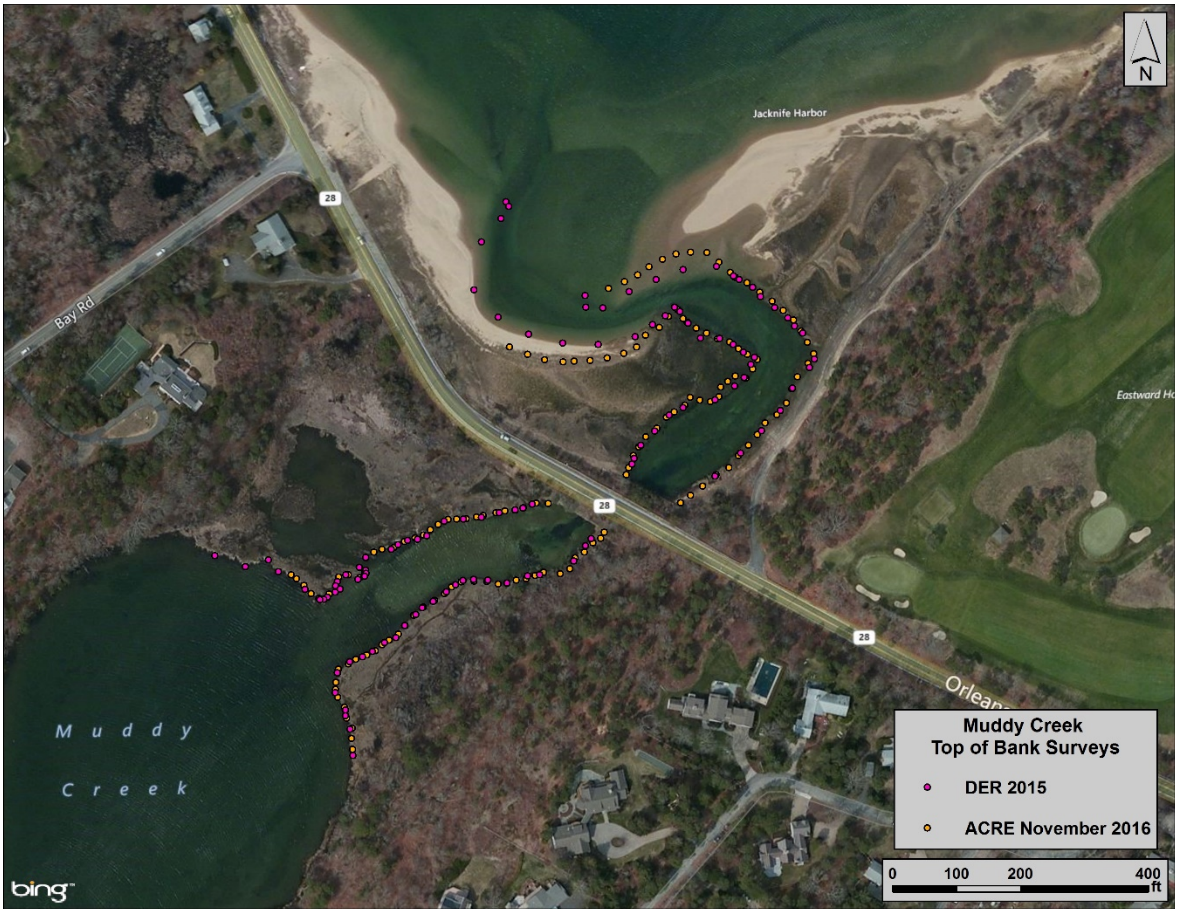

Figure 2. Fall of 2015 (pre-construction) and November of 2016 (post-construction) measured top of bank positions. The measurements are overlaid on a composite 2014 aerial photograph (Bing, 2014) of Muddy Creek. Pleasant Bay is seen in the upper portion of the photo.

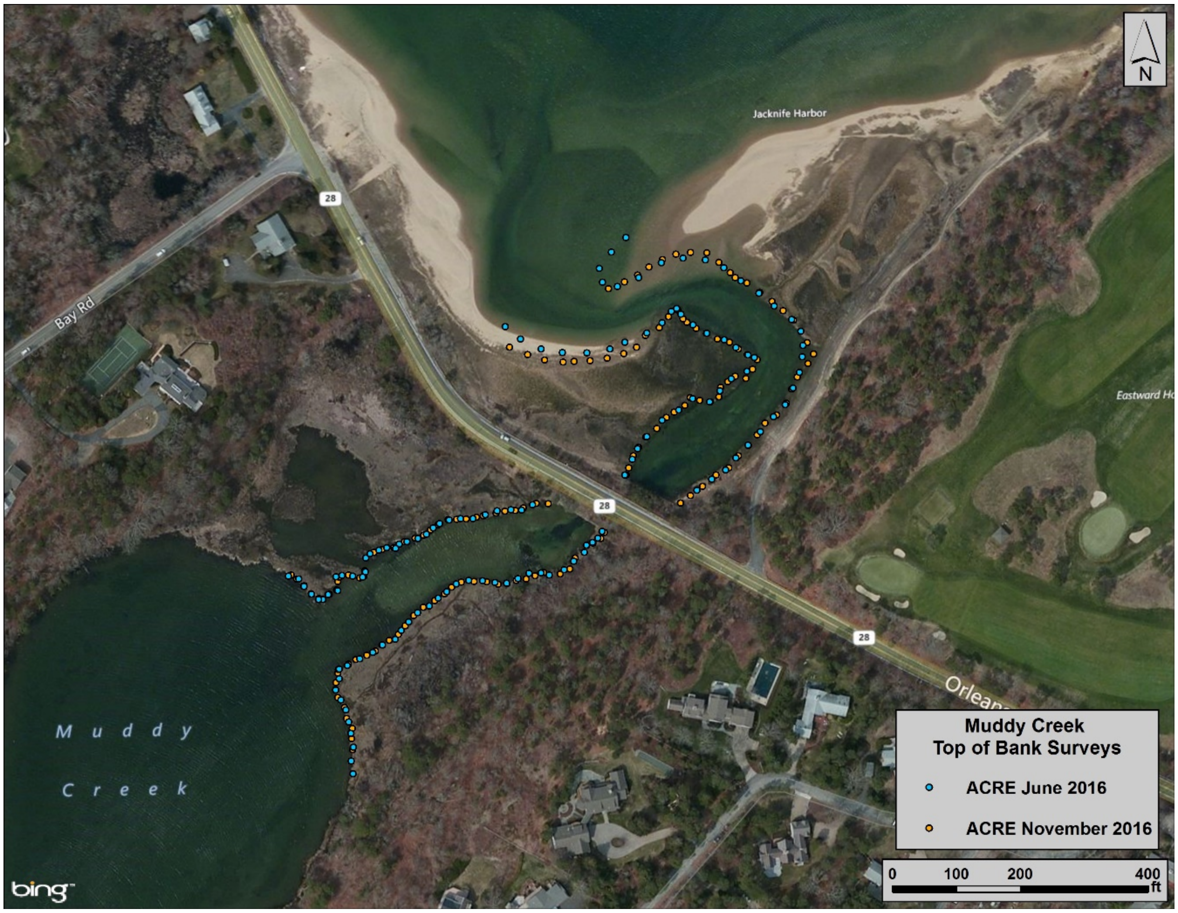

Figure 3. June of 2016 and November of 2016 measured top of bank positions. The measurements are overlaid on a composite 2014 aerial photograph (Bing, 2014) of Muddy Creek. Pleasant Bay is seen in the upper portion of the photo.

