

## SECTION 22 - PLANNING ASSISTANCE TO STATES PROGRAM

# Pamet River Investigation Truro, Massachusetts



November 2019



US Army Corps  
Of Engineers  
New England District



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## EXECUTIVE SUMMARY

### 1. Introduction

The purpose of the Pamet River investigation is to develop and evaluate potential alternatives to improve tidal flow upstream of Wilder's Dike and Route 6 while also improving river drainage following overtopping events at Ballston Beach. During the course of the study, alternatives were evaluated to modify existing culverts and tide gate at Wilder's Dike and Route-6 in Truro, Massachusetts (Figure 1). The United States Army Corps of Engineers (USACE) New England District study team built upon a previous Pamet River analysis conducted by the USACE in 1998 that evaluated tidal flow within the Pamet River and presented the advantages and disadvantages of restoring tidal flow. This study supplements the prior investigation by utilizing robust datasets combined with modern hydraulic and groundwater numerical computer models. The numerical model analyses presented in this report, further define potential impacts with reintroducing tidal flow to the upper portion of the Pamet River.

The Pamet River, located in town of Truro, Massachusetts, is an estuarine and freshwater river system consisting of three stream branches that meet to form Pamet Harbor before discharging to Cape Cod Bay (see Figure 1). The main branch of the river system is the Pamet River, which is about 2.5 miles long extending from Ballston Beach west to Pamet Harbor. The other two branches, Little Pamet River to the north and Eagles Neck Creek to the south, are tributaries to the main branch of the Pamet River. This study focuses on the main branch of the Pamet River system.

The main branch of the Pamet River is divided into two hydrologically separate sections by Wilder's Dike and its associated tide gate. The upper Pamet extends from Ballston Beach to Wilder's Dike and supports a freshwater environment, which is almost entirely contained within the Cape Cod National Seashore. The freshwater portion is fed primarily through groundwater and surface runoff east of Wilder's Dike. The lower Pamet contains saltwater and is located west of Wilder's Dike. The portion west of Wilder's Dike is tidally influenced and contains salt marsh characteristics.

Wilder's dike was constructed in 1869 to replace a wooden bridge that once crossed the Pamet River in this location. The dike includes an approximately 4.0 foot diameter culvert with a tide gate system that has been modified and replaced numerous times since the original "clapper valve" was installed. The tide gate remains open during periods of low tide (allowing the upper Pamet to flow downstream) and closes during high tide to prevent



Saltwater intrusion east of the dike to the upper Pamet. The Route 6 embankment and culvert system was constructed in the 1950s. An open 4.0-foot diameter culvert allows flow through the Route 6 embankment east of the dike.

The freshwater head of the Pamet River is located directly behind Ballston Beach along the Atlantic Ocean. In recent years, there have been numerous instances of oceanic overtopping at Ballston Beach leading to saltwater intrusion at the headwaters of the Pamet.

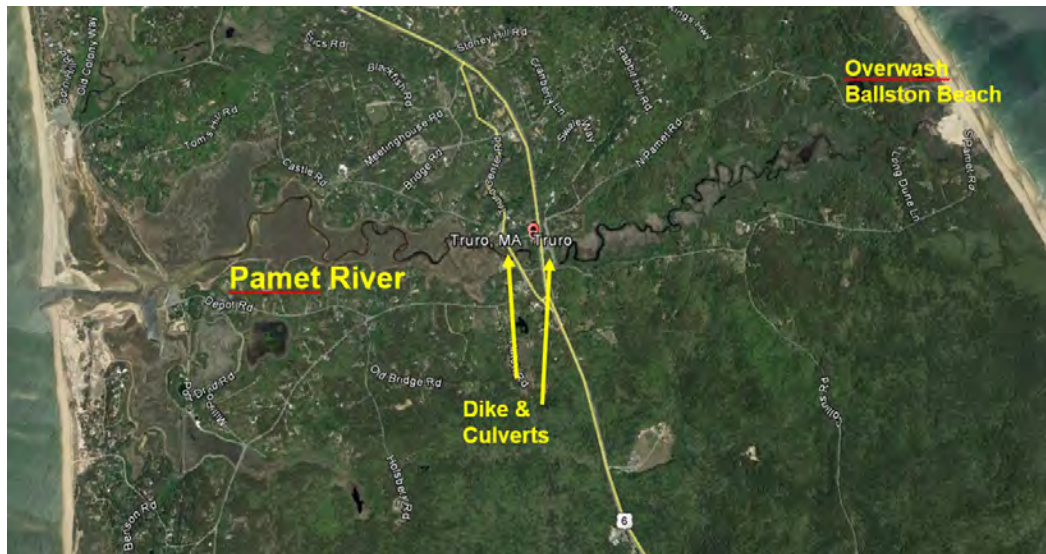


Figure 1. Pamet River Location, Truro, MA

Flooding of the upper Pamet during severe storm events is primarily associated with overtopping at Ballston Beach, results in the subsequent loss or degradation of vegetation due to saltwater intrusion and has been identified as a problem for this watershed . Ballston Beach has been overtopped on numerous occasions with a significant event occurring recently during the Nor'easter storm of March 2018. Despite the destruction of the tide gate at Wilder's Dike during the 2018 event, it took multiple weeks for the large inflow of sea water to drain as a result of culvert constrictions at Wilder's Dike and Route 6. During these overtopping events, these constrictions created adverse flooding impacts to local property owners and roadways by restricting drainage of sea water from the upper river system to Cape Cod Bay.

## 2. Study Authority and Report Organization

Under the authority provided by Section 22 of the Water Resources Development Act of 1974 (PL 93-251), as amended, the Corps of Engineers can provide states, local government,

other non-Federal entities, and eligible Native American Indian tribes assistance in the preparation of comprehensive plans for the development, utilization, and conservation of water and related land resources. Typically, these studies include only planning level of detail; they do not include detailed design for project construction.

Types of studies conducted in recent years under the program include the following: water supply/demand, water conservation, water quality, environmental/conservation, wetland evaluation/restoration, dam safety/failure, flood damage reduction, coastal zone protection, and harbor planning. Efforts under the Section 22 program are cost shared on a 50 percent Federal – 50 percent non-Federal basis. The non-federal sponsor for this effort was the Town of Truro, Massachusetts.

This document presents the supporting data, methodology, analysis, limitations, and conclusions to meet the objectives requested by the non-federal sponsor within the authorized Section 22 Planning Assistance to States framework. Team meetings and conference calls between the USACE project team and the non-federal sponsor were conducted to discuss the investigation and objective status, plus historical and real-time field data collection, and limitations, including (but not limited to):

- USACE Continuous tidal monitoring and hydraulic conductivity data,
- USGS hydraulic conductivity data for groundwater model salinity calibration,
- Dynamic wave over-topping events and associated impacts to the study area,
- Wilder's Dike tide gate impairment during data collection period (Nor'easter of March 2018).

The Pamet River investigation presented in this report is composed of eight chapters. The first chapter details the analysis of culvert modification alternatives at Wilder's Dike and Route 6. Chapter 2 presents a proposed multi-objective watershed planning model, which could be used by the town of Truro to assist and inform water resource decision making within the Pamet watershed. Chapter 3 contains a data/literature review of relevant background information that guided the USACE team during the course of the study. Chapter 4 presents a conceptual site model (CSM) of the freshwater-saltwater interface within the Pamet watershed developed from regional understanding of the groundwater flow paths and applied to the data collected and groundwater modeling conducted, as part of this study. Chapter 5 details the Pamet River field data instrumentation, collection, validation and qualitative-data analysis. The Pamet River Groundwater Modeling analysis (MODFLOW 2000) is presented in Chapter 6 and the Pamet River Riverine Model analysis with proposed alternatives (HEC-RAS) in Chapter 7. Finally, Chapter 8 concludes the report with the upper Pamet River ecosystem survey, assessment and determination.

Due to the large number of figures referenced in the report chapters, these figures are presented separately within six attachments to improve the readability of the report text. These six attachments span “A” thru “F”, and correlate with the identified chapter, as presented in the Table of Contents and referenced. Additionally, the following three attachments will be delivered to the town of Truro through digital means: Attachment G: the raw field data files; Attachment H: the MODFLOW groundwater model; Attachment I: the HEC-RAS riverine model.

### 3. Study Objectives

The Town of Truro requested that the USACE New England District update and expand upon previous Pamet River surface water and groundwater investigations (completed in 1998 by the USACE) to meet the following objectives:

- Recommend alternatives to modify the Wilder’s Dike and Route 6 culvert systems: develop the HEC-RAS model to compute flow rates, calculate appropriately sized culverts and open channel improvements to improve Ballston Beach overwash drainage coupled with considerations to reintroduce tidal exchange to the upper Pamet River for ecosystem restoration.
- Review historical site conditions, field data, investigations, and recommendations applicable to the study area to support proposed alternatives; collect current real-time field data to meet the objectives of this investigation.
- Analyze the Ballston Beach overwash risk potential to residential wells: develop a MODFLOW groundwater model using field data to better understand the sub-surface salt-freshwater interface elevation and system response within the vicinity of residential wells and septic systems that may be vulnerable to saltwater intrusion from Ballston Beach overwash ponding; evaluate drainage improvement alternatives.
- Investigate with intent to confirm the regional hydrogeological saltmarsh-peat-tidal-intrusion characterization under the proposed conditions scenario of reintroduced tidal exchange to the upper Pamet River and evaluate the risk potential of saltwater intrusion to residential groundwater wells and septic systems.
- Evaluate the saltmarsh restoration potential upstream of Wilder’s Dike and Route 6.

## 4. Study Findings

- a) The structural integrity of the Wilder's Dike embankment currently appears weakened, unstable, and vulnerable to partial or full failure. Failure of Wilder's Dike could make Truro Center Road impassable, disrupting traffic flow, and negatively impacting the local economy until funding is acquired and repairs are completed. Triggering conditions that could destabilize Wilder's Dike include:
- Seepage of impounded surface water on the upstream side of the dike after overtopping events at Ballston Beach
  - Seepage from impounding the tide when the tide gate is closed during the daily tidal cycle on the downstream side of the dike causing internal erosion and failure of the dike embankment.
  - The embankment is over 100 years old and was not designed for current roadway standards to withstand modern vehicle traffic loads,
  - Fluctuating hydraulic loads on the downgradient side due to tidal and storm surges and on the upgradient side from ocean overtopping events.

Furthermore, failure of the dike could create a blockage of the river channel and prevent drainage of normal and flood flows along the Pamet River that could create a public safety hazard, especially during an overtopping event at Ballston Beach. More information on Wilder's dike and the analysis of culvert modification alternatives may be found in Chapter 1.

- b) An increased frequency of overwash events has been observed in recent years, affecting the Pamet River Watershed. These overwash events occur when salt water from the Atlantic Ocean overtops the barrier dune system at Ballston Beach inundating the freshwater portion of the Pamet River (upper Pamet River east of Wilder's Dike). Overwash events are expected to continue at a similar frequency in the short-term due to the dune system's current elevation. For example, as this report was being finalized, the Town of Truro DPW reported that waves generated off Ballston Beach during the offshore passage of Hurricane Dorian in September 2019 overtopped the Ballston Beach dune system twice, although the amount of ocean water flooding into the upper Pamet was reported as negligible.

Following a large overwash event in January 2015, the Town of Truro adopted a management strategy at Ballston Beach that prioritizes natural sediment transport process over man-made intervention. Prior to 2015, it was common practice for the Town to rebuild the overwashed dune system at Ballston Beach with truckloads of sand. The timing of this new management strategy coincides with increased frequency of overwash events. According to the Cape Cod Atlas of Tidally Restricted Salt Marshes

(Cape Cod Commission, 2001), overtopping at Ballston Beach flooded the upper Pamet River approximately “three times in recent decades [prior to 2001].” The USACE 1998 Section 22 Study of the Pamet River implied a lower frequency of overtopping events flooding the upper Pamet with observed events limited to 1978, 1991, and 1992; the 1992 event resulted in the upper Pamet River Valley being flooded with four feet of saltwater from the Atlantic Ocean (USACE, 1998).

Since the new management strategy was adopted by Truro, the Ballston Beach dune system has experienced numerous, and significant, overwash events, including two during early 2018 nor’easters that resulted in local flooding of several properties adjacent to the Pamet River floodplain. Following these 2018 overwash events, flood elevations in the upper Pamet were reported to the USACE as being the highest in memory of current residents.

The inundation of the upper Pamet River with salt water from the Atlantic Ocean during overtopping at Ballston Beach is likely to continue at a higher frequency than pre-2015 conditions since the current dune elevation will remain lower than the breach elevation until the dune rebuilds through naturally occurring tidal and wave phenomena and reaches equilibrium with coastal sedimentation processes. The duration of time for the dune at Ballston Beach to rebuild after each overwash event is beyond the scope of this study. More information on this analysis may be found in Chapters 6 and 7 of this report.

- c) Under existing conditions, a potential ocean overtopping consequence scenario at Ballston Beach may include multiple overtopping events occurring in rapid succession, creating negative cumulative impacts within the watershed. For example, if two moderate overtopping flood events occur within days or weeks of each other, the first event may fully drain creating an antecedent high water condition within the upper Pamet floodplain, potentially creating a condition where flood stage and associated negative impacts are compounded.
- d) The ecosystem analysis performed as part of this study casts uncertainty on assumptions hypothesized in earlier studies, such as:
  - 1. Salt marsh restoration upstream of Wilder’s Dike and Route 6 will be successful if sufficient tidal flow is restored, and
  - 2. Salt marsh habitat existed upstream of Route 6 prior to construction of Wilder’s Dike and later Route 6, and was lost and converted to palustrine (freshwater) wetlands due to the presence of the tide gate (assumed initially installed at Wilder’s Dike around 1869) and the hydraulic constriction formed by the Route 6 embankment and 4 foot diameter culvert constructed around 1952.

The ecosystem analysis also evaluated historical aerial photography consisting of three separate time-periods spanning 80 years, to perform an inventory and inter-period comparison of wetland system cover in the main stem of the Pamet River. This analysis included pre-Route 6 construction (1938), post-Route 6 construction (1972), and current conditions (2015). The results of this analysis are presented in Chapter 8.

Furthermore, dense stands of the non-native invasive species *Phragmites australis* were observed as dominating the river banks immediately downstream of the Wilder's Dike tide gate. The *Phragmites* stands extend to approximately 500 feet downstream of the dike at which point there is a transition to native *Spartina* grass. This observation is important because *Phragmites australis* is sensitive to high salinity levels and the expectation is that unrestricted tidal flow (downstream of Wilder's Dike) would contain salinity levels adequate to naturally manage the spread of the species. *Phragmites* are generally intolerant of soil salinity levels nearing 20 parts per thousand. (For reference, ocean water has an average salinity of 35 parts per thousand.) The existing salt water wedge of dense sea water that migrates upstream with each high tide cycle is interpreted to terminate in this area, or not be of sufficient salinity to create soil salinity levels that exceed 20 parts per thousand, therefore allowing *Phragmites* to persist. More information regarding the Pamet River watershed ecosystem analysis may be found in Chapter 8 of this report.

- e) As detailed in Chapter 7 of this report, a predictive surface water riverine model, HEC-RAS, was developed for the Pamet River. This riverine model was used to investigate impacts of different culvert alternatives, consisting of: with and without a tide gate at Wilder's Dike and, with and without overtopping scenarios at Ballston Beach. The model was used to analyze river stage magnitudes and drainage times thru Wilder's Dike and Route 6 culverts, during high flow events from the effects of the tide alone, or tide restoration plus overtopping.

Four alternatives were developed and analyzed as part of this study. The alternatives included Alternative #1-“No Action”, Alternative #2 – box culvert with a self-regulating tide gate; Alternative #3 - no tide gate, larger culverts and Alternative #4 - no tide gate, day-light river with new bridges.

Under Alternatives #3 and #4 scenarios, the removal of the tide gate and larger river conveyance will correlate to higher river stages upstream of Wilder's Dike as the high tides migrate approximately ½-mile beyond the dike. These results reflect a change in water table elevation (groundwater rise) of about 0.5 feet compared to Alternative #1 (existing conditions) or Alternative #2 (with a tide gate at Wilder's Dike).

The analysis showed that Alternative #2, consisting of a 16 feet wide x 4 feet tall culvert with a self-regulating tide gate, would be the most effective at reducing both the river stages and duration of time to drain salt water that had entered the upper portion of the Pamet River during an overwash event. In a scenario where Ballston Beach is overtopped, (such as the event of March 2018), a comparison between existing conditions (Alternative #1-“No Action”) and the three alternatives, consisting of larger culverts, both with and without a tide gate, found that Alternative #2 was the most effective alternative in decreasing overtopping drainage times. The drainage efficiency of Alternative #2 is attributed to a combination of larger culvert capacity (i.e. river conveyance) combined with a tide gate to prevent salt water from passing additional flow volume into the upper Pamet during high tides and storm events that would also need to drain. See Chapter 7 of this report for detailed information on the HEC-RAS evaluation conducted as part of this study.

- f) As detailed in Chapter 6 of this report, a MODFLOW groundwater model was developed for the Pamet River study area. MODFLOW 2000 was selected based on available data and the hypothesized depth of the freshwater-salt water interface. Given the available dataset, MODFLOW produced results that met the goals and objectives of the Pamet River study.

The groundwater modeling approach was deemed sufficient to estimate potential impacts to sensitive receptors such as existing private drinking wells and septic systems based on the predicted water table elevation and resulting groundwater flow direction either toward, or away from, the Pamet River, and will inform future management decisions and data collection recommendations. Groundwater modeling results largely align with the results of the previous Cape Cod Commission groundwater analysis report completed in 1997.

- g) Based on the available dataset, the groundwater model was unable to model salinities or fresh-saltwater interface in the subsurface, and the HEC-RAS surface water model did not model salinities in the river water associated with tidal influences or overtopping event. However, the results of the groundwater modeling are an indicator of the risk potential for negative impacts either to septic systems (from a higher water table) or private drinking wells (from saline surface water infiltration of the aquifer), and the need for additional assessment of risk to these receptors.

Groundwater modeling showed that the removal of the tide gate will result in greater fluctuations in groundwater elevation in the area immediately around the upper Pamet River (about ½-mile upstream of Wilder’s Dike) for normal high tide conditions. The groundwater rise during high tide may cause hydrologic impacts to the nearest septic systems.

Groundwater modeling showed overtopping events create higher groundwater elevations that can cause hydrologic impacts to septic systems, over the entire upper Pamet River. Typical high tide conditions (confined to the ½-mile reach upstream of Wilder's Dike) resulted in smaller groundwater elevation increases. Groundwater modeling showed that improving the drainage conveyances with larger culverts or bridges will slightly reduce the areal extent and duration of groundwater elevation increases due to overtopping.

The groundwater modeling showed that during overtopping events, water from the river infiltrates into the groundwater, a reversal of typical flow directions. Since river water during overtopping events is assumed to be saline, this could result in movement of salt water towards nearby drinking water wells. Based on data available, the model was not able to predict which wells would be impacted, but it is clear that improvement of river conveyance would reduce the amount of time saline river water is trapped in the upper Pamet and will reduce risk to nearby wells. See Chapter 6 for the detailed analysis.

Groundwater modeling results showed that movement of saline water from the upper Pamet River towards drinking water wells is a public health concern, especially as the river surface water and groundwater system become increasingly dynamic associated with: rising sea levels and resulting increase in sea water inflows, extreme precipitation variations, and more frequent overtopping events at Ballston Beach.

- h) Groundwater modeling results for existing conditions (Alternative #1: No Action) showed potential for hydrologic impacts to septic systems due to a higher water table (greater than 1 foot rise) from overtopping. Impacts were identified as far as approximately 0.2 miles (1,000 feet +/-) on either side of the upper Pamet for more than an approximate duration of 8 days while the upper Pamet drained. Many septic systems are estimated to be within this impact area for overtopping events. (Note that distance and to some extent time is based on uncalibrated assumptions and is meant for comparison purposes only.)

Modeling results also show that groundwater flow directions, used as a risk indicator for salinity impacts to aquifer water quality, are toward the river from both sides during typical high tide, which is expected since the tide gate is present and blocking the upstream migration of the tide. However, during an overtopping event, under existing conditions, the trapped water in the upper Pamet results in groundwater flow away from the river. If the water in the river is saline, this results in risk of water quality impacts to drinking water wells if they are near the river and tap the shallow aquifer. This risk may be elevated if overtopping events become more frequent and long-lasting.



- i) Groundwater modeling results (presented in chapter 6) indicate that for the three alternatives with modified culverts (Alternative #2, #3, #4), the presence of a tide gate (Alternative #2) appears to prevent hydrologic impacts to septic systems and water quality impacts from salinity to drinking wells under normal high tide conditions.

Removal of the tide gate (Alternatives #3 and #4) allows the normal high tide to migrate upstream. Groundwater modeling indicates that hydrologic impacts from high groundwater levels might exist near the river immediately upstream of Wilder's Dike due to the restoration of the high tide. Groundwater modeling results indicate a groundwater rise of about 0.5 feet or less compared to existing conditions or Alternative #2 (with a tide gate). The model shows that this increase in groundwater levels could potentially impact septic systems closest to the river from Wilder's Dike to the reach of the river extending about 0.5 miles upstream.

