# Weir Creek Restoration
# Dennis, MA
# Hydraulic Study

**July 2024**

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**Table of Contents**

## List of Figures

## List of Tables

## 1.0 EXECUTIVE SUMMARY

Weir Creek is a tidally influenced estuarine system located in Dennis, MA on Cape Cod. The Weir Creek estuary consists of three (3) small ponds connected to Bass River, and ultimately Nantucket Sound, via a network of small streams and anthropogenic stream crossings. The Weir Creek system consists of five (5) subsections: 1) lower Weir Creek which is the section downstream of Loring Avenue and connects to Bass River, 2) Weir Creek which is the section of the system upstream of Loring Avenue, and bounded by Fisk Street, Lighthouse Road, and Lower County Road, 3) Kelley's Pond which is the approximately 28.3-acre pond and channel upstream of Fisk Street, 4) Uncle Stephen's Pond upstream of Lighthouse Road and including the marsh upstream of Lower County Road adjacent to the pond, and 5) Upper Weir Creek defined as the area upstream of Lower County Road to Main Street/MA 28.

At the farthest point from Nantucket Sound in Upper Weir creek, freshwater from groundwater exfiltration and precipitation runoff collects in a small, 0.4-acre, pond, known as Indian Pond, which then flows via a narrow channel towards Lower County Road. Throughout the marsh flats, runoff and groundwater exfiltration collect in a series of small channels and contribute flow to the main Upper Weir Creek channel mixing with salt water tidal flows from downstream in the system creating a brackish salt marsh system. During ebb tides, water passes under Lower County Road via an undersized 24-inch culvert into Weir Creek mixing with water from the Uncle Stephen's Pond and Kelley's Pond subsystems and ultimately under Loring Avenue into Bass River. At both Fisk Street (36-inch culvert) and the eastern Lower County Road crossing (14-inch culvert), groundwater and precipitation runoff experience limited mixing with saline waters upstream of the culverts as a result of undersized culvert connections with Weir Creek.

This study focused on the two (2) stream connections at Lower County Road to minimize tidal dampening, increase drainage and saltwater influx, while mitigating potential upland flooding. Due to the relatively low elevation of Lower County Road (as low as 4 ft-NAVD88), the upper reaches of the system are subject to flooding during low frequency storm events at the 10% Annual Exceedance Probability (AEP) and the roadway has been previously identified in the 2021 Cape Cod Commission Low Lying Roads project as it is subject to overtopping during coastal events.

To assess the existing hydrodynamics of the Weir Creek system, a numerical model was developed using the Environmental Fluid Dynamics Code (EFDC) to simulate existing conditions and to evaluate a suite of culvert replacement alternatives at both Lower County Road crossings including box culverts ranging from 2ft by 6 ft (width by height) up to 18 ft by 6 ft in four (4) foot increments as well as a "maximum improvement" alternative including channel deepening and widening throughout the system, dredge removal of the large flood shoal immediately upstream of Loring Avenue (shown in Figure 1) and widened openings at both Loring Avenue and Lighthouse Road. The roadway elevation of Lower County Road was raised to 6.5 ft-NAVD88 for all alternatives to prevent roadway overtopping during more frequent (higher AEP) events with no changes to bathymetry except in the "maximum improvement" scenario. Using tidal range as the primary selection metric, an 8 ft by 6 ft box culvert was selected as the preferred alternative as improvements to tidal exchange are incremental without major changes to the entire system while allowing for sufficient drainage following inundation events.

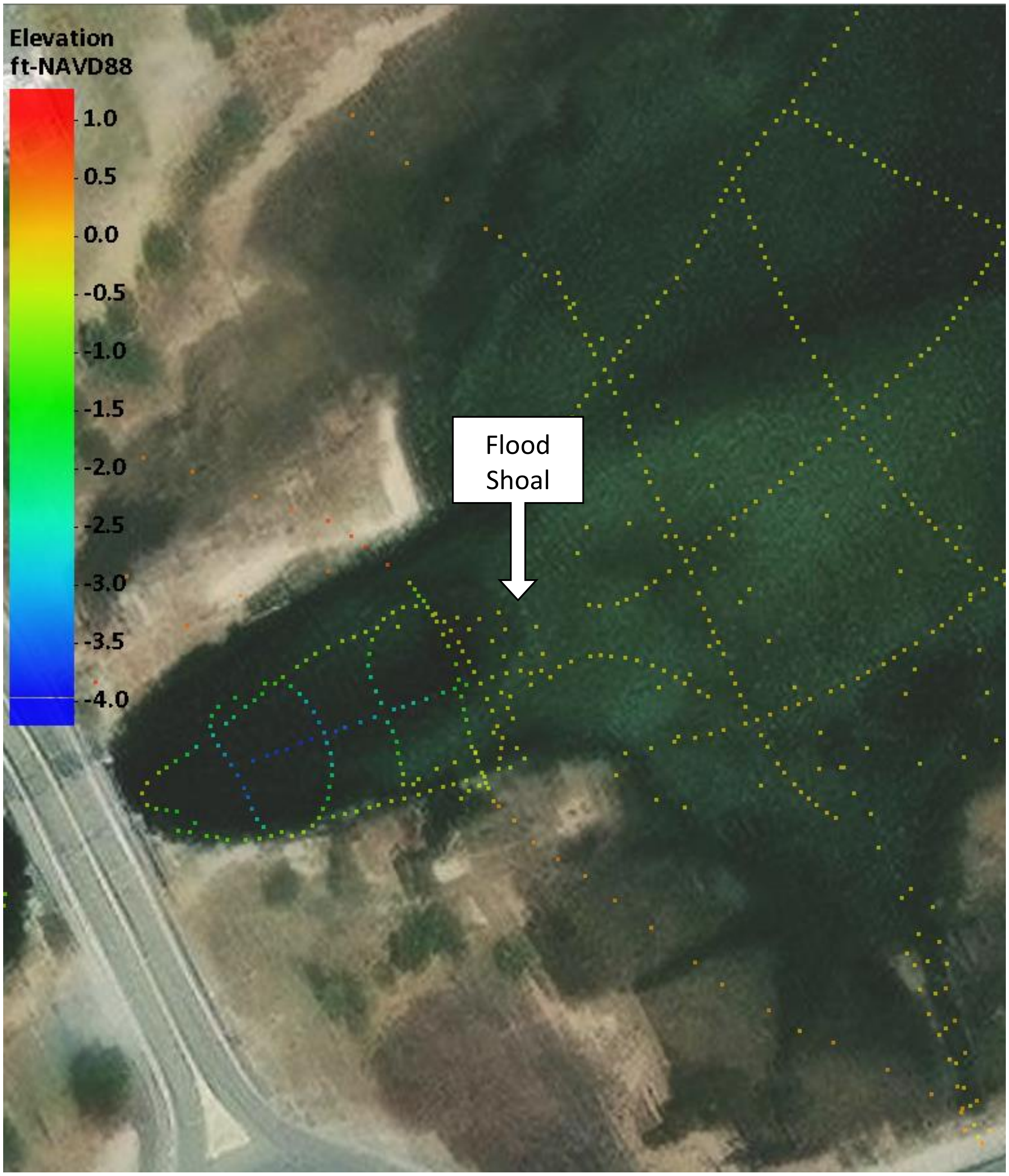


**Figure 1. Bathymetry and aerial imagery at Loring Avenue showing the presence of the large flood shoal limiting drainage of upstream reaches.**

## 2.0 PROJECT DESCRIPTION

Weir Creek is a 200-acre estuarine system comprised of three (3) small ponds and a network of channels, both natural and anthropogenic, connecting the headwaters of the system to Bass River. There are five (5) stream crossings in the estuary: 1) a bridge at Loring Avenue at the downstream section of the system, 2) a 36-inch pipe culvert under Fisk Street providing a hydraulic connection to Kelley's Pond, 3) a 24-inch pipe culvert connecting the western arm of Weir Creek under Lower County Road to the lower section of Weir Creek, 4) a bridge crossing under Lighthouse Road connecting Uncle Stephen's Pond to Weir Creek, and 5) a 14-inch pipe culvert under Lower County Road providing drainage to the smaller, eastern section of the salt marsh to Uncle Stephen's Pond via maintained mosquito control ditches.

In Weir Creek, the three (3) hydraulic connections with culvert structures are undersized and limit the free exchange of salt water from Bass River into the upper sections of the system resulting in habitat evolving from the natural salt marsh ecosystem into a more freshwater marsh system. The Kelley's Pond culvert connection under Fisk Street was replaced in 2016 and was not evaluated for improvement at this time, although the collected field data indicate that there is tidal dampening as a result of the current structure with the study primarily focused on optimizing the two (2) connections at Lower County Road. In order to assess the potential alternatives, the Environmental Fluid Dynamics Code-Weir Creek (EFDC-WC) model was developed using data collected for this project (discussed in Section 3) to evaluate an array of alternatives to optimize restoration while mitigating potential inundation impacts to upstream properties.

## 3.0 DATA COLLECTION

The initial phase of the study included field data collection throughout the Weir Creek estuarine system. Field data collection was conducted for three (3) overarching purposes: 1) to gain an understanding of the hydraulic characteristics in the system as currently configured, 2) to provide an accurate representation of the topography and bathymetry in the system, and 3) to provide information to develop the EFDC-WC model domain and boundary conditions. The field effort consisted of the collection of water level, salinity and temperature data, bathymetry data, and an elevation survey of the marsh surface/hydraulic structures.

### 3.1 WATER COLUMN MEASUREMENTS

Woods Hole Group installed ten (10) tide gauges in the Weir Creek, Kelley's Pond, and Uncle Stephen's Pond systems to examine the existing hydrodynamics, as well as to inform modelling efforts. The stations were located up- and downstream of Loring Ave., Fisk Street, Lower Country Road at Weir Creek (western crossing), Lower Country Road at Uncle Stephen's Pond (eastern crossing), and upstream in Weir Creek, north of Regan Rd. Locations for each of the ten (10) locations are listed in Table 1 and shown in Figure 2.

**Table 1. Tide Gauge locations for the Weir Creek Restoration Project**

| Station | Latitude | Longitude |
|---|---|---|
| WC1 | 41.652818 | 70.173961 |
| WC2 | 41.653071 | 70.172746 |
| WC3 | 41.656278 | 70.168377 |
| WC4 | 41.654322 | 70.169522 |
| WC5 | 41.655707 | 70.166262 |
| WC6 | 41.655863 | 70.166068 |
| WC7 | 41.656506 | 70.168124 |
| WC8 | 41.656359 | 70.173313 |
| WC9 | 41.657946 | 70.175804 |
| WC10 | 41.662461 | 70.164334 |

At each tide gauge station, an In-Situ AquaTroll 200 (AT-200) was deployed measuring temperature, conductivity, and absolute pressure. Gauges were deployed on June 8$^{th}$ and 9$^{th}$, 2023 and recovered on July 18$^{th}$ and 19$^{th}$, 2023, for a total deployment period of 39 days. Additionally, an Onset HOBO pressure sensor was installed in the area to capture site-specific atmospheric pressure to be used in converting total pressure to location specific water surface elevation. All instruments were surveyed upon installation and recovery with a Trimble R8 RTK GPS to provide an instrument elevation relative to the vertical datum NAVD88. Total pressure measured by each AT-200 were adjusted to remove local atmospheric pressure to calculate the height of the water column measured at each location. Surveyed sensor elevation data were used to render the pressure data to water surface elevation relative to NAVD88 from the water column height. On recovery, stations WC6 and WC10 were found to be buried in approximately an inch of light/soft mud. While this impacted some of the salinity data, the pressure record was unaffected. Correlating precipitation data for the 39-day deployment period were acquired from Hyannis Airport (HYA).


**Figure 2.** **Tide gauge locations in the Weir Creek, Kelley's Pond, and Uncle Stephen's Pond systems. Three culverts are in the system located next to stations WC8 under Fisk Street, WC3 and WC7 under Lower County Road.**

### 3.1.1 Methodology

To calculate water level for the tide gauges, barometric pressure was subtracted from the instrument's absolute pressure record. A site-specific barometric pressure record was collected using an Onset HOBO. Upon removing barometric pressure from the absolute pressure records and applying an equation of state for seawater the remaining pressure records are representative of the height of water (distance) above the pressure gauge. The height of water was then converted to water surface elevation using the surveyed elevation of each station.

The time series of water surface elevation (NAVD88 feet) at each station was analyzed to produce the primary tidal constituents and tidal datums for each record. The tidal datums calculated include Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Tide Level (MTL), Mean Low Water (MLW), and Mean Lower Low Water (MLLW). The mean tide range was calculated as the difference between MHW and MLW at each station. Tidal benchmarks were calculated using the 39-day record during equipment deployment and are not comparable to standard NOAA tidal benchmarks, which are computed over a 19-year tidal epoch. Calculated tidal datums at each station are listed in Table 2.

**Table 2. Tidal datums at each tide gauge station in feet-NAVD88.**

| | WC1 | WC2 | WC3 | WC4 | WC5 | WC6 | WC7 | WC8 | WC9 | WC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | Loring Avenue (DS) | Loring Avenue (US) | Lower County Road (West, DS) | Lighthouse Avenue | Lower County Road (East, DS) | Lower County Road (East, US) | Lower County Road (West, US) | Fisk Street (DS) | Fisk Street (US) | Upper Reach: Weir Creek |
| MHHW | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 1.8 | 1.5 | 2.4 | 1.5 | 1.3 |
| MHW | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 1.7 | 1.4 | 2.0 | 1.4 | 1.3 |
| MTL | 0.4 | 0.8 | 0.9 | 0.9 | 1.3 | 1.2 | 0.8 | 0.9 | 1.3 | 1.2 |
| MLW | -1.3 | -0.3 | -0.2 | -0.2 | 0.6 | 0.7 | 0.2 | -0.3 | 1.2 | 1.1 |
| MLLW | -1.6 | -0.4 | -0.3 | -0.3 | 0.5 | 0.7 | 0.1 | -0.3 | 1.1 | 1.1 |
| Mean Tide Range (ft) | 3.3 | 2.3 | 2.3 | 2.2 | 1.4 | 0.9 | 1.2 | 2.3 | 0.3 | 0.1 |

### 3.1.2 Results

For the purposes of this study, the area was divided into four (4) sub-basins: 1) Lower Weir Creek including the area immediately downstream of Loring Avenue and the marsh flats bounded by Fisk Street, Lower County Road (western section), and Lighthouse Road, 2) Kelley's Pond, 3) Upper Weir Creek including the marsh flats upstream of the western Lower County Road crossing, and 4) Uncle Stephen's Pond. Site-specific precipitation data was not collected, however the nearby Hyannis Airport (HYA) weather station provides a nearly collocated estimate of precipitation, specifically useful when comparing changes in salinity in each of the sub-basins. Precipitation data is shown in on Figure 3 with more notable rainfall events occurring on June 16th, June 27th, and July 1st, 2023.

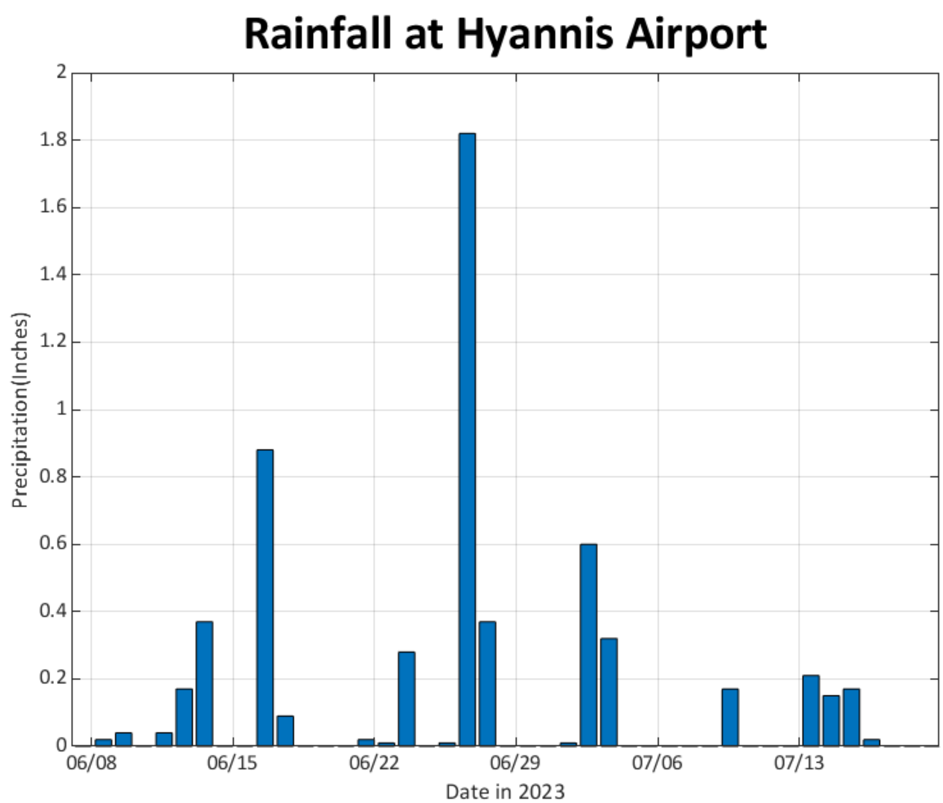


**Figure 3. Precipitation at Hyannis Airport during the 39-day tide gauge deployment period.**

#### *3.1.2.1 Lower Weir Creek Sub-Basin*

The Lower Weir Creek sub-basin measurements were collected at stations WC1, and WC2 bracketing Loring Avenue, station WC3 located at the downstream side of the western Lower

County Road stream crossing, station WC4 at Lighthouse Road, and station WC8 located on the downstream side of the Fisk Street crossing. Figure 4 shows the complete time series of water surface elevations for each of the four (4) gauges in the Lower Weir Creek sub-system. There is minimal phase lag (time delay) between the outermost gauge, WC1 shown in blue, with the other three gauges. Station WC2, shown in cyan, is located upstream of both the Loring Avenue bridge and the large flood shoal which acts as a hindrance during ebb, or outward, flows resulting in higher low tides indicating the upper reaches are effectively perched as a result of shoaling with a reduction in tide range from 3.3 feet at WC1 to 2.3 feet at station WC2. At the other three (3) stations located upstream of the Loring Avenue bridge, there is minimal attenuation of water levels during ebb tides indicating the flood shoal is the primary restriction in the system. The presence of a flood shoal and a deep scour pit on each side of the Loring Avenue bridge indicate that the bridge opening is too small relative to the tidal flows and drainage improvements to the system overall could be realized at this downstream crossing.

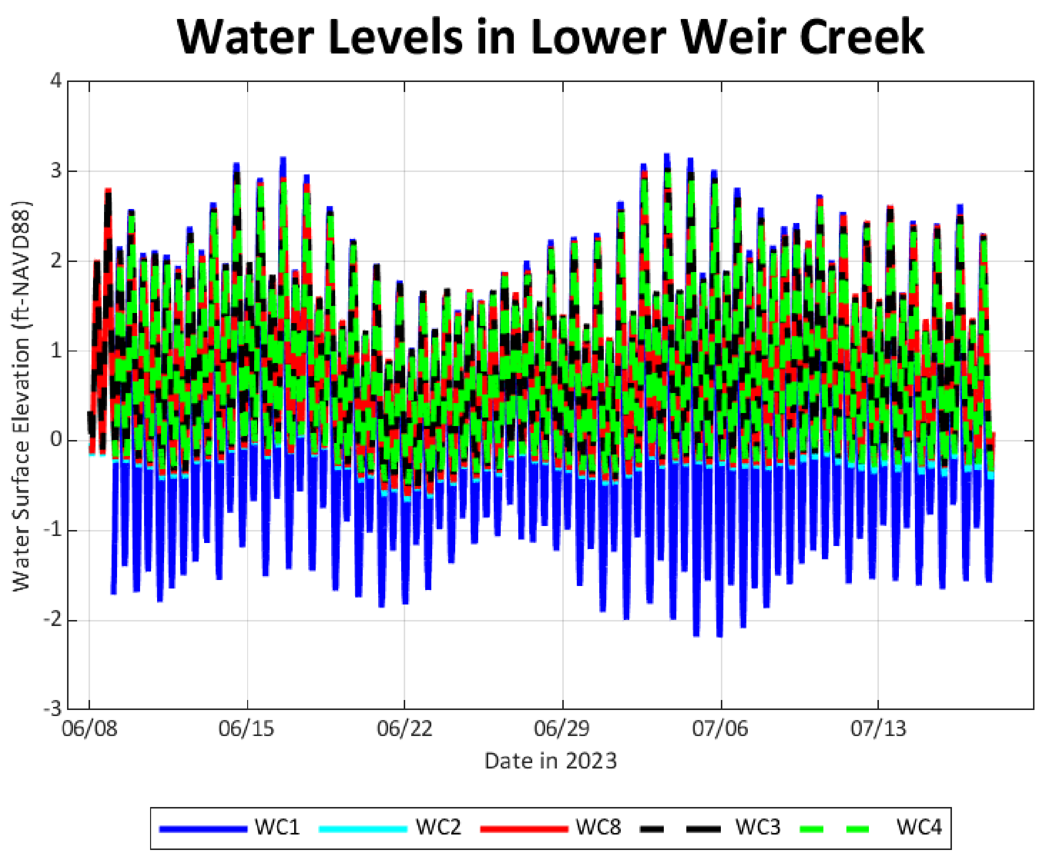


**Figure 4. Time-series of water surface elevation in the Lower Weir Creek sub-system at stations WC1, WC2, WC3,WC8, and WC4.**

Figure 5 shows the measured salinities throughout the Lower Weir Creek subsystem during the 39-day deployment period. At the farthest downstream station, WC1 shown in blue, salinity varies with tidal flows, increasing to approximately 30 PSU during incoming flood tides and lowering to the mid- to high 20s during ebb events as lower saline water from upstream mixes with the waters near the bridge. This same behavior, increasing to approximately 30PSU during flood tides and lowering during ebb tides, can be seen throughout the system with more pronounced effects at the shallowest station, WC3 at the western Lower County Road crossing. The effects of the increased freshwater runoff from the precipitation events at the end of June are visible in all of the signals, with the largest reduction at station WC2 (cyan) occurring shortly after the rainfall event recorded at the Hyannis airport on June 27th.

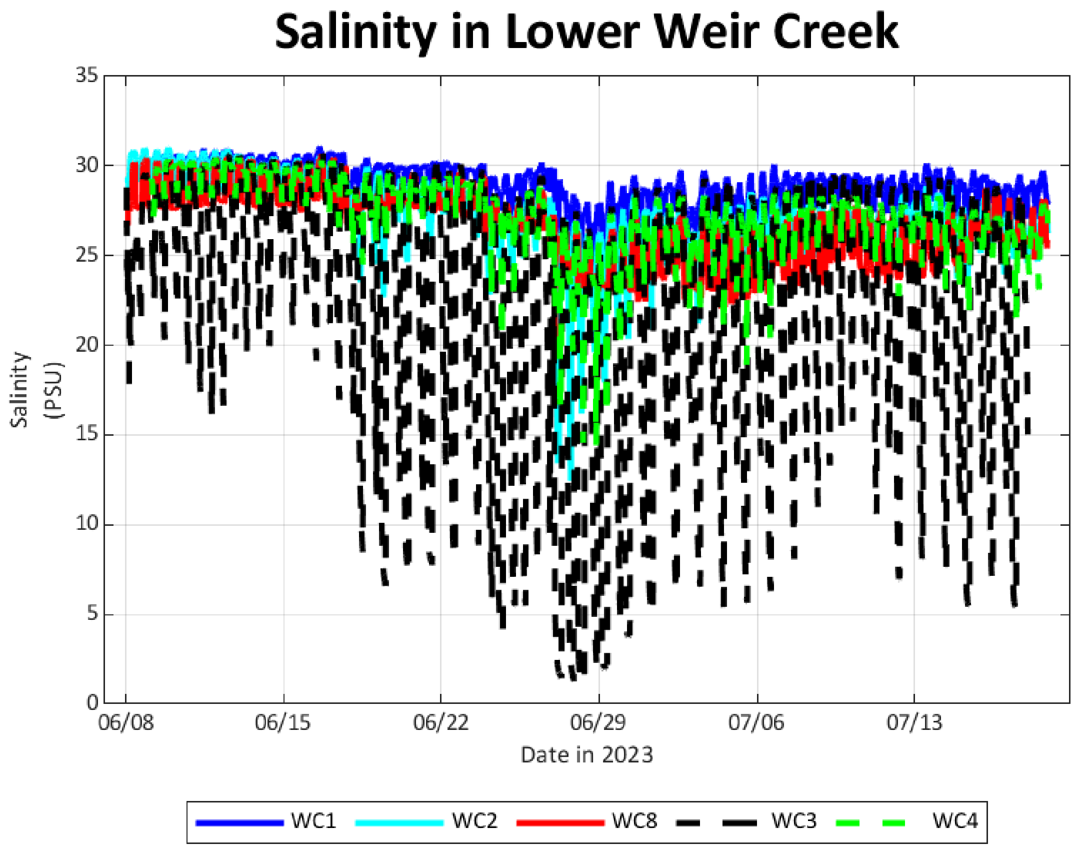


**Figure 5. Time-series of salinity in the Weir Creek system, stations WC1, WC2, WC8, WC7, and WC10.**

#### *3.1.2.2 Kelley's Pond Sub-Basin*

Kelley's Pond sub-basin is located in the northwestern section of the study area and is characterized as a deep pond (relative to the marsh flats in other sections of the system). It is hydraulically connected to Lower Weir Creek by a natural channel and a three-ft concrete pipe culvert under Fisk Street. Observed water levels in Kelley's Pond (dashed cyan line) and just downstream of the Fisk Street culvert (red line) are shown on Figure 6 with observations from WC1 shown in blue for comparison. There is significant tidal dampening across the Fisk Street crossing evidenced by a reduction in the peak water levels at station WC9 as well as higher low tides during ebb flows as a result of the undersized culvert and the large surface area of the pond relative to flows conveyed through the culvert. The mean tide range in Kelley's Pond was calculated to be 0.3 ft while the downstream range at station WC8 was calculated to be 2.3 feet.