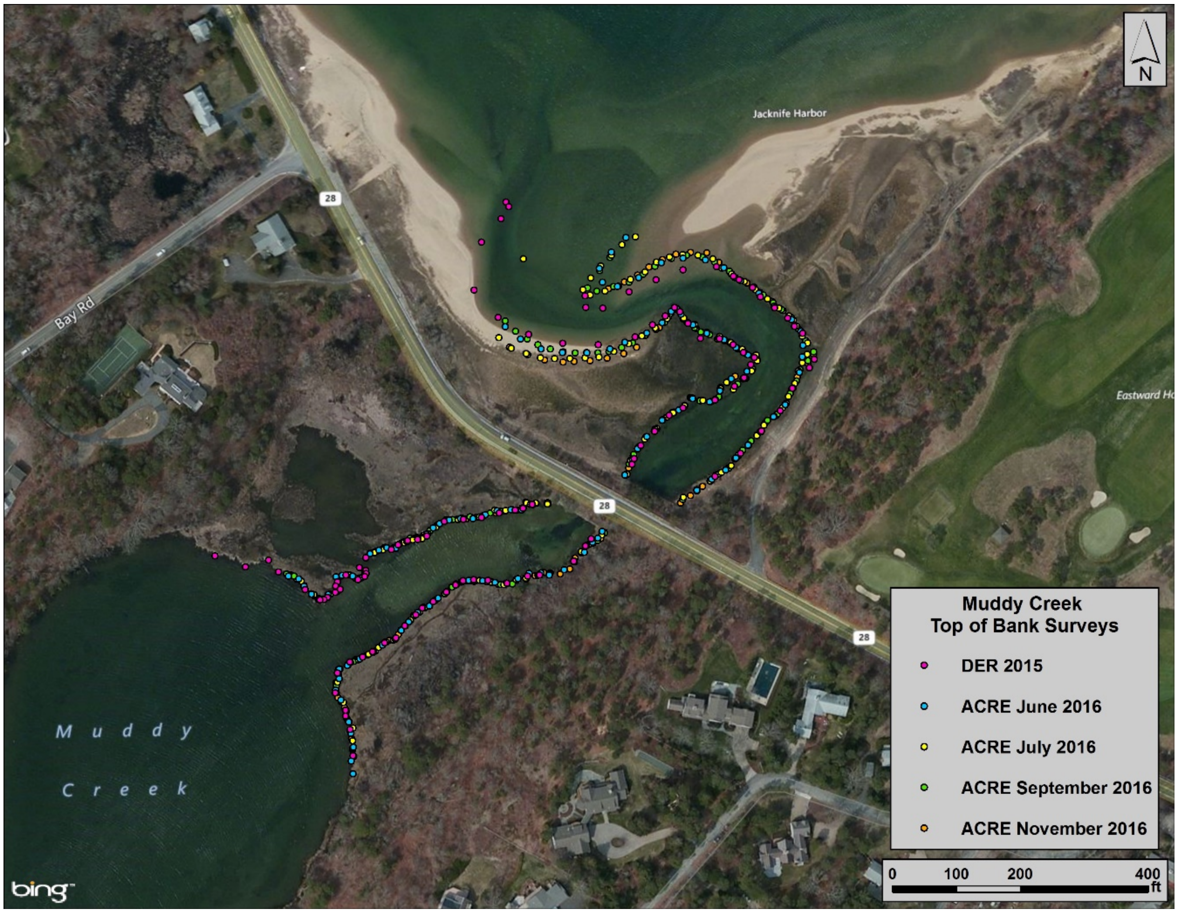

Figure 4. Composite of all the measured top of bank positions. The measurements are overlaid on a composite 2014 aerial photograph (Bing, 2014) of Muddy Creek. Pleasant Bay is seen in the upper portion of the photo.

Figure 5. Muddy Creek tidal channel downstream (seaward) of Route 28 where the marsh bank has been observed cleaving away from the marsh surface.

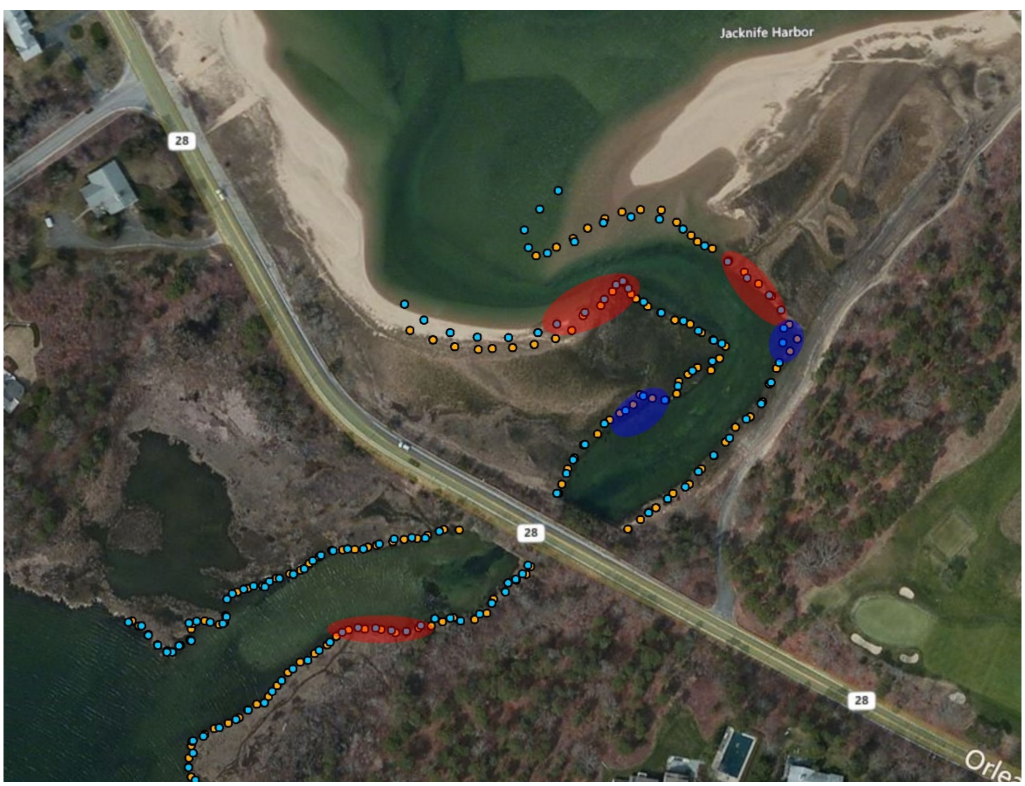

Figure 6. Red areas represent areas where bank erosion has been noted over the monitoring period. Blue areas represent marsh plain that was lower than the adjacent marsh plain prior to construction but have not exhibit significant bank erosion.

3. Cross-Channel Bathymetry Surveys

Cross-channel bathymetry was measured using a RTK-GPS up and downstream of Route 28. During the pre-construction monitoring in the fall of 2015, DER established the location of nine cross channel transects. Four transects were located upstream (landward) of Route 28 and five downstream (seaward) along the outer channel to Pleasant Bay. The transect end-points are permanently marked with PVC pipe set into the marsh. Two additional transects (T10 & T11) were added to the post-construction monitoring. The additional transects were added to the outer channel, in the vicinity of the Jack Knife Beach access road, where there were concerns about erosion and shifting of the channel that potentially could alter the functionality of the access road. Cross-channel bathymetry surveys were conducted on June 22, July 26, September 20, and November 17, 2016.

The starting and end points of the transects are presented in Table 1. The transect location data is presented in northings and eastings in Massachusetts State Plane Horizontal Coordinates (feet). The locations of the transects are shown in Figure 7.

Plots of the cross-channel profile data are presented in Figures 8 through 18. The transect plots are presented out of numerical transect order, however they are organized relative to the transects position progressing upstream from Pleasant Bay (See Figure 7 for the ordering of the transect identification numbers). Each figure shows the data from the Fall of 2015 pre-construction survey and the June, July, September, and November post-construction surveys (There is no pre-construction survey data for Transects 10 and 11).

Table 1. Beginning and End points for the Muddy Creek cross-channel bathymetry transects. The data is in Massachusetts State Plane Horizontal Coordinates (feet).