For all three modified culvert alternatives (Alternatives #2, #3, #4), during an overtopping event of a magnitude similar to March 2018, there was risk potential for hydrologic impacts from a higher water table that could impact septic systems. Under this scenario, the area of impacts (1 foot or greater rise) was confined to a slightly smaller zone that drained more quickly compared to existing conditions. Although the area of impact is smaller, the risk still remains for the septic systems closest to the Pamet River.

For all three modified culvert alternatives with larger culverts (Alternatives #2, #3, #4), groundwater flow directions, which indicate potential for salinity impacts to aquifer water quality and drinking wells, were found to reverse and flow away from the river during an overtopping event, indicating the risk potential for salinity impacts to private drinking wells from saline surface water infiltration to the aquifer from the floodplain.

The impacts to septic systems and drinking wells near the Pamet River from overtopping with improved culverts is lessened compared to existing conditions, but the risk potential still remains to the septic systems and drinking wells closest to the river.

- j) As described in Chapter 5, field water quality measurements of surface water specific conductance in the Pamet River (main stem) both down and upstream of Wilder's Dike after the tide gate was removed in a March 2018 nor'easter, found evidence that fresh water conditions can exist in the river during high tide on the upstream side of Wilders Dike. The unplanned removal of the tide gate by the storm provided a simulation of unrestricted tidal flow for almost six months while the town planned the replacement of the tide gate. These field water quality readings suggest that the saltwater wedge does not migrate very far during high tide on the upstream side of the dike under current river geometry conditions, and raises significant uncertainty on the objective of converting

palustrine wetland habitat in the upper Pamet to salt marsh by permanently removing the tide gate and restoring natural tidal exchange.

- k) Hydraulic and groundwater modeling, in conjunction with the ecosystem analysis performed as part of this study, suggests that the benefits of restoring natural tidal flow to achieve the objective of salt marsh ecosystem restoration are challenging to predict within this dynamic watershed. Groundwater modeling suggests that restoration of tidal flow may put some adjacent septic systems at risk of failure, primarily from hydrologic impacts due to groundwater rise near these septic systems.
- l) Long-term alternative planning (and implementation) with the objective to restore salt marsh habitat and mitigate impacts from overtopping events should prioritize the selection of improvements and alternatives that reduce flood impacts from overtopping events at Ballston Beach. It is recommended that alternative implementation planning take a phased approach beginning with structural improvements at Wilder's Dike.

Groundwater and surface water modeling results, coupled with ecosystem analysis of historical (1938) and current conditions, suggest that the potential for risk of impacts to septic systems and drinking water wells from removing the tide gate is higher than the reward of potentially restoring the salt marsh upstream of Wilder's Dike.

Groundwater and surface water modeling results indicate that the risk of impacts from overtopping events at Ballston Beach is significant and the Town would benefit substantially from implementing improvements to drainage conveyances, such as, enlarging culverts at Wilders Dike and Route 6. (Chapters 5 & 6)

## 5. Study Recommendations:

a) Wilders Dike: Conduct an engineering assessment of the existing fieldstone dike structure. Consider reinforcing or reconstructing the existing dike embankment and including a larger culvert and appropriately-sized self-regulating tide gate (multiple tide gates may be required depending on selected culvert size). Use conceptual Wilder's Dike design alternatives presented in this report as a guide to determine pre-design geotechnical and structural engineering evaluations. These pre-design engineering evaluations will help inform the detailed design of new embankment, headwalls, and culvert, as described in Chapter 1. This investigative design approach is recommended as a long-term solution as opposed to a short term solution of in-kind replacement of existing conduit and tide gate.

Structural Improvements to Wilder's Dike should include a self-regulating tide gate(s) that provides the flexibility to operate the tide gate as either a fully-closed tide gate (similar to the existing condition), or as a tide gate that can be incrementally opened in the future. Adjustments may be made to the self-regulating tide gate(s) depending on how the system reacts (e.g. localized flooding or ecosystem response) along with the results of long-term groundwater monitoring of the system (see recommendation "b" below).

b) Perform Long-Term groundwater and surface water monitoring to establish more robust baseline conditions while town and other stakeholder are reviewing potential alternatives for Wilder's Dike and Route-6 conveyance improvements. A longer period of baseline data collection under existing conditions (with a tide gate, existing culverts) will create a more comprehensive data set for comparison to post-improvement water quality data so that the early-detection of impacts to drinking wells (water quality) and septic systems (groundwater rise) can be recognized and mitigation measures implemented.

Long-term monitoring would ideally be broken down into two phases:

1. Existing drinking wells: following significant overtopping events, continue sampling from high-risk drinking wells, (to be determined based on proximity to flood-prone areas within the upper Pamet watershed). Water samples should be coupled with surface water samples during the same sample event from the portion of the Pamet River nearest to the sampled drinking well. During overtopping events, these data will provide insight to the relationship between saline levels in the river and private drinking water wells.
2. New Monitoring Network: Design new monitoring well network to include new monitoring wells, comprised of nested wells with at least a well couplet, at several locations along the upper Pamet River. New well nests could be located at varying distances and depths from the river to provide greater resolution on variation of hydraulic head under normal, restored tidal, and overtopping events. New well nests should also be located to form transects perpendicular to the river to provide greater resolution on groundwater flow direction horizontally and vertically during average and flooding conditions. The new well nests would also provide greater resolution for sampling of groundwater quality during both normal flow and flooding conditions.
  - Selected monitoring wells should be equipped with an automatic data logging and telemetry system that is capable of alerting the Town via cell phone or we-based communication (i.e. DPW) that a preset water quality target (i.e. elevated conductivity) has been measured, so that increased groundwater and surface water sampling can be performed manually.

This system would serve as an early warning detection system for private drinking wells that may have their water quality adversely impacted either from surface water infiltration of saline floodwaters, or from a shallower fresh-salt water interface due to future removal of the tide gate and restoration of tidal migration in the upper Pamet.

- The early detection monitoring wells can be utilized for additional real-time groundwater data collection for use in future decision making and to monitor impacts of climate change and rising sea levels increasing the dynamic movement and uncertainty of the salt-freshwater interface. This option can serve to correlate with enhanced climate change resiliency, per Federal guidelines and State of Massachusetts initiatives, including the Town of Truro 2017 Hazard Mitigation Plan (HMP). The Town of Truro HMP initiative specifically emphasizes reduction of long-term risk to human life and property from hazards to enhance resiliency.

h) Finally, it is recommended that the Town investigate the feasibility of expanding existing municipal water system services to the Pamet River neighborhoods (North Pamet Road and South Pamet Road) to serve as a backup water supply, or to preemptively connect existing homes with private wells to town water. This is one option to address the uncertainty of future degradation of private water quality due to surface water infiltration of salt or brackish water from overbank flooding of the Pamet floodplain due to overtopping events at Ballston Beach.

# **Chapter 1**

**PAMET RIVER INVESTIGATION  
Truro, Massachusetts**

**ANALYSIS OF CULVERT MODIFICATION ALTERNATIVES AT  
WILDER'S DIKE AND ROUTE-6 WITH  
REAL-TIME WELL MONITORING AND EARLY-WARNING RESPONSE  
RECOMMENDATION**

**C.A.P. SECTION 22  
PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

**CHAPTER 1:**  
**Analysis of Culvert Modification Alternatives at Wilder’s Dike and Route-6 with  
Real-Time Well Monitoring and Early-Warning Response Recommendation**

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**CHAPTER 1:**  
**Analysis of Culvert Modification Alternatives at Wilder’s Dike and Route-6 with  
Real-Time Well Monitoring and Early-Warning Response Recommendation**

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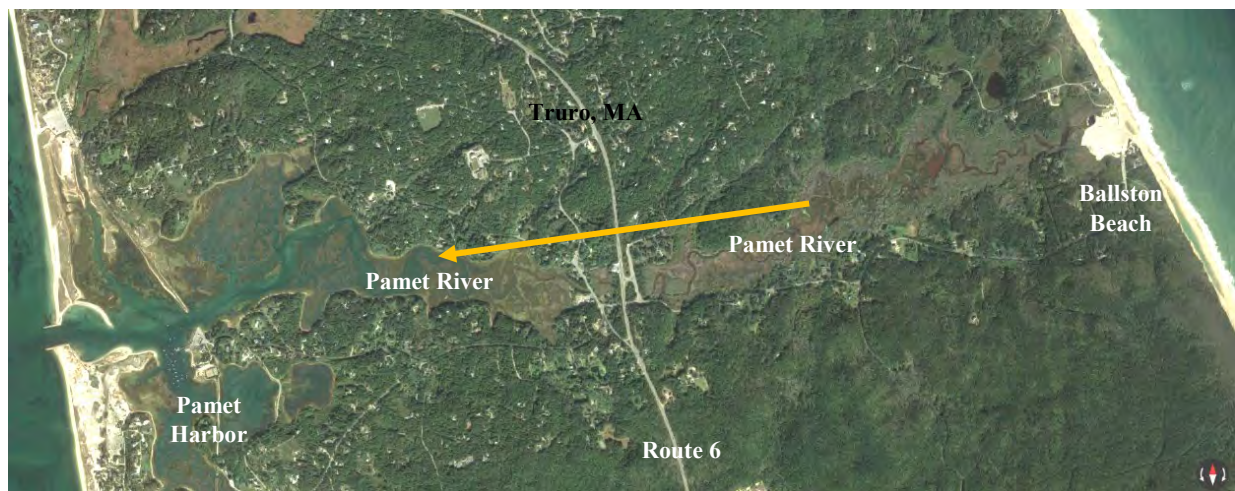


## **2.0 EXISTING CONDITIONS**

### **2.1 Truro and the Pamet River**

Truro is a town in Barnstable County, Massachusetts located just south of the northern tip of Cape Cod (Figure 1). Over half of the land area of the town is part of the Cape Cod National Seashore, established in 1961, and is administered by the U.S. National Park Service.

The Pamet River is an estuarine and freshwater river system consisting of three stream branches that meet to form Pamet Harbor before discharging to Cape Cod Bay. The main branch of the river system is the Pamet River which begins near Ballston Beach in the east and extends westward to Pamet Harbor (Figure 2). The other two branches - Little Pamet River to the north and Eagles Neck Creek to the south - are not the primary focus of this study.



**Figure 2: Location Map- Pamet Harbor, Pamet River Valley, and Ballston Beach**

### **2.2 Culvert Modification Location Map**

The Pamet River consists of two hydrologically different reaches separated by Wilder's Dike, just west of Route 6. Currently, the upper Pamet east of Wilders Dike is a freshwater system, and the lower Pamet west of Wilders Dike is saltwater. The dike was constructed in 1869, but the tide gate and Route 6 embankment was constructed in the mid-1950s. The two constrictions, and focus areas of this design effort, that hinder conveyance between the fresh and saltwater systems are a 56-foot long, 3.5-foot diameter culvert with tide gate through Wilder's Dike, and a 360-foot long, 4.0-foot diameter culvert through the Route 6 embankment and North Pamet Road (Figure 3). The dike's tidal flap gate seals off the tidal influence upstream of the dike approximately 2 hours before high tide, essentially preventing saltwater intrusion east of the dike to the upper Pamet. The river's freshwater system is fed by groundwater and surface runoff.



Figure 3: Location Map - Pamet River - Conveyance Design Focus Area

## 2.3 Topographic Data

The data set used in this study was an LAS format file containing LiDAR point cloud data. The data set was extracted from a larger classified data set and only includes points classified as Ground within the requested geographic bounds. The coverage of the data includes slivers of areas that were missed by previous LiDAR acquisitions. Ground conditions: No snow; Leaf off. Tidally impacted waters within the AOI are expected to be acquired at Predicted MLW  $\pm$  2 hours exclusive of neap tide. Temporal differences from LiDAR collects in and around hydrologic features may manifest in the DEM as differing water levels. In all cases, professional practice was applied to best represent the topography. Data for the task order is referenced to the UTM Zone 19N, North American Datum of 1983 (2011), and NAVD88, in meters. However, a small portion of the AOI crossed into UTM 18 and this data is referenced to the UTM18N, North American Datum of 1983 (2011), and NAVD88 GEOID12A, in meters.

Data was collected using two Leica ALS70 (LiDAR) systems on board a Cessna 404 and Cessna 310 aircraft, LiDAR data, at a nominal pulse spacing (NPS) of 0.7 meters, was collected for this task order (approximately 304 square miles). AGL = 7500 feet - Aircraft Speed = 150 Knots, Field of View (Full) = 32 degrees, Pulse Rate = 239 kHz, Scan Rate = 41.6 Hz, with an average side lap of 25%. Six (6) Global Navigation Satellite System (GNSS) Base Stations were used in support of the LiDAR data acquisition. As a supplement to the USGS task order collection, Woolpert acquired LiDAR data of New York City as part of a 2013 task order for the NGA. This was acquired using a Leica ALS70 (LiDAR) system on board a Cessna 404 and produced LiDAR data, at a nominal pulse spacing (NPS) of 0.91 meters. AGL = 7500 feet - Aircraft Speed = 150 Knots, Field of View (Full) = 40 degrees, Pulse Rate = 239 kHz, Scan Rate = 36.9 Hz, with an average side lap of 30%. For the NGA task order portion of the collection One (1) mission was used. This mission was flown on

August 6, 2013. One (1) Global Navigation Satellite System (GNSS) Base Station was used in support of the LiDAR data acquisition.

A footprint of this data set may be viewed in Google Earth at:

*[https://coast.noaa.gov/htdata/lidar1\\_z/geoid12b/data/4914/supplemental/ne2013\\_2014\\_usgs\\_postsandy\\_m4914.kmz](https://coast.noaa.gov/htdata/lidar1_z/geoid12b/data/4914/supplemental/ne2013_2014_usgs_postsandy_m4914.kmz)*

Refer to the Surface Water Model Appendix for river channel data and interpretations.

## **2.4 Aerial Imagery**

Aerial Imagery shown on the drawings prepared by the Civil Design Section was provided by DigitalGlobe EVWHS. Imagery used was taken in June, 2016. More recent aerial imagery was not used due to lack of image clarity or faulty horizontal positioning.

## **2.5 Utilities**

Based on internal investigations and communications with the Town of Truro, there are no known utilities present in the Design Focus Area that would adversely impact the implementation of improvements proposed below.

# **3.0 CULVERT MODIFICATION AND WELL MONITORING ALTERNATIVES**

**3.1 General.** Roadway culverts crossing the Pamet River at Wilder's Dike and Route-6 were evaluated using the HEC-RAS hydraulic model and analyzed for modification improvements, as described in Chapter 7 of this report. This analysis evaluated the hydraulic capacity and operation of the culverts under several tidal and freshwater scenarios to develop four alternatives as presented below in Section 3.3. This analysis was an extension of the cursory culvert investigation initiated in the USACE 1998 Pamet River Study. This 2019 Pamet River analysis included a construction feasibility assessment to support the four culvert modification alternatives selected that support the design goals of the sponsor.

Both historical and current investigations have investigated local residential well vulnerability to elevated saltwater concentrations associated with Ballston Beach overwash ponding, sub-surface ocean intrusion with fresh-groundwater flow paths and correlation to sea level rise, and the reintroduction of surface-tidal exchange thru Wilder's Dike for salt-marsh restoration as a climate change adaptation mechanism. Results of these investigations conclude a dynamic salt-freshwater interface system sensitive to seasonal, coastal, and precipitation patterns, as supported in Chapters 2-8 of this study.

Thus, pending Town modifications to these existing culverts, the USACE project-team recommends these modifications coincide with a Long-Term Well Monitoring (LTWM) program, as presented in Figure 4. The LTWM program would align with adaptive management strategies for the watershed, providing real-time data with early warning capabilities to support local decisions and concerns. For example, the monitoring well data would support management strategies in response to Ballston Beach overwash events and drainage, rising sea-levels, dynamic sub-surface salt-freshwater interface exchange and reintroduced tidal surface-water exchange to the upper Pamet River. The proposed conceptual LTWM program is discussed below in Section 3.2.

### **3.2 Real-Time Well Monitoring with Early-Warning Capabilities Conceptual Design**

#### **3.2.1 Design Considerations**

The LTWM program conceptual design utilizes both existing monitoring wells and the installation of additional monitoring wells. Selected monitoring wells should be equipped with an automatic data logging and telemetry system that is capable of alerting the Town via cell phone or web-based communication (i.e.: DPW) that a preset water quality target (i.e.: elevated conductivity) has been measured, so that increased groundwater and surface water sampling can be performed. This system would serve as an early warning detection system for private drinking wells that may have their water quality adversely impacted either from sub-surface oceanic infiltration, surface water infiltration of saline floodwaters associated with Ballston Beach overwash or future removal of the tide gate and restoration of tidal migration in the upper Pamet.

The LTWM program should begin prior to construction of culverts and tide gate modifications in order to establish a more robust, and optimal baseline of existing conditions, and continued monitoring post-construction prior to reintroducing surface tidal exchange thru Wilder's Dike to the upper Pamet. Allowing time to establish baseline water quality data collection under existing conditions (with a tide gate, existing culverts) provides a more reliable data set for comparison to post-improvement water quality data so that the early-detection of impacts to drinking wells (water quality) and septic systems (groundwater rise) can be recognized and mitigation measures implemented.

The LTWM program should include objectives to account for impacts of climate change and rising sea levels increasing the dynamic movement and uncertainty of the salt-freshwater interface. This recommendation can served to correlate with enhanced climate change resiliency, per USACE ECB 2018-2 and State MA initiatives, including the Town of Truro 2017 Hazard Mitigation Plan (HMP). The Town of Truro HMP initiative specifically emphasizes reduction of long-term risk to human life and property from hazards to enhance resiliency.

The LTWM program can be implemented in two phases:

a. Phase 1 Existing drinking wells: continue sampling from the most vulnerable, high risk drinking wells, as determined by proximity to flood-prone areas within the upper Pamet River watershed. Routine surface water sampling locations should align with routine sample collection nearest the sampled drinking well, and surface water sampling locations should align with the nearest , flood-prone drinking well wellheads.

b. Phase 2 New Monitoring Network: Design a monitoring well network consisting of monitoring well clusters comprised of nested wells with at least a well couplet, at several locations along the upper Pamet River. New well nests should be located at varying distances and depths from the river to provide greater resolution on variation of hydraulic head under normal, restored tidal, and overtopping events. New well nests should also be located to form transects perpendicular to the river to provide greater resolution on groundwater flow direction horizontally and vertically during average and flooding conditions. The new well nests would also provide greater resolution for sampling of groundwater quality during average and flooding conditions.

### **3.2.2 Conceptual Design and Layout**

A conceptual LTM network of minimal four (4) well clusters, designated Well A through Well D is shown in Figure 4. Each well cluster would have a minimum two or more observation wells screened at different depths, and could be supplemented by data collected from the nearest existing monitoring well (i.e.: Well C near PW-3S/PW-3D/PW-4). Each well cluster should have a deep monitoring well screened below the fresh-saltwater interface, based on a boring that has performed groundwater quality and lithology profiling in the overburden to the top of bedrock. The well clusters below have been located near the tide gate (Well A) or between the Pamet River and a residential home (and existing monitoring well is possible) that is nearest the river and vulnerable to potential impacts from a rising fresh-salt water interface or surface water infiltration of salt water overbank flooding due to overwash at Ballston Beach.