As observed at the Loring Avenue Crossing, there is a deep scour hole on both sides of the Fisk Street culvert caused by localized accelerations as the tidal flows are forced through the undersized culvert.

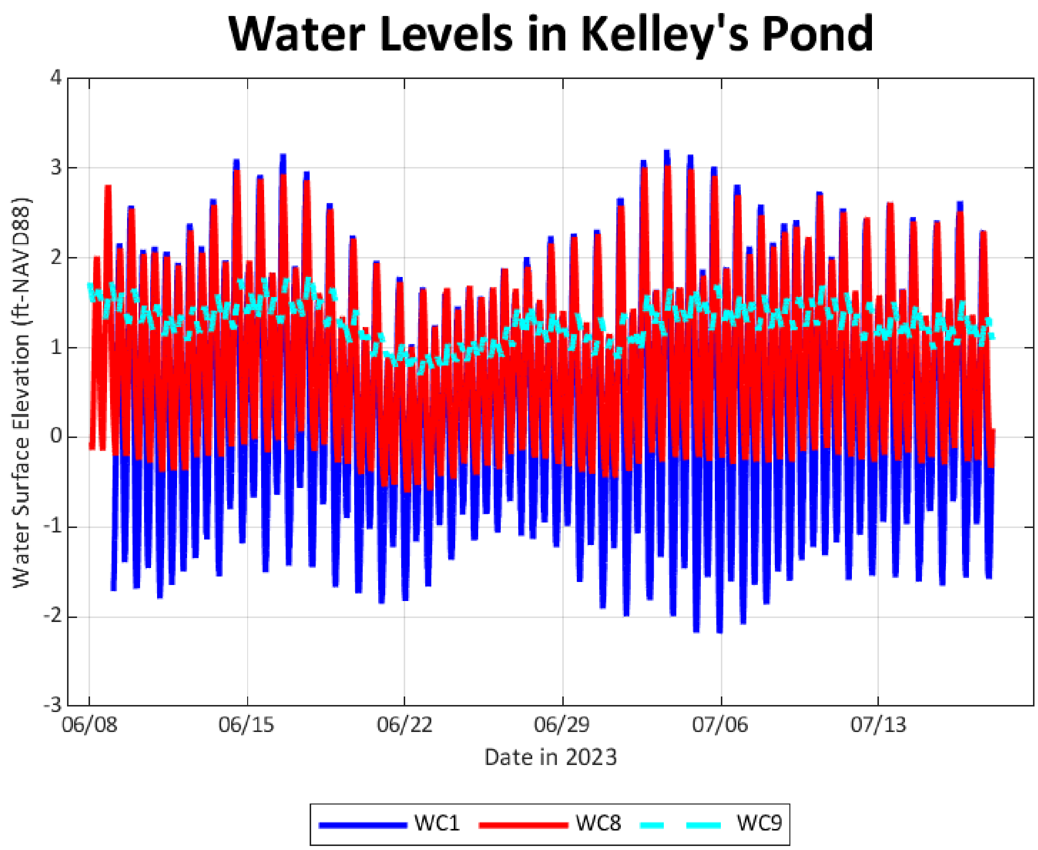


**Figure 6.** **Time-series of water surface elevation in the Kelley's Pond subsystem, stations WC8 (red), and WC9 (dashed cyan) relative to the open boundary at WC1 (blue).**

Figure 7 shows the measured salinities in the Kelley's Pond subsystem on the upstream side of Fisk Street in Kelley's Pond (WC9 in cyan) and downstream in Lower Weir Creek at station WC8 in red. Also shown on Figure 7 is station WC1 in blue for comparison. In Kelley's Pond, the reduced conveyance of the undersized culvert results in minor fluctuation in salinity compared to the measurements downstream. Following rainfall events, like the one on June 27th, the salinity in Kelley's Pond experiences a sharp decline as rainfall and precipitation runoff collects in the pond. During ebb flows, the fresher waters in the pond result in lower salinities at station WC8 while the saline tidal flows from WC1 cause the salinity to rise during flood tides. As a result of the large volume of the pond combined with the restricted conveyance of the culvert, salinity in Kelley's Pond slowly rises to the pre-rainfall event level over the remainder of the deployment.

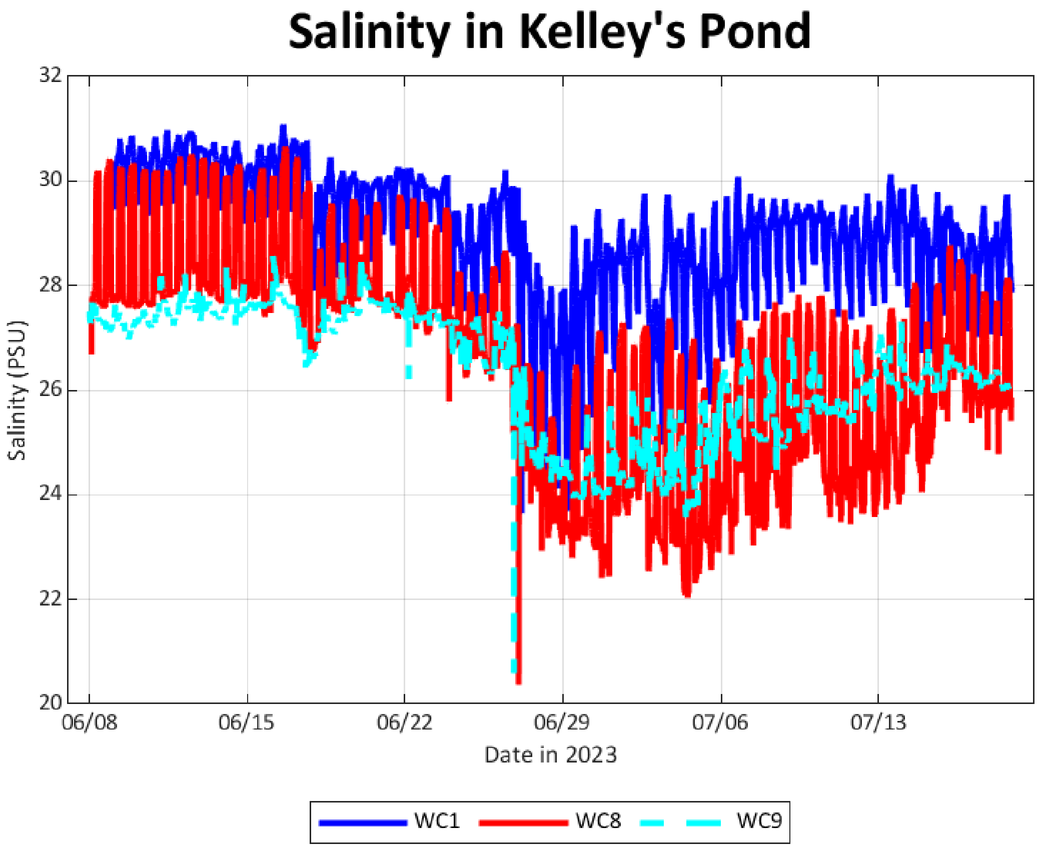


**Figure 7. Time-series of salinities in the Kelley's Pond subsystem, stations WC8 (red), and WC9 (dashed cyan) relative to the open boundary at WC1 (blue).**

*3.1.2.3 Upper Weir Creek Sub-Basin*

The Upper Weir Creek subsystem includes stations WC3 and WC7 which are downstream and upstream of the western Lower County Road crossing and station WC10 located further upstream in the channel of the marsh flats. Figure 8 shows the time series of water surface elevations in the Upper Weir Creek subsystem with the water levels measured at WC1, shown in blue, as reference. During flood tides, water levels on each side of Lower County Road, shown in black for the downstream WC3 station and in magenta for the upstream WC7 station, show the attenuation across the culvert with the higher tides being more significantly reduced by the undersized culvert. During low tides, however, the water levels are slightly higher upstream indicating potential perching of water levels due to the culvert invert. The precipitation event on the 27$^{th}$ of June indicates the culvert provides insufficient drainage for runoff. Farther upstream at station WC10, the high tides are further reduced from WC7 indicating minor dampening occurs within the upstream system while the low tides are significantly higher indicating additional restrictions exist upstream of the roadway. The overall tide range at WC10 is reduced to 0.1 feet from the range at WC7 (1.2 feet) and the open channel at WC1 (2.3 feet).

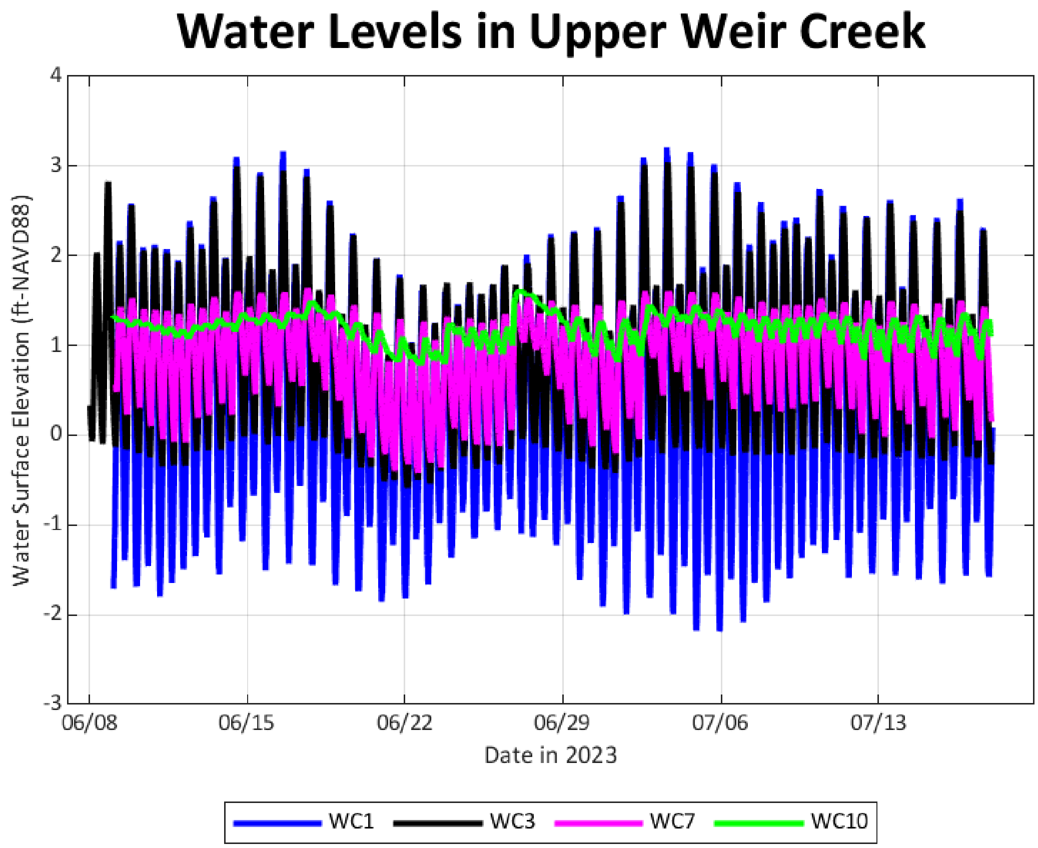


**Figure 8.** **Time-series of water surface elevation in the Upper Weir Creek subsystem, stations WC3 (black), WC7 (magenta) and WC10 (green) relative to the open boundary at WC1 (blue).**

Figure 9 shows the observed salinities in the Upper Weir Creek subsystem for the 39-day deployment. Freshwater flows from groundwater and precipitation result in significant changes in salinity on the upstream side of the Lower County Road crossing (magenta) while the effects of the salinity in the lower system offset the fluctuations at the downstream side (shown in black at WC3). It was noted during tide gauge recovery that station WC10 was covered in a thin deposit of fine sediment from in the uppermost section of Weir Creek which may have affected the salinity signal, shown in green on the figure, however the presence of freshwater shows consistently lower salinities indicating that saltwater has limited penetration into the uppermost reaches of Weir Creek. Following the rainfall event on June 27th, salinity in the upper reaches is nearly 0 PSU indicating the contribution of precipitation runoff is much greater than tidal inflows through the culvert at Lower County Road.

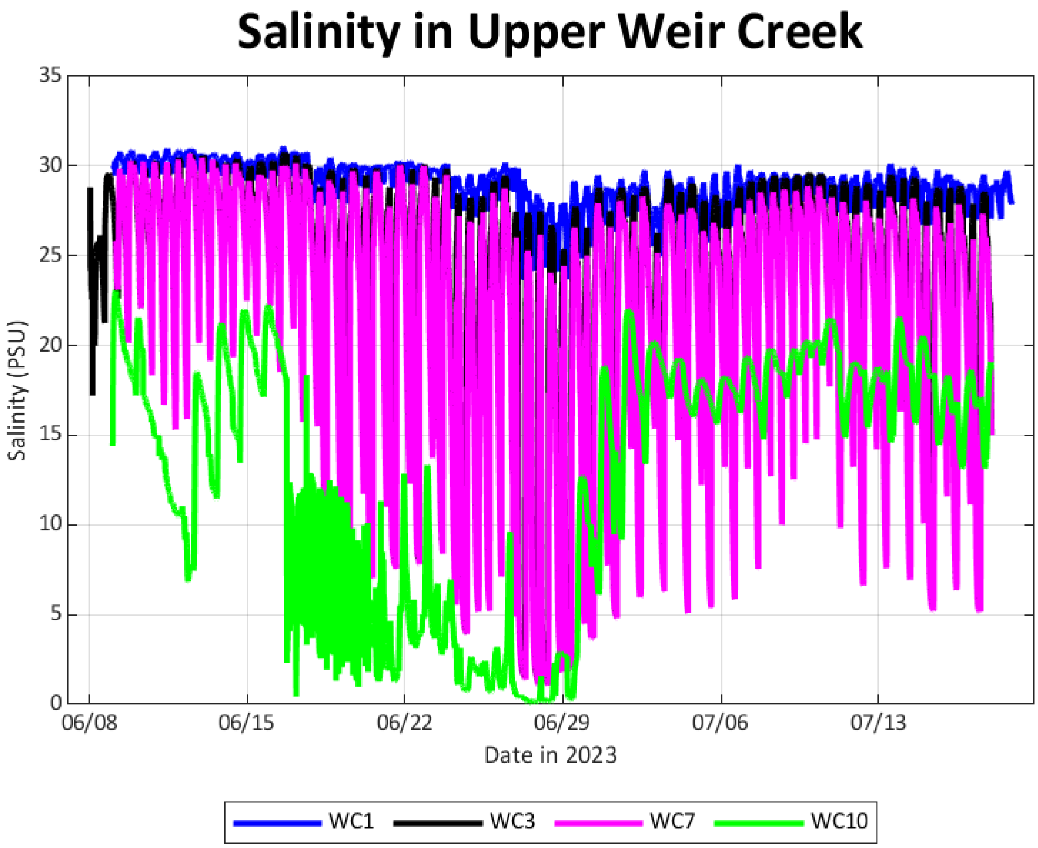


**Figure 9. Time-series of salinities in the Upper Weir Creek subsystem, stations WC3 (black), WC7 (magenta) and WC10 (green) relative to the open boundary at WC1 (blue).**

### 3.1.2.4 Uncle Stephen's Pond Sub-Basin

The last sub-basin in the Weir Creek study area is the Uncle Stephen's Pond subsystem which includes station WC4 upstream of Lighthouse Road and station WC5 and WC6 at the downstream and upstream sides of the eastern Lower County Road stream crossing. Figure 10 shows the observed water levels in the Uncle Stephen's Pond section of Weir Creek with station WC4 shown as a dashed green line, WC5 shown as a dashed red line, and station WC6 shown in yellow. Also on the figure is station WC1 in blue to provide an indication of tidal attenuation to Uncle Stephen's Pond. At Lighthouse Road (dashed green) the primary reduction in tidal exchange occurs during low tides as a result of shoaling upstream of Loring Avenue. Moving upstream in to the system, flood tides at station WC5 downstream of Lower County Road are similar to those at WC4, however the relatively narrow and shallow mosquito ditch leading to the stream crossing results in water levels being perched at station WC5. Upstream of Lower County Road at WC6, the high tide elevations are further reduced and the low tides are slightly higher than at WC5. Overall, the mean tidal range is reduced from 2.3 feet at WC1 down to 1.4 feet at WC5 (downstream of Lower County Road) and then to 0.9 feet upstream of the roadway.

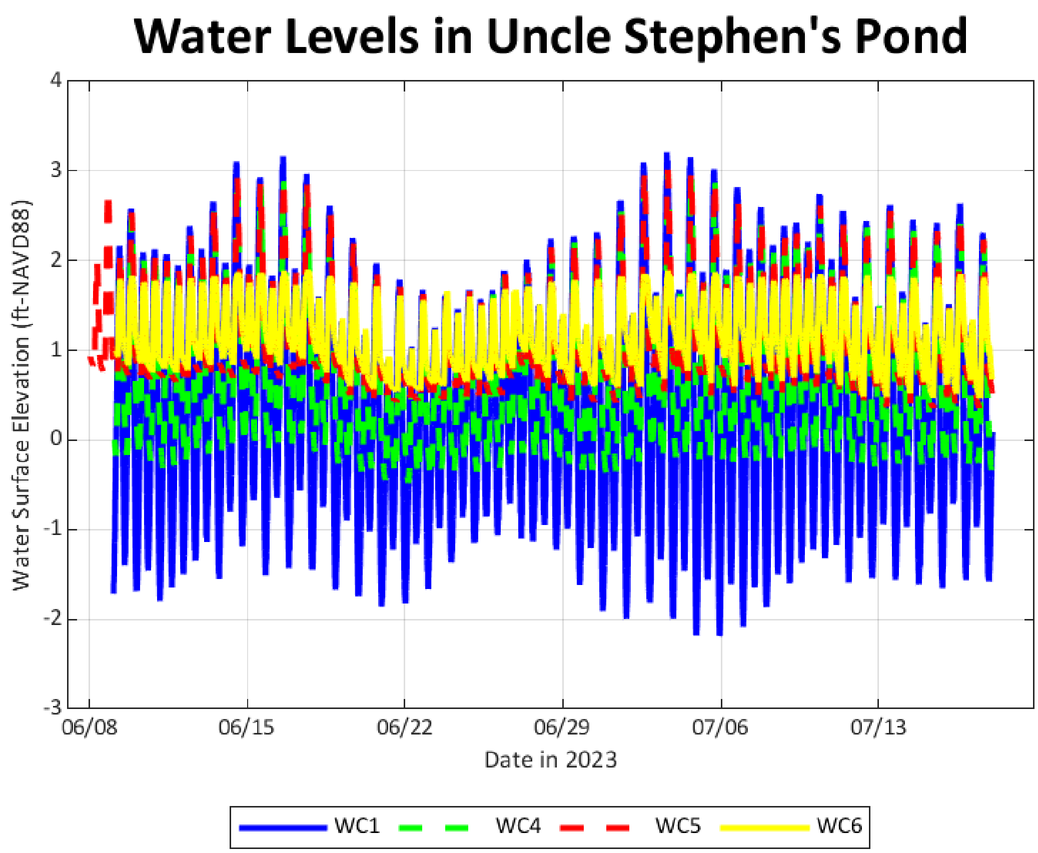


**Figure 10. Time-series of water surface elevation in the Uncle Stephen's Pond subsystem, stations WC4 (dashed green), WC5 (dashed red) and WC9 (yellow) relative to the open boundary at WC1 (blue).**

Salinity measurements in the Uncle Stephen's Pond sub-basin are shown on Figure 11 using the same color schematization as in the previous section. At station WC6, on the upstream side of the eastern Lower County Road crossing, it was noted during equipment recovery that the gauge was covered in a thin layer of fine sediments which may have caused some interference in the salinity signal however the other two (2) stations did not have the same sedimentation issue. Tidal fluctuations in salinity are visible in all of the stations, with stations WC5 and WC6, located in the shallowest and farthest upstream sections of the subbasin, showing the greatest influence of freshwater inflows. During and just after the June 27$^{th}$ rainfall event, both of the upstream stations exhibited a steep decline in salinity, while the same effect was less pronounced at station WC4 (dashed red line) due to the larger amount of salt water in the receiving water body of the pond and Lower Weir Creek.

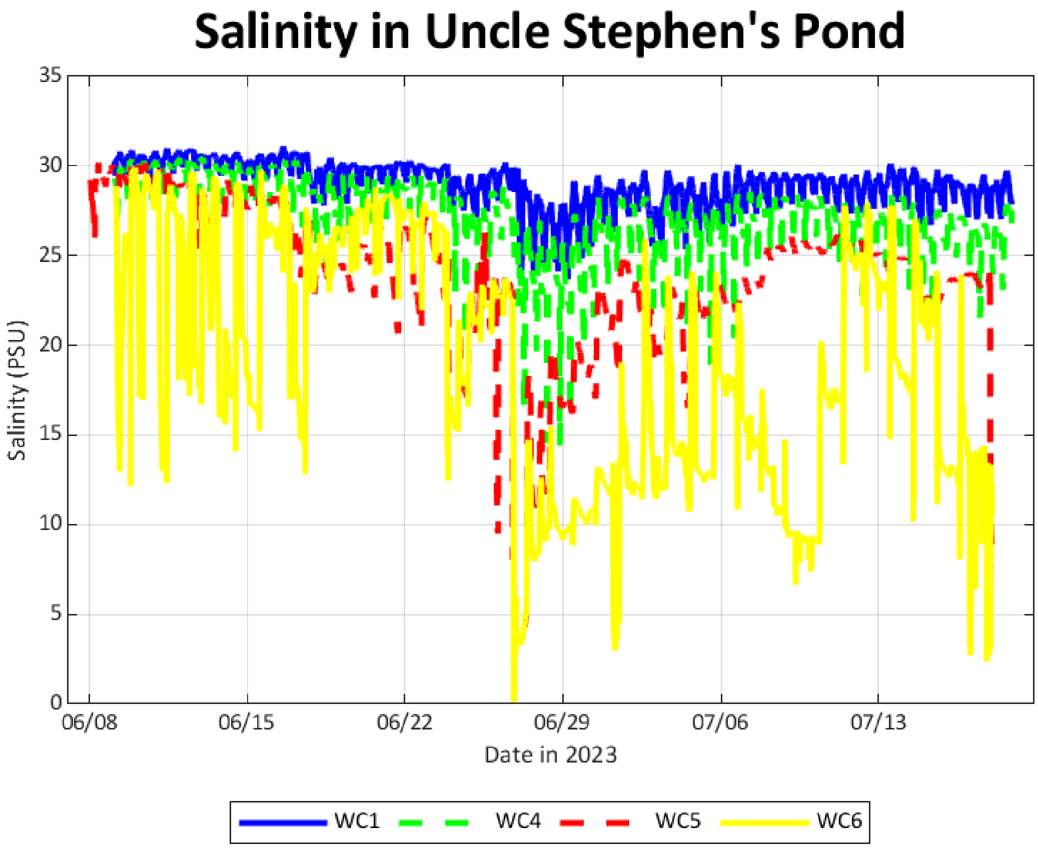


**Figure 11. Time-series of salinities in the Uncle Stephen's Pond subsystem, stations WC4 (dashed green), WC5 (dashed red) and WC9 (yellow) relative to the open boundary at WC1 (blue)**

### 3.1.3 Summary of Hydrologic Data

**Upper and Lower Weir Creek Subsystems**

- Tides within the Weir Creek system fully propagated to the downstream sides of the western culvert under Lower County Road. Upstream of Lower County Road, tides were impeded which caused lower high tides.
- Low tides in the system were perched moving upstream, likely due to increased creek bed elevation, as well as higher culvert inverts.
- Stations WC7 and WC10 experienced the largest increase in water surface elevation during the June 27th rain event, taking 2-3 days to return to pre-storm conditions. This indicates that the culverts prevent upstream drainage during heavy rain events.
- The upstream most sensor (WC10) was lightly buried under soft mud during recovery, which likely impacted salinity data. Burial dampens the signal, allowing the sensor to only record a muted salinity record.
- Salinity in the system decreased moving upstream, with station WC10 recording the lowest salinities (0-23 PSU) within the subsystem and overall though highest variability. Stations

upstream of Lower County Road experienced the strongest response to rain events, with salinities decreasing to <5PSU, particularly at low tides.