Transect	Beginning		Ending	
	N (feet)	E (feet)	N (feet)	E (feet)
T1	2,723,868.8360	1,067,436.5717	2,724,037.5997	1,067,313.0119
T2	2,723,868.8360	1,067,436.5717	2,724,050.3603	1,067,510.3779
T3	2,723,868.8360	1,067,436.5717	2,723,889.1089	1,067,652.3811
T4	2,723,868.8360	1,067,436.5717	2,723,752.9162	1,067,577.0794
T5	2,723,807.2608	1,067,380.8185	2,723,700.7936	1,067,498.0510
T6	2,723,659.1798	1,067,104.1167	2,723,528.3796	1,067,167.9759
T7	2,723,634.3076	1,067,002.1337	2,723,494.7067	1,067,089.9181
T8	2,723,591.8360	1,066,920.8543	2,723,454.4887	1,067,012.5921
T9	2,723,525.6276	1,066,821.6621	2,723,364.2896	1,066,919.0335
T10*	2,723,820.8000	1,067,619.9000	2,723,868.8000	1,067,437.1000
T11*	2,723,772.8000	1,067,323.1000	2,723,660.8000	1,067,437.2000

* Transect added after construction of the bridge

Beginning with Transect 1, shown in Figure 8, and proceeding through Transect 9, shown in Figure 18, the plots of the channel transects show that channel geometry responded quickly to the increased tidal flow associated with installation of the bridge. A majority of the channel geometry alterations were along the outsides of channel bends and the deposition of sediment on the inside of bends as well as changes in the location of shoaling. Channel geometry has remained relatively stable over the four post-restoration monitoring surveys. The stability of the cross-section geometry after the initial response was expected due to the influence of bidirectional tidal flow countering the continued migration influence of the larger tidal prism by transporting sediment upstream during flood cycles and downstream in ebb cycles. In addition, the pre-restoration channel width was determined to be ‘oversized’ relative to the magnitude of tidal flows pre- and post-construction (ACRE, 2015), suggesting that the channel was formed less through daily tidal flows than during severe Nor’easters which generate flows that are large enough to develop meanders. The response of the channel to large Nor’easter type events has not been documented since the channel was constructed and the bridge installed. The new channel opening will allow for a more significant response to coastal storm surge events within Muddy Creek and, therefore, larger flows could reshape the characteristics of the meanders depending on the frequency and magnitude of the events. However, due to the low elevation of the marsh plain downstream of the Route 28 roadway, any significant surge event will quickly crest above the top of the banks, thereby reducing the volume of water conveyed in the channel. A Nor’easter type storm event will likely produce shifts in the channel geometry (position and depth of main conveyance pathways and shoals) and accelerate the scouring of weak sections of marsh bank along the channel edge (red areas highlighted in Figure 6). The outside of channel bends will likely continue to respond to the new tidal conditions, however it is not expected that channel meanders will shift significantly under daily tidal flow. It is expected that weakened areas of marsh bank that have separated from the marsh plain or slumped will eventual be scoured away, however no significant changes in channel position or geometry are anticipated from daily tidal flows. The 2015 review of the inlet channel stability (ACRE, 2015) did not anticipate significant changes to the channel meanders due to Nor’easters, however to date, the system has not experienced any significant storms or Nor’easters to test the stability of the inlet channel. The channel should be monitored after storm events to provide additional observations and data to evaluate the response of the system.

Seaward of Route 28 Bridge

Transect 1 (Figure 8) shows approximately a 3-foot increase in channel depth and shift southward of the main conveyance pathway along the southern edge of the channel. The increase in depth around the outside of the bend has resulted in bank being undercut and loss of salt marsh along the edge of the marsh plain. The channel position and depth has been relatively stable over the post-construction monitoring surveys and is expected to remain so with some minor adjustment as the system continues to respond to the changes in tidal flow and winter storms. Transect 2 (Figure 9) had a large amount of deposition on the inside of the channel bend which is predominately fine to medium grained sand. Transects 3 and 4 (Figures 10 and 12, respectively) had similar trends, the outside bend of the channel deepened due to the increase in flow, while the inside of the channel cross section accreted sediment. The channel geometry at Transect 10 (Figure 11) has the same characteristics as Transects 3 and 4 which are downstream and upstream. The channel bottom at Transect 5 (Figure 13) accreted due to sediment deposition. During both the flood and ebb tide, sediment was deposited in response to the flow velocities decreasing as the channel straightened and widened. Transect 11 (Figure 14) reflects the channel geometry upstream of the bridge at Transect 6 (Figure 15). The main conveyance channel in centered in the cross section, aligned with the bridge opening.

Landward of Route 28 Bridge

Upstream of the bridge, Transect 6 (Figure 15) developed a new conveyance channel centered along the bridge opening. The channel connects and extends the scour hole that existed immediately upstream of the causeway prior to the restoration and is a response to the increased flood tides. A similar response was observed at Transect 7 (Figure 16), the southern channel widened and deepened along the marsh edge due to the increase in the flood tide volume and velocity. Transect 8 (Figure 17) remain stable and did not show any significant transitions in channel geometry, while Transect 9 (Figure 18) accreted as the flood tide shoal extended and transitioned upstream due to the scouring of channel sediment immediately upstream of the bridge.

Figure 7. Locations of the cross-channel monitoring transects. Two additional transects were added to the post-construction monitoring, Transects 10 and 11, which are highlighted in green.

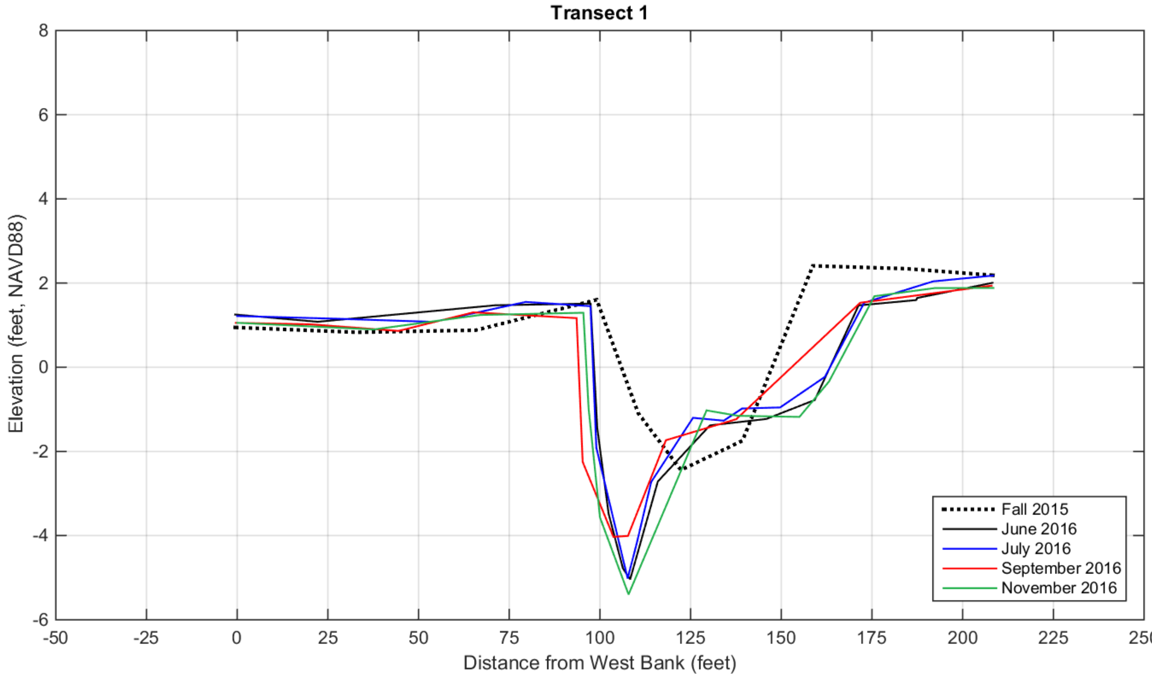

Figure 8. Cross-channel monitoring Transect 1. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