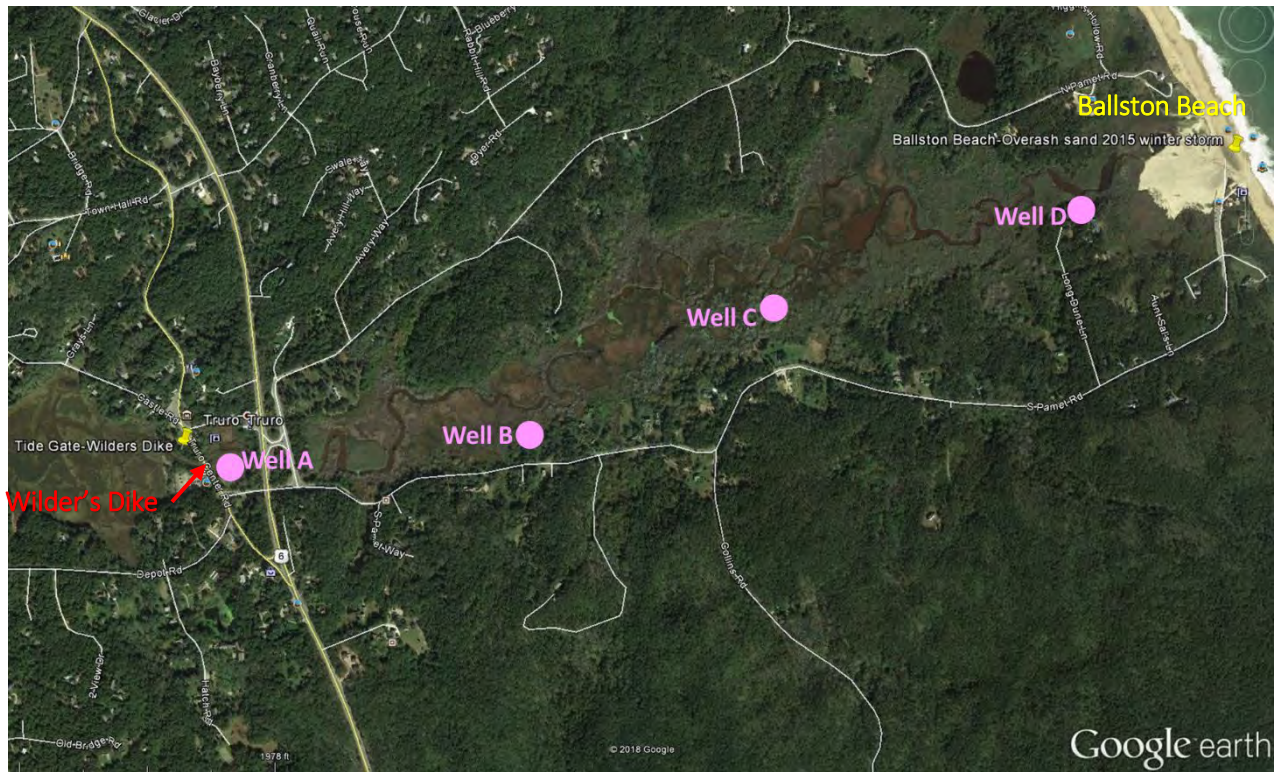


Figure 4: Location Map - Pamet River – LTWM Conceptual Layout

New wells should include installation of one or more new deep monitoring wells to find and intersect the fresh-salt water interface approximately ¼-miles upstream of Wilders Dike, to monitor baseline and potential future tide flow restoration impacts to the position of the fresh-saltwater interface. The recommended conceptual location is based on the results of the area of impacted groundwater level rise predicted by groundwater modeling for the “No Tide Gate” alternatives reviewed in this study (Alternatives #3 and #4). Design monitoring well drilling program should include continuous groundwater sample profiling to determine the position of the fresh-salt water interface at time of drilling. Finished monitoring well construction should accommodate installation of a well couplet, with one well screen below and one well screen above the fresh-salt water interface encountered during well drilling.

### 3.3 Proposed Culvert Alternatives

#### 3.3.1 Alternative #1: No Action

This alternative assumes no action for conveyance improvements at either constriction point and does not require civil design input. Refer to the Hydrologic and Hydraulic modelling efforts existing condition and No Action information.

#### 3.3.2 Alternative #2: Box Culverts with Self-Regulating Tide Gate

See sheet A-102 of the attached drawings

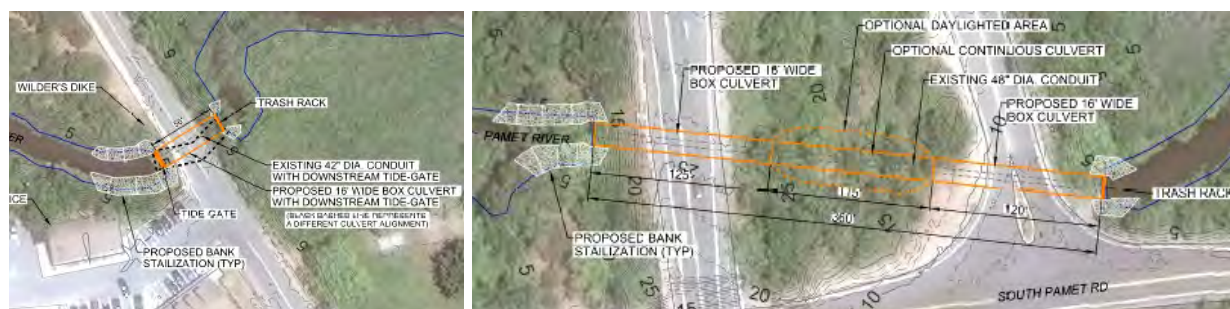


Figure 5: Alternative #2

#### --Wilder's Dike--

Under this alternative, the Wilder's Dike and conduit would be replaced with a 16' x 4' (internal dimensions) concrete box culvert with a Self-Regulating Tidal (SRT) Gate on the downstream/western side, similar to the current configuration. The upstream and downstream faces have concrete headwalls to maintain the dike's integrity during storm and/or high-water conditions. Stone riprap bank stabilization and scour protection was included due to the increased flows from improved conveyance. Stabilized banks were set to be on a 1.5H:1V slope. A trash-rack is recommended to prevent larger upstream debris from causing complications to the culvert and tide gate operations.

#### --Route 6--

Under this alternative, the Route 6 conduit would be replaced with a 16' x 4' concrete box culvert, similar to that of Wilder's Dike above. This box culvert would be approximately the same length as the existing conduit. Concrete headwalls, riprap bank stabilization, and a trash-rack are also included. Due to the length of this culvert, access should be provided, at the midpoint, for inspection and maintenance purposes. This could be achieved by either installing a manhole or by daylighting the central portion of the culvert between Route 6 and North Pamet Road. For the sake of this study, a continuous (non-daylighted) box culvert was selected.



### 3.3.3 Alternative #3: Box Culverts without Tide Gate

See sheet A-103 of the attached drawings

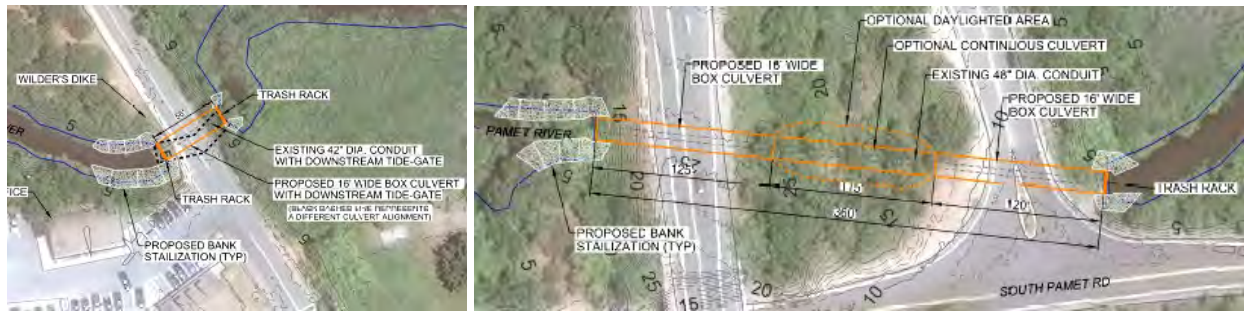


Figure 6: Alternative #3

#### --Wilder's Dike--

The proposed improvements to Wilder's Dike under this alternative are the same as Alternative #2 above, with the exception of the tide gate feature. For conveyance modelling sensitivity purposes, and at the request of the Town of Truro, this alternative was developed and carried forward to present the projected river conditions without the tidal signal control. A trash-rack was included at the downstream face of the dike to prevent debris that is pushed upstream on an incoming tide from complicating the culvert operations.

#### --Route 6--

The proposed improvements to the Route 6 conduit under this alternative are the same as Alternative #2 above with no exceptions.

### 3.3.4 Alternative #4: Open Bridge Span

See sheet A-104 of the attached drawings



Figure 7: Alternative #4

#### --Wilder's Dike--

In pursuit of achieving maximum conveyance, the Wilder's Dike and conduit would be replaced with an open span bridge under this alternative. The bridge decks would be supported by new concrete abutments and reinforced concrete beams. Given the short span, no central (in-river pile) structural features are required. Stone riprap bank stabilization and scour protection for the improved channel slopes and bottom would extend in both directions from the bridge. Stabilized



banks of the open channel and under the bridge were set to be on a 1.5H:1V slope. For the sake of this study, the bridge span width was set to the same as the existing conduit to be replaced (58').

--Route 6--

Under this alternative, the 360-foot long conduit would be replaced with two bridges (Route 6 and North Pamet Road) and a daylighted open channel between them. The bridge decks would be supported by new concrete abutments and reinforced concrete beams. Given the short span, no central (in-river pile) structural features are required. Stone riprap bank stabilization and scour protection for the improved channel slopes and bottom would extend both between and upstream/downstream from the bridges. These banks were also set to be on a 1.5H:1V slope. To reduce flow velocities, a non-linear daylighted channel alignment was selected. Daylighted banks would be riprap from the channel bottom up to an elevation where high flow are no longer anticipated and transition to vegetated slopes which continue to the top of the bank cut.

--Alt. #4 Notes--

While this alternative provides the greatest conveyance for the Pamet River, there are some aspects to this proposal from a design/construction standpoint worth considering. Alternative implementation cost estimates are outside the scope of this study, however, it should be noted that bridge design and construction both incur high costs, and there are three bridges under this alternative. Bridge Operations & Maintenance (O&M) costs (to include inspections, maintenance and replacement) are higher than the box culvert counterparts. Another notable item for this alternative is the duration of construction. Route 6 is the primary thoroughway for all land-based traffic to/from Provincetown, MA. Finally, there would be no tidal signal controls, or even the ability to easily upgrade to include them if desired later on as would be the case with the box culvert without tide gates.

## **4.0 DESIGN CONSIDERATIONS**

**4.1 Conveyance Sections:** The typical Box culvert, Bridge Span, and Open Channel sections shown on sheet C-301 of the attached drawings were developed to support the Hydrologic & Hydraulics team in their effort to model the alternatives and projecting how the Pamet River would respond. The 16' x 4' Box Culvert was selected based on previous studies and reports, which indicated the optimal box culvert dimensions were around the dimensions used herein. Chamfered corners of the culvert's inner opening are typical to these concrete form. Dimensions and invert elevations for the bridge abutment spans and deck heights were developed based on the existing surface elevations at each location. Bridge and daylighted sections were given a channel bottom width based on the average river bottom width throughout the design focus area. Side Slopes were set to a 1.5H:1V incline from the channel bottom and extend to the existing grade from there. Shallower side slopes would be desired, but increase the cut volume significantly and have potential to impact other existing infrastructure nearby (South Pamet Road and the Truro Post Office).

**4.2 Segmental Box Culverts:** Precast Reinforce Concrete Segmental Box Culvert sections are recommended and used in these preliminary designs for several reasons. They are available in many different configurations from a variety of providers. Concrete uniformity and consistency due to better quality control versus cast in place. With little to no formwork needed, the duration of construction is often quicker than cast in place. Skewed culvert segments are available, allowing for non-linear arrangements to optimize design around existing conditions (Figure 7).

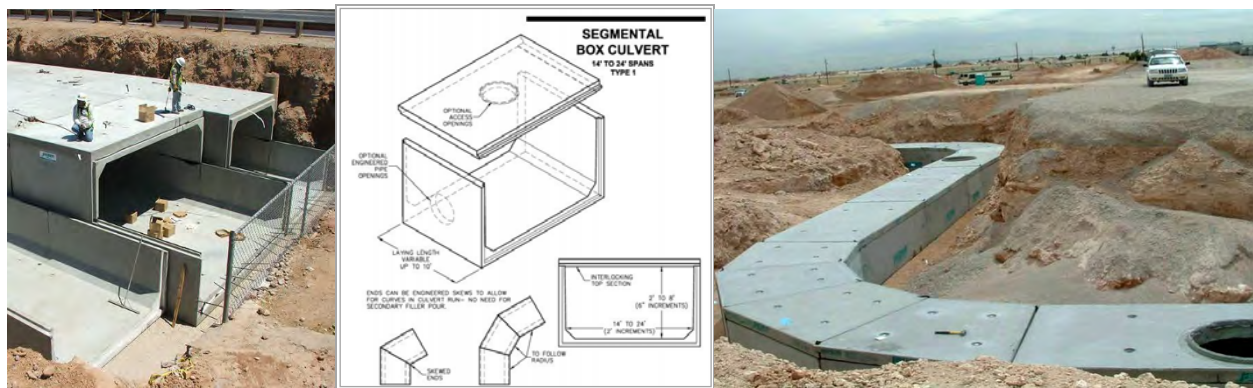


Figure 8: Segmental Concrete Box Culvert

**4.3 Self-Regulating Tide (SRT) Gate:** A variety of tidal gate systems exist, ranging from simple flap gates to computer/electronically operated sluice gates. For the sake of this project, a Self-Regulating Tide (SRT) Gate was selected. Most SRT gates have two separate floats that serve different functions. The lower float is intended to keep the gate as open as possible by resting on top of the water surface, promoting maximum flow. Once water level rises above a certain elevation (customized for each SRT gate), the upper floats are engaged which begin to close the gate and seal it off at/above a certain water level. This system promotes better flow and more control over when the gate fully closes, compared to simple flap gates. If this system is carried forward into a design effort, the decision to use one large gate, or 2-3 smaller gates will need to be investigated.



Figure 9: Self-Regulating Tide Gate

**4.4 Slope Stabilization:** Stone riprap bank/channel stabilization was selected due to being readily available to contractors, and the general ease of construction and maintenance compare to woven or interlocked stabilization systems.

**4.5 Trash-Racks:** Debris has been known to occasionally obstruct the existing conduits. Trash-racks would prevent larger natural and man-made debris from becoming lodged within the box culverts and compromising the systems operations. One consideration for employing trash racks is the need to continuously maintain (check and clear of debris) to prevent debris build-up.



**Figure 10: Trash-Rack Examples**

**4.6 Access/Cleanout - Daylighting vs. Manholes:** For the box culvert alternatives, inspection, cleanout, and maintenance access to these systems is recommended every 200 feet of feature length. Given the length of the Route 6 culvert (approximately 360'), at least one access manhole would need to be installed in the area between North Pamet Road and Route 6. An alternative approach to this would be daylighting the river in this area between the two roadways and only having box culvert under the roads. Since the level of excavation is nearly the same to construct either option, this would be more of an aesthetic decision.

**4.7 Route 6 Complications:** One of the most notable challenges to implementing any of these alternatives, or some other conveyance improvement not discussed herein, is the significant construction effort involved with Route 6. The elevation difference between the Route 6 roadbed and the river-bottom elevation is between 25' to 30'. Most construction efforts for non-bridge alternatives would involve large amounts excavation, requiring large stockpile area needs. Bridges require significant soil removal and disposal. Horizontal boring could be considered, however costly and may not be feasible within a certain proximity to existing bridge over S. Pamet Road. The Duration of construction on this main thoroughway for traffic to/from Provincetown is also problematic. Traffic control options will need to be considered. Utilizing Pamet Center Road for through-traffic may be necessary. All improvement alternatives require coordination with the Massachusetts Department of Transportation

**4.8 Construction approach:** The likely approach to construction at either Wilder's Dike or Route 6 would involve coffer dams and bypass pumping to perform construction activities in the dry.

**4.9 Weir Structures:** While not anticipated, should the improved conveyance create water velocity or level issues in the Pamet River, weir structures could be constructed in the box culverts or within the channel itself to better regulate the system as a whole.



**Figure 11: Box Culvert Weir Examples**

**4.10 Potential Alternative #5:** One alternative that wasn't carried forward for further development and modelling/analysis, but has considerable constructability merit, is shown on sheet C-105 of the attached drawings. The primary feature is to construct a Bypass/Secondary Conduit under South Pamet Road to improve conveyance at the Route 6 constriction with less construction effort (and likely cost) implement. This system could be designed to work in conjunction with the existing conduit, or potentially sized to function as the primary flow path for the river.

# **Chapter 2**

**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**Proposed Multi-Objective Watershed Plan Formulation Model**

**Conducted by,**

**US Army Engineer Research and Development Center (ERDC)**

**S. Kyle McKay, Ph.D., P.E**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

**Pamet River Watershed, Truro, Massachusetts**

**Water Operations Technical Support Program**



## **1.0 INTRODUCTION**

The U.S. Army Corps of Engineers (USACE) New England District (NAE) is conducting a Planning Assistance to States (Section 22) study for the town of Truro, Massachusetts. The scope of the study is broadly focused on basin planning in the Pamet River Watershed with specific goals of establishing baseline conditions of hydrologic and ecological condition, identifying management opportunities to meet social and ecological objectives, assessing the relative effects of management opportunities, and recommending alternative courses of action for the community.

Through the Water Operations Technical Support program (WOTS), NAE requested support to ongoing watershed planning along with guidance regarding recent hydrologic changes in the basin (described below). The focus of this WOTS report largely relates to developing a transparent, multi-objective watershed plan, and this report draws heavily from methods developed in the environmental benefits analysis research program (Fischenich et al. 2013). Technical recommendations are provided on the following subjects based on discussion with the NAE study manager, field visits covering the length of the basin on August 20, 2018 and meetings with the Truro town manager, director of public works, and town planner on August 21, 2018.

- Assessment of basin condition.
- Objective setting and metric development.
- Management alternatives and their effects on objectives.
- Potential decision making frameworks to structure study outcomes.

## **PAMET RIVER WATERSHED**

The Pamet River Watershed is a small drainage spanning the width of Cape Cod (~3.1 miles) in Truro, Massachusetts (Figure 1). The upstream, eastern portion of the basin is largely undeveloped and managed as part of the Cape Cod National Seashore with the general goal of “allow[ing] natural processes to proceed unimpeded” (NPS). The western portion of the watershed is largely unmanaged salt marsh with an outlet through Pamet Harbor. The central segment of the basin is dominated by development with two major transportation thoroughfares (Truro Center Road and Route 6), which bisect the basin. Wilder’s Dike (now Truro Center Road) was constructed in 1869, and hydrologically separates the basin into a downstream salt marsh and upstream freshwater system with very little transitional zone (USACE 1998). Wilder’s Dike is a 4 foot diameter culvert with a tide gate, and the Route 6 embankment also has a 4 foot diameter culvert with no tide gate. The long period of tide gate operation has altered basin hydrology, sediment deposition, and salinity dynamics substantially (Figure 2A).

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Figure 1. Aerial photo of the Pamet River Watershed (Image © 2018 TerraMetrics via Google Earth).

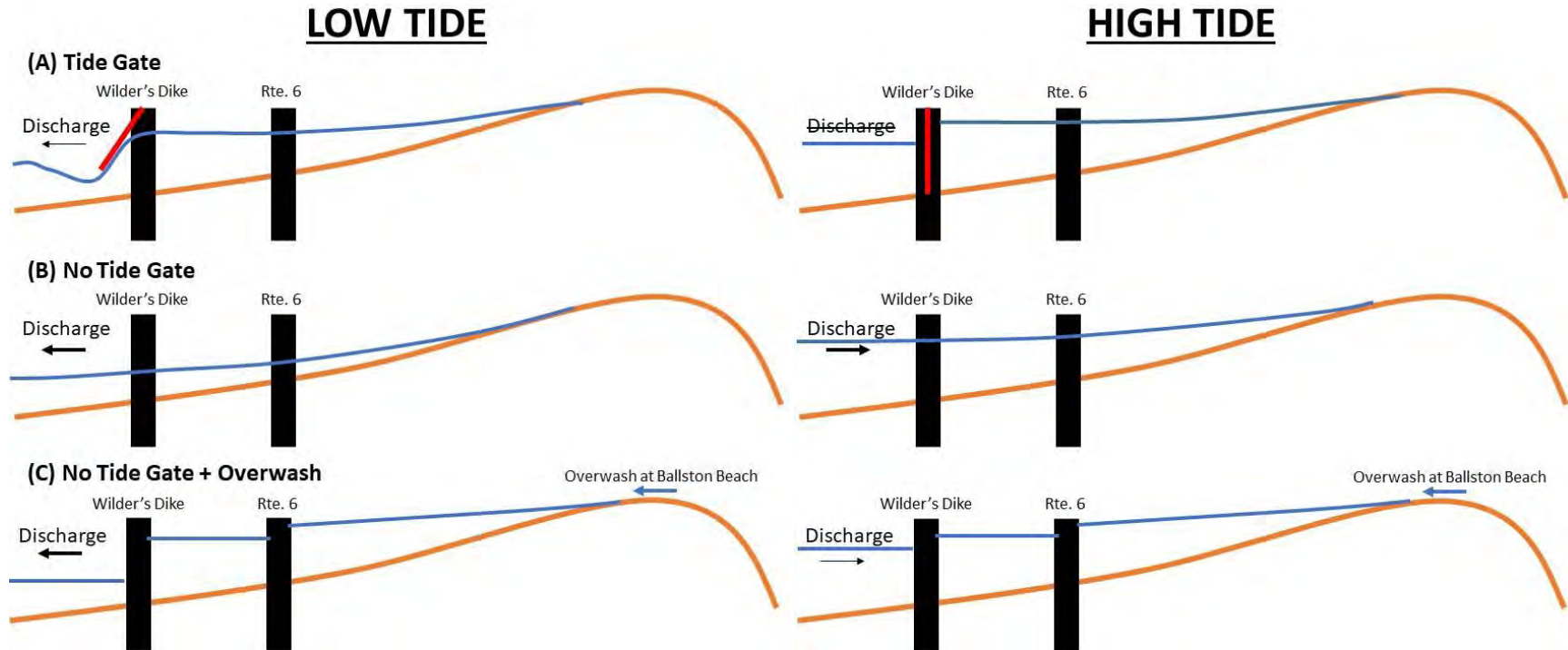


Figure 2. Conceptualization of Pamet River hydrology.