**Kelley's Pond Subsystem**

- Tides within the Kelley's Pond subsystem fully propagated to the culvert under Fisk Street. Upstream of Fisk Street, tides were impeded by the culvert which caused lower high tides.
- Low tides in the system were perched moving upstream, likely due to increased creek bed elevation, as well as higher culvert inverts.
- Station WC9 experienced the largest increase in water surface elevation during the Jun 27th rain event, taking 2-3 days to return to pre-storm conditions. This indicates that the culverts prevent upstream drainage during heavy rain events.
- The response in water surface elevation in Kelley's Pond was not as pronounced as the Weir Creek system, possibly due to a higher water storage capacity.
- Salinity in the system decreased moving upstream, with station WC9 recording the lowest salinities (20-28 PSU), though highest variability. Salinity in the Kelley's Pond subsystem was less impacted by rain events than Weir Creek or Uncle Stephen's Pond.

**Uncle Stephen's Pond Subsystem**

- Tides within the Uncle Stephen's Pond subsystem fully propagated to the downstream side of the eastern culvert under Lower County Road. Upstream of Lower County Road, tides were impeded by the culvert which caused lower high tides.
- Low tides in the system were perched moving upstream, likely due to increased creek bed elevation, as well as higher culvert inverts.
- Station WC6 experienced the largest increase in water surface elevation during the Jun 27th rain event, taking 2-3 days to return to pre-storm conditions. This indicates that the culverts prevent upstream drainage during heavy rain events.
- Similar to the Kelley's Pond subsystem, the response in water surface elevation in Uncle Stephen's Pond was not as pronounced as the Weir Creek system, again possibly due to a higher water storage capacity.
- The most upstream sensor (WC6) was lightly buried under soft mud during recovery, which likely impacted salinity data. Burial would damp the tidal signal, allowing the sensor to only record a muted salinity record.
- Salinity in the subsystem decreased moving upstream, with station WC6 both recording the lowest salinities and having the largest range (0-30 PSU) in both the subsystem and overall.

### 3.2 Topographic and Bathymetric Data Collection

High quality, publicly accessible elevation datasets are maintained by the National Oceanographic and Atmospheric Administration (NOAA) on their Data access viewer web portal. LiDAR provides an accurate and spatially dense collection of elevation datapoints in areas where coverage is available. For the Weir Creek restoration project, the 2021 United States Geological Survey (USGS) LiDAR dataset for the study area was obtained. As is common with LiDAR datasets as a result of how the data is obtained, areas that are inundated, especially areas with relative opaque water bodies, are not resolved in the data and as shown on Figure 12 as areas without colored contours. The LiDAR point cloud provides excellent resolution for the upland areas and was used in conjunction with survey data collected specifically for this study.

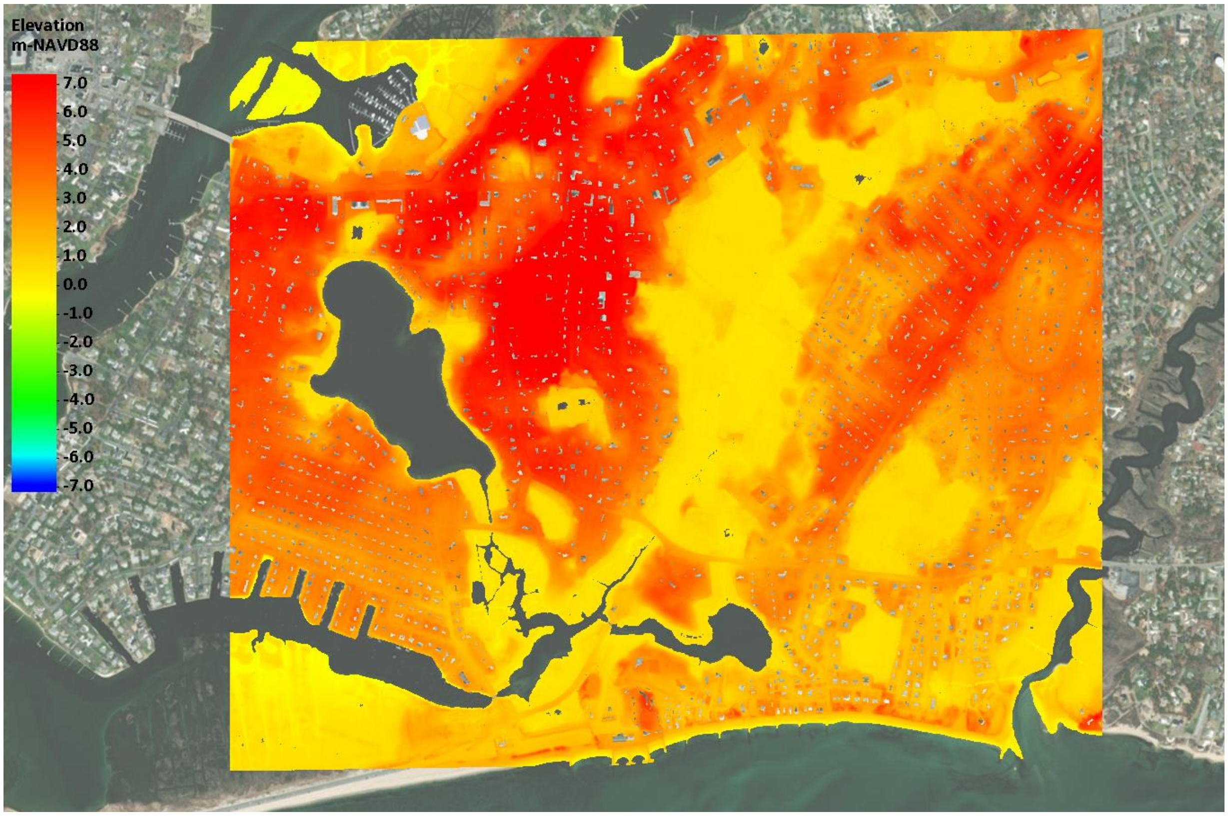


**Figure 12. 2021 USGS LiDAR dataset for Weir Creek. Note coverage gaps in Kelly's Pond and Uncle Stephen's Pond.**

To supplement the publicly available LiDAR data, Woods Hole Group conducted study specific surveying in three (3) phases to both fill in the coverage gaps and to provide a "ground-truthing" of the LiDAR point cloud to assess if any subsidence or deposition resulted in elevation changes in the system. The first phase of elevation data collection was conducted on August 11, 2023 using a vessel-mounted echo sounder to measure bathymetry in the deeper sections of Lower Weir Creek, Uncle Stephen's Pond, and Kelley's Pond. In shallower areas where the boat was not accessible, Woods Hole Group deployed a survey team with a Trimble Real-time Kinematic (RTK) GPS to conduct topographic surveying of the channel banks, thalweg (deepest section of the channel), and points along the marsh flats. Phase two of the survey data collection was conducted on August 22-23, 2024. The final phase was conducted on September 22, 2023, using a RTK GPS for measuring the shallow pond in the eastern section of Lower Weir Creek and the channel connecting the Fisk Street crossing to Kelley's Pond. The combined survey points from all three (3) phases of topographic and bathymetric data collection are shown on Figure 13


**Figure 13. 2023 Woods Hole Group topographic and bathymetric survey points.**

## 4.0 ENGINEERING METHODS

To further investigate existing conditions and to evaluate resilience and culvert alternatives, a 2-D hydrodynamic model was developed for Weir Creek. The 2-D model provides additional insight into spatial variations in tidal benchmarks and salinity within the system. Sections 4.1 and 4.2 describe the development of the hydrodynamic model; details are provided for the model configuration, boundary conditions, and calibration steps performed. Section 4.3 describes results from the existing conditions model runs, while Section 4.4 describes the alternatives evaluated using the 2-D model.

### 4.1 MODEL DESCRIPTION

The Environmental Fluid Dynamics Code (EFDC) model, originally developed at the Virginia Institute of Marine Science (VIMS) (Hamrick, 1992), was chosen to model the hydrodynamics of the complex estuarine system of Weir Creek. The EFDC model can be applied as a two- or three-dimensional model with capabilities for simulating a diverse range of environment flow and transport problems. The model has been applied to numerous aquatic systems including Chesapeake Bay (Hamrick, Linking Hydrodynamic and Biogeochemical Transport Models for Estuarine and Coastal Waters, 1994), Mobile Bay in Alabama, Cape Fear River in North Carolina, and the Suwannee River in Florida. The model has been applied to studies of circulation, discharge dilution, water quality, TMDL, and sediment transport. EFDC can predict hydrodynamics and water quality in multiple dimensions and is a widely accepted EPA approved model. EFDC is also capable of simulating 22 water column state variables (e.g., nitrogen, algae, DO, phosphorus, carbon).

The EFDC model solves the two-dimensional, vertically hydrostatic, free surface, turbulent-averaged equations of motions for a variable-density fluid. The model includes dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity, and temperature. In addition, the EFDC model simulates cohesive and noncohesive sediment transport, eutrophication processes, both near field and far field dilution of discharges, and transport and fate of toxic contaminants. The model can simulate multiple size classes of cohesive and noncohesive sediments along with the associated deposition and resuspension processes and bed geomechanics. The transport of toxins in both water and sediment phases is simulated. The model allows for the wetting and drying of shallow areas using a mass conservation scheme. The effects of waves can also be incorporated in nearshore simulations by specifying externally generated radiation stresses. Externally specified wave dissipation due to wave breaking and bottom friction can also be incorporated in the turbulence closure model as source terms. EFDC also includes measures for simulating flow control structures and highly vegetated areas. An embedded single and multi-port buoyant jet module is also included for coupled near and far field mixing analyses.

The EFDC model implements a mass conservation solution scheme for the Eulerian transport equations, which is at the same timestep or twice the time step of the momentum equation solution. The advective step of the transport solution uses either a central difference scheme or a hierarchy of positive definite upwind difference schemes. The horizontal diffusion step is explicit in time, while the vertical diffusion step is implicit. Horizontal boundary conditions include material or constituent inflow concentrations, which can be specified as being depth-dependent and both constant and time-variable. The EFDC model can be used to drive a number of external water quality models using internal linkage processing procedures (Hamrick, 1992) .

## 4.2 Model Configuration

This section presents the site-specific data utilized to configure the EFDC model. The development of the Weir Creek model required configuration so that the underlying bathymetry/topography and hydrodynamics of the marsh system and the various hydraulic controls were adequately represented in the model. The required data included topographic-bathymetric data to define the model geometry, culvert geometry data to define the hydraulic structures, and measured water characteristics to provide boundary conditions and calibration points throughout the system.

### 4.2.1 Computational Grid Generation

Grid generation is one of the first steps in developing a 2-D model. The computational grid represents a generalization of topography and bathymetry of the study area with varying resolution. The extent of the EFDC-WC model was created by visual inspection of aerial imagery and LiDAR elevations of the upland areas. The model extents were chosen to encompass Weir Creek, the freshwater marsh upstream of Lower County Road (Upper Weir Creek), Kelley's Pond, and Uncle Stephens Pond and the degraded salt marsh upstream of Lower County Road. EFDC uses a curvilinear model grid made up of quadrilateral cells. The curvilinear grid allows for variable computational cell sizes for more detailed resolution in areas of importance, and varying cell face widths, allowing for more accurate representation of a system's geometry, which is especially important in marshes with complicated channels like the Weir Creek estuary.

For the Weir Creek system, a minimum resolution in the order of 5 feet to 8 feet was used to define the most complex areas of the model domain with coarser resolution up to 70+ feet in areas of higher base elevation and in the uppermost sections of the system near Route 28. Ensuring adequate cell coverage within the channels and around structures helped to increase model stability and improve model accuracy. The EFDC-WC model grid is made up of 91,208 computational cells. Figure 14 shows the model domain representing the Weir Creek study area.

**Figure 14. EFDC-WC curvilinear model domain, computational cell faces are in black, the model boundary is shown in brown.**

### 4.2.2 Model Topography and Bathymetry

The topography and bathymetry specified at each cell in the EFDC-WC Model were defined using a combination of hydrographic and topometric surveys conducted in 2023 (discussed in section 3.2) in support of this project. Elevations for cells outside of the surveyed areas were specified using the 2021 USGS LiDAR dataset for Central Eastern Massachusetts. The topographic and bathymetric datasets were utilized to refine the computational grid and the best available datasets for each area within model domain (combining all the topographic and bathymetric surveys, LiDAR datasets, and RTK survey points) were interpolated to the curvilinear grid.

No bathymetric data were collected in Indian Pond near the headwaters of Upper Weir Creek due to accessibility and elevations were not available in the LiDAR dataset. An estimated pond bottom elevation of approximately -1 ft-NAVD88 (-0.27 m-NAVD88) was applied to cells corresponding to the pond in the aerial imagery to allow freshwater to collect prior to flowing downstream. Figure 15 shows the final topography and bathymetry of the model domain developed using these datasets.

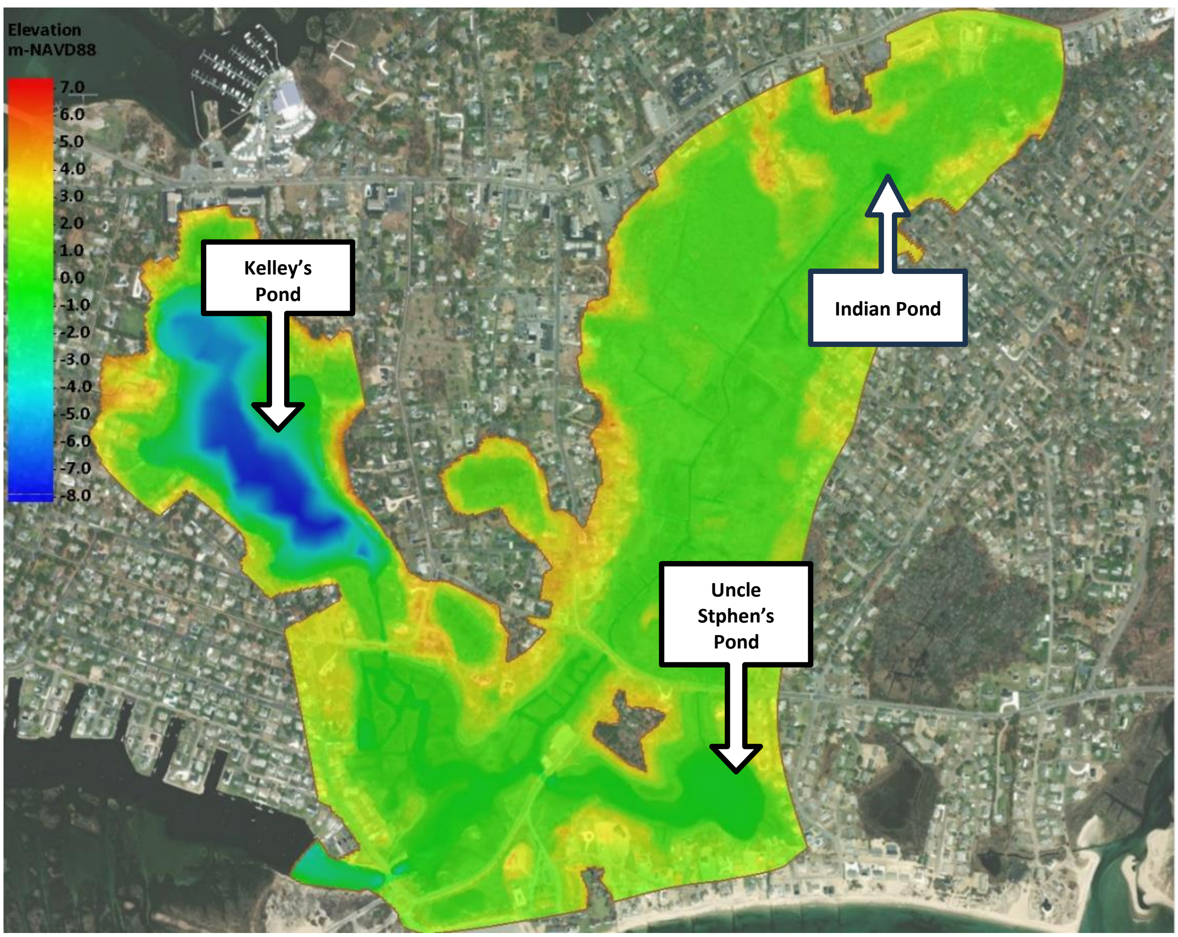


**Figure 15. EFDC-WC topography and bathymetry for Weir Creek model domain.**

### 4.2.3 Hydraulic Structures

In the Weir Creek estuary, five (5) structures provide hydraulic connections in the system and are shown in Figure 16. Of the structures, only the two (2) pipe connections under Lower County Road (shown in Figure 15 circled in red) were evaluated for replacement. The two (2) bridge structures (circled in blue) were assumed to either remain as-is or potentially be replaced in kind. Similarly, the pipe connecting Kelley's Pond to Weir Creek (yellow) was not included in the replacement analyses. In the EFDC-WC model for existing conditions, the hydraulic structure parameters listed in Table 3 were applied. Manning's roughness coefficients (n) for the three pipes were specified as 0.03 at the Fisk Street crossing and 0.015 and 0.028 for the western and eastern Lower County Road crossings, respectively. Manning's n values were selected to be reflective of the head loss across each crossing while still being within realistic values for roughness coefficients for culverts, as specified in *Open Channel Hydraulics* (Chow, 1959).

**Table 3. Hydraulic Connection/Structure Parameters**

| ID | Structure Type | Opening/Span Size | Length | Upstream Invert (ft NAVD88) | Downstream Invert (ft NAVD88) |
|---|---|---|---|---|---|
| **Lower County Road (East)** | Pipe | 14- inch Diameter | 71 ft | -0.8 | -0.8 |
| **Lower County Road (West)** | Pipe | 21-inch Diameter | 76 ft | -1.2 | -1.3 |
| **Fisk Street** | Pipe | 36-inch Diameter | 65 ft | -1.2 | -1.4 |
| **Lighthouse Road** | Bridge | 30 ft | 36 ft | -3.0 | -2.9 |
| **Loring Ave** | Bridge | 21 ft | 36 ft | -2.9 | -2.9 |

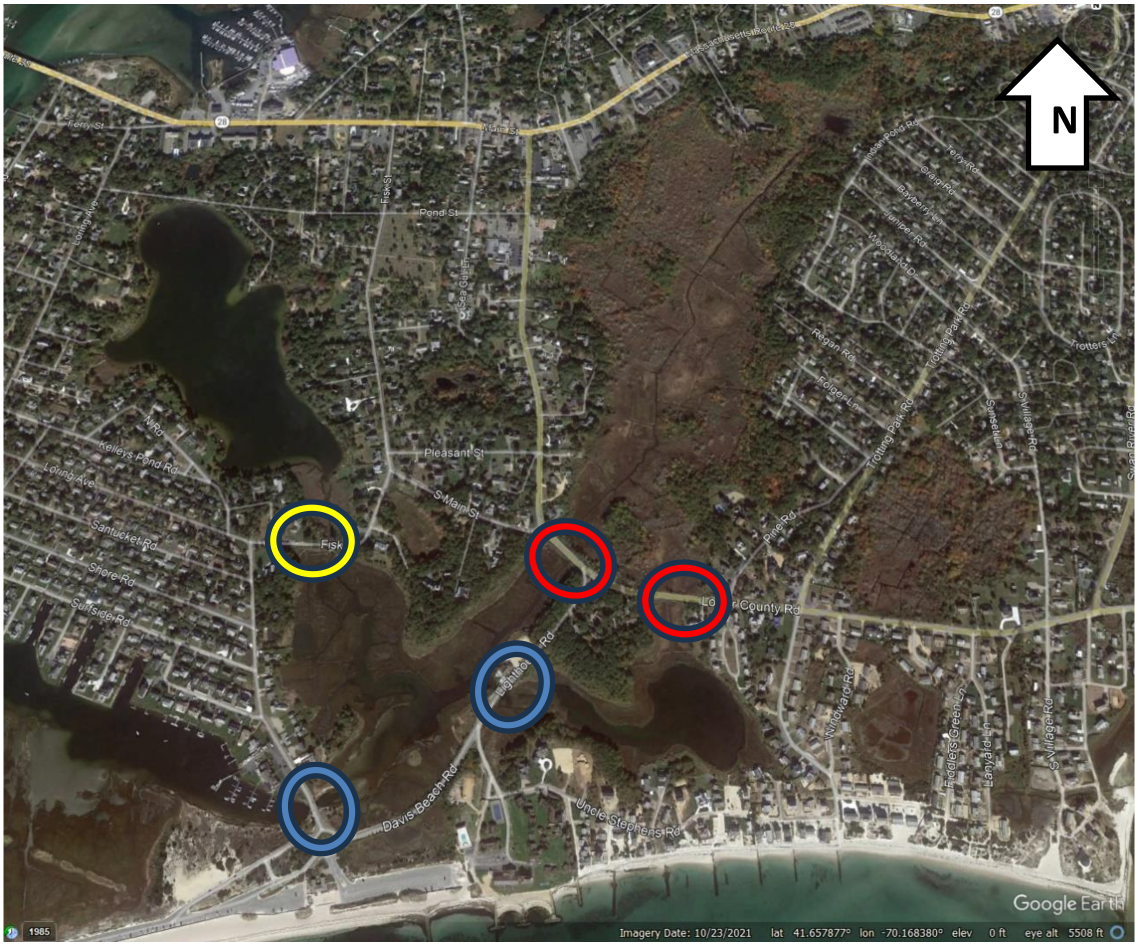


**Figure 16. Location of Lower County Road culverts (red), Fisk Street culvert (yellow) and bridge structures (blue) in the Weir Creek estuarine system.**

### 4.3 Model Calibration & Validation (Existing Conditions)

After completion of model setup, the model was calibrated to the measured water level and salinity data collected by Woods Hole Group. Model calibration is the process in which model parameters are systematically adjusted within a range of acceptable values and results are examined using standard error metrics to determine which configuration provides the best agreement between modeled variables and the measurements. Two types of boundary conditions were applied in the hydrodynamic model as follows: 1) a water level boundary at the Lower Weir creek near the Dennis Yacht Club using the measurements at station WC1, and 2) four (4) time-constant freshwater inflows located in the Indian Pond in Upper Weir Creek, the ponded area upstream of the eastern Lower County Road stream crossing and two locations in Kelley's Pond. The time-constant inflows were adjusted several times in the calibration process to a value of 0.295 cfs in Upper Weir Creek, 0.004 cfs upstream of Uncle Stephen's Pond, and both flows in Kelley's Pond at 1.49 cfs. Hourly precipitation from the available from the Hyannis Airport was also applied in the model to account for additional freshwater inflows on the model domain from rain events.

EFDC accounts for bottom friction losses in the model by applying a spatially variable roughness length. For the EFDC-WC model, variations in friction were applied using an elevation-based schematization, where the roughness length was specified for cells within a set range of elevations (i.e., deeper cells having a lower roughness length and shallower cells, which are subject to vegetative resistance etc., having a higher roughness length). In the Upper Weir Creek and Uncle Stephen's Pond systems, an additional increase in roughness was specified (by a factor of 4.25 and 1.5, respectively) as the variation in channel elevations and narrow width of the channels themselves contribute to greater frictional losses. Table 4 lists the roughness lengths used in the EFDC-WC model based on the grid cell elevations.

**Table 4. Roughness length specified in the EFDC-WC model by elevation range.**

| Elevation (ft-NAVD88) | Roughness Length |
|---|---|
| Elevation less than -3.05 | 0.0001 |
| Elevation between -1.0 & -3.05 | 0.0005 |
| Elevation between -1 & -0.34 | 0.0009 |
| Elevation between -0.34 & 2.0 | 0.0032 |
| Elevation greater than 2.0 | 0.0037 |

Model results for the seven (7)-day calibration period were first inspected visually to determine model efficacy in representing conditions in Weir Creek at the ten (10) monitoring stations. Both salinity and water levels were compared with observations to assess that the model was accurately representing the tidal hydraulics and freshwater/saltwater exchange. Figure 17 through Figure 28 show time series of water levels and salinities for the EFDC-WC model results and observations at the open boundary, upstream and downstream of the Lower County Road crossing, and in Upper Weir Creek. In general, the EFDC-WC model performs well in replicating existing conditions with the model and observations exhibiting similar behaviors and ranges with respect to water levels and reflect the trends in salinity variability. Of note, the observed salinity at WC6 on the upstream side of the eastern Lower County Road crossing (Figure 28) and observed salinity at station WC10 (Figure 24) were likely affected both by sedimentation as noted during equipment recovery which is likely a cause for the deviations at those stations and groundwater inflows throughout the system rather than point sources used in the model. Also at station WC10, the EFDC model tends to overpredict the amount of water (Figure 23) able to penetrate the main channel as a result of model resolution not capturing all of the branching mosquito channels providing alternate pathways for water and potential obstructions in the main channel.