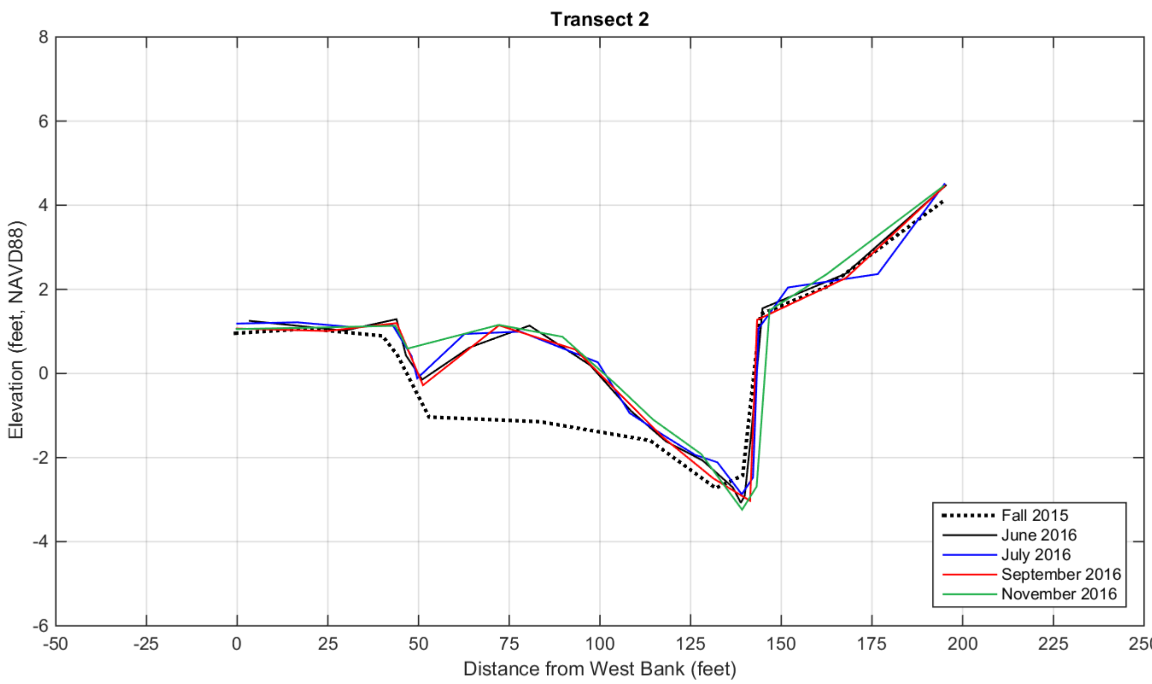

Figure 9. Cross-channel monitoring Transect 2. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

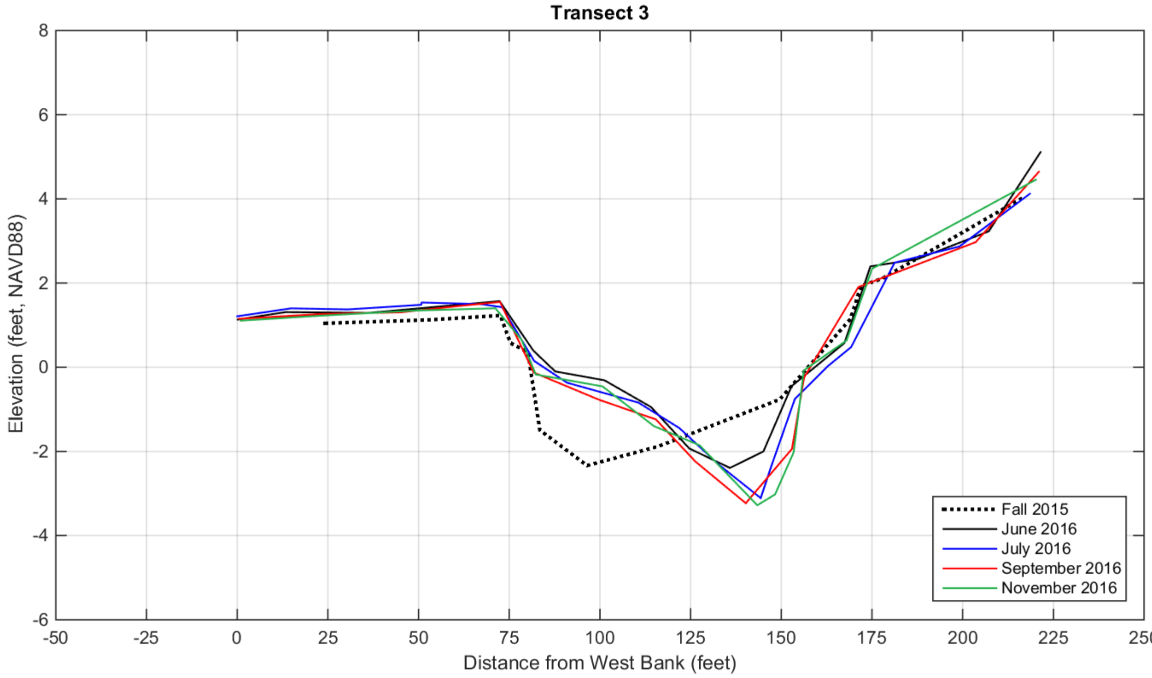

Figure 10. Cross-channel monitoring Transect 3. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

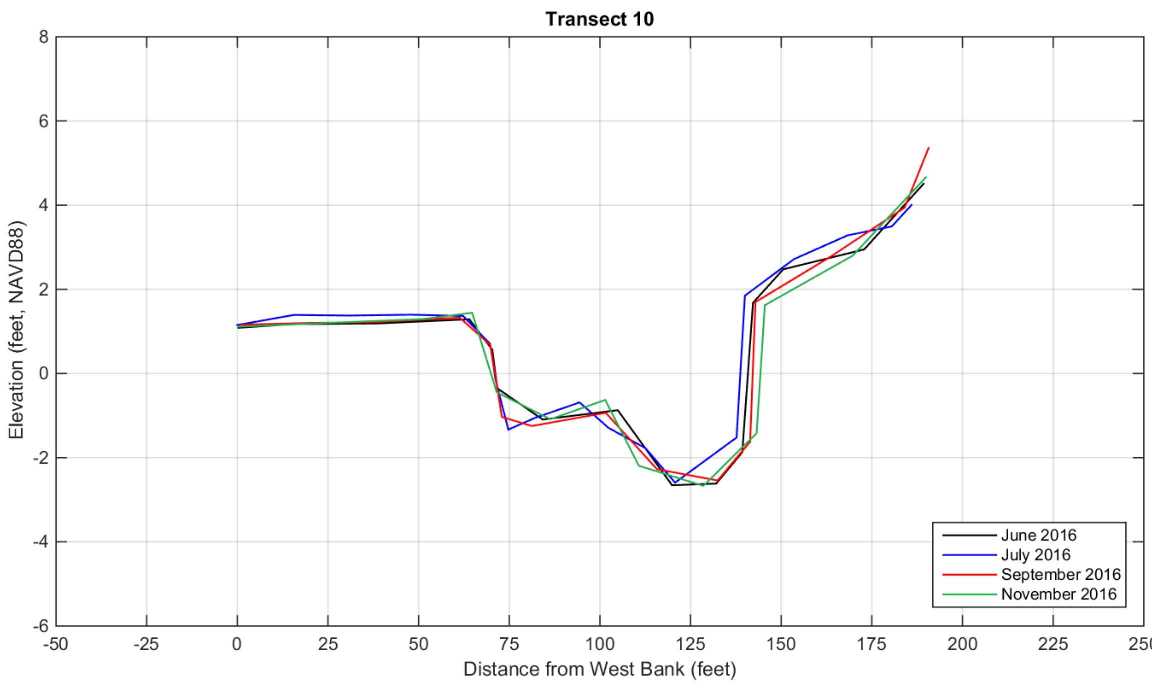

Figure 11. Cross-channel monitoring Transect 10. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

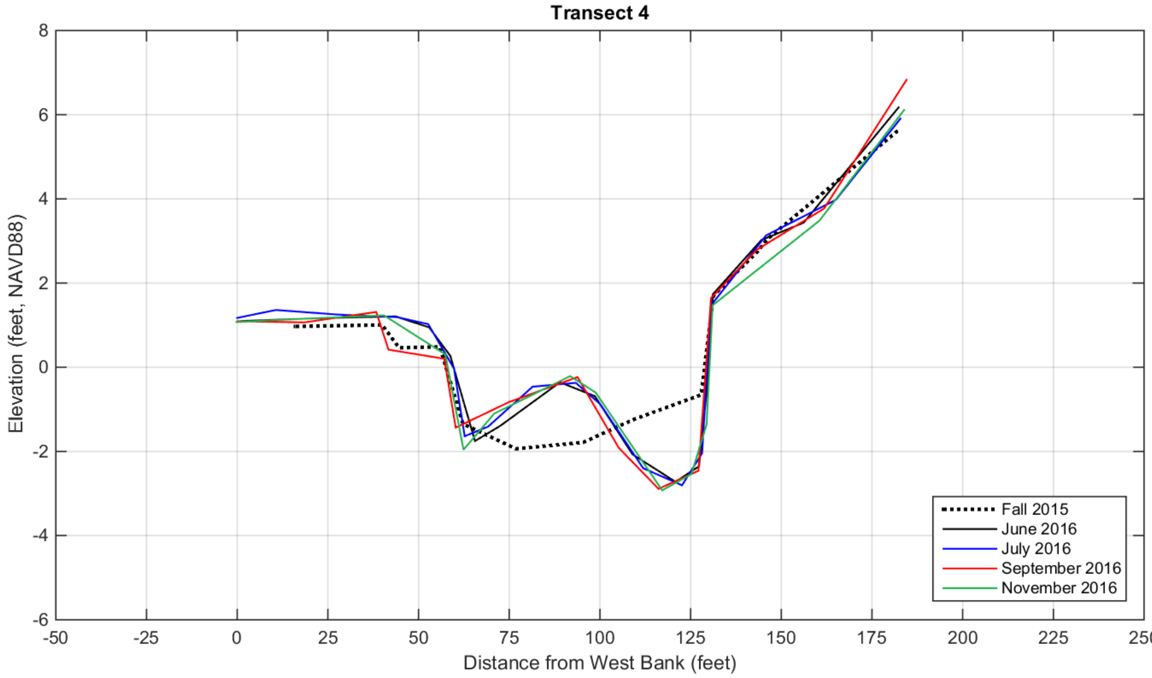

Figure 12. Cross-channel monitoring Transect 4. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