Since 2013, numerous major overwash events have occurred from the Atlantic Ocean at Ballston Beach into the watershed (Borrelli et al. 2016). Historically, these events were relatively rare (i.e., 3 major identified overwash events prior to 2013). However, more than a dozen events in the last five years indicate that overwash from the Atlantic Ocean is becoming more frequent and the magnitude of these events may be increasing. Overwash introduces a major source of saltwater and sediment, which substantially alter the water, sediment, and salinity budgets of the Pamet Watershed. A period of extended overwash in March 2018 increased water levels in the basin substantially, and subsequently led to the failure of the tide gate at Wilder's Dike. The tide gate was replaced in August 2018 with a newer lighter gate with different hydraulic performance.

Thus, multiple hydrologic conditions have been observed over the prior year, and Figure 2 conceptually summarizes some of the flow regimes experienced in the basin during this period. The USACE study is monitoring water levels at select locations throughout the watershed and constructing a hydraulic model in HEC-RAS to better understand and forecast basin hydrologic regimes.

From March-August 2018, the wetland complexes in the freshwater section of the Pamet River experienced a dramatic die-off event. This period included significant overwash inputs from upstream as well as a change in hydraulic controls downstream (i.e., the failure of the tide gate in March 2018). Multiple hypotheses could explain the die-off. First, the duration of high water levels could induce mortality on the woody trees, some of which may not have high flood tolerance<sup>2</sup>.

Second, flood duration could have been controlled not by the overwash volume, but instead by the inability to drain the system via the culverts at Route 6 and Wilder's Dike. Third, the wetland system was historically predominantly freshwater, which could indicate a salinity intolerance from the upstream overwash. Fourth, salinity induced mortality could have occurred due to the loss of the tide gate and a downstream influx of salinity. Fifth, multiple overwash events could have introduced salinity to the wetland soils and subsequently a critical tipping point could have been reached within the soil (rather than the water column). Ongoing hydrologic studies (both monitoring and modeling) will be crucial to understanding the mechanisms of the die-off event, and the potential for management actions to improve ecological conditions.

From this preliminary basin assessment, a few key observations emerge:

- The range of hydrologic conditions in 2018 provide crucial empirical data and insight on the Pamet River's hydrologic regime, which is driving many socio-ecological outcomes.
- Regardless of the mechanism, wetland die-off is a significant management concern to the city, and guidance on future ecosystem management actions is needed.
- The hydrologic controls at Wilder's Dike and Route 6 are key leverage points for management, given their central location at the freshwater-saltwater interface.

<sup>2</sup>The following may provide sources of information on general flood tolerance of riparian plants. Cape Cod's species may not be explicitly on these lists, which may require assumptions about appropriate analogs.

[https://www.nrcs.usda.gov/Internet/FSE\\_DOCUMENTS/nrcs144p2\\_030196.pdf](https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_030196.pdf)

[https://trace.tennessee.edu/utk\\_agexfores/60/](https://trace.tennessee.edu/utk_agexfores/60/)

<https://www.srs.fs.usda.gov/pubs/1548>

## **2.0 OBJECTIVE SETTING**

A clear and complete articulation of project objectives has long been acknowledged as crucial to all forms of environmental and water resources decisions (Yoe and Orth 1996, Gregory and Keeney 2002). A “good” set of objectives then provides the template from which decision metrics may be developed, models constructed or selected, and alternatives developed. This section focuses on setting objectives in the Pamet River, and additional information on setting and evaluating objectives may be found elsewhere (e.g., McKay et al. 2010, McKay et al. 2012ab, Fischenich et al. 2013).

An overarching goal establishes a consistent vision for a project and sets the general direction for subsequent objective statements. This goal must be aligned with broader goals of the city, but the goal statement must also be system-specific and highlight the unique aspects of this ecosystem and associated management activities. The following statement is proposed as a preliminary goal for refinement with Town of Truro officials.

**Overarching Goal:** *Highlight the Pamet River as a unique ecological asset that benefits current residents and connects the community with its historical roots.*

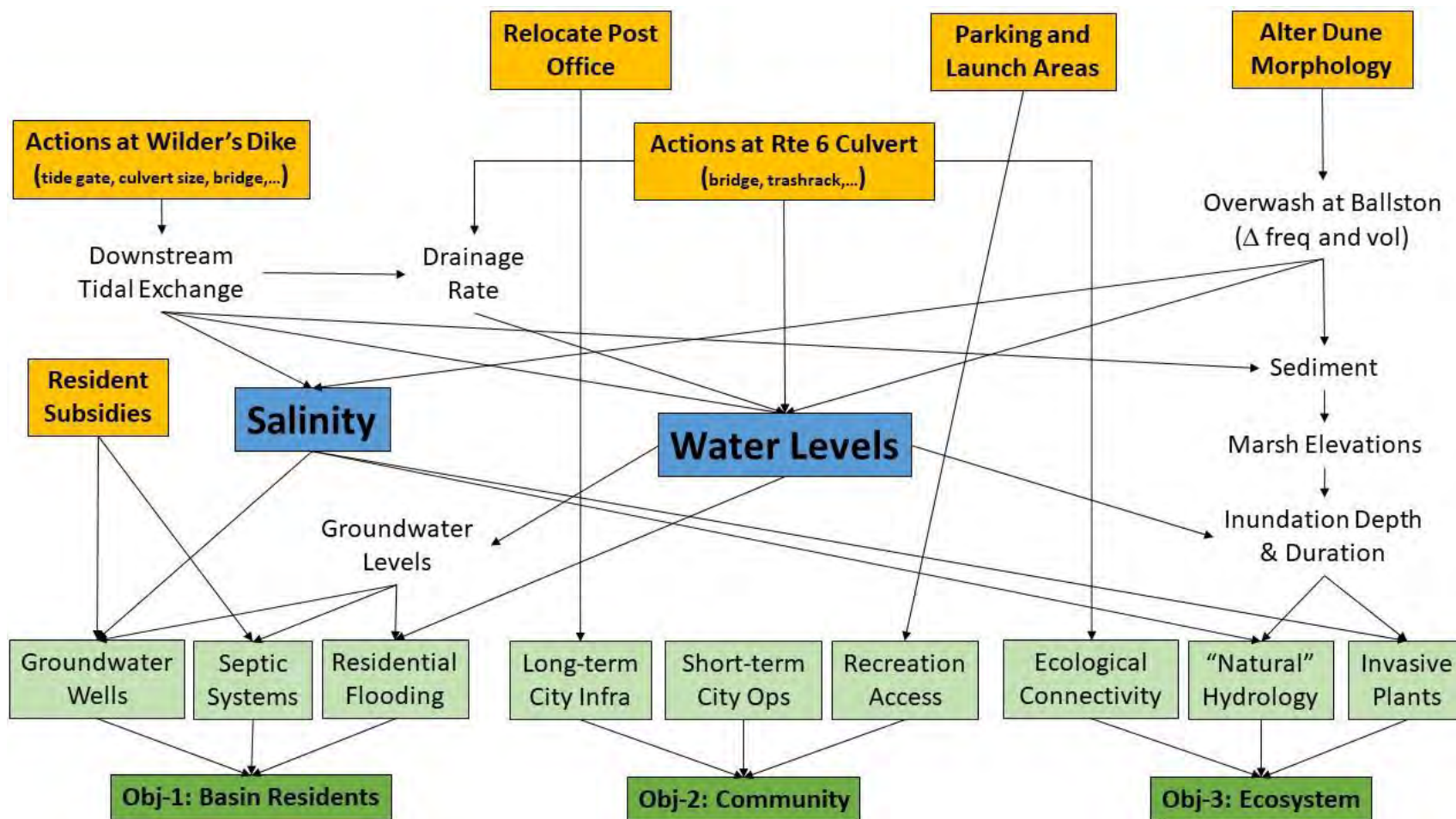
A goal provides the vision for a project, and objectives refine and articulate that vision as measurable, achievable, and actionable statements. A hierarchy of objectives is often required, which separates the highest-order, fundamental objectives from the actionable, means objectives. Fundamental objectives represent the highest ideals of a project and are often identified by asking “Why does that matter?” A fundamental objective is often found when the answer is “Because it is what we care about.” Means objectives are the steps to achieving that fundamental objective. For example, a fundamental objective associated with restoring an imperiled trout species could involve means objectives of reducing temperatures, improving habitat, or removing movement barriers. Table 1 presents a preliminary set of fundamental objectives (i.e., 1, 2, 3), associated means objectives (e.g., 1a, 1b, 1c), and potential metrics that could be relevant in the Pamet Watershed study. Importantly, all objectives may not be equally important to decision-makers, and the relative importance of objectives could be important to consider in recommending actions.

**Table 1.** Pamet Watershed Initial Impact Objectives Outline.

| Objectives and Sub-Objectives                                                                                                        | Potential Metrics                                                                                                                   |
|--------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| <i>1. Minimize impacts to <b>basin residents</b>.</i>                                                                                |                                                                                                                                     |
| 1a. Minimize nuisance flooding of private property.                                                                                  | Acreage of flooded land during the 2018 simulation period (based from local tax parcel maps and hydraulic models)                   |
| 1b. Avoid private groundwater well impacts from salinization.                                                                        | Number of private wells with ANY potential for salinity impacts                                                                     |
| 1c. Provide a safe mechanism for wastewater disposal.                                                                                | Number of septic systems affected by Pamet River hydrology                                                                          |
| <i>2. Make the Pamet River a focal point and source of pride for the <b>community</b>.</i>                                           |                                                                                                                                     |
| 2a. Minimize long-term risk to critical city infrastructure.                                                                         | Number of critical city assets potentially affected by tidal, overwash, or alluvial flooding (e.g., post office)                    |
| 2b. Minimize short-term risks to city operations (e.g., transportation routes).                                                      | Days of road closure due to construction                                                                                            |
| 2c. Maximize recreational opportunities in the Pamet River.                                                                          | Number of safe access points for fishing, kayaking, and hunting                                                                     |
| <i>3. Restore a lush, verdant mosaic of saltwater, brackish, and freshwater habitats in the unique <b>Pamet River ecosystem</b>.</i> |                                                                                                                                     |
| 3a. Facilitate a hydrologic regime that “allows natural processes to proceed unimpeded” (NPS).                                       | Departure of the water level regime from a “reference” regime defined by unimpounded hydrology (at key gage locations in the basin) |
| 3b. Reduce barriers to the movement of wildlife (e.g., otter and other mammals) and fishes (e.g., migratory and resident).           | Number of potential movement barriers between the headwater and estuary (relative to a generalized mammal and fish life history).   |
| 3c. Minimize the extent of invasive, nuisance plants.                                                                                | Acreage of Pamet Watershed suitable for <i>Phragmites australis</i> (based on depth and salinity)                                   |

### **3.0 MANAGEMENT ALTERNATIVES**

Pamet River Watershed management could involve actions by partners including the Town of Truro, the National Park Service, Departments of Transportation, private land owners, and other entities (e.g., USACE, NGOs, etc.). A comprehensive listing of management measures is beyond the scope of this report, but general families of potential measures and alternatives were identified. Figure 3 presents a conceptual model of how management actions (shown in yellow) could influence project objectives (shown in green). Conceptual models are useful for increasing understanding, identifying potential alternatives, and facilitating team dialog, and ultimately, these models help “tell the story” of a project (Fischenich 2008). A Pamet River conceptual model (or set of conceptual models) is recommended to facilitate communication about this complex ecosystem and the multi-objective outcomes of interest. As an example, Figure 3 shows the relative effects of management actions, and in doing so, **highlights salinity and water level as crucial system variables for management.**



**Figure 3.** Pamet Watershed Conceptual Model linking management actions to objectives and sub-objectives. Yellow boxes are groups of management actions, blue boxes are key variables impacting many sub-objectives, light green boxes are sub-objectives, dark green boxes are overarching objectives, and variables not in boxes represent intermediate outcomes.

## **4.0 DECISION FRAMEWORK**

Environmental management decisions are often characterized by many stakeholders with competing values, multi-objective outcomes, complex ecological processes, and dependencies between actions. Owing to these challenges, structured decision making has emerged as an important tool for organizing values, linking alternatives to those values, and transparently making trade-offs (Gregory and Keeney 2002, Fischenich et al. 2013). A key product of many structure decision processes is a decision matrix or consequences table, which cross-walks alternatives and their relative achievement of objectives. Table 2 presents an example decision matrix for the Pamet Watershed. This consequences table provides a mechanism for organizing project outcomes for decision-makers and explaining the relative benefits and costs of alternatives. Early in project planning, these matrices are often populated with qualitative outcomes (such as those shown here). Typically, these qualitative outcomes are replaced with quantitative metrics as a project gathers data and analyses are conducted. For instance, the objective related to residential flooding (Obj-1a) is currently assessed directionally based on observations and discussions from the August 20-21 site visit, but these data could be replaced with a quantitative metric such as the acreage of flooded private property under a particular alternative assess via the intersection of modeled water levels and local tax maps. Table 1 provides some examples of quantitative metrics that could replace the qualitative outcomes. Importantly, qualitative assessments may be conducted rapidly for many alternatives, which provides a transparent mechanism for screening alternatives prior to cost- or time-intensive quantitative analyses.

**Table 2.** MODEL Decision Matrix for the Pamet Watershed. Matrix is populated with example alternatives and qualitative responses for discussion for planning alternatives evaluated in Chapters 6-7. **THESE VALUES DO NOT REPRESENT USACE study outcomes and are purely illustrative.** The qualitative assessments are scored as: ↓ = strong negative effect, ↓ = weak negative effect, 0 = no effect, ↑ = weak positive effect, and ↑ = strong positive effect.

| Alternative                                                                                                              | Residents |           |            | Community      |              |                | Ecosystem     |                  |               |
|--------------------------------------------------------------------------------------------------------------------------|-----------|-----------|------------|----------------|--------------|----------------|---------------|------------------|---------------|
|                                                                                                                          | 1a. Flood | 1b. Wells | 1c. Septic | 2a. City Infra | 2b. City Ops | 2c. Recreation | 3a. Hydrology | 2b. Connectivity | 3c. Invasives |
| No action                                                                                                                | ↓         | 0         | 0          | ↓              | ↓            | 0              | ↓             | ↓                | ↑             |
| Installation of bridges at both Wilder's Dike and Route 6.                                                               | ↑         | 0         | ↑          | ↑              | ↓            | 0              | ↑             | ↑                | ↓             |
| Removal of tide gate at Wilder's Dike                                                                                    | ↓         | 0         | 0          | ↓              | ↓            | 0              | ↑             | ↑                | ↓             |
| Installation of bridge at Wilder's Dike + Large box culvert at Route 6 + Access point for recreation at North Pamet Road | ↑         | 0         | ↑          | ↑              | ↓            | ↑              | ↑             | ↑                | ↓             |

#### 4.1 Other potential analytical strategies may prove useful, including:

- *Establish “baseline” hydrology:* Empirical water level data and ongoing hydraulic and groundwater modeling will be crucial to informing Pamet River planning. A “reference” condition may provide a useful baseline against which to compare all alternatives. For instance, an unimpeded hydrologic condition (i.e., without any culverts or gates) could provide a useful point of relative comparison for other alternatives. The departure from a “reference” flow regime could be a useful metric.
- *Simulation period:* USACE project planning typically proceeds based on a 50-year planning horizon. However, this study may benefit from a different simulation approach. A consistent two-year simulation period may be sufficient for assessing project outcomes. For instance, the 2017-2018 tidal forcing and known overwash dynamics could serve as a baseline for alternative comparison, which would simplify the challenge of long-term forecasting. This short-term simulation period seems particularly appropriate since the city is not required to use the annualized cost-benefit framework applied by USACE.
- *Scenario analysis:* This baseline simulation period could then be manipulated to examine scenarios representing alternative futures. At a minimum, the following four scenarios would provide a strong basis for assessing the relative performance of alternatives and “stress testing” them with respect to expected climate change in the region.
  - Existing condition with 2017-2018 tidal and overwash forcing (but altered infrastructure to reflect the new tide gate for the entire period)
  - Low sea level rise + minor increase in overwash volume and frequency
  - Medium sea level rise + significant increase in overwash
  - High sea level rise + major increase in overwash volume and frequency
- *Monitoring data:* The 2017-2018 water level data will provide a crucial source of calibration data for hydraulic analyses, particularly given the changes in boundary conditions (e.g., gate – no gate – gate). However, a strategy should be developed to transition monitoring to city operational staff (or USGS) for long-term data management. Water level data will provide useful success monitoring metrics, if management actions are implemented.

## 5.0 SUMMARY

This WOTS report was developed with the intent of providing decision-making framework on the Planning Assistance to States project in the Pamet River Watershed in Truro, Massachusetts. Four topics have been addressed briefly: (1) observations about basin condition based on a preliminary site visit, (2) objective setting to inform watershed planning, (3) potential management alternatives and their mechanistic link to objectives, and (4) recommendations for structuring study outcomes and analyses. All recommendations presented here should be considered as preliminary, qualitative, and non-representative of USACE study outcomes.



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# **Chapter 3**

**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**POLICY, INITIATIVES, AND  
HISTORICAL DATA LITERATURE REVIEW  
TIMELINE & SUMMARIES**

**C.A.P. SECTION 22  
PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

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## CHAPTER 3: Policy, Initiatives, and Historical Data Literature Review, Timeline & Summaries

### 1.0 FEDERAL, STATE AND LOCAL CLIMATE ADAPTATION AND MITIGATION INITIATIVES, POLICIES & RESOURCES

#### 1.1 Federal USACE Adaptation Guidance:

1.1.1 Engineering Regulation (ER) 1110-2-8162 Incorporating Sea Level Change in Civil Works Programs.

1.1.2 Engineering Construction Bulletin (ECB) 2018-2 Implementation of Resilience Principals in the Engineering & Construction Community of Practice.

1.1.3 Engineering Construction Bulletin (ECB) 2018-14 Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs and Projects.

#### 1.2 State MA and Local Adaptation Initiatives:

1.2.1 SEP 2016, Executive Order 569, Establishing an Integrated Climate Change Strategy for the Commonwealth, Office of the Governor-Commonwealth of Massachusetts.

1.2.2 DEC 2016, Pamet River Restoration Designated Priority Project by MA Division of Ecological Restoration (DER), Office of the Governor-Press Release.

Description: The Pamet River restoration will connect tidal habitat along the river and its tributaries *to improve salt marsh condition and strengthen coastal resiliency.*

1.2.3 2017 Town of Truro MA Hazard Mitigation Plan (HMP)

Description: This plan underwent a 1.5 year long evaluation 2015-2017. *As stated, the purpose of this plan is to reduce damages resulting from natural hazards by implementing sustained actions to reduce or eliminate long-term risk to human life and property from hazards and create resiliency. Upon approval by both MEMA/FEMA and adopted by the Board of Selectman, the Town becomes eligible to receive funding from FEMA's Hazard Mitigation Assistance (HMA) program.*

1.2.4 SEP 2018, MA Statewide Hazard Mitigation and Climate Adaptation Plan.

1.2.5 Massachusetts Climate Change Adaptation Coalition (MCCAC).

<https://www.massadapt.org/news.php>

Description: Making MA Resilient in the Face of Climate Change. The MCCAC is comprised of engineers, architects, planners, and conservation and environmental organizations working to reduce the Commonwealth's vulnerability to the impacts of climate change.

#### 1.2.6 Association to Preserve Cape Cod (APCC)

<https://apcc.org/climatechange/index.html>

A. Pamet River (Truro, MA) High Priority Salt Marsh Restoration; Additional hydrological modeling needs to be completed on the Pamet River restoration project to understand potential impacts of increased tidal flow on public water supply and abutting properties. Potential of 158 restoration acres which may alleviate flooding during storms and erosion.

B. In 2016 U.S. Geological Survey (USGS), in cooperation with the APCC, released a final report and model of the effect of sea level rise on the Cape Cod groundwater and is developing policies for adaptation to inundation of septic systems, stormwater and infrastructure.

## **2.0 Geology of the Outer Cape & Pamet River Groundwater Lens.**

2.1 Following retraction of glacial ice sheets, sea level rose and the original outwash plains were eroded back to the present day shoreline and groundwater flow lenses of the Lower Cape Cod aquifer system. In addition, east-west-trending stream valleys, or pamets, were carved into the outwash-plain surfaces. The geologic trends in sediment distribution deposits coarsen upward and become finer with distance from the sediment source. The depositional sediments in the Truro plains / Pamet River groundwater lens include glacial sediment deposits from a source much closer in distance than deposits of other areas of the Cape. This closer distance to the sediment source between outwash plains is reflected in the subsurface lithologic borings that confirm, *thick sequences of fine, medium, and coarse sand and gravel extending several hundred feet below land surface near the center of the lens, approximately one hundred feet below Pamet River, and decreasing depth tapering up adjacent to the coastal discharge inter-change zones.* (2004 Masterson).