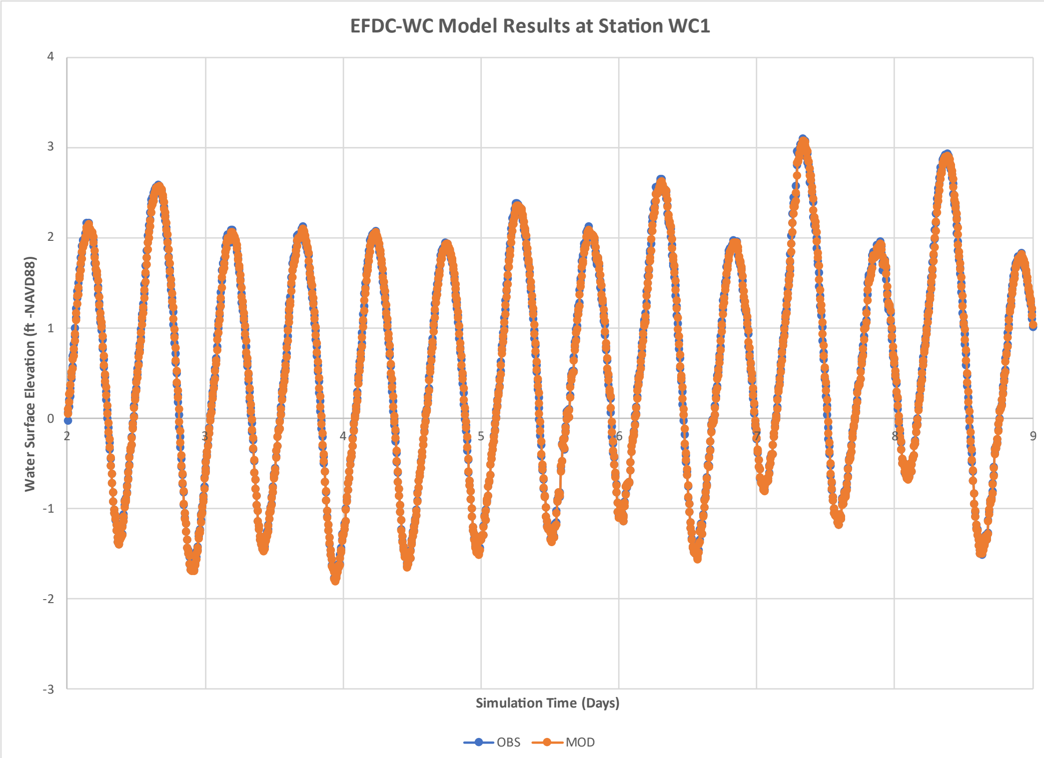


**Figure 17.** **Model Calibration of water levels at Station WC1 (Dennis Yacht Club).**

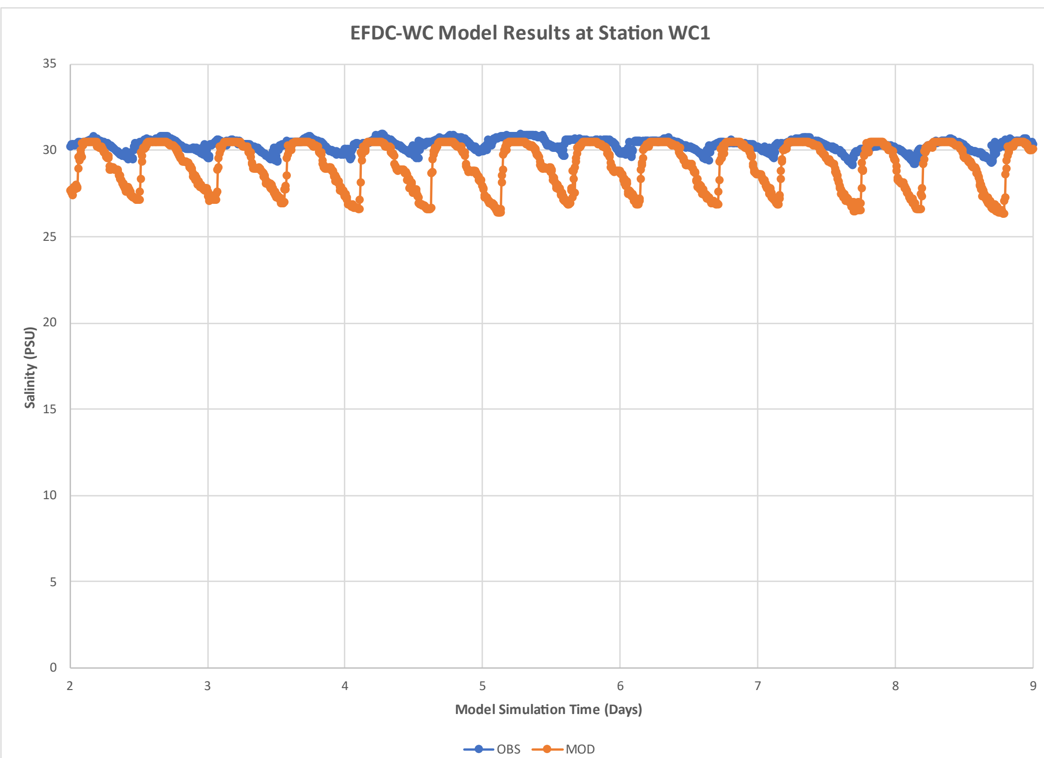


**Figure 18.** **Model Calibration of salinity at Station WC1 (Dennis Yacht Club).**

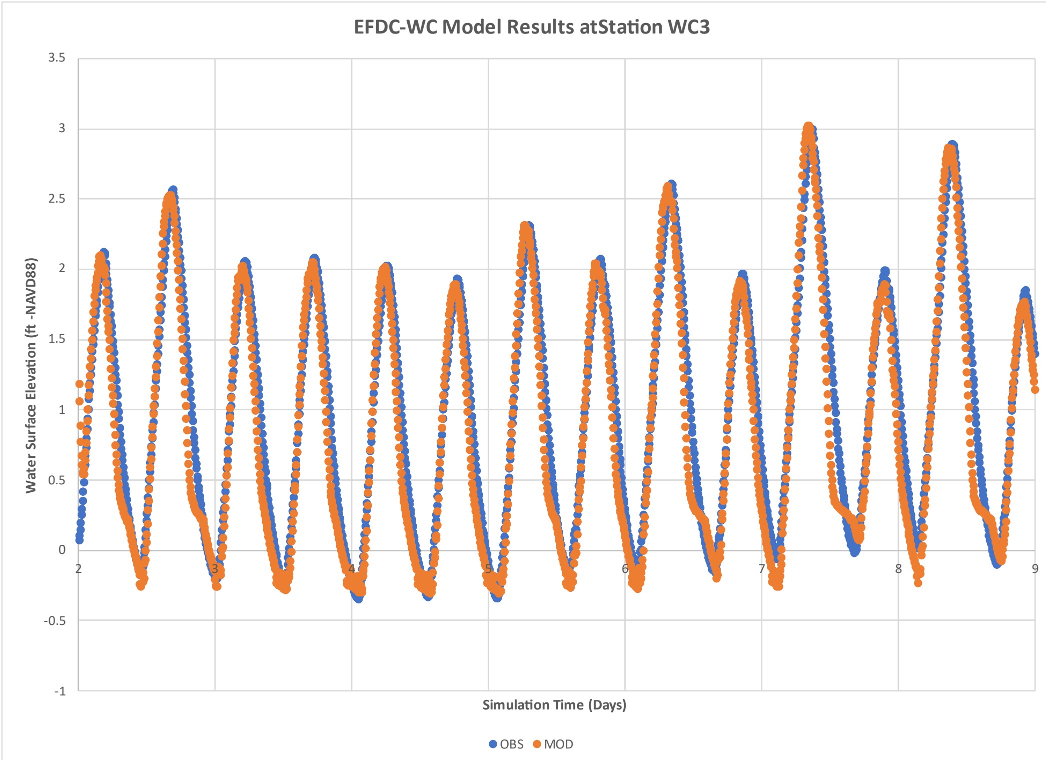


**Figure 19. Model Calibration of water levels at Station WC3 (Lower County Road-West).**

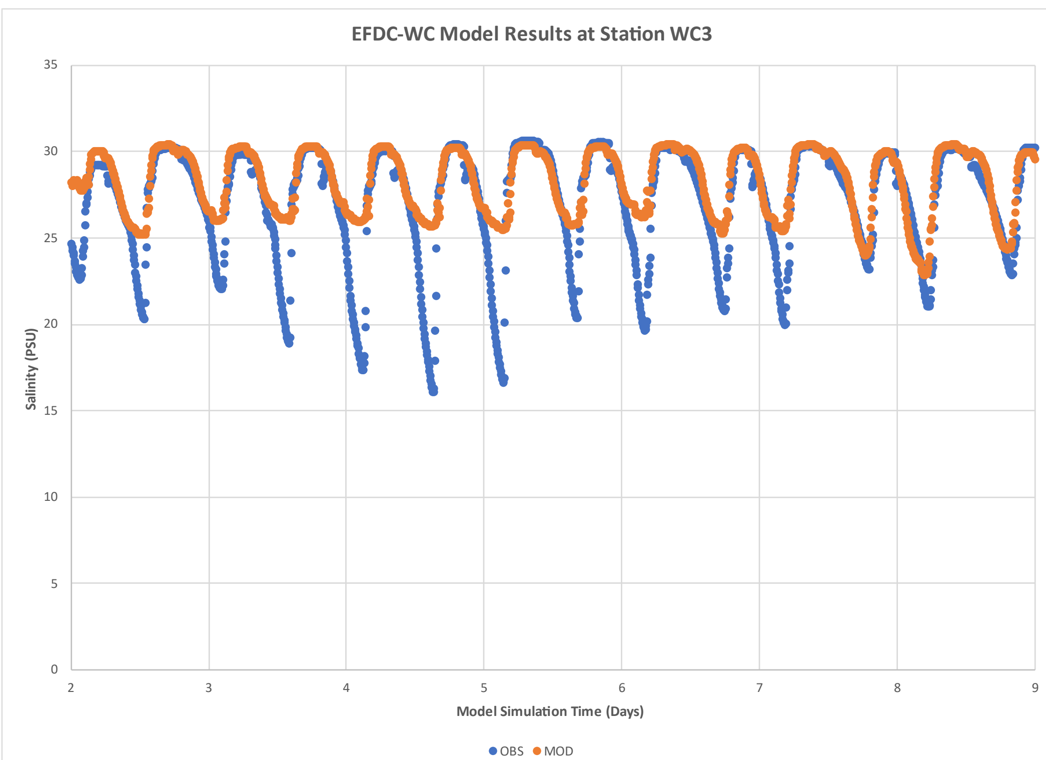


**Figure 20. Model Calibration of salinity at Station WC3 (Lower County Road-West).**

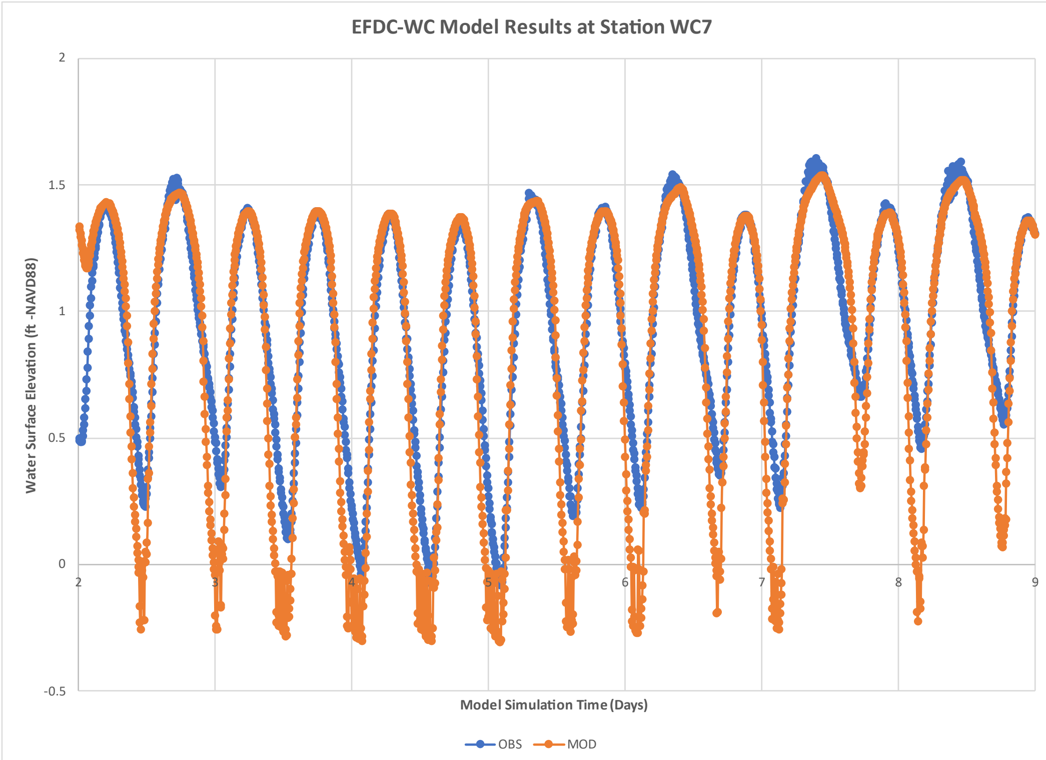


**Figure 21. Model Calibration of water levels at Station WC7 (Lower County Road-West).**

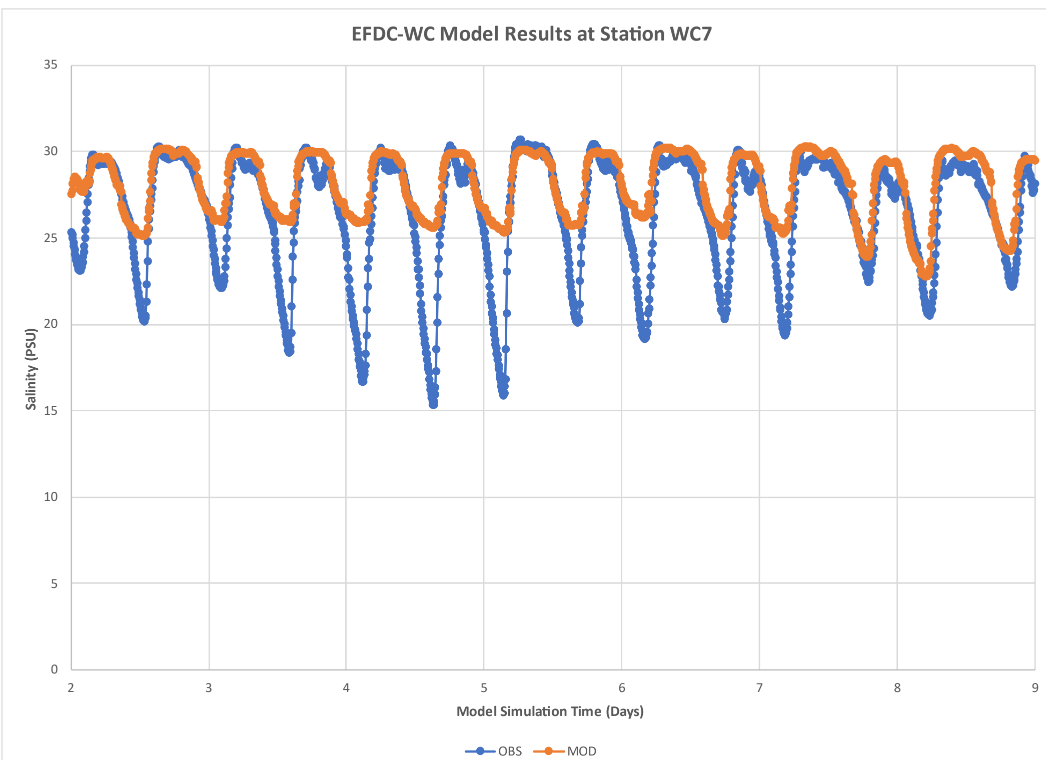


**Figure 22. Model Calibration of salinity at Station WC7 (Lower County Road-West).**

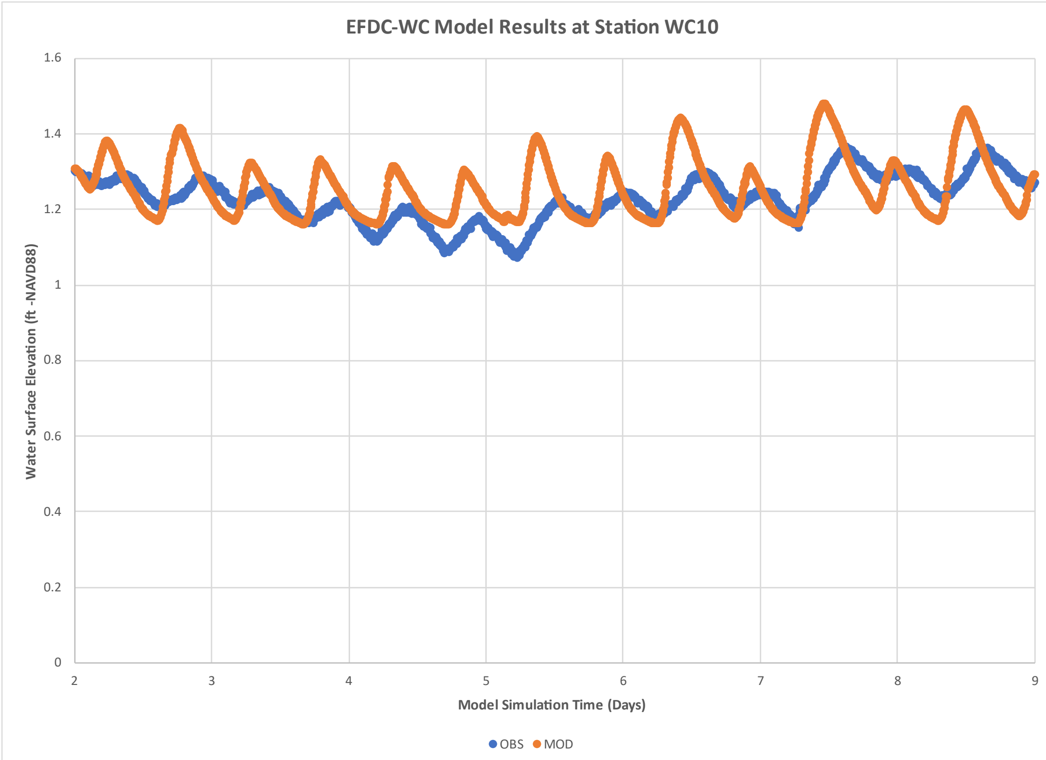


**Figure 23. Model Calibration of water levels at Station WC10 (Upper Weir Creek).**

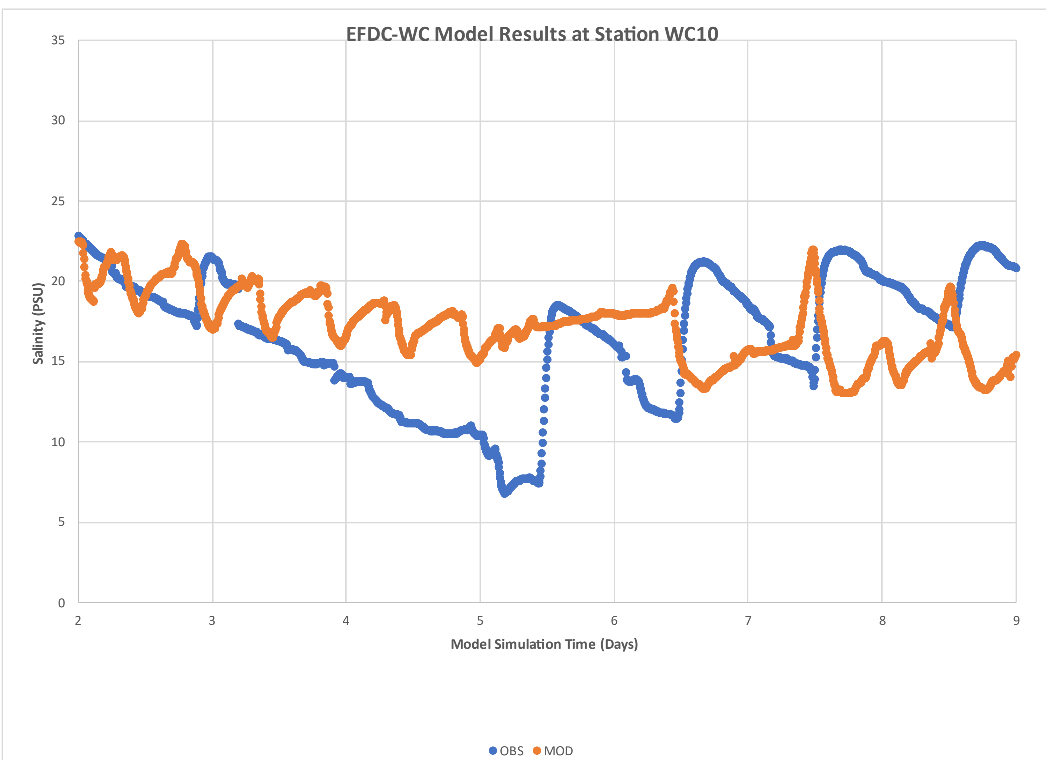


**Figure 24. Model Calibration of salinity at Station WC10 (Upper Weir Creek).**

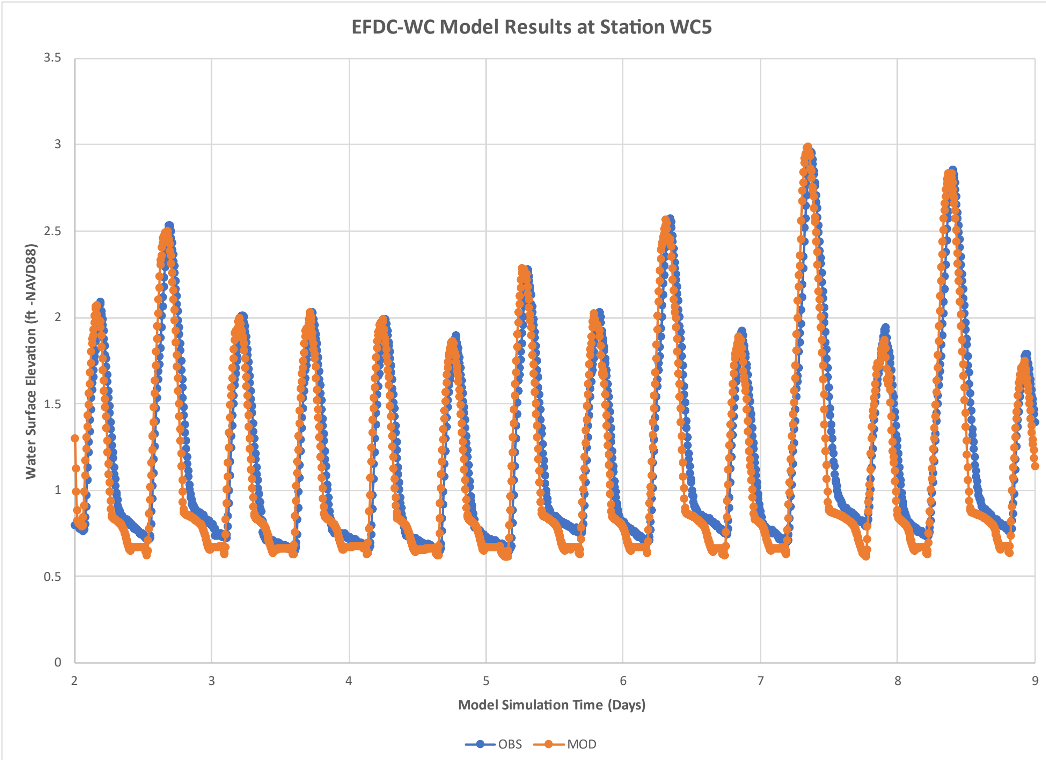


**Figure 25. Model Calibration of water levels at Station WC5 (Lower County Road-East).**

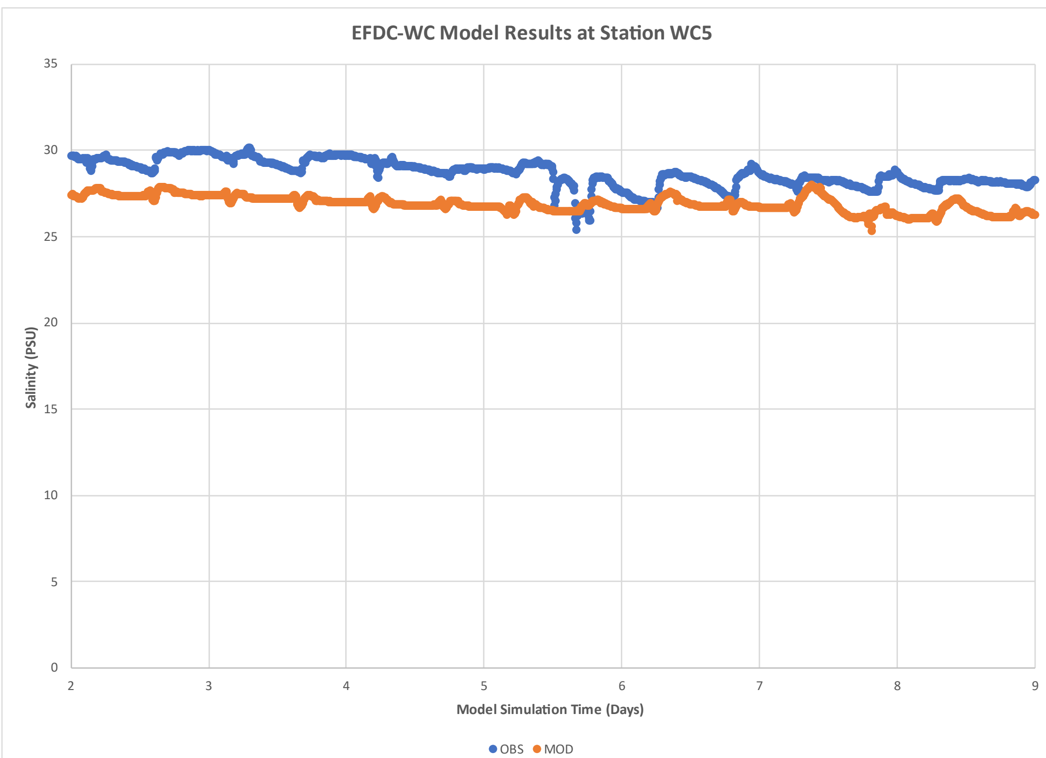


**Figure 26. Model Calibration of salinity at Station WC5 (Lower County Road-East).**

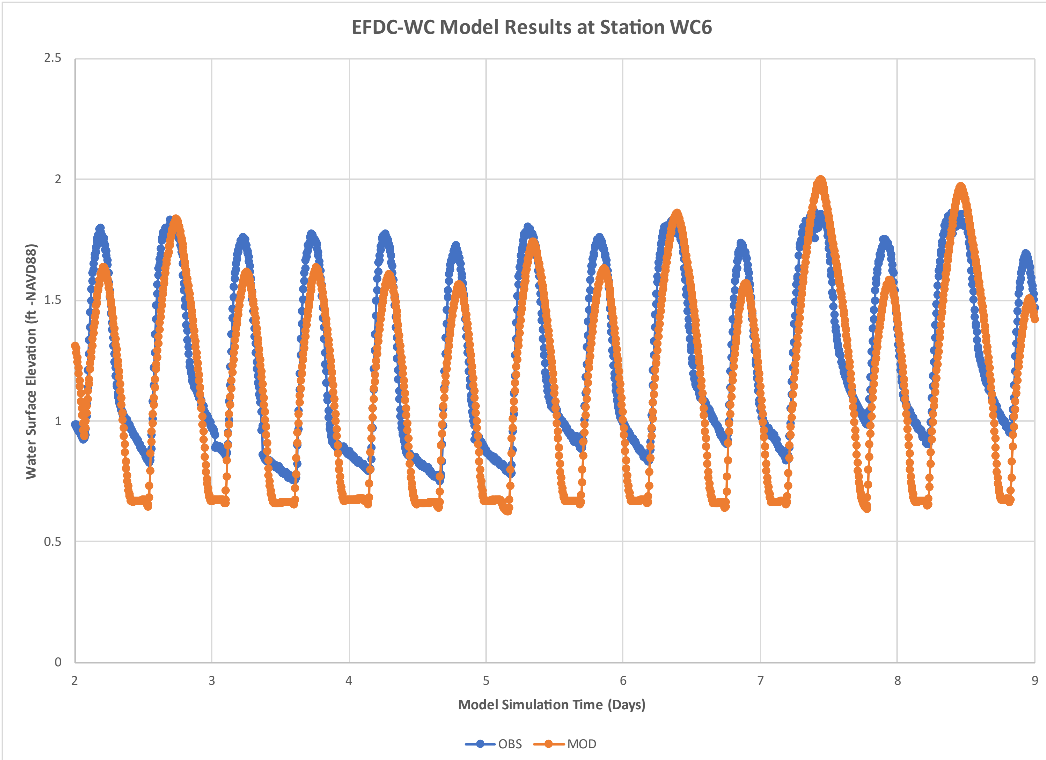


**Figure 27. Model Calibration of water levels at Station WC6 (Lower County Road-East).**

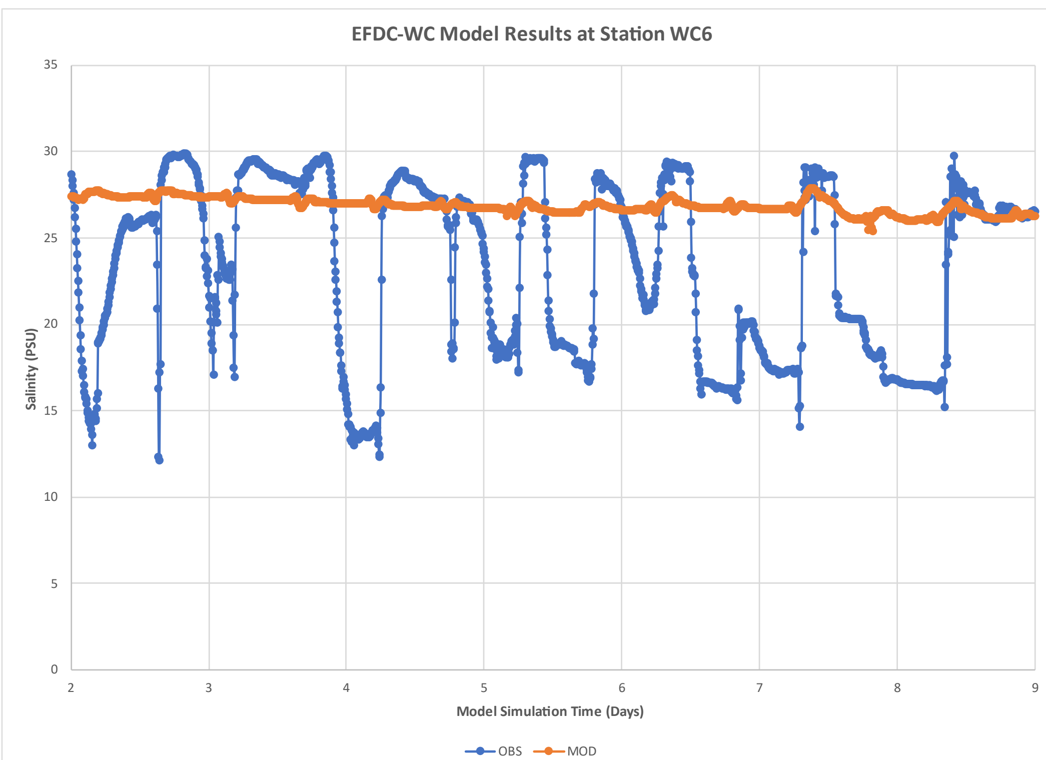


**Figure 28. Model Calibration of salinity at Station WC6 (Lower County Road-East).**

In addition to the visual comparison provided by the time series plots, statistical model error parameters were calculated including Bias, Root Mean Square Error (RMSE), and relative error based on discrete modeled and observed values from the time series. The Bias, RMSE, and relative error are calculated as follows:

$$Bias = \frac{\sum_{1}^{n}\left(p_{\text{mod}} - P_{obs}\right)}{n} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{1}^{n}\left(p_{\text{mod}} - p_{obs}\right)^2}{n}} \quad (2)$$

$$\boldsymbol{Relative\ Error} = \frac{\overline{\boldsymbol{P_{mod}}} - \overline{\boldsymbol{P_{obs}}}}{\overline{\boldsymbol{P_{obs}}}} \quad (3)$$

where $P_{mod}$ and $P_{obs}$ are the modeled and observed values respectively and *n* is the number of discrete values in the time series.

The bias provides a measure of how close on average the modeled results are to the observed data.  A positive value indicates that the model is over-predicting the observation, while a negative value indicates that the model is under-predicting the observations; a bias of zero indicates that, on average, the model accurately reproduces the observations. As such, a low bias value indicates the model is simulating the observed data reasonably.  The RMSE is an average of the magnitude of the error.  RMSE is always positive with smaller values indicating better model performance.

The error parameters for the EFDC-WC model calibration are shown in Table 5 for water levels and Table 6 for salinity. These data indicate a good comparison between the modeled and observed data at the ten (10) calibration points (RMSE less than 4.4 inches at all stations) and that the model can be applied to represent the relative changes expected from the various alternatives evaluated. The U.S. EPA gives technical guidance on error statistic criteria for calibrating estuarine water quality models (EPA, 1990). In these guidelines, relative errors computed for hydrodynamic model variables (e.g., water surface elevation) should be less than 30% in order to achieve adequate calibration. The relative errors associated with the Weir Creek model are well below these EPA guidelines (20% being the highest at WC2) and the visual comparisons also indicate the model is well calibrated for existing conditions and can be utilized for the assessment of different scenarios and alternatives.

**Table 5. Error Statistics for Water Surface Elevation throughout Weir Creek**

| | RMSE (ft) | Bias (ft) | Relative Error (%) |
|---|---|---|---|
| **WC1** | 0.04 | 0.00 | 0.55 |
| **WC2** | 0.35 | -0.19 | 20.06 |
| **WC3** | 0.25 | -0.11 | 11.40 |
| **WC4** | 0.37 | -0.07 | 7.69 |
| **WC5** | 0.23 | -0.05 | 4.44 |
| **WC6** | 0.19 | -0.03 | 6.86 |
| **WC7** | 0.23 | -0.07 | 7.31 |
| **WC8** | 0.31 | -0.15 | 15.24 |
| **WC9** | 0.08 | -0.07 | 6.03 |
| **WC10** | 0.08 | 0.03 | -2.43 |

**Table 6. Error statistics for salinity throughout Weir Creek**

| | RMSE (PSU) | Bias (PSU) | Relative Error (%) |
|---|---|---|---|
| **WC1** | 1.65 | -1.18 | 3.96 |
| **WC2** | 1.82 | -1.34 | 4.51 |