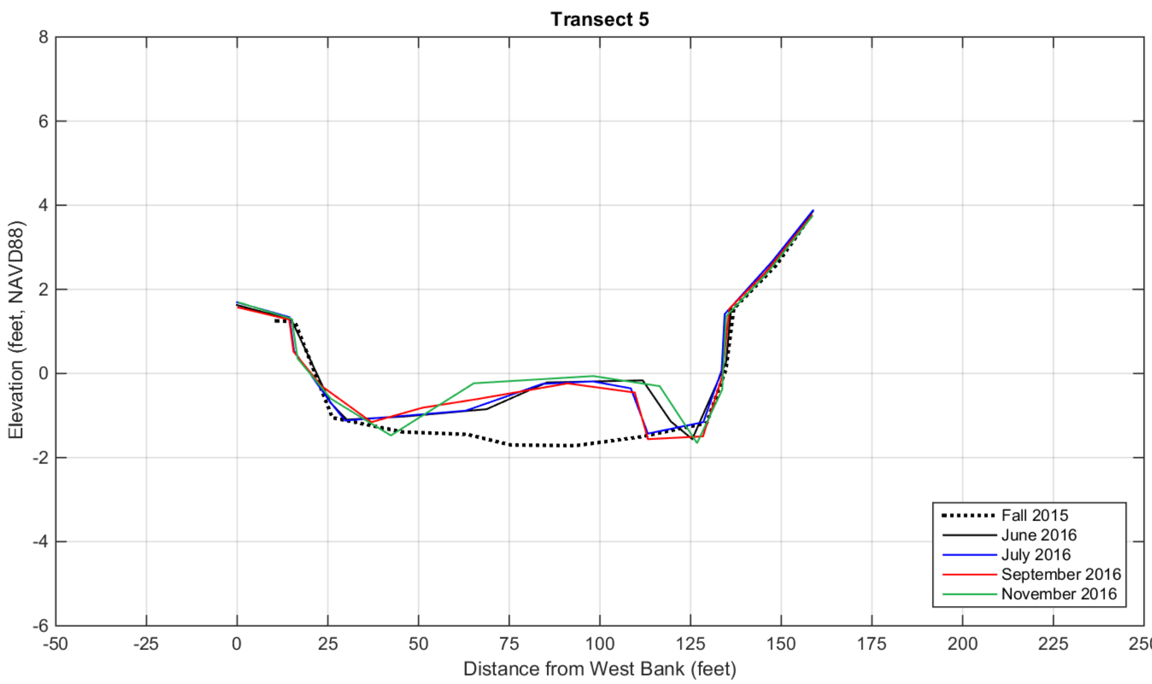

Figure 13. Cross-channel monitoring Transect 5. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

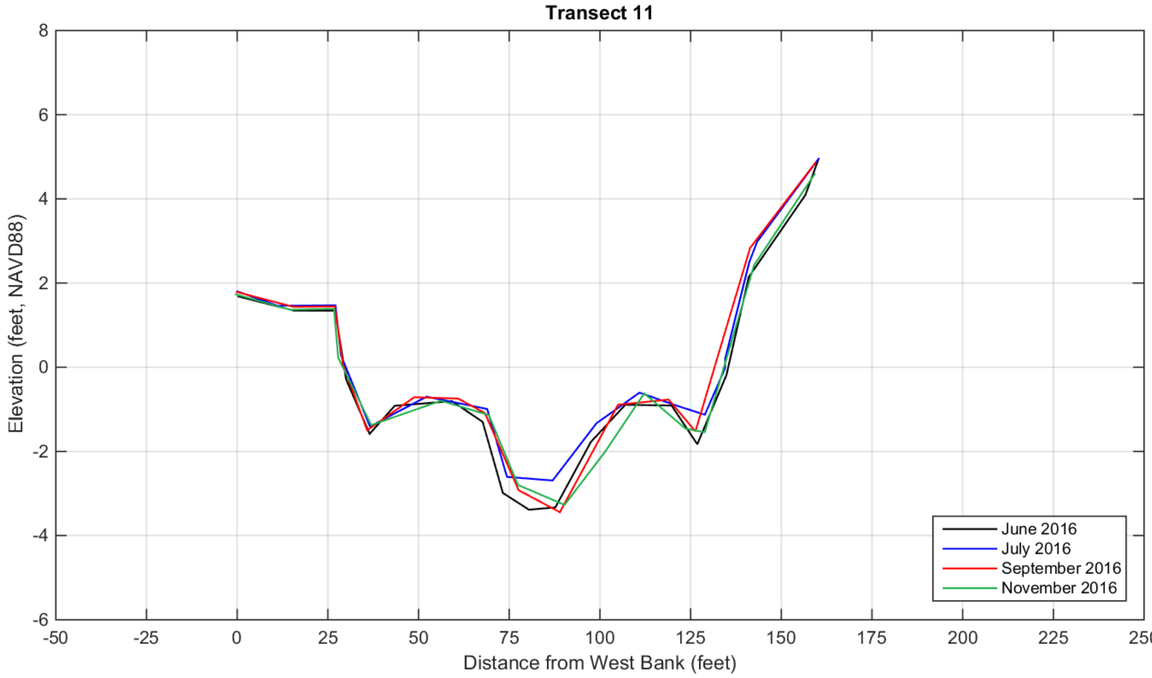

Figure 14. Cross-channel monitoring Transect 11. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

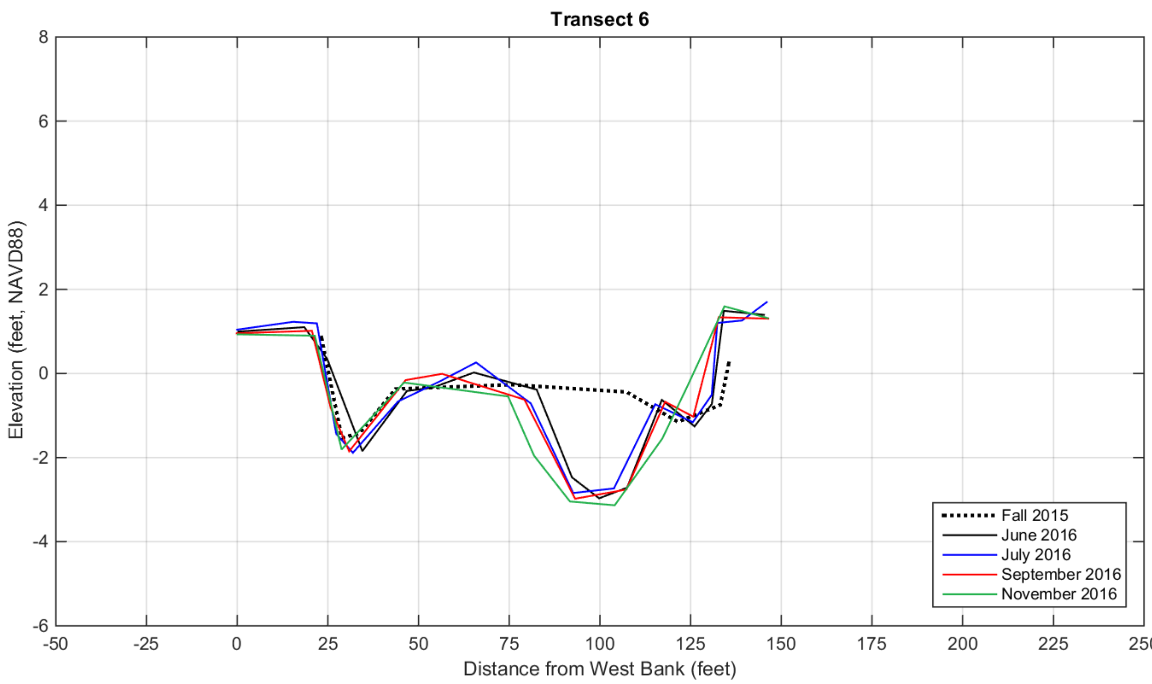

Figure 15. Cross-channel monitoring Transect 6. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