## **3.0 Municipal Wells & Structural Features within the Pamet Groundwater Lens**

3.1 1869: The Town of Truro replaced a bridge at Truro Center Road with a dike commonly known as "Wilder's Dike". The dike was constructed with a culvert and clapper valve to prevent tidal flow from Pamet Harbor exchanging upstream of the dike, but still allow freshwater to flow from the upstream reaches of upper Pamet River, discharge through the culvert and clapper valve to Pamet Harbor at ebb tide. The valve is closed 2-hours before and 2-hours after a high tide cycle.



**3.2 1950-1952:** Route 6 highway was constructed bilateral across the Pamet River and a 48-inch culvert installed under the highway, parallel along the Pamet River centerline, to allow upper Pamet groundwater streams and stormwater runoff to discharge to Pamet Harbor.

**3.3 Public Water Supply:** The Town of Provincetown Water Department operates and maintains a total of three groundwater sources, all located within the Town of Truro at the northern end of the Pamet Freshwater Flow Lens of the Cape Cod Aquifer: the Knowles Crossing Wellfield consisting of three gravel packed wells; the Paul Daley Wellfield consisting of six active gravel packed wells; the North Union Field Well site consisting of two gravel packed wells (Truro Water Department, 2016). The Pamet lens extends from the north side of the Pamet River to Pilgrim Lake. From these municipal public water supply wells, the Provincetown Water Department supplies drinking water to the Town of Provincetown and several areas within the Town of Truro.

**3.4 1954-1955:** Knowles Crossing well field observed saltwater intrusion as a result of increased demand at 0.49 Mgal/d, which was lowered to 0.20Mgal/d (per 2002). At this time a secondary well field at South Hollow (also known as Paul Daley well field) began operation that included eight pumping wells at 0.57 Mgal/day (per 2002).

**3.5 1954-1955:** Knowles Crossing well field observed saltwater intrusion as a result of increased demand at 0.49 Mgal/d, which was lowered to 0.20Mgal/d (per 2002). At this time a secondary well field at South Hollow (also known as Paul Daley well field) began operation that included eight pumping wells at 0.57 Mgal/day (per 2002).

**3.6 1978:** North Truro Air Force Base (NTAFB) well operation began and has provided seasonal water to Provincetown [June – November] at 0.16 Mgal/d (per 2002).

**3.7 2018:** Clapper gate at Wilder’s Dike broke off during the March 2018 overwash event and was replaced in August 2018 with a lighter weight gate.

#### **4.0 Observed / Documented Ballston Beach Over-Wash Events & Investigations**

**4.1 Ballston Beach Over-Wash Events:** 2/7/1978, 10/30/1991, 12/12/1992, 3/8/2013, 1/27/2015, 2/15/2015, 1/24/2016, 1/2017, 3/6/2018

**4.2 2015, Ballston Beach and the Upper Pamet River, A Perspective for Long Term Management, NPS**

**4.3 2016, Ballston Beach Over-wash:** Understanding Over-wash Events for Science-based Management, Center for Coastal Studies, Provincetown, Massachusetts.

Over-wash Management Recommendations: Return the parking lot and southern dune back to its natural state since over-wash events deposit sand in the lowest areas, closest to the over-wash site. Return the entire Pamet River to pre-disturbed natural conditions since ecosystems are unparalleled for both the ecosystem habitat, contaminant filtration and flood control, and *build resiliency against sea level rise*.

**5.0 PAMET GROUNDWATER LENS SALT-FRESHWATER INTERCHANGE INVESTIGATIONS & SEA LEVEL RISE**

**5.1 1985-1998:** Investigations characterizing the hydrogeology and ground-water lenses of the Lower Cape Cod. The Pamet River is at the margin of two groundwater lenses, with upward gradients toward the river, confirming that the Pamet River is a discharge area for these lenses.

**5.2 1989,** Hydrogeologic Assessment of the Truro Landfill.

Purpose: This study was conducted at the recommendation of, A Groundwater Management Study (1985) and preliminary Hydrogeologic Investigation of the Town Landfill, Truro (1987) to define the nature and extent of groundwater contamination and impacts to downgradient private wells and the Pamet River.

Results: The Truro Landfill is located within the Chequesset Lens of the Cape Cod Aquifer, which extends to the Pamet River. Two leachate plumes were identified northwest of the landfill. Installation of monitoring wells confirmed subsurface conditions of gravels and sand with irregular occurrences of silts and clays. The low permeability of these fine grained materials impedes groundwater movement and to a large extent controls groundwater direction.

Groundwater travel times were calculated for the distance of 3,600 feet from the landfill to the Pamet River using the sub-regional velocity migrating the distance from the landfill to the Pamet River in approximately 9 years. The plume width, as defined by the 1,000 foot specific conductance contour was determined to be approximately 600 feet wide and ¼ mile long, in the general northerly direction and possibly extends further north and the monitoring data indicated.

The median sodium concentration in the Chequesset Lens is 21 mg/l based on data from 302 private wells (Janik, 1987). Sodium in the lower Cape senses occurs naturally from

sources such as, ocean spray and areas where wells are located close to the salt-freshwater interface.

As the plume progresses nearer to the Pamet River it probably surfaces and may affect shallow wells located near the river. The ultimate path of the plume is dictated by the configuration of the less permeable silty layer found under the sandy soils.

The plume contamination leaching from the Truro Landfill has been identified by elevated concentrations of the following constituents and the greatest recorded concentration: specific conductance (2150 micromhos/cm), alkalinity (527 ppm), pH (6.7), nitrate (16 ppm), sodium (297 ppm), iron (19 ppm), volatile organic compounds (23.8 ppb). Nitrate values were highest in wells (TRU-1S) and TRU-2S indicating separate and shallower plume of groundwater contamination emanating from the seepage pits.

### **5.3 1997, Pamet River Investigation Groundwater Assessment Study, Truro, Massachusetts, prepared by Cape Cod Commission under contract with USACE.**

Purpose: Investigated impacts to groundwater in association with removing the culvert at Wilder's Dike, prepared by the Cape Cod Commission under contract with the U.S. Army Corps of Engineers.

Field Data & Modeling Conclusions: The modeling results suggested only minimal increases (<0.01 ft) to groundwater levels 500-ft from the river (the distance to the closest house and septic systems). The field data and modeling reflect that the thick, dense peat layer (10-20 ft deep) of the former salt marsh along the upper Pamet River valley would block reintroduced tidal flows from intruding the groundwater. Additionally, the significant thickness of the subsurface aquifer (100-150 feet) and upward groundwater gradients suggest that saltwater flow from the river in to the surrounding groundwater lenses would be prevented.

Eastern-Pamet Lens / Ballston Beach Parking Lot well PW-2 data: Freshwater was not encountered. Groundwater generally measured 13.5-24% salinity. A 1989 investigation indicated salinity of 20 ppt at head of Pamet River, then immediately decreases to 0 ppt.

Eastern-Pamet Lens / Atlantic Ocean Salt-Freshwater Interchange / Exchange: The PW-2 salinity and specific conductive measurements indicate freshwater from the Pamet lens discharges to the ocean and ocean saltwater intrudes into the eastern-pamet lens immediately adjacent to the ocean then drops steeply below Pamet River. See (Fig 8 & 9 1997 CCC) (Fig 7 2004 Masterson) and 2019 CHAPTER 4 (Geophy Ghyben-Herzber relation).

Future Recommendations: Establish long term stream flow monitoring streamflow and groundwater, improve understanding of impacts to surface water flows on groundwater levels and vice-versa, and establish an overwash response plan to facilitate the removal of saltwater following the overwash of Ballston Beach.

#### **5.4 1998, Truro Municipal Landfill Comprehensive Site Assessment (Vol. 1)**

Results: Geologic Groundwater Elevation Profile / Cross-Section between Pamet River to Truro Landfill.

#### **5.5 2002, Hydrogeologic Investigation of the Pilgrim, Pamet, Chequesset, and Nauset Lenses Water Table Map of the Outer Cape: May 21-23**

#### **5.6 2004, Simulated Interaction Between Freshwater and Saltwater and Effects of Ground-Water Pumping and Sea-Level Change, Lower Cape Cod Aquifer System, USGS in cooperation with the NPS.**

Purpose: This regional-scale study at the Outer Cape began in 2000 and characterized the hydrogeology of the four groundwater flow lenses of the Lower Cape Cod aquifer system as described in studies conducted 1985-1998. The 2000 analysis modeled the salt-freshwater interface to address concerns of municipal groundwater pumping and recharge due to residential development, sea level rise predictions, and climate change induced drought conditions.

Coastal-Pamet Lens Freshwater Interchange: The model calculated that about 68 percent of the freshwater moving through the aquifer discharges directly to the coast, 31 percent flows thru the aquifer discharging into streams, and the remaining 1 percent discharge into public-supply wells.

Salt-Freshwater Interchange Location: The depth to the freshwater/saltwater interface varies throughout the study area and is directly proportional to the height of the water table above sea level. Simulated increases in sea level appeared to increase water levels and streamflows throughout the Lower Cape Cod aquifer system, while decreasing the depth of the freshwater/saltwater interface. The changing depth in water levels and freshwater/saltwater interface is largely controlled by non-tidal freshwater streams; thus, pumping from large capacity municipal supply wells increases the potential to disrupt this interface.

Sea Level Rise Impacts on Salt-Freshwater Interface Uncertainty: Based on this analysis, sea level rise over time results in a thinning of the aquifer in the Pamet Lens. The areas of greatest thinning occur near non-tidal streams and wetlands. The rate of rise of the

freshwater / saltwater interface is affected by the lag in response of the interface to changes in water table altitude. (Masterson 2004) *The model was adjusted to account for the lag; thus, water levels computed in this study have a range of uncertainty plus annual seasonal influences. It is concluded that private drinking water wells in the vicinity of the interface would benefit from long term monitoring under rising sea level conditions. (USACE Section 22 2019).*

**5.7 2008**, Plan for Watershed Management for the Pamet Groundwater Lens.

**5.8 2016**, Potential Effects of Sea-Level Rise on the Depth to Saturated Sediments of the Sagamore and Monomoy Flow Lenses on Cape Cod, Massachusetts (USGS).

Findings: The USGS found that rising sea level could potentially raise the water table and decrease depths to groundwater in some areas, which can adversely affect infrastructure.

**5.9 2018**, Recent Groundwater and Lake-Stage Trends in Cape Cod National Seashore: Relationships with Sea Level Rise, Precipitation, and Air Temperature (Smith and Medeiros).

Findings: This study analyzed trends between 2000 – 2017 in eleven groundwater wells and nine kettle ponds situated with Cape Cod National Seashore. The results suggested that sea level rise may be partially driving the longer-term trend of rising groundwater levels in several wells.

## **6.0 REINTRODUCING TIDAL EXCHANGE TO UPPER PAMET RIVER & POTENTIAL IMPACTS OF SALTWATER INTRUSION TO GROUNDWATER**

**6.1 1995**, Hydrogeology and Analysis of Ground-Water-Flow System, Sagamore Marsh, Prepared by USGS

**6.2 1997**, Pamet River Investigation Groundwater Assessment Study, Truro, Massachusetts, prepared by Cape Cod Commission under contract with USACE.

Impacts of reintroducing tidal flow thru Wilder's Dike: minimal increases (<0.01 ft) in the range of groundwater fluctuations 500 ft from the river (the distance to the closest residence) and nearly unmeasurable changes in the water levels near septic systems and wells greater than 500-feet from the river. The low permeability characteristics of the marsh peat serve to dampen tidal impacts on groundwater levels. Additionally, the thickness of the aquifer system (100-300 feet) and upward groundwater gradient suggest that saltwater flow from the river into the surrounding groundwater lenses will be prevented.

### 6.3 2004, Herring-River Salt Marsh Restoration, NPS

## 7.0 IMPACTS OF SEA LEVEL RISE ON: 1. PAMET GROUNDWATER LENS INTERFACE, 2. IMPACTS OF WILDER'S DIKE TIDE-GATE CONTROL STRUCTURE REMOVAL, AND 3. IMPACTS OF FUTURE MUNICIPALWELL PUMPING

**7.1 2004,** Simulated Interaction Between Freshwater and Saltwater and Effects of Ground-Water Pumping and Sea-Level Change, Lower Cape Cod Aquifer System, USGS in cooperation with the NPS.

Results: Three sea level rise scenarios were simulated, including, 1. Rate of sea level rise assumed to be zero 2002-2050, 2. Sea level was assumed to continue to rise at 0.104 in/yr. from 2002-2050, and 3. The rate of sea-level-rise was assumed to increase to 0.236 in/yr. from 2002-2050, as hypothesized by Donnelly and Bertness (2001).

Pamet Lens Results Summary: Based on the analysis described above, sea-level rise over time results in a thinning of the aquifer in the Pamet flow lens. This thinning results because the rate at which the water table increases is less than the rate at which sea level rises resulting in a net decline in the water-table altitude, which results in an increase in altitude of the salt-freshwater interface. The areas where the effect on the position of the salt-freshwater interface is the greatest are those areas near non-tidal streams and wetlands (i.e. freshwater streams and wetlands). The effect is substantially less where the water-table rise is not limited by non-tidal streams and wetlands. The rate of rise of the salt-freshwater interface is affected by a lag in the response of the interface to change in water-table altitude.

Chequesset Lens Results Summary: In the Chequesset flow lens, there are a substantial number of non-tidal surface-water discharge areas, and the rate of water-level rise in these flow lenses is much less than the rate of simulated sea-level rise. There is no appreciable change in the model-calculated interface position beneath this flow lens as was computed beneath the Pamet flow lens. A possible reason for this difference in the response of the interface could be differences in subsurface lithology simulated in the flow lenses, resulting in a much slower response times of the salt-freshwater interface.

Impacts of Sea-Level-Rise on Wilder's Dike Tide Gate: This 2004 study referenced both the 1991 USGS (Fitterman and Dennehy) and the 2001 Herring River modeling simulations and analysis. The 1991 USGS study concluded that, based on a sea-level-rise of 1.5 ft., in the vicinity of Chequesset Neck, removal of the tide-gate structure would have little effect on the total thickness of the freshwater lens. The 1991 conclusion was not supported by the 2001 modeling results that assessed the response of the flow system to moving the location of the tide-control structure. The results indicate a sea-

level-rise of 2.5 ft. resulted in a decrease in groundwater discharge and subsequent rise in the water table and the altitude of the salt-freshwater interface decreased, thinning the freshwater lens with time.

**7.2 2016**, Potential Effects of Sea-Level Rise on the Depth to Saturated Sediments of the Sagamore and Monomoy Flow Lenses on Cape Cod, Massachusetts, *prepared by USGS in cooperation of the Cape Cod Commission and Massachusetts Environmental Trust.*

## **8.0 WILDER'S DIKE & ROUTE-6 IMPROVEMENT HYDRAULICS**

**8.1 1998**, Pamet Tidal Water Study by USACE

# **Chapter 4**

## **PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**Regional Outer Cape Cod & Local Pamet River Characterization  
(Ghyben-Herzberg Relationship) of Saltwater Interface and  
Saltmarsh Peat Layer Barrier**

**Qualitative Data Analysis**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**



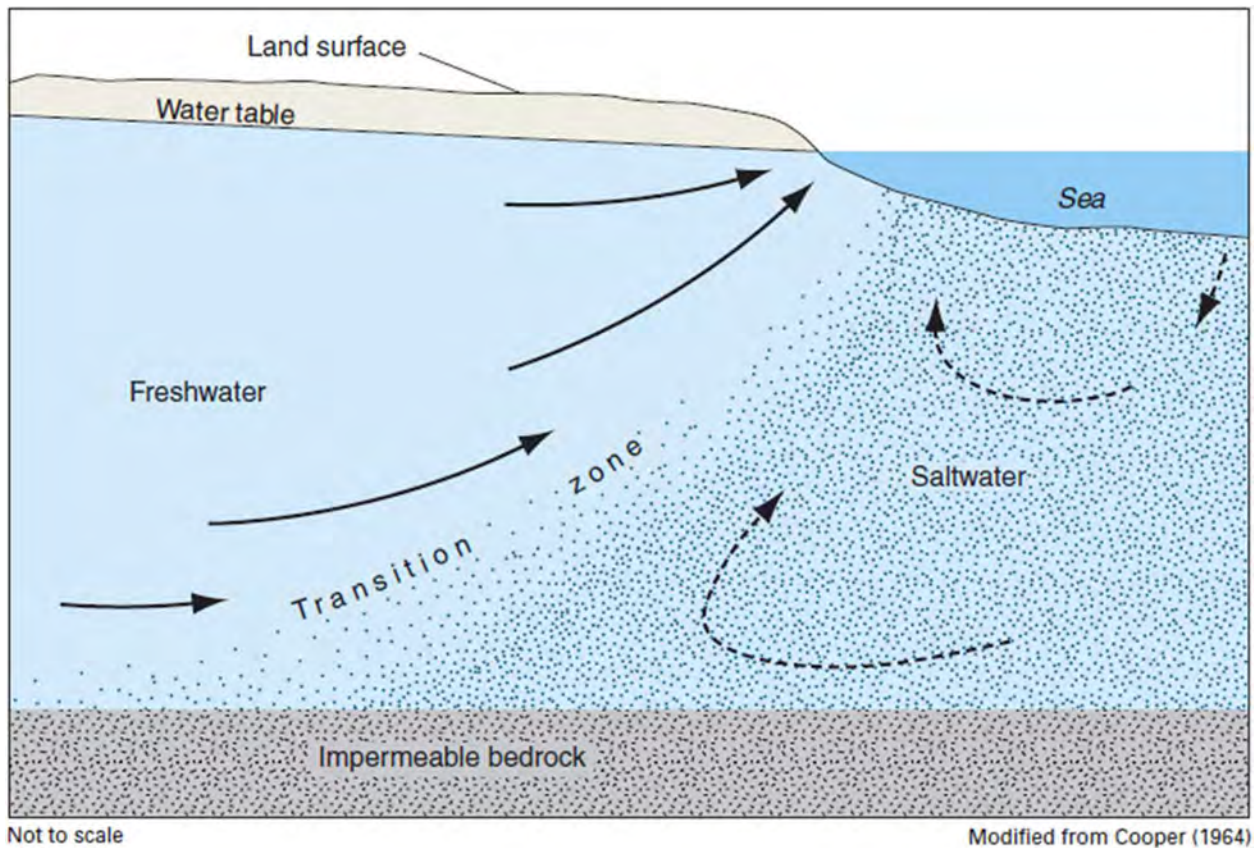
## **4.0 Saltwater Interface (Ghyben-Herzberg Relationship)**

### **4.1 Theoretical Depth To Freshwater-Saltwater Interface**

The Conceptual Site Model (CSM) for the Pamet River aquifer system suggests that the depth to the fresh-salt water interface is relatively deep, at least 100 feet below ground surface (ft. bgs), based on fresh-saltwater interface hydrogeological theory. The principal theory for estimating the depth to the fresh-saltwater interface are presented in this section.

The freshwater and saltwater zones within unconfined coastal aquifers are separated by a transition zone, where freshwater and saltwater mix (Figure A-1). Typically this transition zone is characterized by water quality using total dissolved solids (TDS) concentration (milligrams per liter or mg/L) or of chloride concentration, measured from groundwater samples collected from observation wells.

Accepted ranges for defining the transition zone use concentrations of TDS from about 1,000 to 35,000 mg/L, or chloride from about 250 to 19,000 mg/L. Within the transition zone, freshwater flowing to the ocean mixes with saltwater by dispersion and diffusion (Barlow, 2003).



**Figure A-1:** *Ground-water flow patterns and the freshwater-saltwater transition zone in an idealized coastal aquifer. A circulation of saltwater from the sea to the transition zone and then back to the sea is induced by mixing of freshwater and saltwater in the transition zone.*

The depth to the fresh-saltwater interface was observed by two investigators working independently along the European coast in the 1930s, where they found that the depth to salt water occurred below sea level at a depth about 40 times the height of fresh water above sea level (Todd, 1980). They attributed the distribution and thickness of fresh water above salt water to a hydrostatic equilibrium existing between the two fluids with different densities, and the equation that was derived to explain their observations is named after the two investigators: the Ghyben-Herzberg relation.

For hydrostatic conditions between freshwater and saltwater in a U-tube as shown in Figure A-2, pressures on each side must be equal as shown in Figure A-2.

$$\rho_s g z = \rho_f g (z + h_f)$$

where

:

$\rho_s$  = density of saltwater

$\rho_f$  = density of freshwater

$g$  = acceleration of gravity

$z$  and  $h_f$  are height below and above mean sea level for saltwater and freshwater, respectively

Solving for  $z$  yields equation 1:

$$z = \frac{\rho_f}{\rho_s - \rho_f} h$$

Eq. 1

The elevation of the water table above sea level is  $h$ , and  $z$  is the depth to the fresh-saltwater interface (Figures A-3, B-1).