| **WC3** | 2.31 | 1.13 | -4.17 |
| **WC4** | 1.16 | -0.84 | 2.83 |
| **WC5** | 1.89 | -1.79 | 6.22 |
| **WC6** | 6.15 | 3.58 | -15.36 |
| **WC7** | 2.64 | 1.56 | -5.86 |
| **WC8** | 2.45 | -2.22 | 7.72 |
| **WC9** | 2.10 | -1.97 | 7.17 |
| **WC10** | 4.95 | 0.66 | -4.01 |

### 4.4 Design Alternative Initial Screening

To assess the restoration benefits of potential design alternatives, two (2) metrics were selected for the screening process: 1) mean tide range (MTR), or the difference between MHW and MLW, and average salinity $S_{ave}$. MTR provides an indication of the volume of water entering and exiting the system during a tidal cycle with larger values indicating greater tidal exchange, and $S_{ave}$ indicates the potential for saltmarsh restoration, elimination of invasive flora, and potential habitat for anadromous fishes and shellfish. The initial potential restoration alternatives included box culverts at the Lower County Rd crossings with an opening height of 6 feet and widths varying from 2 to 18 feet, as well as a "maximum restoration" alternative which included 20-foot single span bridges at each Lower County Road crossing, optimized bridge spans at Loring Avenue and

Lighthouse Avenue, removal of the flood shoal in Lower Weir Creek, and dredging and widening of the channels in Upper Weir Creek and Uncle Stephen's Pond. The "maximum restoration" scenario was not considered as a potential design alternative at this time but was modeled to provide an indication of potential maximized restoration under normal tidal forcing relative to the existing conditions in the Weir Creek system. Restoration metrics for salinity, water level, and tide range are listed in Table 7. Increasing the culvert width greater than six (6) feet provided minimal increases in both salinity and tide range. Of note, the large size of the eighteen-ft box culvert relative to the computational grid size resulted in some model instability with a slightly lower tide range than the 14-ft culvert. Peak velocities associated with each restoration alternative are listed in Appendix D.

**Table 7. Restoration assessment metrics for design opening selection.**

| Opening | $R_H$ (ft) | MHW (ft-NAVD88) | MLW (ft-NAVD88) | MTR (ft) | $S_{max}$ (PSU) | $S_{min}$ (PSU) | $S_{ave}$ (PSU) |
|---|---|---|---|---|---|---|---|
| Existing | 0.44 | 1.36 | 1.17 | 0.19 | 22.48 | 16.00 | 19.18 |
| 2 FT | 0.71 | 1.50 | 1.20 | 0.30 | 29.39 | 21.86 | 23.82 |
| 6 FT | 1.40 | 1.61 | 1.18 | 0.43 | 30.19 | 23.13 | 24.89 |
| 10 FT | 1.73 | 1.65 | 1.22 | 0.44 | 29.72 | 23.10 | 24.93 |
| 14 FT | 1.94 | 1.68 | 1.22 | 0.46 | 30.32 | 23.09 | 25.28 |
| 18 FT | 2.00 | 1.57 | 1.20 | 0.36 | 30.33 | 23.40 | 25.50 |
| Max | 2.23 | 1.87 | 0.89 | 0.99 | 30.43 | 16.36 | 25.69 |

In order to provide a consistent representation of the potential restoration benefits over existing conditions, plots of the hydraulic radius ($R_H$) of each alternative opening versus tide range (Figure 29) and average salinity (Figure 30) are provided. $R_H$ is defined as the ratio of the cross-sectional flow area (A) divided by the wetted perimeter ($P_{wet}$). The flow area for the box structures was calculated using the depth of flow at MHW (H) and the width (W) of the opening while the pipe was calculated using the diameter (D) of the opening, as shown in Equation (2) below. Similarly, the wetted perimeter was calculated using the depth at MHW and the width of the opening. For all box alternatives and bridge scenario, the depth of flow does not reach the low chord of the opening, therefore the width of flow is used only once in calculating the perimeter of flow (as shown in Equation (3)).

$$R_H = \frac{A}{P_{wet}} \quad (1)$$

$$A = H * W \text{ or } A = \frac{\pi}{4} D^2 \quad (2)$$

$$P = 2 * H + W \text{ or } P = \pi D \quad (3)$$

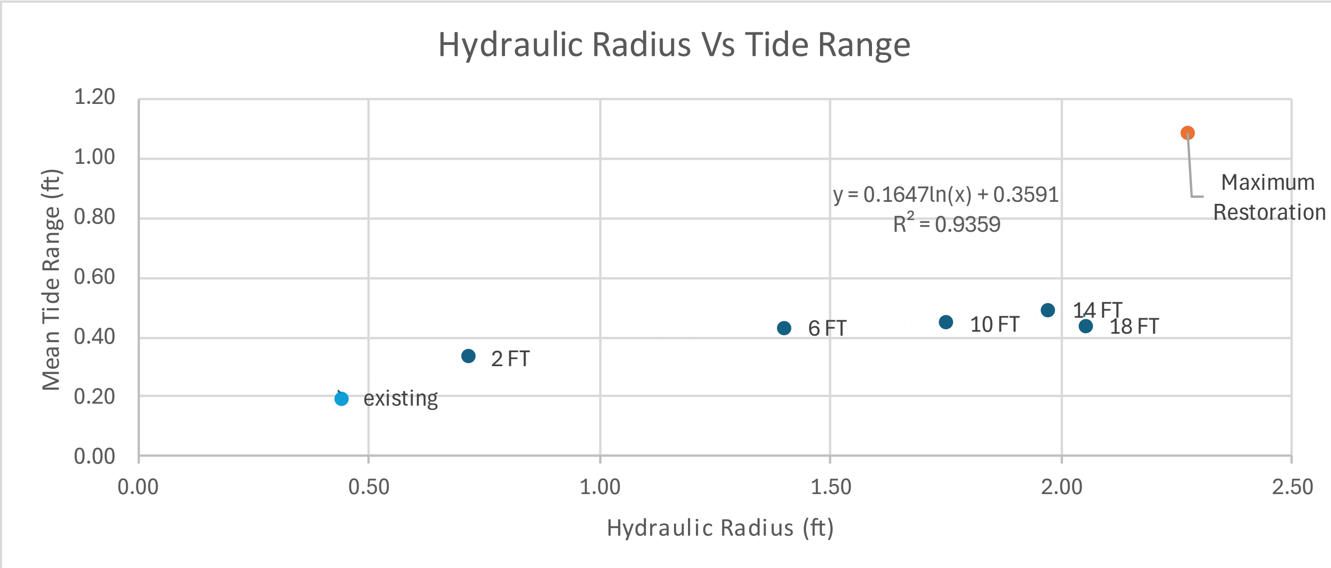


**Figure 29.** **Mean tide range (MHW-MLW) at Station WC10 (Upper Weir Creek) related to hydraulic radius of the design alternative.**

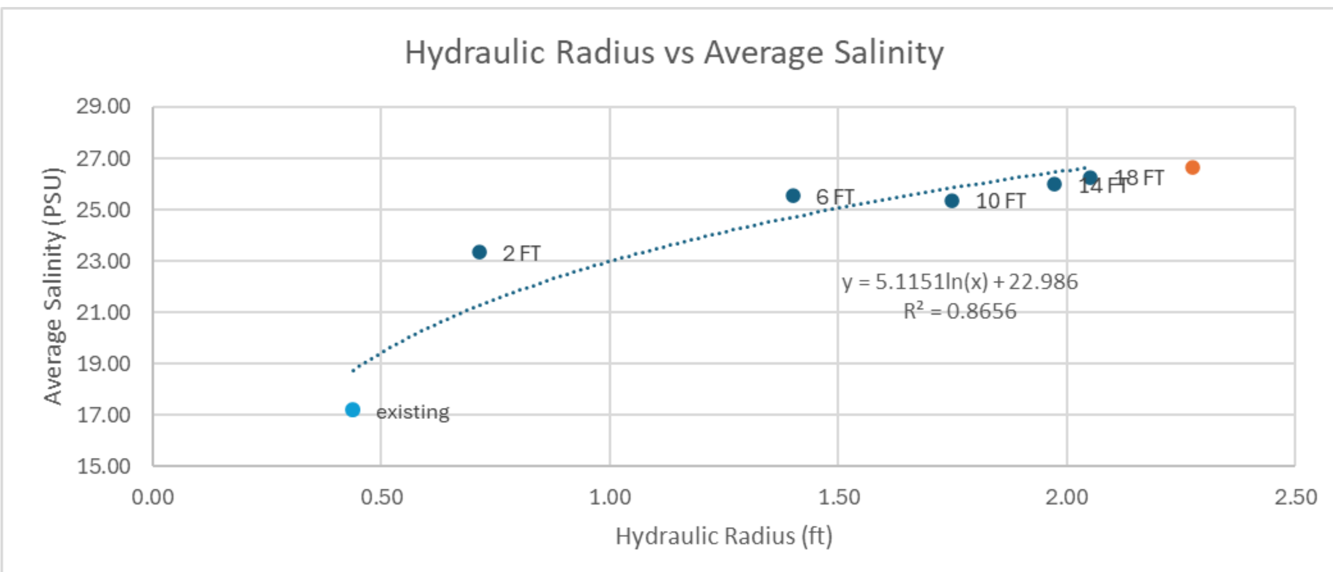


**Figure 30.** **Average salinity at Station WC10 (Upper Weir Creek) related to hydraulic radius of the design alternative.**

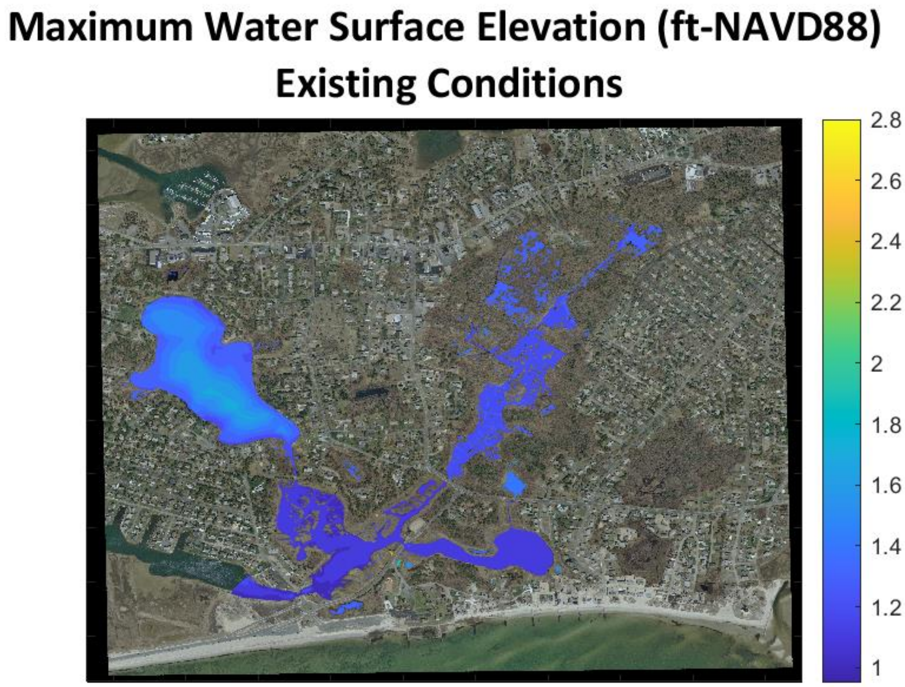


**Figure 31. Contours of maximum water levels (ft-NAVD88) throughout the Weir Creek system for existing conditions.**

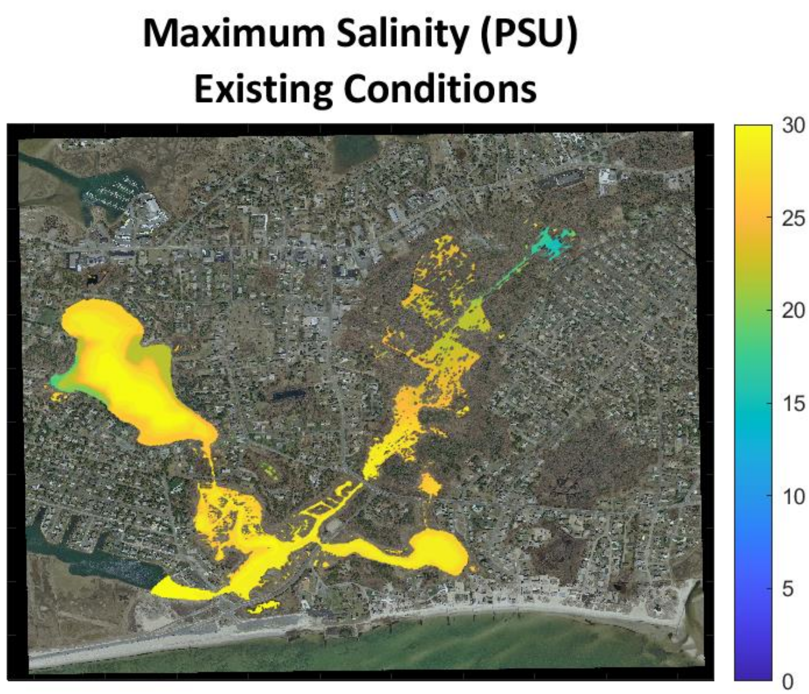


**Figure 32. Contours of maximum salinity (PSU) throughout the Weir Creek system for existing conditions.**

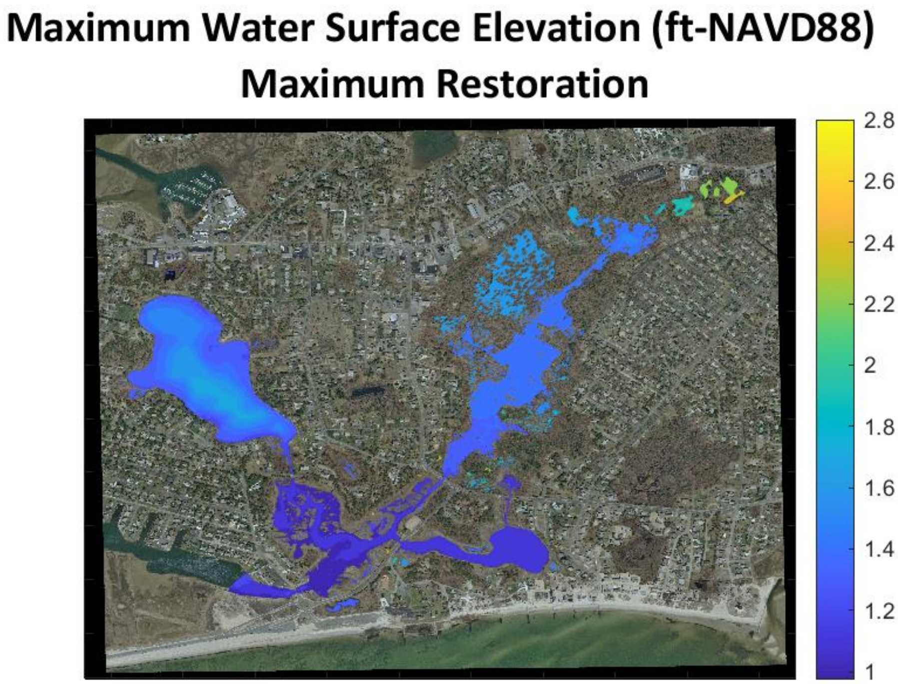


**Figure 33. Contours of maximum water levels (ft-NAVD88) throughout the Weir Creek system for the "maximum restoration" scenario.**