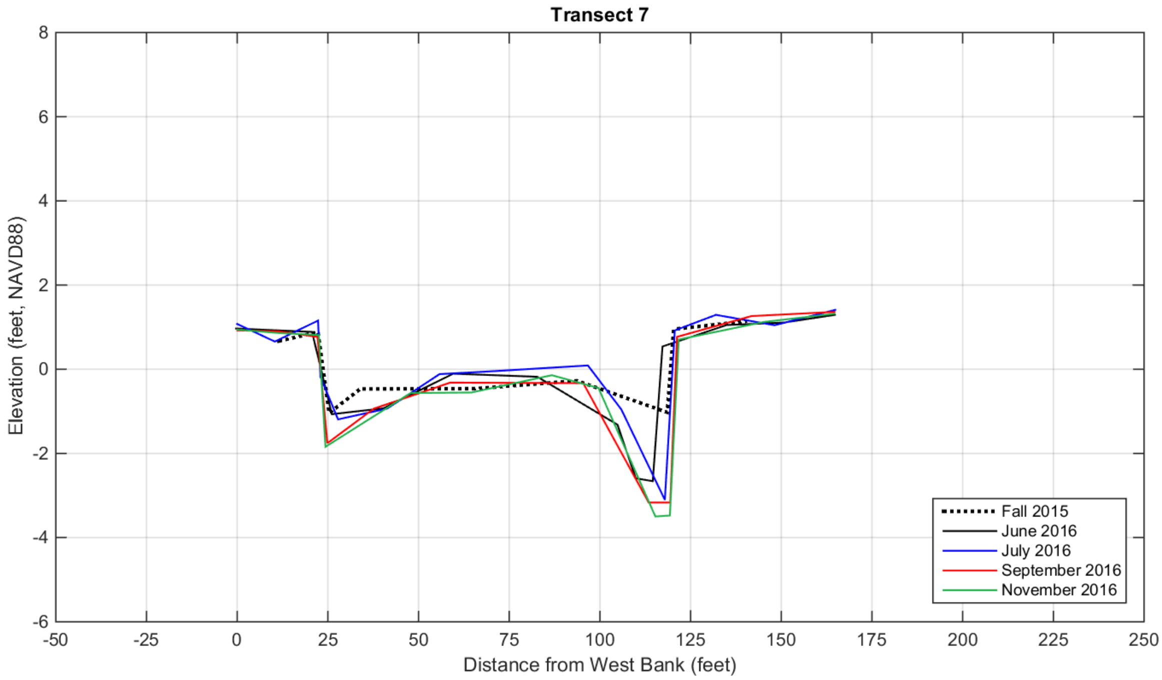

Figure 16. Cross-channel monitoring Transect 7. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

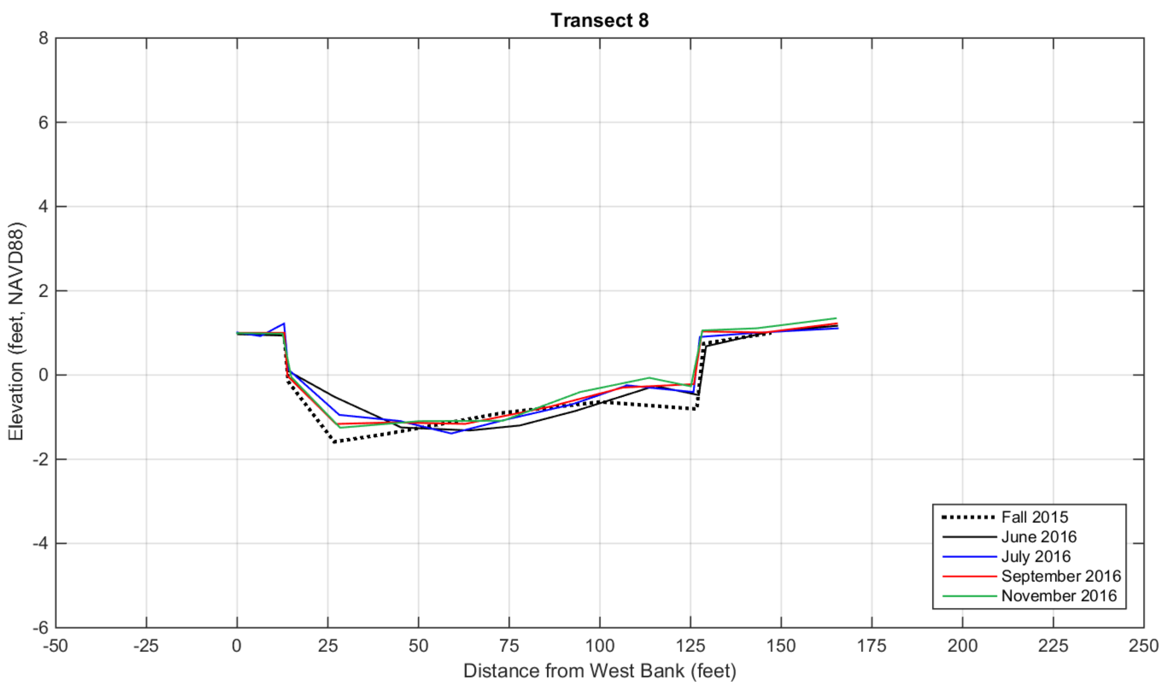

Figure 17. Cross-channel monitoring Transect 8. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

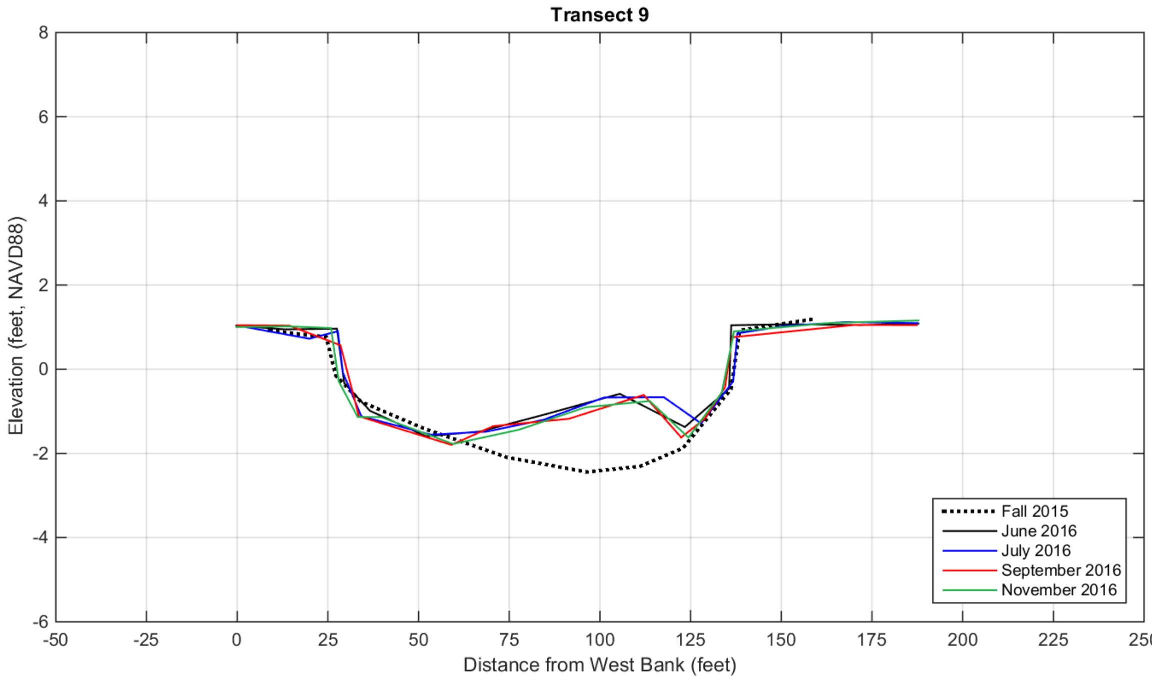

Figure 18. Cross-channel monitoring Transect 9. Distance are relative to the West Channel Bank and datum elevations are given relative to NAVD88.