Typical seawater has a density of about 1.025 grams per cubic centimeter ( $\text{g/cm}^3$ ), and freshwater has a density of about 1.000  $\text{g/cm}^3$ . Equation 1 indicates that the small density contrast between freshwater and saltwater results in 40 ft of freshwater below sea level for every 1 ft of freshwater above sea level, or as shown as Equation 2 (Barlow, 2003):

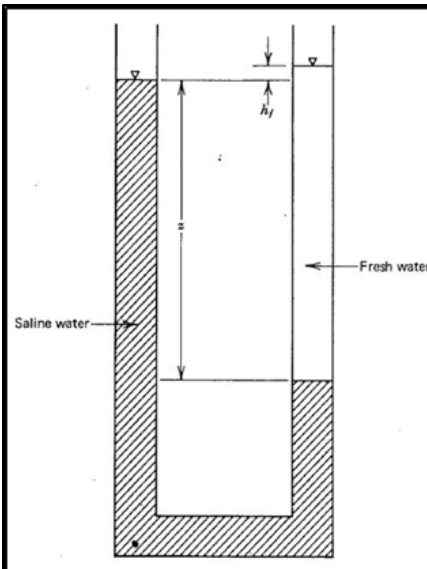
$$z = 40h_f$$

Eq. 2

Although the transition zone is often depicted as a sharp interface, the interface calculated by Eq. 2 is often interpreted as the position of a mixture of 50% freshwater and 50% saltwater in the transition zone (Izuka and Gingerich, 1998).

The Ghyben-Herzberg relation is based on the buoyancy of freshwater floating over denser salt water. The G-H equation also assumes the water-table elevation total head and the total head at the freshwater-saltwater interface are equal, which can only be valid for static (no flow) conditions that are unlikely in nature, or for horizontal flow where no vertical gradients exist (Figures A-3 vs. A-4). Since hydrostatic conditions cannot exist (or else a horizontal interface would develop), then hydrodynamic balance conditions must exist with freshwater flowing toward the sea (Todd, 1980). It is important to note from the Ghyben-Herzberg relation that fresh-salt water equilibrium requires that the water table (or piezometric surface for confined aquifers): (1) lie above sea level, and (2) slope downward toward the ocean under condition of freshwater flowing toward the sea and discharging into the ocean (Todd, 1980). Without these conditions, seawater will advance directly inland (Todd, 1980).

An example of the application of equations 1 and 2 is shown below, in Figure B-2 (Barlow, 2003).

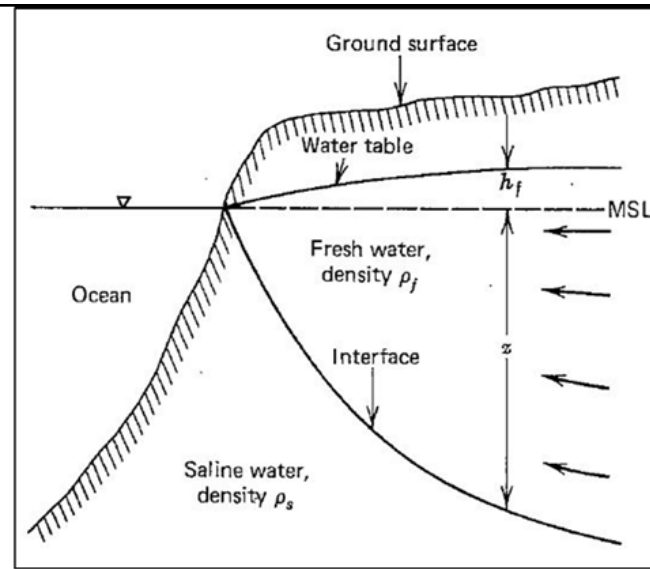


**Figure A-2**

**Fig. 14.1** Hydrostatic balance between fresh water and saline water illustrated by a U-tube.

$$\rho_s g z = \rho_f g (z + h_f)$$

$\rho_s$  = density saline water  
 $\rho_f$  = density fresh water  
 $g$  = acceleration of gravity  
**(Todd, 1980)**

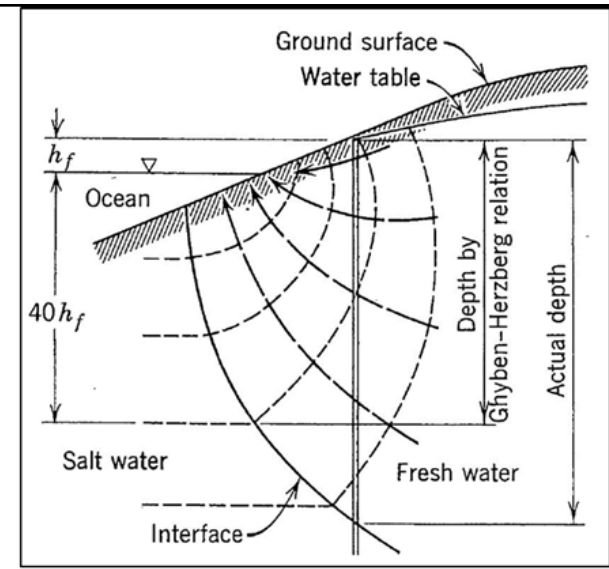


**Figure A-3**

**Fig. 14.2** Idealized sketch of occurrence of fresh and saline groundwater in an unconfined coastal aquifer.

$$\text{Eq. 2 } z = 40 h_f$$

Note: Hydrodynamic balance between fresh and salt water assumes fresh water is flowing toward the sea. Without freshwater flow, a horizontal interface would develop with fresh water everywhere floating above saline water (Todd, 1980).



**Figure A-4**

**Fig. 12.2.** Discrepancy between actual depth to salt water and depth calculated by the Ghyben-Herzberg relation (after Hubbert<sup>17</sup>).

Note: Flow net of flow lines (long dash) and equipotential lines of total head (short dash). Because the total head along an equipotential line is constant and the flow lines are sloping upward, the depth to the interface given by the G-H relation is less than the actual depth for upward vertical gradients. For flat gradients the difference remains small, but for steep gradients large errors may be incurred (Todd, 1959).

Figures A-2 to A-4: Ghyben-Herzberg relation Idealized vs Vertical Gradients



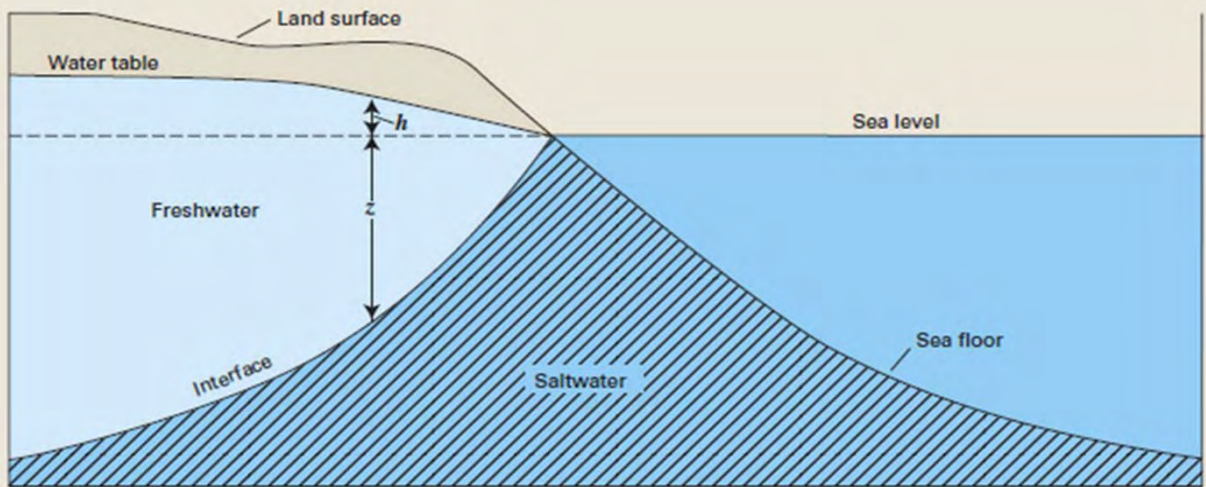


Figure B-1. Simplified freshwater-saltwater interface in a coastal water-table aquifer.

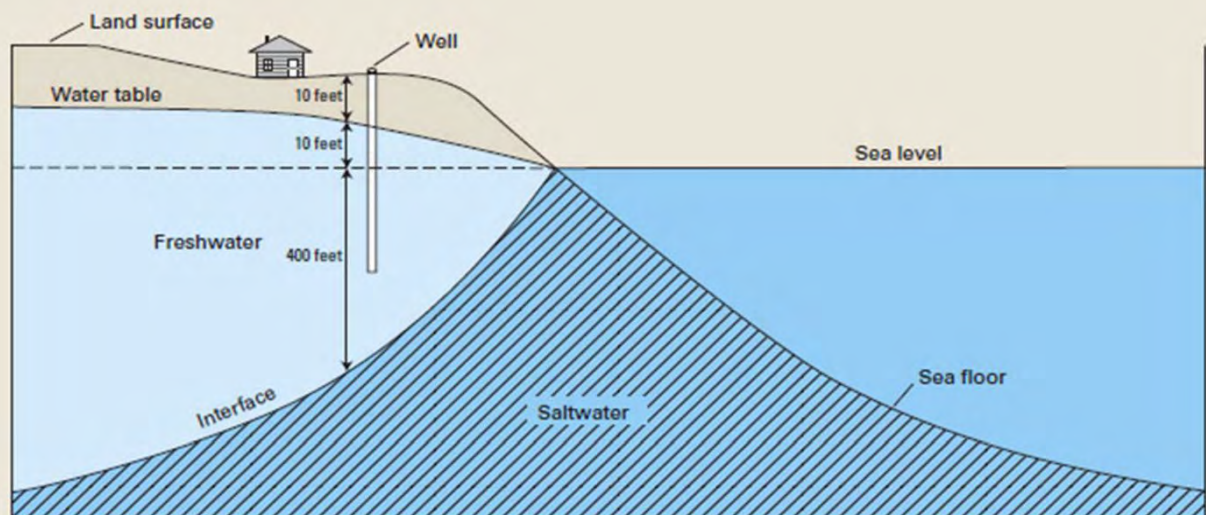


Figure B-2. Example application of equations 1 and 2 for estimating the thickness of freshwater in a coastal water-table aquifer: A freshwater-supply well near the coast has deteriorated with time and has not been pumped for a number of years. The owner of the well would like to know the total thickness of freshwater that might be available for development at the well site and, as a first approximation, has decided to estimate the total thickness by using equations 1 and 2. A topographic map of the area indicates that land surface on the property is about 20 feet above sea level. The depth to the water table measured in the unpumped well is about 10 feet. The elevation of the water table ( $h$ ) therefore is about 10 feet above sea level, and the estimated thickness of the freshwater zone below sea level ( $z$ ), estimated by use of equation 2, is 400 feet. The total thickness of freshwater at the site ( $h + z$ ) therefore is estimated to be about 410 feet.

Figures B-1& B-2: Example application of Ghyben-Herzberg relation  $z = 40h$  (Barlow, 2003)

## 4.2 Saltmarsh Peat Layer Barrier Saltwater Intrusion

This theory was regionally analyzed at Sagamore Marsh, applied at Herring River and in the historical data summary.

The presence of a peat layer with a low hydraulic conductivity near the main stem of the Pamet River, was suggested by the previous groundwater investigation performed in 1997. If an aurally extensive layer of peat exists at the surface of the upper part of the aquifer near the banks of the Pamet River, such a low permeability layer could act as a barrier to lateral seepage of saline water from the river into the aquifer under the temporary “losing stream” hydraulic gradient conditions that could exist during high tide. A low permeability peat layer (or layer of fine textured sediment as silt or clay) could also act as barrier to surface water infiltration of saline water into the aquifer during overbank flooding from overwash events at the headwaters of the Pamet River at Ballston Beach.

The lateral extent, vertical depth, and aerial continuity of a low permeable peat or fine textured sediment layer at the surface of the overburden aquifer can only be inferred using existing boring data, and should be investigated as part of the establishment of a new long-term monitoring well network.

## 4.3 Conclusions and Recommendations

The Conceptual Site Model (CSM) presented in Chapter 4 suggests a relatively deep fresh-salt water (greater than 100-ft) with the interface groundwater/surface water interaction described by the Ghyben-Herzberg relation and analyzed regionally at Sagamore Marsh and the Herring River.

Data collection efforts conducted as part of this study substantiated the regional Ghyben-Herzberg relations at the Pamet River as presented in Chapter 5, and the groundwater modeling results presented in Chapter 6.

The results of this analysis and the understanding that the Pamet River groundwater aquifer-surface water system support this system as both very dynamic and sensitive to seasonal precipitation and draught conditions, as well as, increasing sea level rise. Thus, additional data collection for the purpose of modeling the predictive fresh-saltwater interface impacts to residential groundwater wells is not recommended at this time.

As presented in the Executive Summary and described in Chapter 1, this study recommends implementing a long-term monitoring program to develop an adaptive management strategy for the watershed. The data and understanding gained from the monitoring program can provide an iterative learning process that builds on new data, and knowledge gained, as improvements to the river drainage system are implemented

by the town. Improvements, including, the Wilder's Dike and Route-6 culvert modifications proposed in Chapter 1.

#### **4.4 REFERENCES:**

Barlow, Paul M., 2003. Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast. US Department of the Interior, USGS Circular 1262.

Izuka, Scot K. and Gingerich, Stephen B., 1998. Estimation of the Depth to the Fresh-Water/Salt-Water Interface from Vertical Head Gradients in Wells in Coastal and Island Aquifers. *Hydrogeology Journal* (1998) 6:365-373.

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# **Chapter 5**

PAMET RIVER INVESTIGATION

Truro, Massachusetts

2016-18 PAMET RIVER FIELD DATA INSTRUMENTATION,  
COLLECTION, VALIDATION AND  
QUALITATIVE ANALYSIS

C.A.P. SECTION 22  
PLANNING ASSISTANCE TO STATES

NOVEMBER, 2019



**CHAPTER 5:**  
**2016-18 Pamet River Field Data Instrumentation, Collection & Validation**  
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## **1.0 INTRODUCTION**

Chapter 5 presents the Pamet River 2017-18 recorded field data instrumentation, collection, and validation. Results of the data collection effort are both described and compiled in tabularized form in Chapter 5. Correlating Figures are presented in Attachment B and Attachment C as referenced throughout Chapter 5.

The purpose of the tasked field data collection effort is to support:

- Qualitative verification of local Pamet River, groundwater flow paths, salt-fresh water intrusion and exchanges against regional Cape Cod characterizations of these phenomena investigated as part of previous scientific studies as presented in Chapter 4 and Chapter 8,
- Quantitative evaluation the Pamet River salt-freshwater groundwater lens location and movement by developing a data-driven mathematical groundwater model (MODFLOW) presented in Chapter 6,
- Quantitative evaluation the Pamet River tidal-surface-water regime and Ballston Beach overwash drainage by developing the data-driven mathematical riverine flow model (HEC-RAS) presented in Chapter 7,

To meet the study objectives presented in the Executive Summary, including:

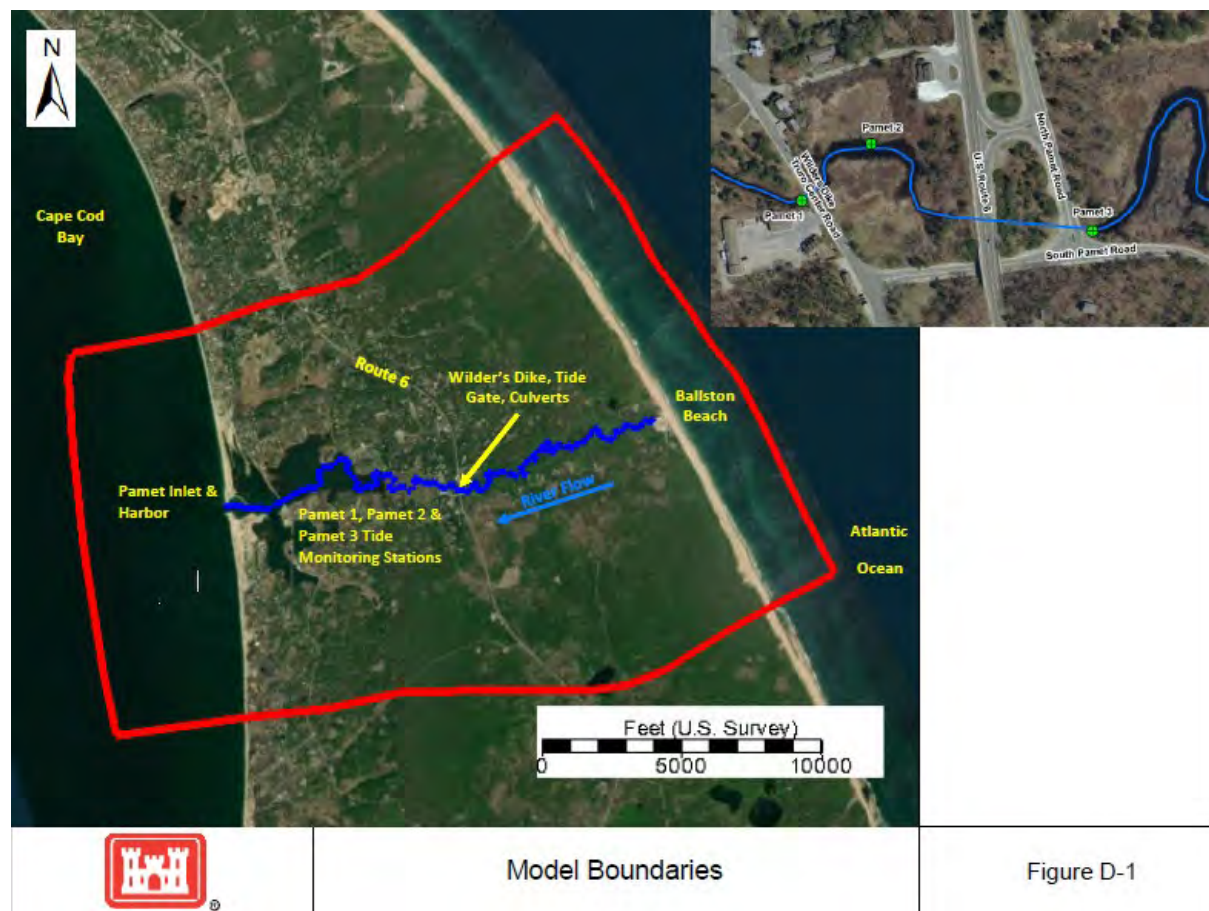
- Develop and analyze alternatives to improve Wilder’s Dike and Route 6 culverts to improve stormwater drainage generated during Ballston Beach overtopping events,
- Better understand the salt-freshwater interface location and potential risks to saltwater intrusion at local wells,
- Evaluate reintroduced tidal exchange to the upper Pamet River for the purpose of potential ecosystem (saltmarsh) restoration

This Pamet River field data collection effort supports the qualitative analysis to verify historical data collection-investigations that regionally characterized Cape Cod groundwater flow paths, aquifer parameters, fresh-saltwater interchange, and sea level rise impacts are referenced in Chapter 3 “Background Data Review Timeline and Summaries”, including: May 1997 Groundwater Assessment, 1988-1989 Hydrogeologic Truro Landfill Assessments, 2004 Fresh and Saltwater Interaction with Sea Level Change Investigation by John P. Masterson. Additionally, a broad scale Ghyben-Herzberg Theory in the Ballston Beach vicinity was published by the USGS based on assumed saltwater and freshwater densities in relation with subsurface hydraulic conductivity as described in Chapter 4.

The field data collection efforts supporting the quantitative analyses: a riverine computer model (HEC-RAS) and a groundwater computer model (MODFLOW) developed to simulate and evaluate

predicted alternatives in tandem under the subsurface and surface-tidal scenario's outlined in the objectives. Both models are based on available field data, calibrated and verified with observed conditions and events to the best extent practicable, and then used to predict the impact of alternatives on the system. Computational models can provide important value to the analysis of a hydrogeologic system but they depend on the data availability and confidence of that data used for calibration. Models built on insufficient and/or uncertain data will require assumptions and estimates and will have greater error and uncertainty in the results.

The first step of this study was to develop a data collection effort to support the study objectives outlined in the Executive Summary. Collected data included tidal stage data and salinity of the Pamet River, groundwater level (elevation) data, and groundwater chemistry data.



Location Map: Pamet River System

## **2.0 FIELD DATA METHODOLOGY**

### **2.1 Collection Dates and Phases.**

This study initiated four separate phases of water parameter monitoring and data collection from December 2016 to September 2018 to support study objectives:

#### **2.1.1 Phase 1: Tide Monitoring [Dec. 2016 – June 2018]**

Installation of three new riverine tide monitoring stations recording real-time stage and elevation data, named Pamet 1, 2, & 3.