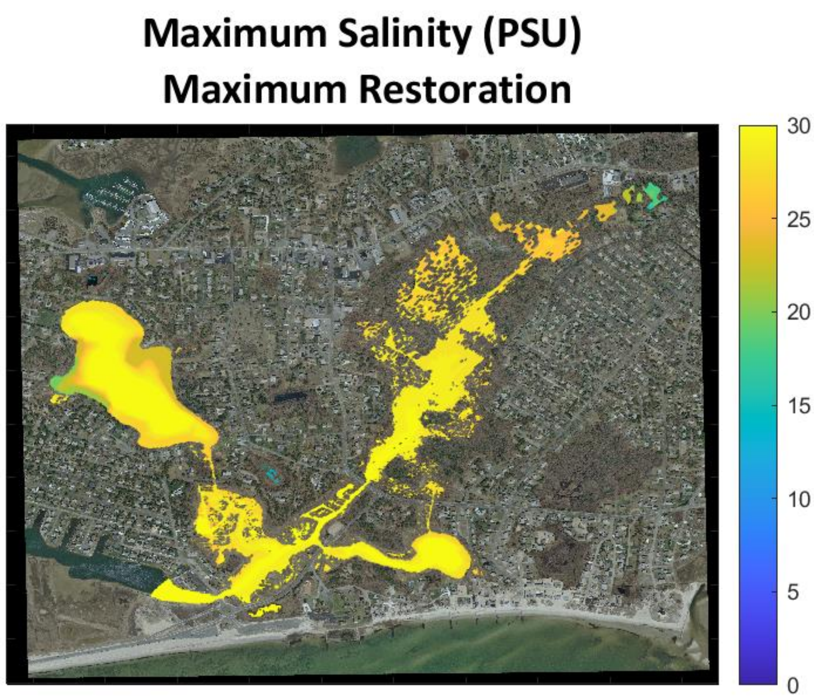


**Figure 34. Contours of maximum salinity (PSU) throughout the Weir Creek system for the "maximum restoration" scenario.**

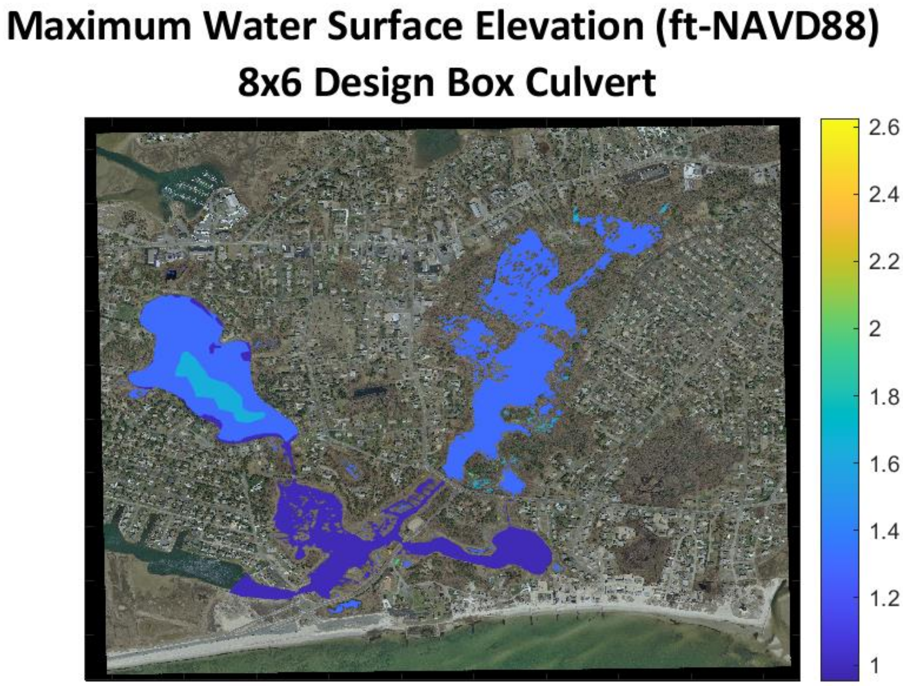


**Figure 35. Contours of maximum water levels (ft-NAVD88) throughout the Weir Creek system for the 8x6 design scenario.**

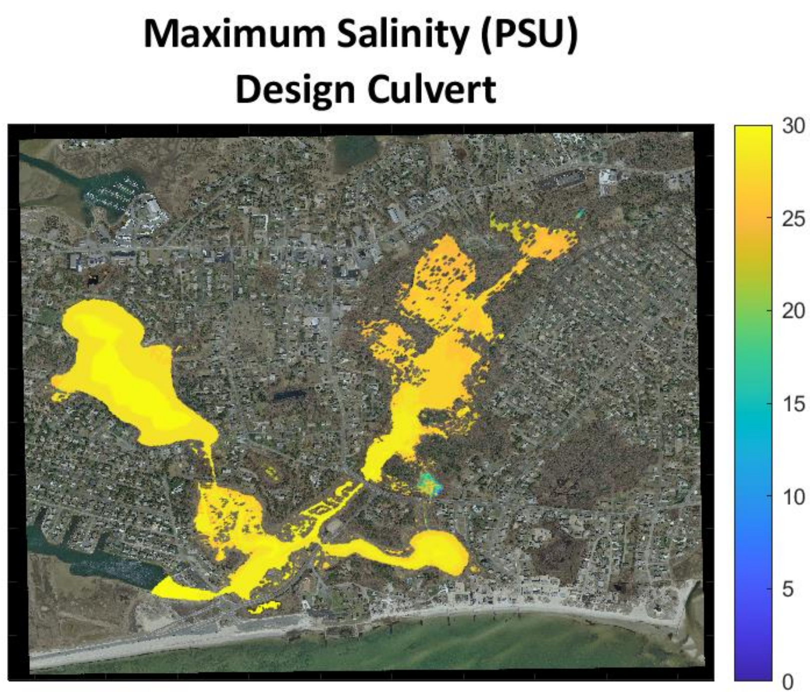


**Figure 36. Contours of maximum salinity (PSU) throughout the Weir Creek system for the 8x6 design scenario.**

# 5.0 PREFERRED ALTERNATIVE ASSESSMENT

All of the design alternatives provide both enhanced tidal exchange and an increase in average salinity in the Upper Weir Creek subsystem, however the increase in tide range is limited during low tides as a result of the channel elevations and the flood shoal at Loring Avenue (station WC2). While comprehensive changes to the system, referred to as the "maximum restoration" alternative in the previous section, provided the greatest tide range and the greatest penetration along -channel as a result of wider and deeper channels, it is not considered a viable alternative at this time and instead provided a conceptual upper limit for restoration. After reviewing the restoration alternatives from the previous section, an 8-ft by 6-ft (W x H) box culvert was selected as it provides the greatest restoration benefits by maximizing the tide range, thereby reducing residence time of water in the upper reaches. While the larger culverts evaluated did provide some minor incremental benefits, larger spans would incur a significant cost increase with minimal additional restoration. The 8 ft by 6 ft culvert meets the intended restoration benefit while not incurring the additional permitting and design requirements larger openings would require. Of note, as the channel in Upper Weir Creek remains unchanged in all of the culvert alternatives, saline waters do not penetrate as far into the system longitudinally but results in slightly more inundated area in the marsh flats laterally.

For the preferred alternative, the road elevation for Lower County Road was raised to 6.5 ft-NAVD88 to prevent overtopping during high frequency storm events (1% AEP, 5% AEP and tides with sea level rise). Although it is not anticipated for MassDOT to have jurisdiction on reviewing the proposed culvert designs, the roadway is classified as an urban minor arterial or rural major collector, and MassDOT's hydraulic standards indicate the replacement structure should pass a 4% AEP (25-year) storm with 2-feet of freeboard as well as consider future SLR. This would require a roadway elevation of 10.25 ft-NAVD88 to allow for two (2) feet of freeboard above the 8.25 ft-NAVD88 peak storm surge. This additional increase in elevation would provide limited protection as there are alternate flood pathways into the system and would not be practical based on the existing infrastructure and impacts to environmental resource areas adjacent to the project site. The low point along this section of roadway is currently at 3.5 ft-NAVD88. Raising the roadway is recommended as it would provide increased resiliency for coastal storms and future sea level rise. Based on review of the approach roadway elevations and adjacent properties, it was determined that raising the roadway to 6.5 ft-NAVD88 would be achievable and minimize impacts to adjacent infrastructure and resource areas with a low chord elevation of 5.25 ft-NAVD88 for both culverts.

## 5.1 PREFERRED ALTERNATIVE HYDRAULIC DESIGN SCENARIOS

To ascertain the performance of the preferred alternative under a wide range of possible conditions, five (5) scenarios were simulated with the preferred alternative in place. These hydraulic design scenarios were selected to replicate a robust array of surge events, determine the effects of projected sea level rise, and generate tidal benchmarks for the system. The intent is to assess extreme flow conditions that might lead to overtopping, scour and other potentially hazardous and damaging situations. The following model runs were completed for the preferred alternative:

- Typical tides (30-day simulation)
- Typical tides in 2070 (with 4.1 ft SLR) (7-day simulation)
- 10% AEP (10-year) surge event (7-day simulation)
- 2% AEP (50-year) surge event (7-day simulation)
- 1% AEP (100-year) surge event (7-day simulation)

Water levels corresponding to the calibration period at Lower Weir Creek at the Dennis Yacht Club (station WC1) were selected as the typical tide boundary conditions for these simulations (results discussed in previous section). To generate the future 2070 condition, 4.1 feet of sea level rise (SLR) was combined with the tidal measurements at station WC1 for the 2070 boundary conditions.

Low-frequency surge events causing extreme water levels in Weir Creek were developed based on the Massachusetts Coast Flood Risk Model (MC-FRM) which provides detailed data related to current and potential future flood conditions caused by coastal storm events, coupled with the changing climate (sea level rise and oceanic changes). MC-FRM was developed by Woods Hole Group under a separate contract with MassDOT. Peak water levels from the MC-FRM are listed in Table 8 along with the corresponding flood water levels used by FEMA for the current flood risk maps and water levels from The United States Army Corps of Engineers (USACE) North Atlantic Coast Comprehensive Study (NACCS). Additional FEMA maps for the area are listed in Appendix A, and MC-FRM data and maps for this area are provided in Appendix B.

**Table 8. Extreme coastal storm elevations extracted from FEMA, the MC-FRM, and the USACE North Atlantic Coastal Comprehensive Study for current Climatology.**

| Storm Event (2020) | FEMA (ft, NAVD88) | MC-FRM (ft, NAVD88) | NACCS ft, NAVD88) |
|---|---|---|---|
| **10% AEP** | 4.9 | 7.0 | 6.3 |
| **2% AEP** | 7.5 | 9.0 | 8.0 |
| **1% AEP** | 9.1 | 9.8 | 9.1 |

For the Weir Creek restoration, MCFRM water levels were selected as they are more recent and statistically robust than the FEMA water levels and provide an additional level of conservatism to the NACCS water levels. For storm simulations, the peak storm elevations from MC-FRM (listed in Table 8) were superimposed onto the observed water levels at the Dennis Yacht Club (station WC1). For each of the storms, a 48-hour duration was specified, with storm surge starting after 24 hours, peaking at 48 -hours, and returning to a normal, non-storm, tidal signal at 72 hours. While New England experiences storm surges from both hurricanes and nor'easters, hurricanes tend to have a shorter duration and the more significant flooding comes from the slower moving, longer duration nor'easters hence the 48-hour storm duration as opposed to a 24-hour duration more typical of a hurricane. The extreme storm time series of water levels are shown in Figure 37 for the 1% AEP (100-year), 2% AEP (50-year), 4% AEP (25-year), and 10% AEP (10-year) storm surge events for the current climatology while the projected 2070 storm water levels are shown in Figure 38, also based on MC-FRM including both increased storm frequency and projected sea level rise.

Currently, the road elevation of Lower County Road, shown as a blue line in Figure 39, has low points that coincide with the existing culverts (5 ft-NAVD88 in the west, and 3.5 ft-NAVD88 in the east) and are subject to overtopping below the 10% AEP, 10-year Annual Return Period (ARP) storm event. For the proposed design conditions, the model roadway centerline elevation was raised to 6.5 ft-NAVD88 to mitigate potential flooding during storm events at higher frequency levels. The proposed elevation, shown as a black dashed line was selected as any additional increase in elevation would require extensive grading affecting adjacent properties and to tie into existing gradation at the intersection of School Street, S. Main Street and Lower County Road to the west of the study area. While raising the roadway is not expected to provide substantial protection to the Upper Weir Creek sub-basin during storm events, the increased capacity of the 8x6 foot box culvert will allow storm surge to recede faster, reducing the duration of ponding following a storm.

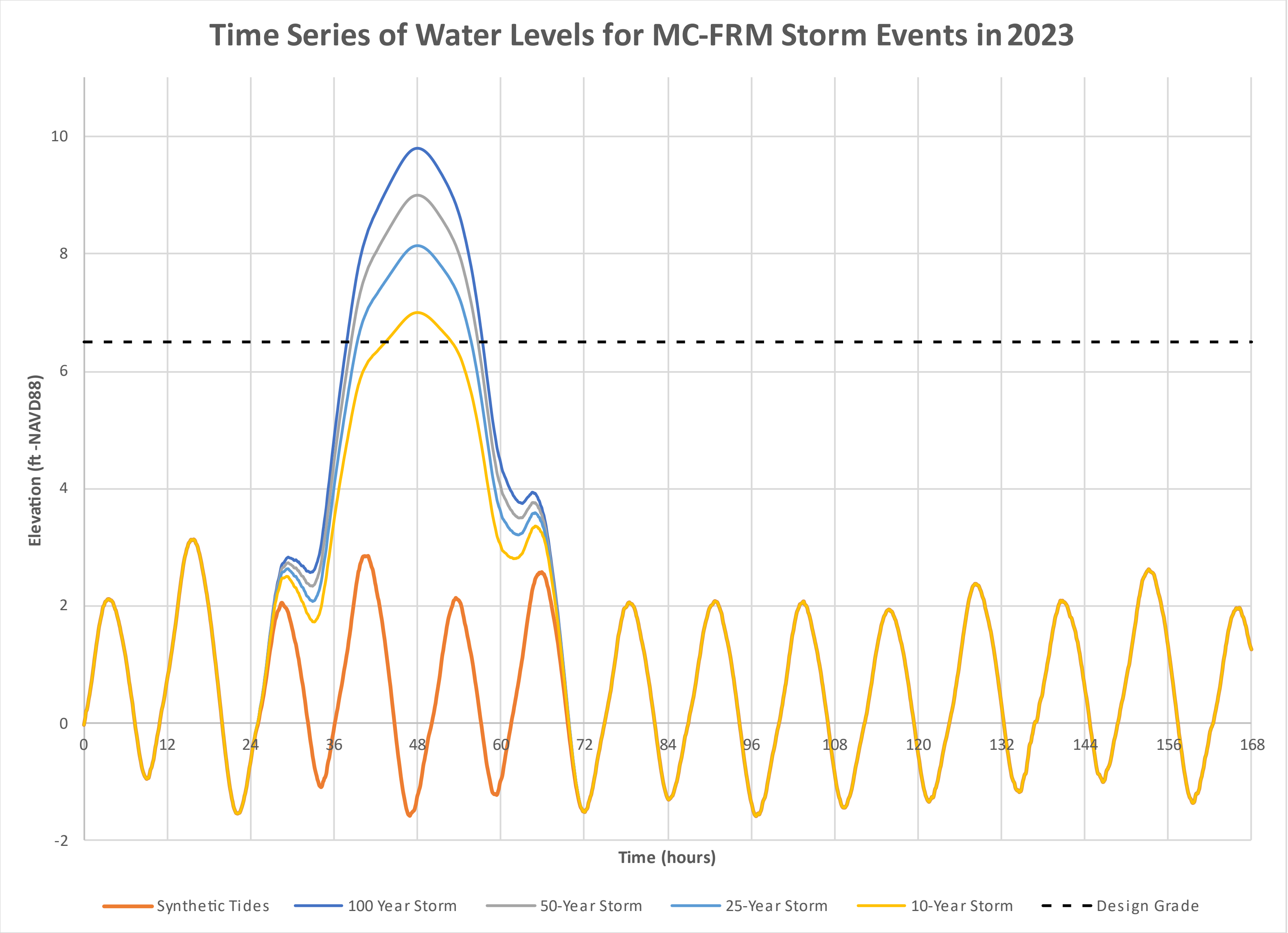


**Figure 37. Peak water levels from the MC-FRM superimposed on the observed water levels at station WC1 in Weir Creek in 2023.**

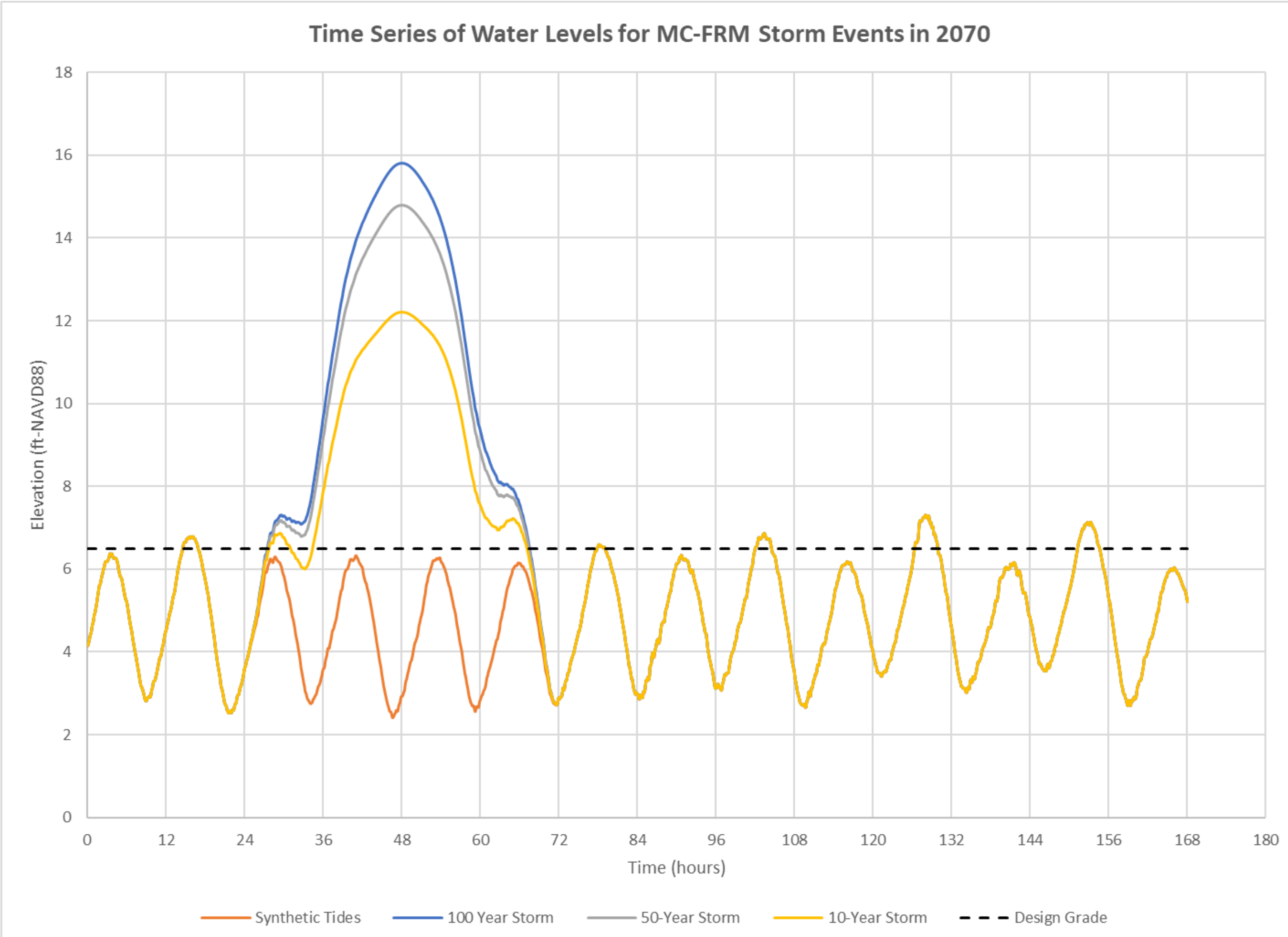


**Figure 38.** **Peak storm water levels from the MC-FRM in Weir Creek in 2070.**

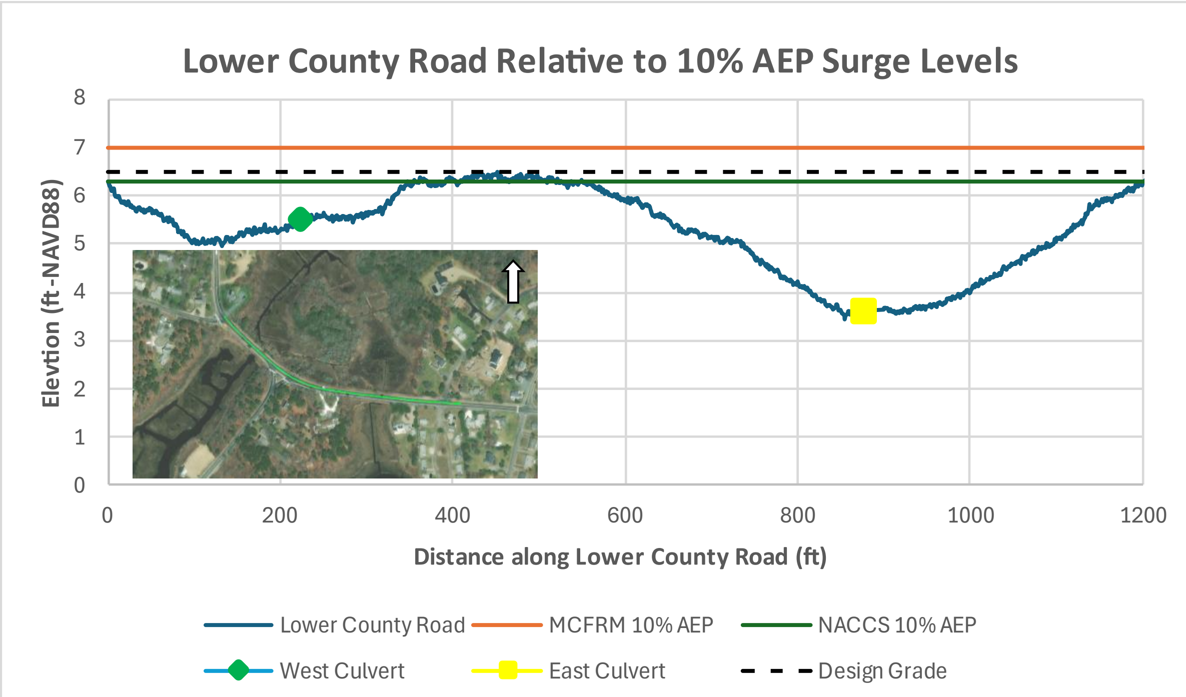


**Figure 39.** **Elevation profile along the Lower County Road centerline. Transect shown as a green line on the inset image.**

## 5.2 PREFERRED ALTERNATIVE SIMULATION RESULTS

### 5.2.1 Future Climatology Tidal Simulation Results

Both the preferred alternative and existing conditions were assessed during typical tidal conditions, discussed as part of the selection process, as well as tidal conditions with 4.1 ft of SLR in order to determine what changes might be expected to occur relative to existing conditions. Each simulation was conducted for a 7-day period to allow for direct comparison to sea level rise response for existing conditions. Figure 40 shows times series of water levels at the western crossing of Lower County Road (stations WC3 and WC7) while Figure 41 shows water levels a progressively farther upstream in the Upper Weir Creek subsystem (WC7 and WC10). A design roadway elevation of 6.5 ft-NAVD88 at Lower County Road is potentially overtopped during higher high tides with the conservative 4.1 feet of sea level rise, however the larger culvert (shown on all figures in blue) is expected to provide additional drainage capacity compared to the existing culverts (shown in orange). The existing (blue) water levels started at a lower initial water level (1.3 ft-NAVD88) however, after the initial flood tide, the water levels during ebb tides are higher upstream with the existing culvert as a result of reduced drainage capacity.