4. Tidal Monitoring

Tide data was collected upstream and downstream of the bridge for a 34-day period beginning June 22, 2016 and ending on July 26, 2016. Temperature Depth Recorders (TDR) were used to record tide data at two stations: 1) offshore of Muddy Creek in Pleasant Bay, the gage was located at the Wequassett Resort attached to a wooden pier along the main dock that extends into Pleasant Bay (downstream), and 2) west of Route 28 bridge, in the main body of Muddy Creek (upstream). The tide gage locations were selected to correspond historic gaging locations to allow for comparisons of the datasets. The locations of the two gage stations are shown in Figure 19.

The tide gauges used for the study were Brancker XR-420 TG. Data recording was set for 10-minute intervals, with each observation resulting from an average of 60 1-second pressure measurements on 10-minute intervals. These instruments use strain gauge transducers to sense variations in pressure, with resolution on the order of 1 cm (0.39 inches) head of water. Each gauge was calibrated prior to installation to assure accuracy.

Once the data were downloaded from each instrument, the water pressure readings were corrected for variations in atmospheric pressure. Hourly atmospheric readings were obtained from the NOAA recording station in Nantucket Sound (site 44020), interpolated to 10-minute intervals, and subtracted from the pressure readings, resulting in water pressure above the instrument. Further, a (constant) water density value of 1025 kg/m^3 was applied to the readings to convert from pressure units (psi) to head units (for example, feet of water above the tide gauge). The elevation of each gauge was surveyed relative to North American Vertical Datum of 1988 (NAVD88) using a RTK-GPS system. The geographic locations of the gages are presented in Table 2 in Massachusetts State Plane Coordinates. The survey information was used to provide vertical rectification of the water level to a known vertical datum. The result from each gauge is a time series representing the variations in water surface elevation relative to NAVD88.

Table 2. Location of the tide gages in the Muddy Creek, Chatham and Harwich, MA. Coordinates are Massachusetts State Plane Coordinates, NAD83 (2011), feet.

Location	Northing (feet)	Easting (feet)
Gage 1 – Pleasant Bay	2,727,152.96	1,067,237.81
Gage 2 – Muddy Creek	2,723,318.20	1,066,842.79

Plots of the tide data are shown in Figure 20, for the 34-day deployment. The spring-to-neap variation in tide can be seen in this plot. Examining the plot shows that offshore the tide reached its maximum spring tide range of approximately 4.8 feet on July 6th. Six days later the neap tide range was smaller, approximately 3.3 feet. A visual comparison of the two gage records in Figure 21, shows that there is a reduction in the tide range as the tide propagates from Pleasant Bay into Muddy Creek. The loss of amplitude with distance from the inlet channel through the bridge is described as tidal attenuation. Frictional mechanisms dissipate tidal flow energy, resulting in a reduction of the height of the tide. Tide attenuation is accompanied by a time delay (or phase lag) in the time of high and low tide (relative to the offshore tide). The lag can be visually observed on the flood and ebb tide between Pleasant Bay and Muddy Creek as shown in Figure 21.

Standard tide datums were computed from the 34-day records. These datums are presented in Table 3. For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data was available; however, these datums still provide a useful comparison of tidal dynamics within the system. The Mean Higher High (MHHW) and Mean Lower Low (MLLW) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW.

As the tide propagates from the Atlantic Ocean into and through Pleasant Bay and then into Muddy Creek attenuation of the tide occurs. This is observed as a reduction in the tide range and also as a delay in the time of high and low tide during each tide cycle. The tides in Pleasant Bay and Muddy Creek, are semi-diurnal, meaning there are typically two tide cycles in a day. There is usually a small variation in the level of the two daily tides. This variation can be seen in the differences between the MHHW and MHW, as well as the MLLW and MLW levels.

Table 3. 2016 Tide datums computed from the 34-day tide records collected at Muddy Creek, Chatham and Harwich, MA. Datum elevations are given relative to NAVD88.

Tide Datum	Gage 1 – Pleasant Bay	Gage 2 – Muddy Creek
Maximum Tide	3.7	3.4
MHHW	2.9	2.6
MHW	2.5	2.2
MTL	0.6	1.1
MLW	-1.2	-0.1
MLLW	-1.3	-0.1
Minimum Tide	-1.5	-0.3
Mean Range (MHW to MLW)	3.7	2.3
Peak Range (MHHW to MLLW)	4.2	2.7

To examine the influence the recently constructed Route 28 Bridge has had on the tides entering and exiting Muddy Creek, the tide datums from the 2009 study which examined various opening alternatives for Muddy Creek are presented in Table 4. The 2009 tidal signal within Pleasant Bay had a slightly larger amplitude range relative to the 2016 dataset. The changes in tidal amplitude are due to differences in tidal forcing over the short monitoring periods, transformation and evolution of the tidal inlets into Pleasant Bay from the Atlantic Ocean, and variability in meteorological forcing over the monitoring periods. The key difference upstream of the Route 28 causeway is the significant increase in tidal amplitude from 2009 to 2016. The mean tidal range went from 0.5 feet in 2009 to 2.3 feet in 2016. Which is a 1.8-foot increase in mean tidal range (MHW to MLW) and 2.1-foot increase in peak tidal range (MHHW to MLLW) and within Muddy Creek due to the improved channel opening (Table 5). A visual comparison also shows the significant increase in amplitude (height between high and low tide), Figure 21 shows the tidal variations with the new constructed bridge and Figure 22 shows the historic tidal variations with the stone box culverts.

Table 4. 2009 Tide datums for Muddy Creek, Chatham and Harwich, MA. Datum elevations are given relative to NAVD88.

Tide Datum	Gage 1 – Pleasant Bay	Gage 2 – Muddy Creek
Maximum Tide	4.0	2.0
MHHW	3.3	1.6
MHW	3.0	1.5
MTL	0.9	1.3
MLW	-1.2	1.0
MLLW	-1.4	1.0
Minimum Tide	-1.5	0.7
Mean Range (MHW to MLW)	4.2	0.5
Peak Range (MHHW to MLLW)	4.7	0.6

Table 5. Comparison of Mean and Peak tidal ranges.

Location	2009	2016	Difference
Pleasant Bay			
Mean Tidal Range (MHW -MLW)	4.2	3.7	-0.5*
Peak Tidal Range (MHHW -MLLW)	4.7	4.2	-0.5*
Muddy Creek			
Mean Tidal Range (MHW -MLW)	0.5	2.3	1.8
Peak Tidal Range (MHHW -MLLW)	0.6	2.7	2.1

*The decrease in tidal range within Pleasant Bay is attributable to the migration and evolution of the inlets from Atlantic Ocean into Pleasant Bay.

5. Summary

The post construction monitoring indicates the outside of inlet channel bends continue to respond to the new tidal conditions in Muddy Creek. While the overall position of the channel has remained stable since completion of the bridge, there has been minor erosion of the marsh bank on the outside of the channel beds in response to the larger tidal flows. The cross-sectional geometry upstream and downstream of the bridge adjusted quickly to the new tidal conditions, with only minor fluctuations over the monitoring period. It is expected that under daily tidal conditions that channel will continue to remain stable. The areas of marsh bank that have begun to slump into the channel will continue to erode, but further expansion of those erosional areas is not expected under normal tidal conditions. The system has not experienced any significant Nor'easters or coastal storms since the inlet was fully opened. No conclusions can be drawn from the monitoring data at this point on storm induced changes. The channel should be monitored after storm events to provide additional observations and data to evaluate the response of the system.

Upstream of Route 28 the tide range has increased significantly due to the construction of the bridge. The mean tidal range increased from 0.5 feet in 2009 to 2.3 feet in 2016, a 1.8-foot increase in mean tidal range. Examining the tidal datums show that the inlet channel elevations limit extent water levels can drop within the marsh.

Based on the stable channel conditions over the 5-month monitoring period, no significant changes to the tidal conditions within the marsh are expected.

Figure 19. The markers show the locations of the tide recorders deployed for this study.