#### **2.1.2 Phase 2: GW Well Redevelopment and Monitoring [Jan. 2017 – Sept. 2017]**

Existing groundwater wells were selected for redevelopment and monitored for water level depth and conductivity to verify and better understand the regional groundwater-surface water characterizations, and attempt to monitor the position of the existing aquifer fresh-salt water interface. The work was performed by the USACE with the assistance of the National Park Service, Cape Cod National Seashore staff locating wells and retrieving data, lending five Onset water level and 5 Onset Conductance loggers used along with five USACE loggers,. Automated water level and conductivity loggers were programmed to take readings with a 15 min sample collection rate.

#### **2.1.3 Phase 3: Salinity Grab Sample Collection [Sept. 26, 2018, and Nov. 8, 2018]:**

Manual surface water salinity sampling was collected during two separate periods.

## **2.2 Stationing**

### **2.2.1 Tide Stations**

Beginning in December 2016, three river / tide monitoring stations were deployed in the Pamet River. The stations were named Pamet 1 (Wilder's Dike adjacent to the Post Office downstream of tide gate), Pamet 2 (located upstream of the tide gate in the phragmites marsh between Truro Center Road and Route 6, and midstream between Pamet 1 and 3), and Pamet 3 (located on the upstream concrete wall inlet to the smaller culvert at the North Pamet Road on-ramp to Rt 6). The locations of the three tide gages are shown on See Figures B-1 to B-4 (Attachment B) for Station Locations.

The stations were automated with Sutron X-link data loggers with cellular modems and river stage sensors that measured water level as pressure set to monitor every 15 minutes.



Location Map: Tide Monitoring Stations (Attachment B: Figure B-1)

### 2.2.2 Groundwater Well Stationing, Redevelopment and Instrumentation

Wells selected as most suitable or usable for use as input data sources for the groundwater / surface water modeling had been installed for previous studies. In total, ten groundwater wells were selected for automated 15 minute data collection of water level and temperature, of which eight were existing wells needing redevelopment. Two wells were new shallow steel wellpoints installed by USACE and designated: USACE-1 (Head of Pamet near Ballston Beach) and USACE-2 (Truro Harbor off Depot Road), both hand driven to 3-4 feet below ground surface and consisting of a 3 ft stainless steel tip and 2-inch diameter steel casing / riser with cap. See Figures B-7 to B-11 (Attachment B) for Station Photos and Figures C-1 to C-50 (Attachment C) for Station Locations. A table presenting a well construction summary and rationale for monitoring is shown in Figure B-12.





**Location Map: Groundwater Monitoring Stations (Attachment D: Figure D-2)**

The two new well points and eight existing monitoring wells were installed and / or redeveloped from January 2017 and February 2018. The eight existing wells installed by the Cape Cod Commission or others, and the two “new” wells, USACE-1 at the head of the Pamet near the tip of the overwash alluvial fan, and USACE-2 at the outflow of the Pamet into Truro harbor. Attachment B, Figures B-13 & B-16, present the Pamet River Well Redevelopment Field Sheets, Figures B-14 & B-15 present the YSI 6020 Real Time Parameter Analysis used during the Well Redevelopment, and Figures B-17 & B-18 present the Pamet River Well Logger deployment.

Redevelopment of eight (8) existing monitoring wells, and two (2) new wellpoints installed by USACE, was performed using a Waterra inertial plastic checkvalve (“footvalve”) with a Waterra surge block accessory, attached to ½-inch x 5/8-inch diameter HDPE plastic tubing. The footvalve and surge block were set inside the well screen at the end of appropriate length tubing. The tubing was raised up and down to create a surge action in the well screen by a Waterra Hydrolift-2 3/4 horsepower mechanical arm powered by a portable electric Honda generator. The Hydrolift-2 generated a 4-inch stroke of the tubing at up to 200 cycles per minute.

Redevelopment status was determined by observation of changes in turbidity in the discharged water from the monitoring well, and tracking stabilization of water quality parameters using a YSI 650 sonde multiparameter field water quality meter. Redevelopment was also tracked by pumping a minimum of three well volumes from the well. Once sufficient well volume had been pumped, and water quality parameters appeared stable, it was considered that no further improvement in redevelopment could be achieved and the well was considered redeveloped. Downhole transducer equipment was then deployed in the monitoring well or wellpoint casing that included an automated stage (groundwater level) sensor in all locations, and conductivity loggers in selected locations. Sensor equipment was a combination of equipment loaned from the National Park Service, or acquired by USACE for the project. Data loggers in the ten wells were downloaded manually.

Significant cost savings were achieved by installing the data collection probes in eight existing groundwater monitoring wells. Two additional well points were driven by hand for the collection of additional shallow groundwater levels without the added expense of full well drilling and installation. Additional savings were achieved by borrowing the groundwater monitoring equipment for a short period from the National Parks Service (NPS) instead of purchasing new equipment for this project. The following sections will provide the data collected and discuss the value of the data to the modeling effort.

### **2.2.3 Groundwater Well Logger Deployments**

Groundwater wells were equipped with automatic data loggers to collect stage and conductance data in January & February 2017 thru September 2017. Results were used for groundwater modeling, evaluation of groundwater-surface water interactions, and attempt to determine the position of the fresh-saltwater interface.

### **2.2.4 Salinity (Surface Water) Grab Sample Data**

Surface water grab samples collected from the main stem of the Pamet river during August, September, and November 2018 were used to develop assumptions regarding the transition from saline water to fresh water in the Pamet River both down- and up-stream of the Wilder's Dike tide gate, and to refine understanding of boundary conditions for groundwater modeling and the regional characterizations. During August 2018, field data measured salinity using a refractometer probe (measured as conductivity and converted to salinity by calculation by the field instrument). In September and November 2018 grab samples were collected and sent for laboratory analysis to measure salinity from the following water quality parameters: chlorides, total dissolved solids (TDS), total sodium, dissolved sodium, and specific conductance. The Massachusetts DEP-certified laboratory, Barnstable County Health Laboratory analyzed the samples. Locations and lab results are shown in Figures B-5 & B-6 (Attachment B),

Additionally, two surface water sampling locations were located downstream of Wilder's Dike (Downstream 1 and Downstream 2), one at Wilder's Dike / Pamet 1 (harbor or downstream side of dike), one at Pamet 2, and one at Pamet 3.

Per the removal of the Wilder's Dike tide gate during the March 2018 nor'easter, the August 2018 field data was scheduled to be collected before the tide gate was replaced on August 14, 2018. The absence of the tide gate for approximately five months from March to August 2018 afforded a unique opportunity to obtain the surface water grab samples from the Pamet River to determine the extent of tidal salt prism migration upstream of Wilders Dike. Surface water grab samples collected at the same stations after the tide gate was replaced provided field verification to calibrate the HEC-RAS model and upper Pamet salt marsh restoration potential.



Location Map: Salinity Grab Sample Stations (Attachment B: Figure B-5)

### 3.0 Recorded Field Data Validation and Monitoring Observations

#### 3.1 Tidal Recorded Data

The three (3) tide gages were installed at locations in the main stem of the Pamet River shown on Figure C-51. Photos of each gage location are shown in Figures C-52 to C-54. Pamet 1 was installed at Wilders Dike on the downstream side of the dike at the tide gate (Figure C-52). Pamet 2 was installed upstream of Wilders Dike between Rt. 6 and Rt. 6A (Truro Center Road). Pamet 3 was installed at the concrete headwall on the upstream side of Rt. 6 (Figure C-54). The



tide gages consist of an automatic water level pressure transducer installed in a steel riser pipe and perforated screen exposed to the entire open water depth of the river.

### **3.1.1 Boston Tides vs. Pamet 1 Observed Tides from Dec. 27, 2016 to June 15, 2018**

On Figure C-55, the data at Pamet 1 (the most downstream gage location on the downstream side of the tide gate at Wilders Dike) is compared to data collected at the NOAA tide gage at Boston. Boston tidal signal matched well against Pamet 1 tidal signal from Dec. 27, 2016 to May 17, 2017. However, starting in mid-May 2017, the amplitude of the tide at Pamet 1 was significantly reduced. Several zoomed sections of the data are shown in Figures C-55 to C-58. The amplitude reduction doesn't appear to be natural and it doesn't occur 1 year later in May 2018. This big difference between Boston and Pamet 1 lasts until 27 Dec. 2017. At that point, the good match returns for a few days until Pamet 1 stops collecting data at end of 2017. When Pamet 1 returns to collecting tide data in mid-March 2018, there is good agreement against the Boston station except for tidal elevations greater than +4.0 NAVD88. At that point, the observed tidal signal was out of range for the Pamet 1 station.

The Boston tide attained record levels during a nor'easter on January 4, 2018, when the timing of the storm coincided with an astronomically high tide. The high tide was the highest on record since recording began in Boston Harbor in 1921, exceeding the high tide recorded in Boston Harbor during the Blizzard of 1978.

### **3.1.2 Pamet 1 vs Pamet 2 Observed Tides from Dec. 27, 2016 to June 15, 2018**

The impact of the tide gate on the tidal signature is shown in Figure C-59, which compares Pamet 1 (downstream of the gate) to Pamet 2 (upstream of the gate). A tidal signature is visible in the data recorded at Pamet 2 on the upstream side of the old tide gate (pre-March 2018 before removed by storm), with an amplitude of about 1 foot at Pamet 2, compared to an amplitude of about 3 to 5 feet at Pamet 1. The 7 month decrease in amplitude that occurred at Pamet 1 starting mid-May 2017 did not happen at Pamet 2 (see zoomed plot in Figure C-60). The fact that Pamet 2 didn't see same drastic reduction in tidal signal that Pamet 1 saw, suggests that there were equipment recording issues at Pamet 1.

The March 2, 2018 nor'easter storm event that blew off the tidal gate at Wilder's dike can be seen in Figure C-59. Once gate was off, the tidal amplitude of Pamet 2 increased and the high/low tidal levels increased as tidal salt water prism was allowed to migrate upstream through the 3.5-foot diameter culvert pipe under Wilders Dike. There is no tidal data from Pamet 1 for the March 2, 2018 event.

### **3.1.3 Pamet 1 vs Pamet 2 vs. Pamet 3 Observed Tides from Dec. 27, 2016 to June 15, 2018**

The same reduction in amplitude that happened at Pamet 1 between Mid-May and end of December 2017 also occurred at Pamet 3 as shown in Figure C-61. The tidal amplitude reduction is not as apparent at Pamet 3 because the tidal amplitude at Pamet 3 is smaller compared to

Pamet 1. Reduction in amplitude does not appear to be natural and didn't occur one year later in May 2018. See Figure C-61 & Figure C-62.

### **3.1.4 March 2-4, 2018 Nor'easter**

The peak hourly tide at Boston on March 2, 2018 was 9.0 ft. NAVD88. The peak was the second-highest at Boston since January 2017 which was the start of the Pamet tidal data collection program; therefore the tide stage monitoring at the Pamet River occurred during the period when storms resulted in the two highest tides in Boston Harbor ever recorded since data collection began at Boston in 1921. (A higher peak of 9.52 ft. NAVD88 was observed at Boston on Jan. 4, 2018 that set a new record high tide since recording began in 1921 in Boston Harbor.) Two of the tidal stations in the Pamet River (Pamet 2 and 3) were recording during the March event and showed peak water levels two days after the Boston peak on March 4, 2018. The tide gate at Wilders Dike was blown off during the March 2-4, 2018 storm event. Additionally an overwash event occurred at Ballston Beach, introducing large volumes of seawater to the upper Pamet River.

Pamet 1 wasn't recording during the March 2-4, 2018 event but the other 2 stations were. Even though the Jan. 4, 2018 peak was higher than the Mar. 2, 2018 peak at Boston, that wasn't the case for tides observed at Pamet 2 and Pamet 3 as the following figures show. The peak of the tides on the Pamet appear to happen 2 days after the Boston peak on Mar. 4, 2018. Also, it should be noted that the recorded high peaks at Pamet 2 during the Mar. 2-4, 2018 event appear to have exceeded the range of the gage and are truncated. See Figure C-63.

After the tide gate was blown off during the March 2-4, 2018 storm event, water levels at Pamet 3 did not recover to the "new" post-storm conditions until about March 18th. This observation indicates that it took about 2 weeks to drain the stored-up volume resulting from the overwash from the upper Pamet River (even without the Wilder's Dike tide gate in place).

The impact of the Wilder's Dike tide gate on tidal conditions can be assessed by comparing two time windows: January 10 – February 28, 2018 and March 18 – May 6, 2018. Dates were removed from the data sets to allow a comparison of conditions with and without the tide gate as hydrographs of tidal elevation vs elapsed time in hours. This allows the inference of general trends. Note that storm events were not removed from the datasets, so some variability in tidal highs and lows remains. Comparisons at Pamet 2 are shown in Figure C-63 and at Pamet 3 in Figure C-65.

The tidal amplitude at Pamet 2 doubled from approximately 1 foot to over 2 feet after the removal of the tide gate. The Pamet 2 graph (Figure C-64) also shows that the low water elevations with the gate in-place was around 0.5 feet NAVD88 and increased to 1.25 feet after the gate was removed. High water elevations increased even more after the gate was removed. Typical high water elevations went from 1.5 feet NAVD88 to over 3.0 feet NAVD88.

At Pamet 3, unlike at Pamet 2, the tidal amplitude remained relatively unchanged at 1 foot after the removal of the tide gate (Figure C-64). This indicates that the culvert under Route 6, rather than the gate at the dike, is the controlling factor in the tidal amplitudes recorded at Pamet 3. The data also shows that the overall water level elevations increased by about a foot after the tide gate was removed.

### **3.2 Salinity Grab Sample Data Analysis**

### **3.3 Groundwater Data Collection Analysis**

Continuous water levels using downhole transducers were measured at 10 wells in the vicinity of Pamet River during the winter, spring and summer months (January – September 2017). The well locations are referenced in the figures presented in Figures C-1 to C-50 (Attachment C). Groundwater levels were converted to elevation in feet NAVD88. Instantaneous conductance measurements were made in nine of the wells using a YSI meter. Continuous conductance measurements were collected at six of the wells using Hobo probes: USACE-1, PW-3D, PW-4, TRU-5D, TRU-7, USACE-2. Estimated relationships between conductance and TDS were used to convert the conductance data to total dissolved solids (TDS), which is more easily used in the groundwater model. TDS is often used as an analog for salinity concentration in water, (for reference, seawater generally has a TDS of 35,000 mg/L). Since the majority of dissolved solids by weight in seawater consists of sodium and chloride, salinity concentrations is approximately the same as the TDS of seawater. Salinity is expressed by several types of concentration units in supporting literature. For example, typical seawater salinity is 35 parts per thousand (ppt). Expressions of salinity in other concentration units are: 35 grams salt per 1000 grams seawater; 35,000 milligrams per liter (mg/L), and 35,000 parts per million (ppm). The Massachusetts drinking water salinity concentration standard is 500 mg/L. For the purposes of this report, water with TDS less than 500 mg/L will be considered fresh water. Water with higher salinity (or TDS) than fresh water but less than sea water is generally referred to as brackish water.

Quality of monitoring well stage and conductance data was regarded as good overall excepted as noted in Figures B-5 & B-6 (Attachment B).

**TABLE 1**  
**DATA COLLECTION ANALYSIS SUMMARY**  
**GROUNDWATER MONITORING WELLS**

| Well ID | Tidal Sign-ature | Precip. Event Sensitive & Seasonal | Data Results Indicating Subsurface & Aquifer Characteristics                                    | Data Validated CSM | Data Subsurface Under-standing                                                |
|---------|------------------|------------------------------------|-------------------------------------------------------------------------------------------------|--------------------|-------------------------------------------------------------------------------|
| C-5     | No               | No                                 | Freshwater TDS / Water Level Change From Precip. Attenuated By Thick Unsat. Zone                | Yes                | Benefit / Confirms Aquifer BUT NOT Interface w / Overwash                     |
| C-1     | No               | Yes                                | Same as C-5                                                                                     | Yes                | Benefit                                                                       |
| USACE-1 | No               | Yes                                | Overwash Infiltrated Well / salt-fresh interface / freshwater flow dampens tidal signature      | Yes                | Benefit / Supports Freshwater Flow Lens Interaction/ Overtopping Infiltration |
| PW-4    | No               | Yes                                | Rapid Precip Infiltration                                                                       | Yes                | Benefit / Wetland Parameters                                                  |
| PW-3D   | No               | Yes                                | Potential Crack in Casing                                                                       | Limited            | Not As Expect.                                                                |
| TRU-5S  | No               | Yes                                | Upward GW Gradient                                                                              | Yes                | Benefit / GW Flow Direction                                                   |
| TRU-5D  | No               | Yes                                | Upward GW Gradient                                                                              | Yes                | Benefit / GW Flow Direction                                                   |
| TLF-005 | Inconclusive     |                                    | Peat / Interface / TDS increased w/ temps.                                                      | Caution            | Benefit / Wetland Parameters                                                  |
| TRU-7   | Yes              | Yes                                | Seasonal TDS Variation Related to Groundwater Level/Tide Cycle/Freshwater River Flow Variations | Caution            | Benefit / Wetland Parameters/Gro undwater Discharge                           |
| USACE-2 | Yes              | Not Discernable due to Tide        | TDS Max Slightly Less than Seawater                                                             | Caution            | Benefit                                                                       |

\*\* Note: Monitoring well probe sensors that recorded questionable TDS due to unknown or unverified reasons, may be associated with winter temperature sensitivity-density characteristics, build-up of biofilm, and/or an indication of subsurface characteristics or freshwater lag / base-water influences. THIS DATA SHOULD NOT BE USED AS BASELINE DATA, BUT USED WITH CAUTION TO INVESTIGATE OBJECTIVES *QUALITATIVELY* OR *QUANTITATIVELY* WITH A STRESS ANALYSIS.

**TABLE 2**  
**TOTAL DISSOLVED SOLIDS (TDS) ANALYSIS / GROUNDWATER MONITORING WELLS**

| WELL ID | Tidal Signature | TDS Designation        | Instan. TDS (mg/l) | Range TDS (mg/l)                 | As Exp-ected | Location                                                |
|---------|-----------------|------------------------|--------------------|----------------------------------|--------------|---------------------------------------------------------|
| C-5     | No              | Very Low               | 96                 | Min.                             | Yes          | Hill 0.9Mi S. River<br>upper Pamet<br>Well Depth 90 ft. |
| C-1     | No              | Very Low               | 149                | Min.                             | Yes          | Hill 0.2Mi S. River<br>Lower Pamet<br>Well Depth 40 ft. |
| USACE-1 | Yes             | Brackish               | 20,000             | Min.                             | Yes          | Low 700 ft Inland<br>Ballston Bch.<br>Well Depth 7 ft.  |
| PW-4    | No              | Very Low               | 73                 | Min.                             | Yes          | Low 0.1Mi S. Riv.<br>upper Pamet<br>Well Depth 38.5ft   |
| PW-3D   | No              | Brackish               | 5,100              | Declines<br>Caution              | No           | Co-Located PW-4<br>Well Depth 150-ft                    |
| TRU-5S  | No              | Very Low               | 57                 | Min.                             | Yes          | Wetland S. River<br>upper Pamet<br>Well Depth 20 ft     |
| TRU-5D  | No              | Very Low               | 77                 | Min.                             | Yes          | Co-Located TRU-5D<br>Well Depth 60 ft.                  |
| TLF-005 | No              | Low                    | 299                | Increases<br>Caution             | No           | Wetlands S Riv.<br>upper Pamet<br>Well Depth 14 ft.     |
| TRU-7   | Yes             | Brackish               | 7,000              | Variable<br>Impacts from<br>Tide | Yes          | D.S. Wilders Dike<br>Lower Pamet<br>Well Depth 15 Ft.   |
| USACE-2 | Yes             | Seawater /<br>Brackish | 10,000 –<br>35,000 | Declines<br>Caution              | No           | Confluence S.Side<br>Lower Pamet<br>Well Depth 9.5 ft.  |

\*\* Note: Monitoring well probe sensors that recorded questionable TDS due to unknown or unverified reasons, may be associated with winter temperature sensitivity-density characteristics, build-up of biofilm, and/or an indication of subsurface characteristics or freshwater lag / base-water influences. THIS DATA SHOULD NOT BE USED AS BASELINE DATA, BUT USED WITH CAUTION TO INVESTIGATE OBJECTIVES *QUALITATIVELY* OR *QUANTITATIVELY* WITH A STRESS ANALYSIS.

### **3.3.1 Monitoring Well C-5**

Well C-5 is located about 0.85 miles south of the river on the ocean side of the Cape Cod peninsula, on Collins Road at the entrance to dirt vehicle trail. The approximate location of this well is shown on Figure C-1. A photo of the well is provided in Figure 2. At this location the ground surface is approximately 70 ft above sea level and the depth of the well is 90 ft, so the well is measuring groundwater about 20 feet below sea level. The well screen is set approximately 10 feet below the water table.