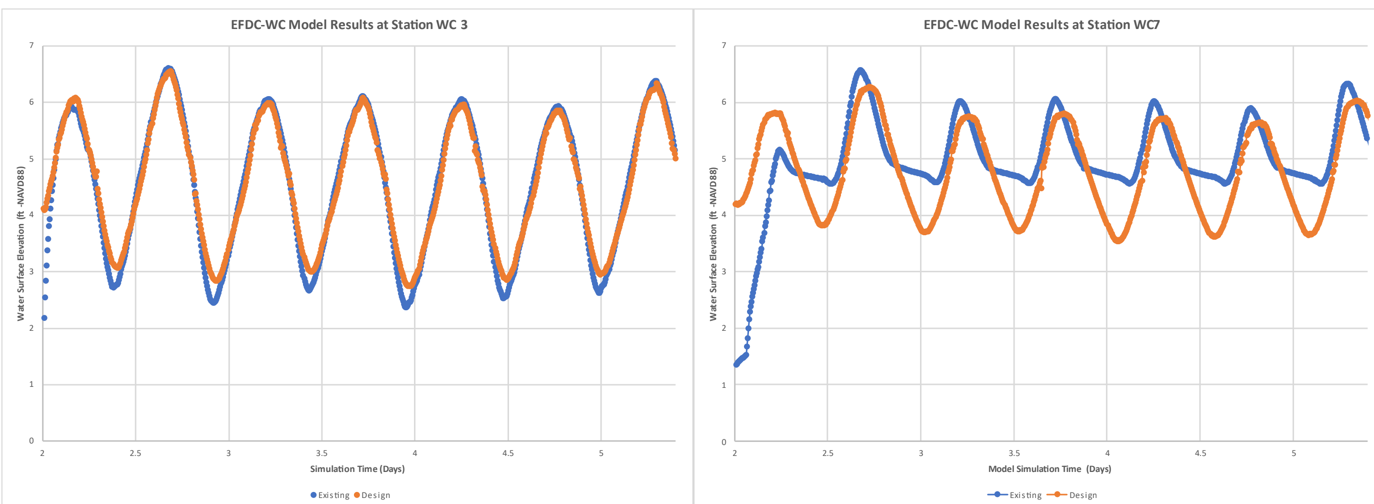


**Figure 40. Downstream (left) and upstream (right) water levels in Weir Creek in 2070 tides at the western crossing for the existing pipe (blue) and the 8x6 design culvert (orange).**

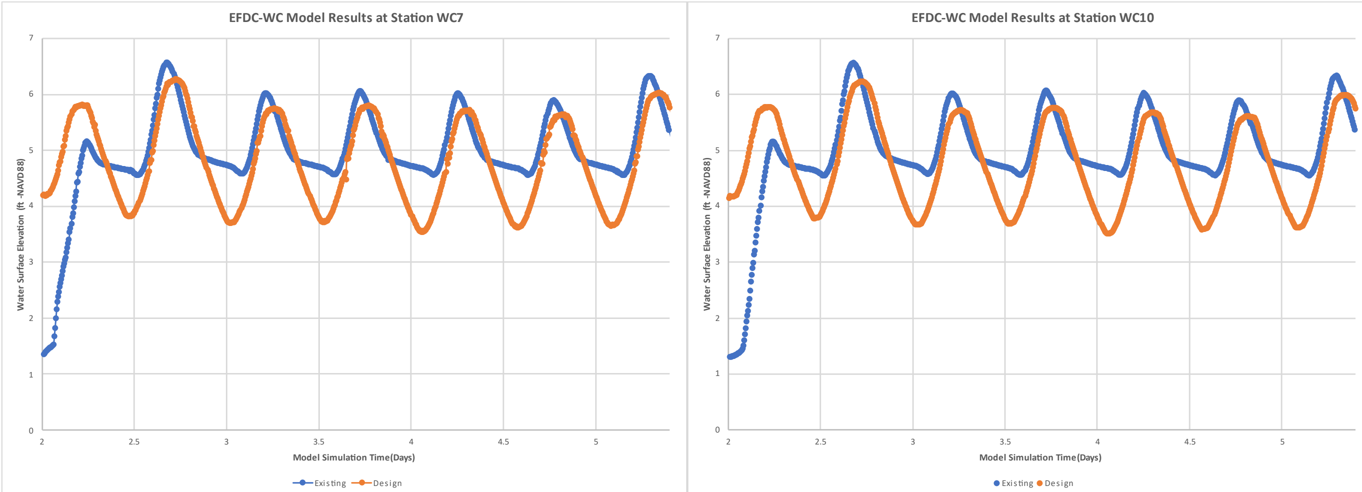


**Figure 41. Immediately upstream (left) and of the western crossing and father upstream in the Upper Weir Creek subsystem (right) for the existing pipe (blue) and the 8x6 design culvert (orange).**

Water levels at each of the other monitoring points in the restored Weir Creek estuarine system are shown in Figure 42 through Figure 45 for typical tides with 4.1 feet of SLR representing conditions in 2070. On each figure, the existing culvert configuration is shown in blue and the 8x6 design culvert configuration is shown in orange. At stations WC2, WC4, and WC8, there is a slight reduction in water levels with the existing culvert, as more of the tidal flow is stored in the upstream basins (this can be attributed to the lower initial water level). After the Lower Weir Creek system equilibrates to the new higher water level, the tidal signals are similar between existing conditions and the proposed culvert. At station WC10 in the upper Weir Creek sub-basin, water levels are higher after equilibration with the existing culvert due to sheet flows over the roadway and the reduced drainage capacity leading to higher low tide elevations.

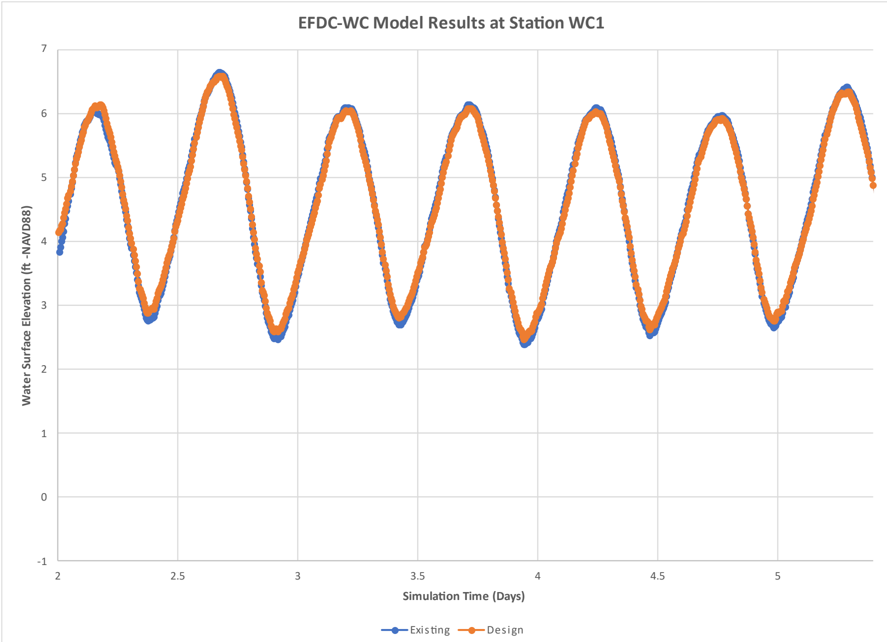


**Figure 42.** **Comparison of water levels in Weir Creek at the Dennis Yacht Club (WC1).**

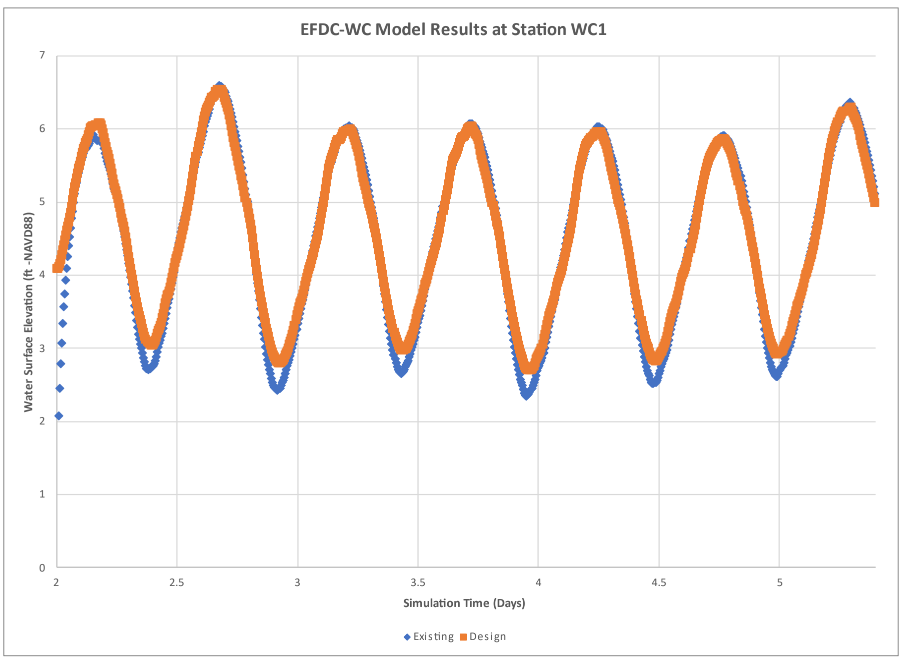


**Figure 43.** **Comparison of water levels in Weir Creek upstream of Loring Avenue (WC2).**

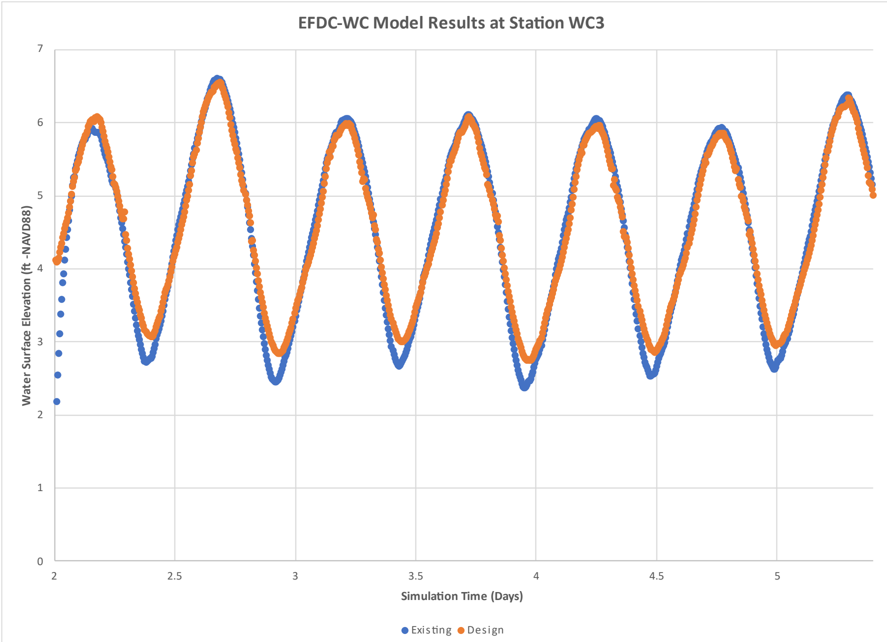


**Figure 44. Comparison of water levels at Lighthouse Road (WC4).**

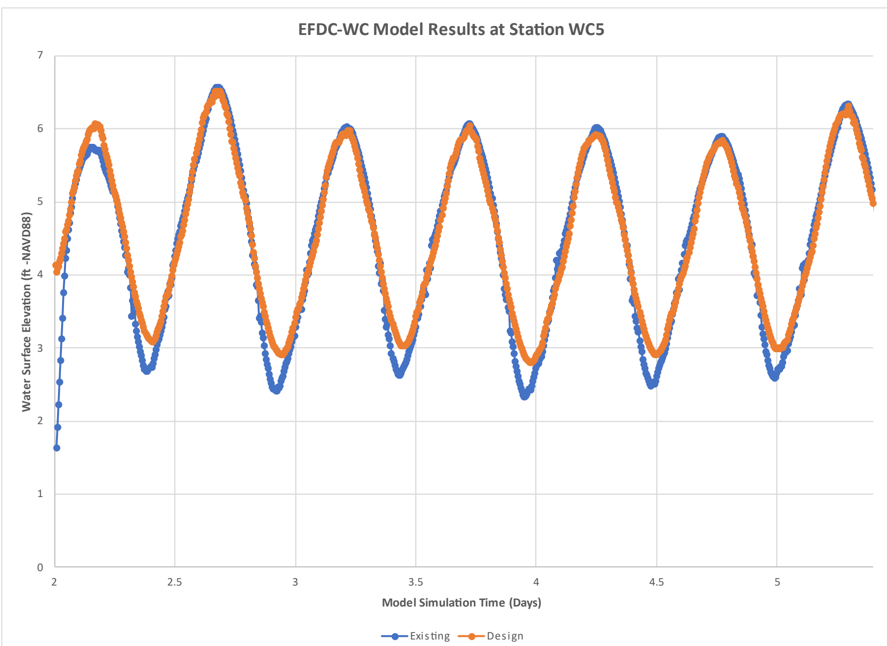


**Figure 45. Comparison of water levels in the Uncle Stephen's Pond sub-basin (WC5).**

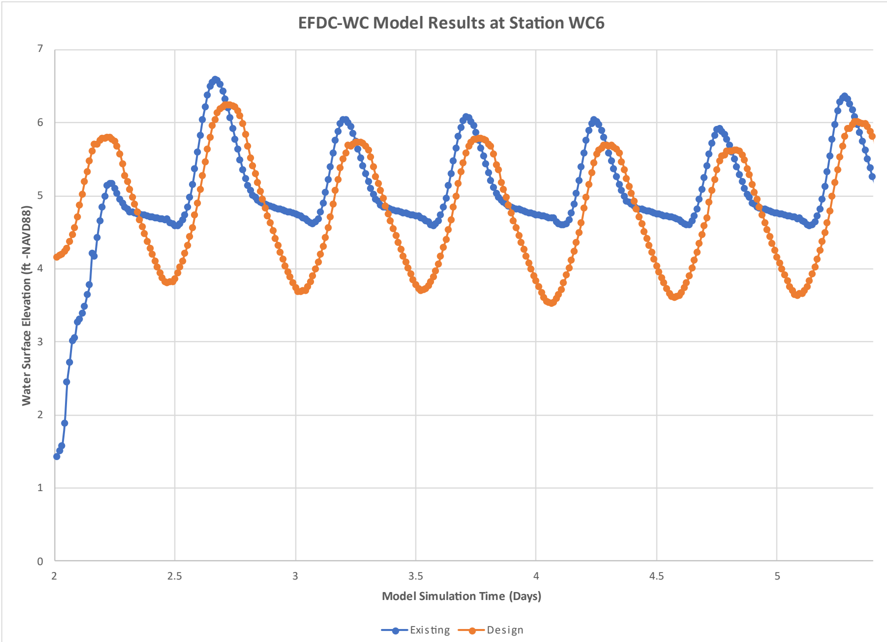


**Figure 46.** **Comparison of water levels in the Uncle Stephen's Pond sub-basin upstream of Lower County Road (WC6).**

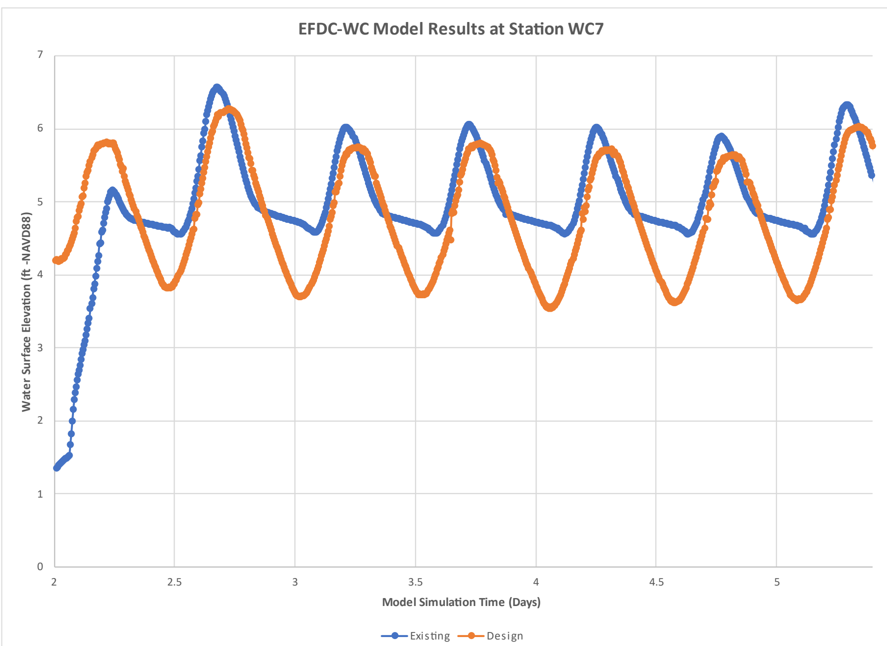


**Figure 47.** **Comparison of water levels in Upper Weir Creek upstream of Lower County Road (WC7).**

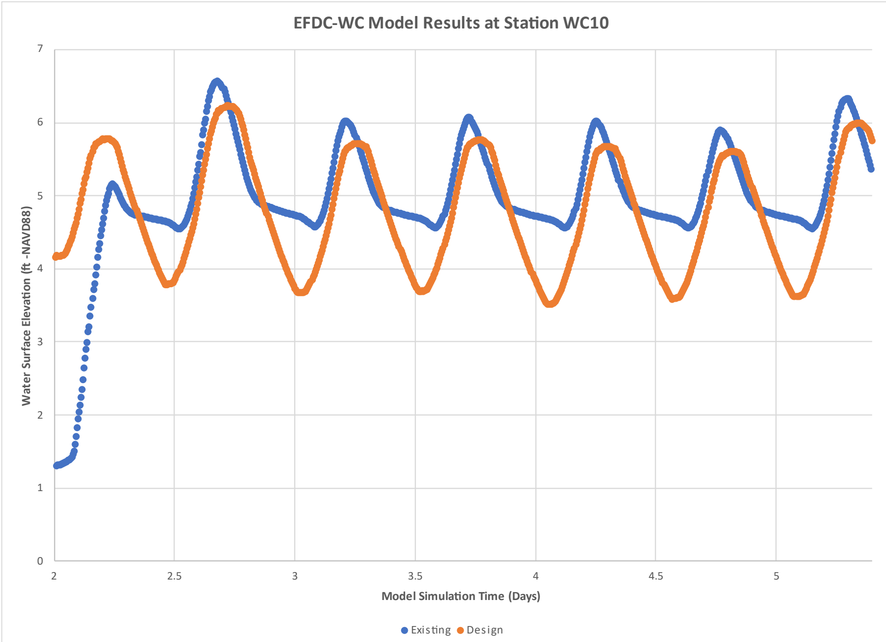


**Figure 48. Comparison of water levels in Upper Weir Creek upstream in Upper Weir Creek (WC10).**

### 5.2.2 Storm Simulation Results

Three different storm scenarios were simulated for each design alternative corresponding to the 2% AEP, and 1% AEP storm events. While the proposed culvert will allow more water into the system prior to roadway overtopping, the current road elevation and culvert configuration overtop earlier in the storm resulting in similar flood patterns. Not included in the EFDC-WC model are the potential for alternate flood routes into the system over the barrier dunes and properties to the southeast, although during lower frequency storms water from Nantucket Sound is likely to enter the system directly rather than exclusively through the Loring Avenue bridge opening.

Flood events for both existing and design conditions are shown for each storm event in Figure 49 for the 10% AEP storm, Figure 51 for the 2% AEP storm, and Figure 52 for the 1% storm. Flooding for all storm events is similar both in elevation and extents as shown in the center panel of each of the figures. Following the surge events, water levels in Upper Weir Creek return to pre-surge tidal levels with the following tide for the improved culvert crossing, while flood waters remain in the upper reaches for multiple days under existing conditions as shown on Figure 50.

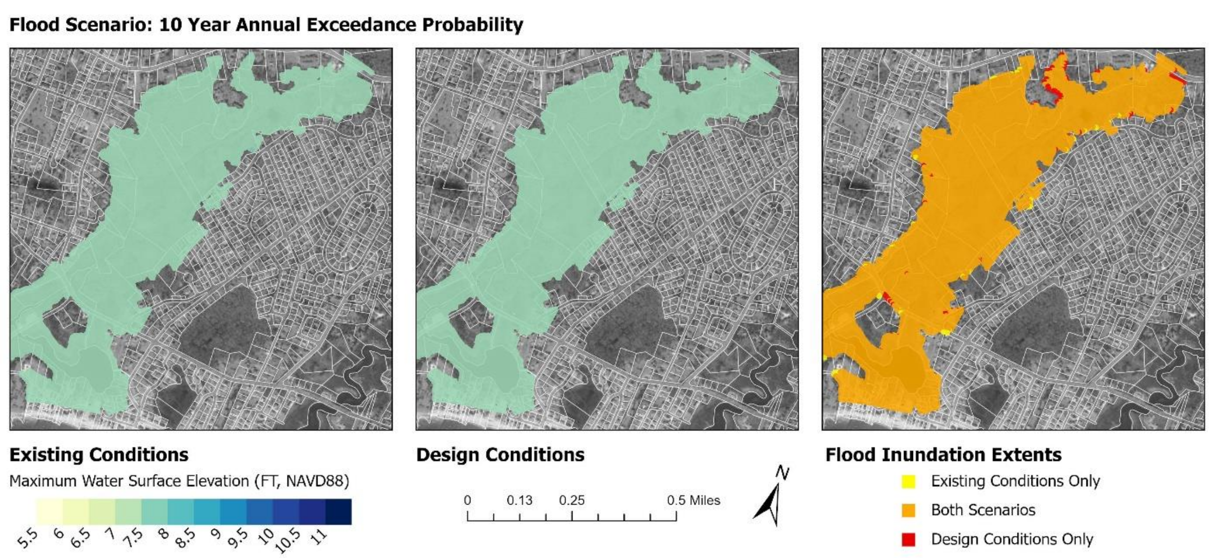


**Figure 49.** **Flood extents in the Weir Creek system for the present day 10% AEP storm event for existing (left) and design (center) conditions.**

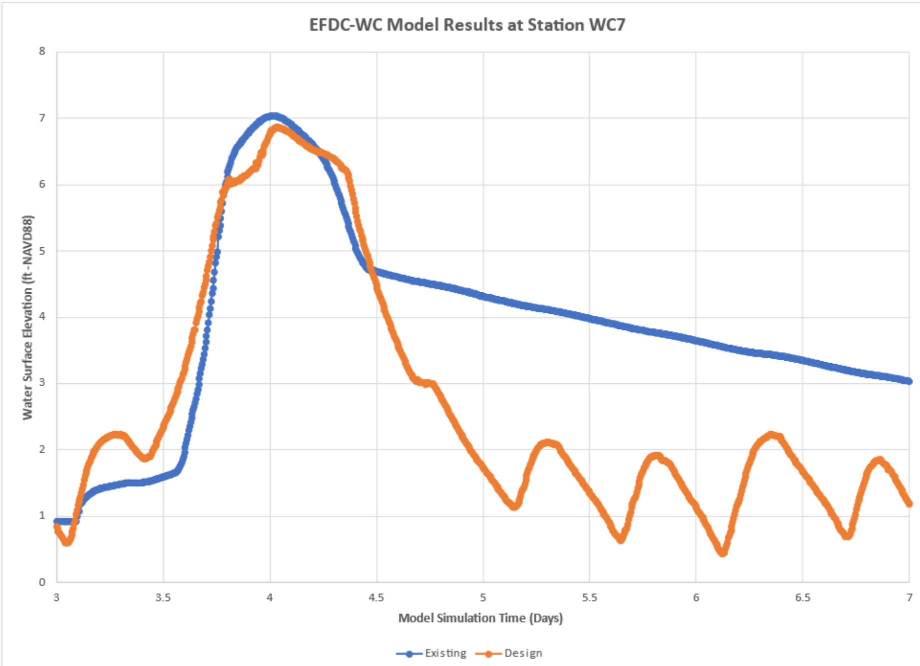


**Figure 50. Time series of water surface elevations upstream of the western Lower County Road crossing during the 10% AEP storm event.**