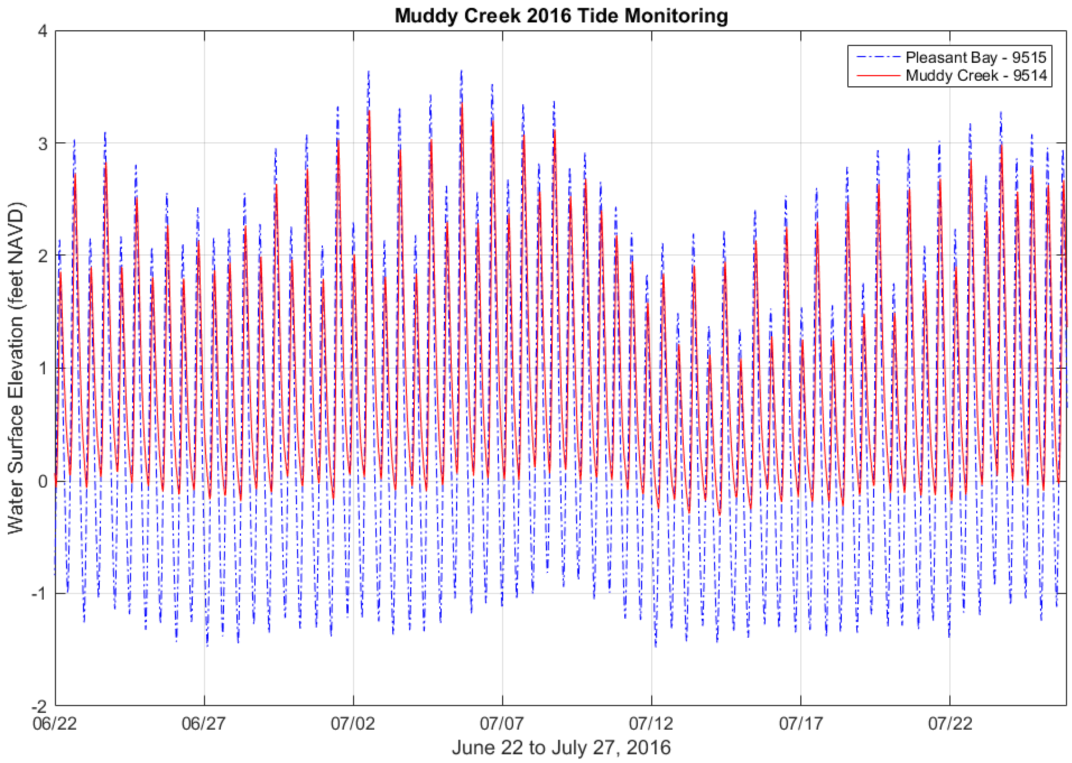

Figure 20. Plots of observed tides for the Muddy Creek, Chatham and Harwich, MA, for the 34-day period between June 1, 2016 and July 16, 2016. The blue line shows tide offshore in Pleasant Bay. The red line shows the tide inside Muddy Creek upstream of the new Route 28 Bridge. All water levels are referenced to the NAVD 88.

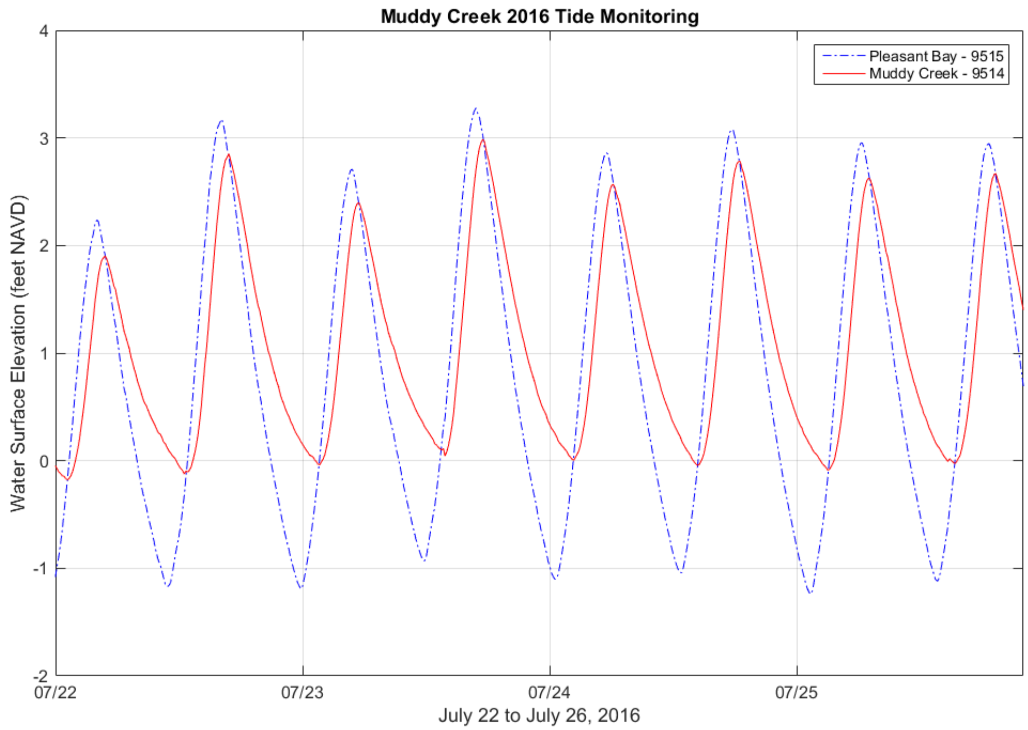

Figure 21. Plot showing three tide cycles in Pleasant Bay and upstream of the new Route 28 Bridge in Muddy Creek.

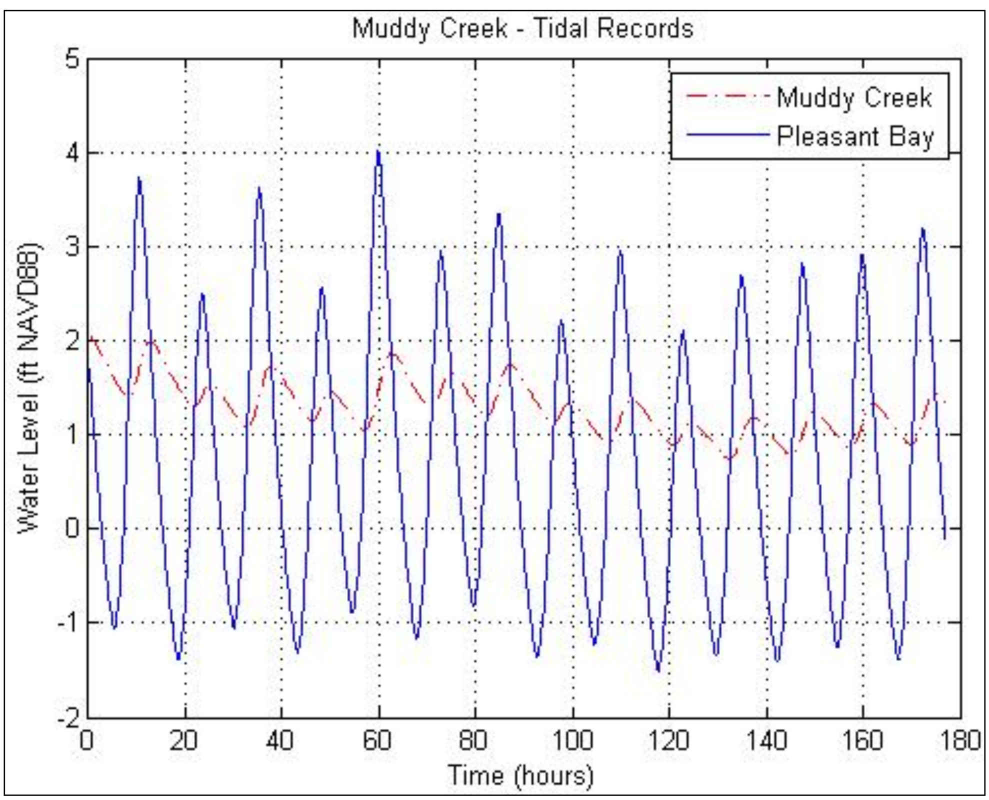

Figure 22. Tide gage records from November 2009 (pre-construction) upstream and downstream of the Route 28 culvert. In 2009, Pleasant Bay was connected to Muddy Creek through a pair of stone box culverts approximately 2.5-feet wide, 3.75-feet in height, and 100-feet in length.