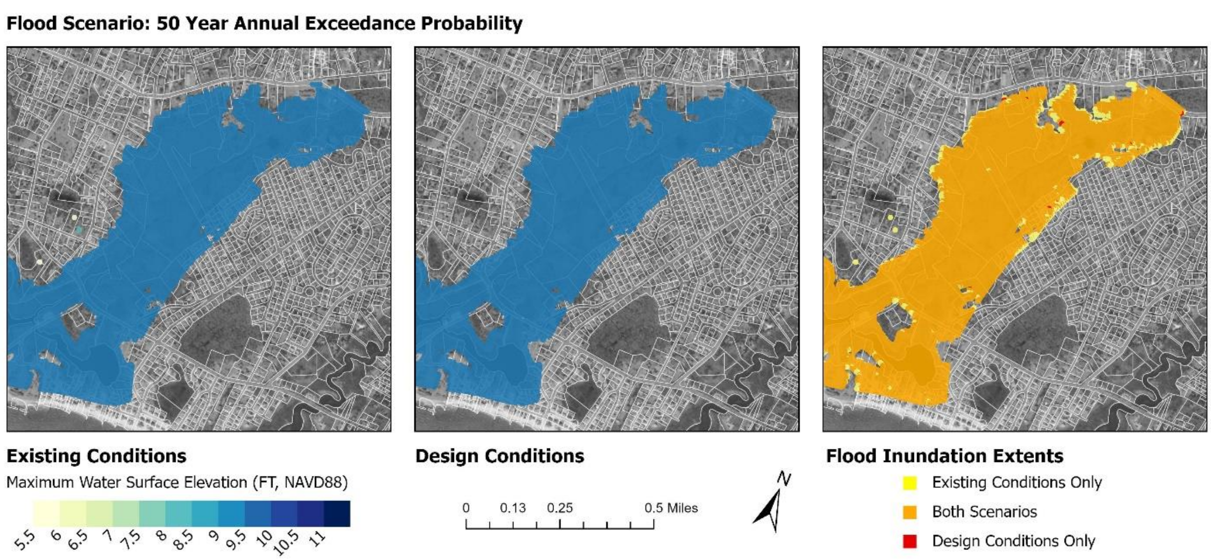


**Figure 51. Flood extents in the Weir Creek system for the present day 2% AEP storm event for existing (left) and design (center) conditions.**

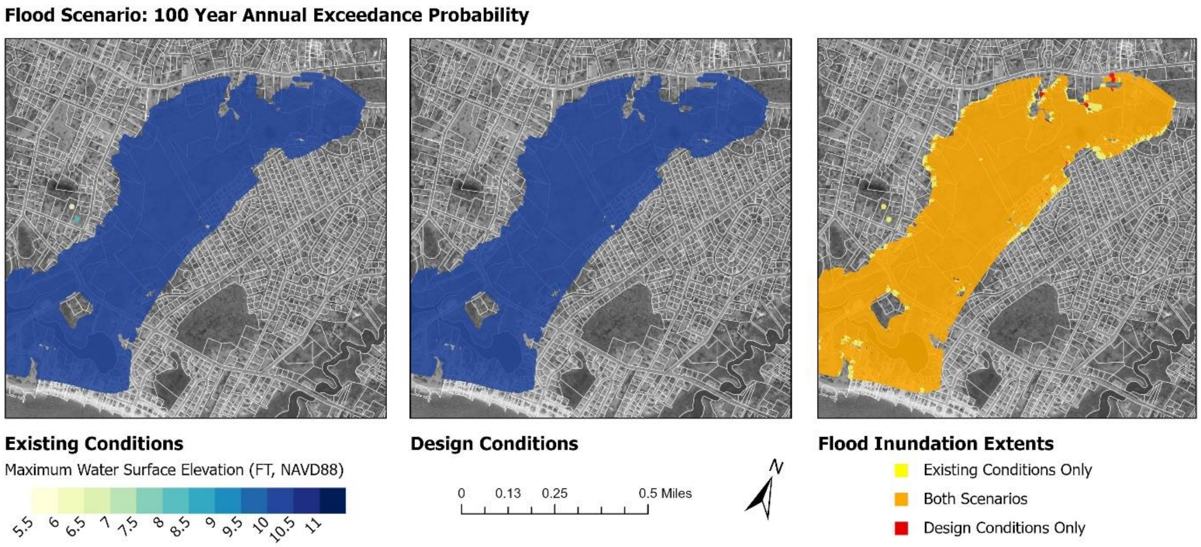


**Figure 52. Flood extents in the Weir Creek system for the present day 1% AEP storm event for existing (left) and design (center) conditions.**

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

This H&H study was focused on restoring tidal flow through the crossings at Lower County Road and thereby restoring salt marsh habitat in the upper reaches of Weir Creek while increasing drainage during low-frequency surge events and with future projections of sea level rise. While the crossing at Fisk Street was shown to restrict tidal exchange between Weir Creek and Kelley's Pond, the existing Fisk Street culvert was not considered in the evaluation of potential restoration/improvement alternatives.

The study included a field assessment to gain a better understanding of the existing tidal hydrology within the system. Ten (10) tide gauges were deployed to understand the existing tidal dynamics in Lower and Upper Weir Creek, Kelley's Pond, and the Uncle Stephen's Pond subsystems, with gauges located upstream and downstream of each of the roadways. Water levels were collected over a 39-day deployment which showed a marked reduction in tide range moving upstream from 2.3 feet at the Dennis Yacht Club to a minimum of 0.3 feet in the upper Weir Creek sub-basin.

To further investigate existing conditions and to evaluate possible resilience and marsh restoration alternatives, a 2-D hydrodynamic model (EFDC-WC) was developed for the estuarine system. Key findings with regards to water levels, potential for restoration, added benefits for resiliency, and any secondary adverse impacts are listed as follows:

- The bridge crossing at Loring Avenue restricts flows during ebb tides as a result of the large flood shoal created by high velocity flows depositing sediments upstream of the bridge crossing.

- The low roadway elevations at Lower County Road allow for surge events to propagate over the roadway at approximately the 10% AEP (10-year) storm level.

- A maximum restoration scenario, involving expanded bridge openings at both Loring Avenue and Lighthouse Road and dredging of the ebb shoal, and channels in Upper Weir Creek and Uncle Stephen's Pond will allow for a reduction in water levels during ebb tides, but was not considered a feasible alternative at this time due to uncertainty of bridge replacement.

- Replacement of the existing pipe culverts at both the eastern and western crossings of Lower County Road will allow additional saltwater to enter the upper reaches of the system increasing the average salinity thereby encouraging salt marsh habitat and reducing invasive vegetation.

- Increasing the existing roadway elevation of Lower County Road to 6.5 ft-NAVD88 will prevent overtopping of the roadway during storm events lower than the 10% AEP storm level and mitigate overtopping of the roadway with a projected estimate of 4.1 feet of sea level rise in 2070 while raising the roadway elevation to 7.25 ft-NAVD88 would prevent overtopping at the 10% AEP level and prevent overtopping of the roadway in 2070 after incurring 4.1 feet of sea level rise.

- In order to maintain construction clearance for a roadway elevation of 6.5 ft-NAVD88, a maximum opening height of 6 feet at each crossing is allowable at existing channel gradation. Larger height box culverts can be utilized with the bottom of the culvert covered in native sediment.

- Replacement of the existing culverts with two (2) 8'x6' box culverts will provide additional tidal exchange with an increase in MHW levels to meet the goals of the tidal restoration project.

- Following storm events, the larger 8'x6' culverts will provide additional drainage capacity allowing the system to return to pre-surge water levels more quickly than the undersized culverts currently in place.

## 7.0 REFERENCES

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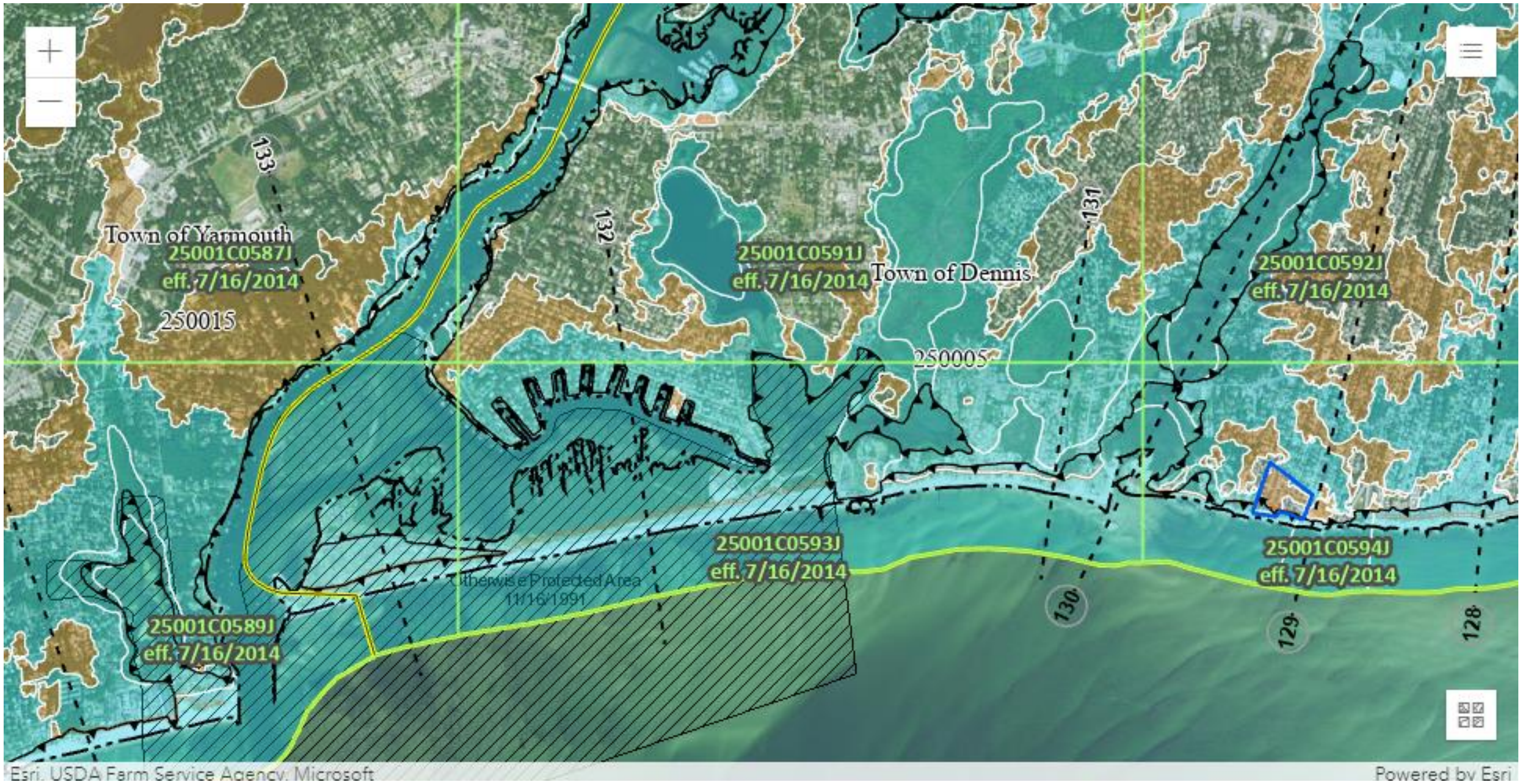
## APPENDIX A: FEMA DATA AND MAPS

| FEMA Stillwater Elevations (Barnstable County Flood Insurance Study, Effective July 16, 2014) in FT-NAVD88 | | |
|---|---|---|
| | Coastal Transect 132 | Coastal Transect 133 |
| 10%-Annual Chance | 4.9 | 4.9 |
| 2%-Annual Chance | 7.5 | 7.5 |
| 1%-Annual Chance | 9.1 | 9.1 |
| 0.2%-Annual Chance | 13.9 | 13.9 |

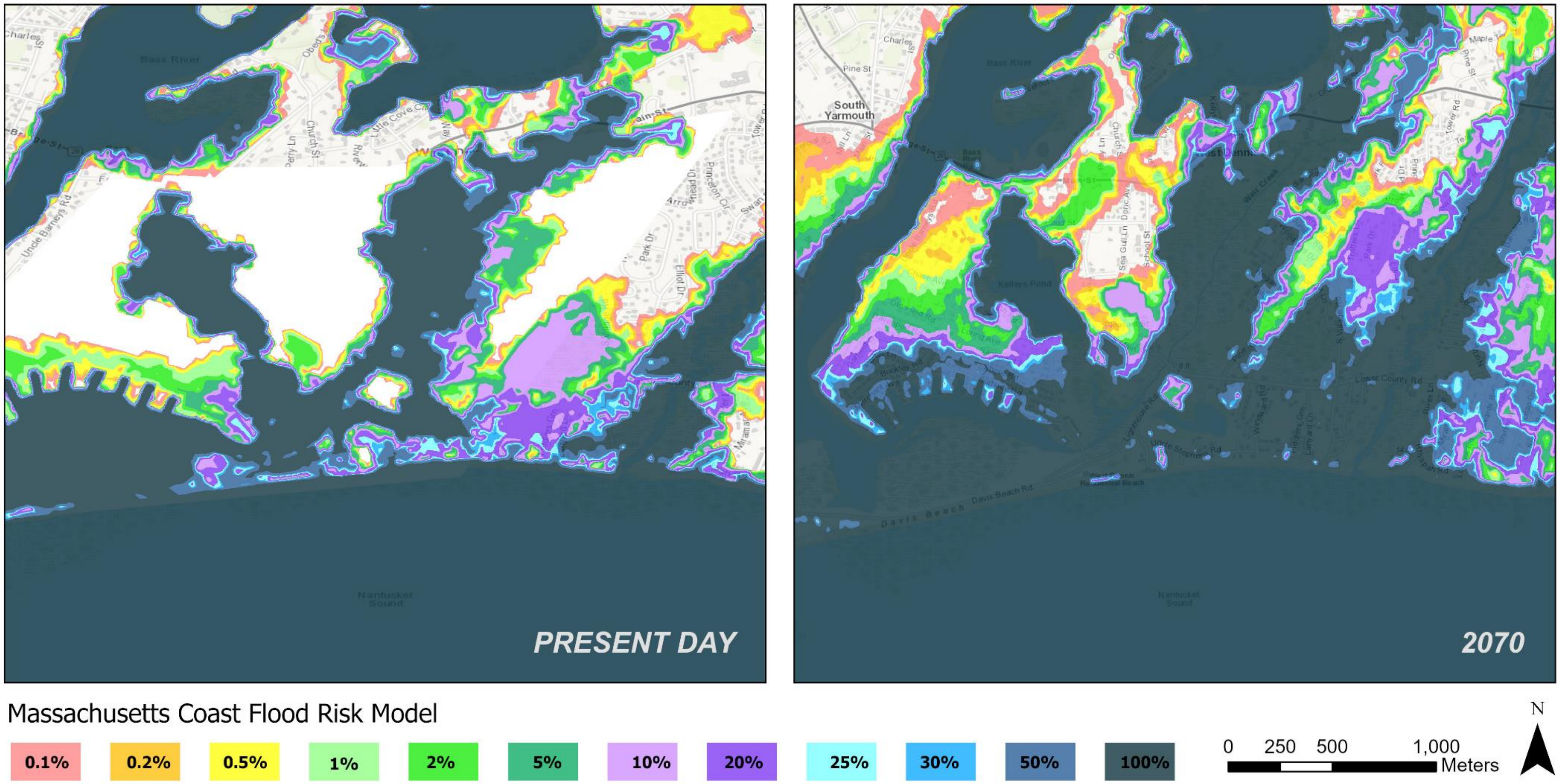

Town of Yarmouth
25001C0587J
eff. 7/16/2014
250015
133
132
25001C0591J
eff. 7/16/2014
Town of Dennis
250005
131
25001C0592J
eff. 7/16/2014
25001C0593J
eff. 7/16/2014
25001C0594J
eff. 7/16/2014
25001C0589J
eff. 7/16/2014
130
129
128
Esri, USDA Farm Service Agency, Microsoft
Powered by Esri

## APPENDIX B: MC-FRM DATA AND MAPS

This table consists of the low frequency storm event water levels from the Massachusetts Coast Flood Risk Model (MC-FRM) for Bass River in Dennis, MA for the respective Annual Exceedance Probability (AEP) and Average Recurrence Period (ARP). The present-day Water Surface Elevations (WSEs) reflect storm current climatology and sea levels, while the future climatology WSEs account for both future changes in storm climatology and sea level rise.

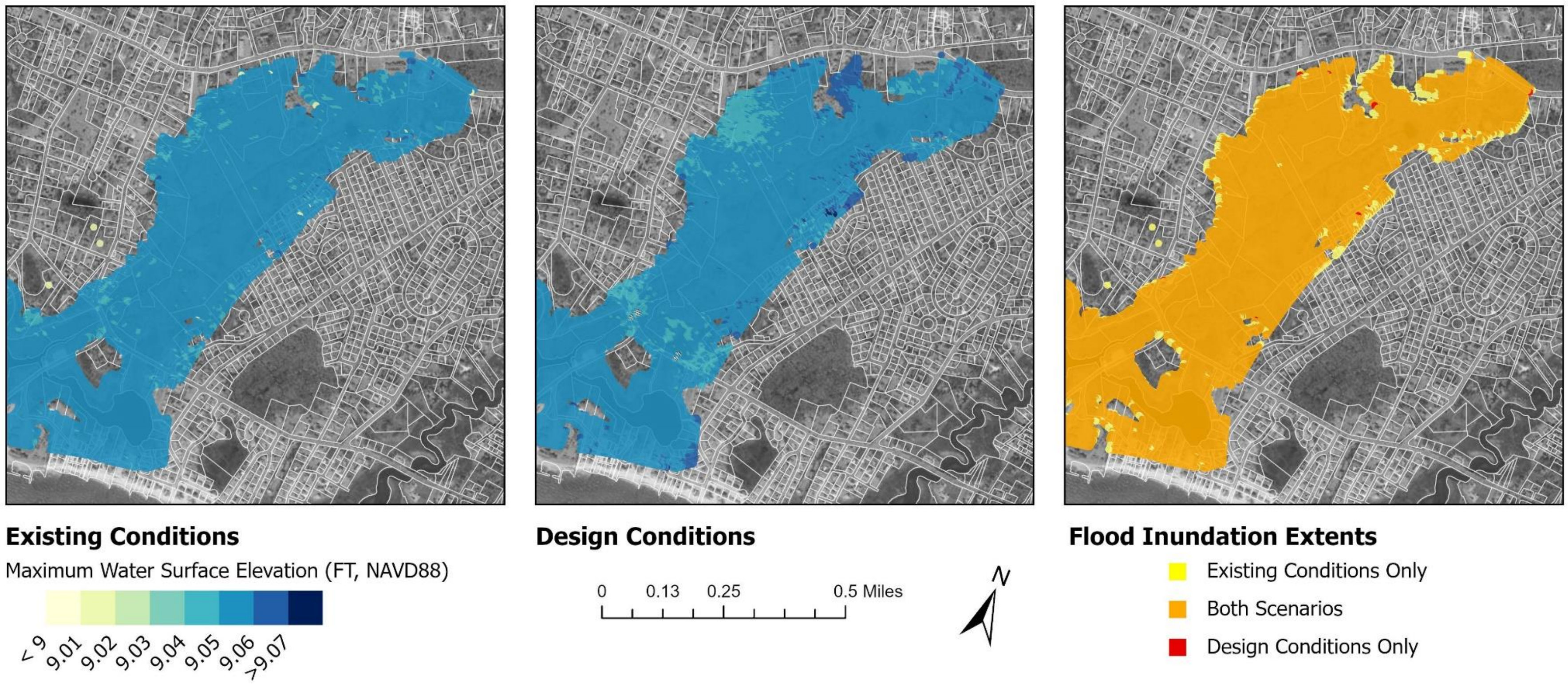
**Low frequency storm event water levels for present and future climatology. All Elevations are ft-NAVD88.**

| AEP (%) | ARP (years) | Present | 2030 | 2050 | 2070 |
|---|---|---|---|---|---|
| 0.5 | 200 | 10.6 | 11.7 | 15.5 | 16.9 |
| 1.0 | 100 | 9.8 | 10.9 | 14.4 | 15.8 |
| 2.0 | 50 | 9.0 | 10.1 | 13.3 | 14.8 |
| 5.0 | 20 | 7.9 | 9.0 | 11.8 | 13.3 |
| 10.0 | 10 | 7.0 | 8.2 | 10.7 | 12.2 |

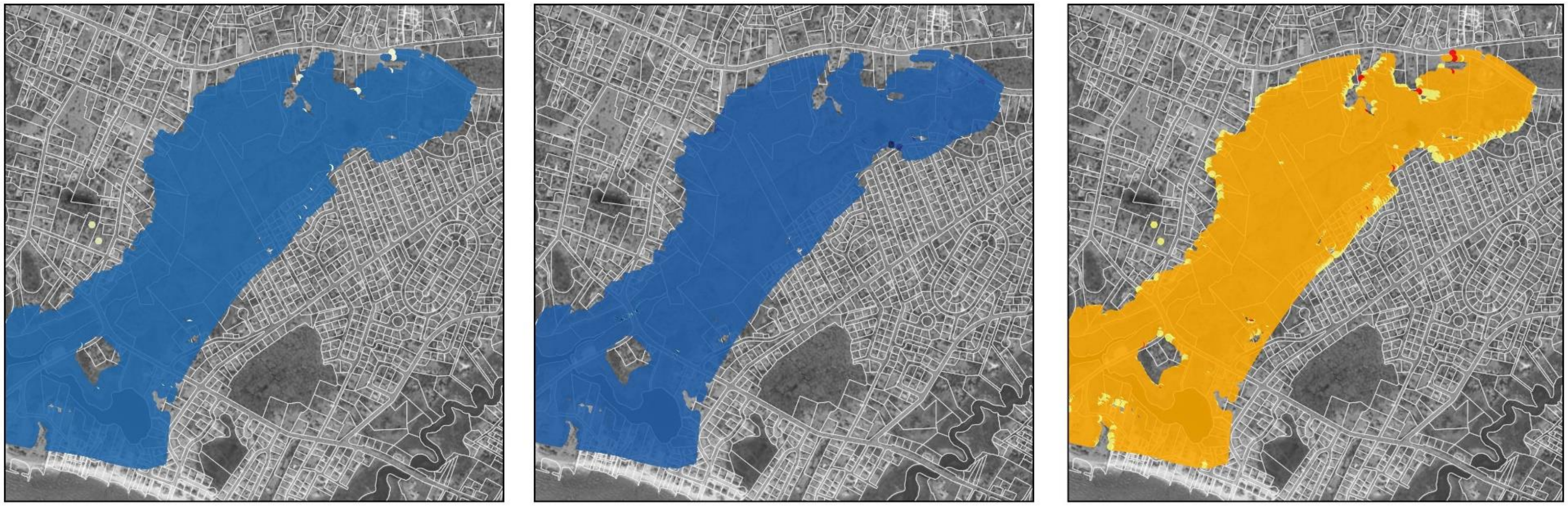

PRESENT DAY
2070
Massachusetts Coast Flood Risk Model
0.1%
0.2%
0.5%
1%
2%
5%
10%
20%
25%
30%
50%
100%
0
250
500
1,000
Meters
N

## APPENDIX C: INUNDATION EXTENTS FROM EFDC-WC MODELING

**Flood Scenario: 50 Year Annual Exceedance Probability**



**Flood Scenario: 100 Year Annual Exceedance Probability**



**Existing Conditions**

Maximum Water Surface Elevation (FT, NAVD88)

9.2 9.3 9.4 9.5 9.6 9.7 9.8 9.9 10.0 10.1 >10.2

**Design Conditions**

0 0.13 0.25 0.5 Miles

N

**Flood Inundation Extents**

- Existing Conditions Only
- Both Scenarios
- Design Conditions Only

## APPENDIX D: ALTERNATIVES ANALYSIS VELOCITIES

**Peak instantaneous velocities during normal tides for each restoration alternative.**

| | Channel at Eastern Crossing of Lower County Road | | | | Channel at Western Crossing of Lower County Road | | | |
|---|---|---|---|---|---|---|---|---|
| **Opening** | **Upstream Invert (ft-NAVD88)** | **Downstream Invert (ft-NAVD88)** | **Upstream Peak Velocity (ft/s)** | **Downstream Peak Velocity (ft/s)** | **Upstream Invert (ft-NAVD88)** | **Downstream Invert (ft-NAVD88)** | **Upstream Peak Velocity (ft/s)** | **Downstream Peak Velocity (ft/s)** |
| Existing | -0.75 | -0.77 | 0.25 | 0.86 | -1.2 | -1.3 | 0.16 | 0.65 |
| 2 FT | -0.75 | -0.77 | 0.62 | 1.00 | -1.2 | -1.3 | 1.15 | 1.63 |
| 6 FT | -0.75 | -0.77 | 0.87 | 1.01 | -1.2 | -1.3 | 1.57 | 1.12 |
| 10 FT | -0.75 | -0.77 | 1.15 | 1.38 | -1.2 | -1.3 | 1.38 | 1.27 |
| 14 FT | -0.75 | -0.77 | 1.35 | 1.50 | -1.2 | -1.3 | 1.01 | 1.43 |
| 18 FT | -0.75 | -0.77 | 2.48 | 1.15 | -1.2 | -1.3 | 1.60 | 1.59 |
| Max | -0.82 | -0.82 | 2.75 | 0.60 | -0.81 | -0.81 | 0.90 | 1.81 |