The continuous water levels (heads) measured from NAVD88 in feet are shown in Figure C-3 along with the daily total precipitation measured in Truro. Water levels range from about 2.7 ft up to 4.3 ft NAVD88 and show a general increase during the spring, which is likely due to the seasonal rise of water levels caused by increased rainfall and snowmelt during the months of April and May. Peak water levels occur in the middle of July and they drop off slightly through the end of the summer. There is little or no immediate impact on groundwater levels caused by individual precipitation events. Some large events show an immediate, small rise in water level on the day of precipitation, but other similarly sized events show nothing, so immediate impacts from rainfall are probably small enough to be hidden in the noise of the data. There is no tidal signature in the data.

There are inconsistencies in the water level data collected on March 20, 2017 where the head suddenly rises by about 0.2 ft. This sudden increase occurs on the day when the probe was pulled from the well for a periodic data download and then replaced. It is believed that the probe was placed at a slightly different elevation, which resulted in the sudden change in reported head. This head change is well within the error tolerance which would be expected during calibration of a model of this scale and is not concerning from a model calibration standpoint.

Although a continuous monitoring device for water quality was not used in this well, three instantaneous water samples were measured for conductance on February 3, 2017 and the data was converted to TDS. On average, the samples were estimated to have about 96 mg/L of TDS, meaning that the water in this well is fresh. The TDS measurement along with the head data is shown in Figure C-4.

### **3.3.2 Monitoring Well C-1**

Well C-1 is located downstream of Route 6 and the Wilders Dike tide gate, about 0.15 miles south of the Pamet River on a small hill with a casing elevation of 32.8 ft. The location of the well is shown in Figures C-5 and C-6 and a photo is provided in Figure C-7. The depth of the well is 40 ft and was constructed about 10 feet below the water table, putting the bottom of well screen about 7 feet below sea level.

The continuous water levels (heads) measured from NAVD88 in feet are shown in Figure C-8 along with the daily total precipitation measured in Truro. Water levels range from about 2.2 ft

up to about 3.4 ft and show a general increase over the spring and early summer with a slight decrease in levels during the late summer, which is likely due to the regular rise of water levels in the spring caused by increased rainfall and snowmelt during the months of April and May followed by lower precipitation and higher evapotranspiration in the summer reducing recharge.

The dataset shows several peaks lasting about 2-3 weeks and involving an increase in groundwater of about 0.5 feet. The cause of these variations is unknown. The groundwater level is impacted by precipitation events greater than about 0.5 inches. The impact is slightly delayed and damped with the peak groundwater level often occurring 2-5 days after the precipitation event. There is no tidal signature in the water levels measured at C-1.

Three groundwater samples were measured in the field for conductance using a YSI meter on February 2, 2017 and showed an average TDS of 149 mg/L (Figure C-9). The water in this well is fresh.

Data collected from Monitoring Well C-1 aligns with the regional groundwater characteristics expected in the Outer Cape. The 40 ft of unsaturated sediment retards and attenuates the downward flow of water after the storm events. This indicates that there may be some layers of material that do not easily conduct groundwater flow between the surface and the measurement point of the well. The lack of a tidal signature is not surprising given that the well is on a hill and outside the wetlands area. The location and depth also protect the well from salt water in the tidal section of the Pamet River.

### **3.3.3 Monitoring Well USACE-1**

USACE-1 was driven by hand 7 ft into the sand just inland from Ballston Beach near the head of Pamet River. The casing elevation is 7.5 feet above NAVD88, so it is measuring water levels just below sea level. Its location is shown in Figures C-10 and C-11. A photo of the wellpoint and landscape setting is provided in Figure C-12. The wellpoint location is at a discharge boundary between the Pamet and Chequesset freshwater flow lenses, and on the Atlantic Ocean (east) side of both lens such that groundwater flow would be expected as to the east toward Ballston Beach. The range of groundwater heads is generally about 2.3 ft to 2.9 feet with higher heads during the February 15, 2017 overwash event.

The water level (head) data is shown with the precipitation data in Truro on Figure C-13. There is a strong impact to the groundwater levels during each precipitation event. Water levels rise steeply even during smaller events and fall at fairly steep rates immediately after the event, often returning to pre-storm levels within 5-7 days. The overtopping event on February 15, 2017 is also clearly shown when the water levels jump upward by nearly a foot despite only moderate rainfall in Truro. There is no tidal signature shown in the head data at this well despite its proximity to the coastline.

This well had a continuous water quality monitoring probe (Hobo) for several months (Figure C-14). Conversion from conductance to TDS requires an estimate of salinity conversion. Because

this well has brackish water, between freshwater and seawater levels, the conversion was made twice, once with each estimate. The results are similar, showing a TDS of around 20,000 mg/L. The TDS does not seem to be impacted by either precipitation, groundwater level changes or the tide.

Because the well is shallow and placed in sand, which is usually highly conductive, rainfall events cause an immediate, large rise in groundwater levels. The overtop event likely caused significant flooding in this area and the increased water depth at the surface manifested itself in the groundwater elevation with a sudden, steep rise in groundwater levels. It took a couple of weeks for the groundwater levels to return to pre-overwash levels. Although the well is only about 700 feet from the coastline, this distance is sufficient to dampen any tidal signature.

Based on local tide ranges, it is expected that the flow of groundwater at USACE -1 would be towards the Ocean. (For example, the tide at Lydia Cove, about 22 miles south of Ballston Beach varies between about 2.7 and -2.81 ft NAVD88 which supports this observation.) ,. The source of the salinity at this well is most likely from occasional overwashes, or unusually high tides or seas which occasionally push salt water towards the well and make the fresh-saltwater interface more shallow temporarily. The cause of the gradual rise in salinity and the causes of two small inconsistencies in the data in early April 2018 are unknown.

#### **3.3.4 Monitoring Well PW-4**

PW-4 is located in a low-lying area about 0.1 miles south of the non-tidal section of the Pamet River (well above the tide gate) on a parcel of privately owned property on South Pamet Road, co-located with PW-3D. The depth of this well is 38.56 ft below ground surface (bgs) and depth to static groundwater is approximately 2.5 ft bgs. The location of this well is approximately 500 feet south of the main stem of the Pamet River and is shown on Figures C-15 and C-16; and a photo is provided in Figure C-17.

The water levels at PW-4 are immediately and significantly impacted by precipitation events exceeding approximately 0.5 inches of rainfall (see Figure C-18). There is a clear seasonal rise in water levels as the spring months progress and precipitation begins to occur more frequently followed by a mild drop in heads during the late summer with increased evapotranspiration reducing recharge to the aquifer. There is no tidal signature in the groundwater levels at this well.

The YSI probe was used to obtain field measurements of instantaneous TDS estimates from three samples on January 27, 2017. The average TDS for these samples was 73 mg/L. A Hobo automatic conductivity probe was also left in the well for about 4 months to collect instantaneous water quality data. The TDS at this well varied from 74.23 mg/L to 75.74 mg/L, a surprisingly narrow range (see Figure C-19).

The data at this well is generally as expected from a regional groundwater perspective. Immediate impacts from individual precipitation events indicates that there are no layers of low-



conductivity material separating the well measurement point from the ground surface. No tidal signature would be expected for a well located upstream of the Wilder's Dike tide gate during the period of automatic monitoring of groundwater level and conductance (TDS) in 2017.

The groundwater at this well is fresh as would be expected since the well is located above the tidal section of the river. The TDS estimates show it to be very fresh water, although the narrow range of data during precipitation events is somewhat suspicious in the summer months. The CSM indicates that groundwater should be flowing north in this part of the Chequesset freshwater flow lens to discharge to the Pamet River. The freshwater aquifer TDS trends are interpreted to be a result of steady groundwater baseflow from upland recharge areas toward discharge areas at the Pamet River to the north of PW-4D that is sustained by regional precipitation patterns.

### **3.3.5 Monitoring Well PW-3D**

PW-3D is co-located with PW-4 in a low-lying area about 0.1 miles south of the non-tidal section of the Pamet River (well above the tide gate) on the Mooney Property, approximately 500 feet south of the main stem of the Pamet River. The well is 150 ft deep, and depth to static groundwater is approximately 2.6 ft bgs. This is the deepest well used in this data collection effort. The location of this well is shown in Figures C-20 and C-21. A photo is provided in Figure C-17.

The water levels at PW-3D are shown in Figure C-22 with the precipitation data, and in Figure 23 with the TDS data. Immediate, significant groundwater rise occurs during each major precipitation event. Smaller increases in groundwater levels occur after smaller precipitation events. There is no tidal signature shown in this data, as would be expected from a deep well far from the tidal section of the river.

Given the well depth as compared to PW\_4 groundwater level data at PW-3D is not as expected. Groundwater level rises should be delayed and attenuated in a well this deep after a precipitation event. Figure C-24 compares the heads at PW-4 and PW-3D, which are co-located but have depths varying by over 100 ft. This plot shows very little difference between the water levels in the two wells. There is no discernible difference in the impact of the precipitation events. There are at least two possible explanations for this behavior:

- The subsurface is very coarse and homogeneous so that water and pressure can flow easily through the space between the two wells. This can be verified by finding and inspecting the drill logs for the wells. The driller's boring log for this well, drilled in 1996, indicates that the overburden interval between the screen depth of PW-3D and PW-4 consists generally of tan coarse/medium sand with some gravel.
- The casing for PW-3D is cracked or damaged and providing a shorter pathway (short circuiting) for infiltrating water so it can pass directly into the well without flowing

through the subsurface sedimentary material. This could be verified with a downhole video camera.

If the similarity between the groundwater levels of PW-3D and PW-4 is caused by the coarse, homogeneous nature of the subsurface material, this data is useful for developing the groundwater model. However, if the similarity between the two datasets is caused by a faulty well casing, this data is useless for the groundwater model because it does not reflect the conditions in the subsurface. Without additional study and analysis, this data is questionable at best.

The TDS data at PW-3D consists of instantaneous field measurements using a YSI probe which reported the TDS to be 5100 mg/L in the brackish zone, higher than would be predicted based on the conductance data of about 100 – 150 umhos/cm (60 – 90 mg/L TDS) collected by groundwater profiling performed while drilling in 1996. The continuous measurements taken by the Hobo probe showed a smooth, gradual drop in TDS until April 8, 2017. After April 8, the TDS data becomes more noisy and seems to be impacted slightly by large storms (small reduction in TDS after storms larger than 0.5 inches). It is possible that purging the well at the beginning of the measurement period filled the well casing with salt water which took some time to dissipate. However, it is suspicious that the nature of the data line changed so suddenly. It is tempting to accept the data after April 8 as valid, but given the questions regarding the groundwater levels at this well and the fact that PW-4 and PW-3d have almost identical head datasets but very different TDS datasets (see Figure C-25), all data at both wells should be used with care.

### **3.3.6 Monitoring Well PW-TRU-5S**

TRU-5S was drilled in 1994 and is located about 2,000 feet downstream of PW-4 and PW-3D, still about 2500 feet upstream of the Wilders dike at the edge of the wetland about 350 feet south of the river on the Kelly Property on South Pamet Road. This well is 20 feet deep with a static depth to groundwater of approximately 2.5 ft bgs. TRU-5S is the shallow well of a three well cluster (shallow, medium, deep screens). See Figures C-26 and C-27 for the location of this well. A photo is provided in Figure C-28.

The groundwater level data for this well is shown in Figure C-29. There is an immediate, significant rise in groundwater levels associated with each major precipitation event. There is no tidal signature in this data. The strong, immediate impact from precipitation events is caused by the shallow location of the well and indicates coarse, homogeneous alluvium between the ground surface and the well measurement point. No tidal signature would be expected at a well next to the non-tidal section of the river.

Field measurements of instantaneous TDS data were taken for three samples on January 26, 2017 using a YSI probe and showed the TDS to be 57 mg/L, well below the threshold for freshwater (Figure C-30). Freshwater would be expected for a shallow well near the non-tidal freshwater section of Pamet River.

### **3.3.7 Monitoring Well PW-TRU-5D**

TRU-5D was drilled in 1994 and is co-located with TRU-5S, about 2,000 feet downstream of PW-4 and PW-3D, still about 2500 feet upstream of the dike at the edge of the wetland south of the river on the Kelly Property. This well screen is 60 feet deep, with a static depth to groundwater of about 2.4 ft bgs. See Figure C-31 and C-32 for the location of this well and Figure C-33 for a photo.

The head data for this well is shown in Figure C-34. Like TRU-5S, there is an immediate, significant rise in groundwater associated with each major precipitation event. There is no tidal signature in this data.

This data indicates that the subsurface material between TRU-5S and TRU-5D is fairly coarse and homogenous. See Figure C-36 for a comparison of the heads at the two wells. The water level at TRU-5S is always about 0.1 ft lower than the water level at TRU-5D indicating a slight-upward vertical hydraulic gradient, which would be expected where groundwater is flowing upward towards the Pamet River. This may lend credence to The Cape Cod Commission 1997 Pamet River Investigation which concluded that groundwater flow to the Pamet River occurs near the edges of the wetlands and then flows overland towards the river, which is separated from the groundwater by thick layers of peat. This groundwater flow pattern would also be consistent with the CSM for groundwater flow direction on the north side of the Chequesset freshwater flow lens.

It is noteworthy that the relative impact of rainfall on both wells is nearly identical, despite the difference in depth, and mostly notably that the upward gradient continues throughout each rainfall event. This likely indicates that rainfall reaches the wells by flowing downward in areas away from the river (recharge areas) and then flows laterally towards these wells before flowing up towards the river (discharge areas). This scenario would require coarse and homogeneous conditions away from the river since it occurs so quickly.

The lack of a tidal signature is as expected for a well near the non-tidal section of the river, upstream of the tide gate.

The TDS data measured in a field sample with a YSI probe on January 26, 2017 showed a TDS of 77 mg/L. The continuous TDS data estimated from conductance data collected by the Hobo probe showed a suspiciously narrow range of TDS, between 75.52 mg/L and 78.95 mg/L over a period of about 4 months (see Figure C-35). The freshwater is expected for a well close to the non-tidal section of Pamet River. However the lack of variability in the data over time may indicate a data error perhaps associated with a fouled or faulty sensor.

### **3.3.8 Monitoring Well PW-TLF-005**

TLF-005 is a 1-inch diameter PVC wellpoint installed in 1996, and is located off South Pamet Road just south of the river at the edge of the wetland and about 0.2 miles upstream of the tide gate and about 500 feet upstream of tide gage station Pamet 3. Field personnel noted that the area

was very peaty. This well is 14 feet deep, and static depth to groundwater is about 1.2 ft bgs. See Figures C-37 and C-38 for the location of this well. No photo is available.

The head data for TLF-005 along with precipitation data from Truro is provided in Figure C-39. Water levels in this well began nearly 5 feet below sea level, much lower than the river stage at this location and slowly increased throughout the data collection period approaching an asymptotic water level at a little over 2 feet NAVD88.

This data indicates that the well is either clogged or it is set in a tight section of peat which does not easily transmit and recharge water into the well screen from the surrounding stratigraphic layer.

The initial low water level is the result of well redevelopment efforts and purging for water quality sampling on the day the continuous monitoring equipment was installed. The material surrounding the well of low hydraulic conductivity in and it was observed to have taken over 4 months for the water level to recover to ambient conditions.

Regional investigations indicate peat acts as a barrier with low hydraulic conductivity. Groundwater guidance recommends field verifying data discrepancies to rule out equipment malfunction. The hydraulic conductivity of the peat at this location were not verified; thus, its impacts to the data collection and groundwater model are uncertain. If the data correlates to equipment malfunction, then it would not be useful for the groundwater model except to estimate the asymptotic water level which would have been reached sometime in the late summer.

The YSI meter field measurement estimated the TDS at 299 mg/L on February 3, 2017, which is freshwater (Figure C-40). This is as expected given the proximity of the well to the freshwater section of the Pamet River.

### **3.3.9 Monitoring Well PW-TRU-7**

TRU-7 is located on the west side of Truro Center Road (Rt. 6A) on the north bank of the Pamet River, just north of Wilder's Dike. TRU-7 is a 2-inch diameter PVC well that is 15 feet deep, with a static depth to groundwater of about 6.6 ft bgs. Its location is shown on Figures C-41 and C-42. A photo is provided in Figure C-43. The well was equipped with an automatic water level logger and a conductance logger.

The groundwater level data for TRU-7 is shown on Figure C-44 and shows a strong tidal signature and a strong impact for large and moderate precipitation events. The tidal swing is almost 1 foot during the beginning of February and then shrinks to about 0.1 – 0.2 feet for most of the spring. Beginning in April, the tidal variation begins to grow again and is about 0.6 feet by the end of the measurement period in May. The reason for the change in tidal amplitude is unknown. The tidal swing may be influenced by variation in groundwater discharge rates to the river near TRU-7 that may sustain river stage during periods of high groundwater discharge and small tidal

swings. Tidal amplitude was compared to air temperature data in an attempt to explain the amplitude change, but there was no discernible correlation.

The continuous and instantaneous TDS data at TRU-7 is shown in Figure C-45. The TDS varies from just over 0 mg/L to just over 10,000 mg/L and is generally in the brackish range. The YSI probe showed a TDS of 6500 mg/L). There is a very close inverse correlation between TDS and groundwater level. When groundwater levels rise (usually due to precipitation), the TDS levels drop as additional freshwater is added to the system. The tidal signature is also visible during some periods of the TDS dataset where it seems to be impacted by saltwater coming up the river with the rising tide and freshwater flowing down the river with the falling tide. The amplitude of the TDS tidal variations is also quite variable with larger variations occurring during a few periods of the late spring of 2017. The reason for the variation in amplitude is unknown but may be related to the fact that tidal forces seem to be unable to reach this well at times. Similarly, well USACE-2 shows gradual, months-long reduction of TDS between February and June during periods of reducing precipitation; this may indicate sensitivity to winter temps at installation, tampering, probe sensor malfunction or building up of biofilm, as indicated above.

#### **3.3.10 Monitoring Well USACE-2**

USACE-2 is a 2-inch diameter steel wellpoint with 3 feet of screen that was hand-driven into a shoreline area of Pamet Harbor, about 2,000 feet upstream of where the Pamet River discharges into Cape Cod Bay. USACE-2 was installed on the south side of Pamet River off Depot Road near the Town boat ramp, which was dry during low tide and inundated during high tide. USACE-2 has a depth of about 9.5 ft bgs, but had a large stickup of about 10 ft above ground surface to accommodate wide swings in tide levels, so it was measuring water levels in a well screen set to a bottom depth only 9.5 feet below the ground surface. The static depth to groundwater at the time of installation was about 3.5 ft bgs. See Figure C-46 and Figure C-47 for the location of this well. A photo is provided in Figure C-48.

The groundwater levels in USACE 2 are shown with the precipitation data from Truro in Figure C-49. This well has a strong tidal signature with an amplitude of about 4 feet. The tidal signature is so strong that it drowns out any impact from the several large precipitation events that occurred during the measurement period.

The strong tidal signature is expected at the location and depth of screen for USACE-2. The proximity of the well to the tidal portion of Pamet River and the shallow nature of the well result in the strong tidal signature in the groundwater level data.

The TDS data at this well is shown in Figure C-50. The instantaneous YSI measurements indicated a TDS of 28,400 mg/L just below that of seawater. The continuous measurements show levels dropping gradually from over 25,000 mg/L in February to below 10,000 mg/L by June. There is variability in the trend and the tidal signature is discernible through most of the dataset. Large reductions in TDS tend to occur a few days after a large precipitation event. The

fact that the TDS is below seawater concentration is likely caused by the mixing in tidal water with freshwater flowing down the river. Reductions in TDS right after a storm are likely caused by an additional volume of freshwater flowing down the river, delayed by the time required for rainfall to flow overland to the river and down the river, some of it being delayed by the tide gate. However, the gradual, months-long reduction on TDS from 27,000 mg/L in February to 9,000 mg/L in June is unexpected and the reason is unknown. It is possible that the sensor on this probe gradually became scaled by the dissolved constituents or a biofilm and the probe gradually fell out of calibration.

## **4.0 Recommendations**

### **4.1 Groundwater Data**

Additional groundwater elevation data and salinity data would yield a better understanding of the impact of the tidal river on the groundwater conditions. Very few of the existing wells provided meaningful salinity data and additional wells at varying distances and depths from the river along the tidal and non-tidal sections would be useful. It is currently unknown at what distance or depth the tide impacts groundwater heads or quality. A few lines of closely spaced wells perpendicular to the river would be helpful in predicting the impact of the alternatives on both drinking water wells and septic systems.

The existing dataset does not clearly indicate the vertical flow of groundwater and seems to indicate that deep and shallow heads are quite similar. This is unexpected in a system where groundwater is believed to be discharging into the river (gaining stream). Additional sets of nested wells with varying depths will help to clarify the vertical movement of groundwater.

A recommended long-term monitoring (LTM) program could conceptually include the following components executed in phases beginning before a final drainage alternative is implemented, and should include groundwater and surface water components:

- a. Existing Drinking Wells: continue sampling from adjacent privately-owned drinking wells, with a priority determined based on proximity to the Pamet River floodplain. Well water sampling should be coupled with a surface water sample from the Pamet River nearest the sampled drinking well. During a flood event surface water samples should be obtained at locations within the inundated floodplain at surface water encroachments closest to private well heads.
- b. New Monitoring Wells: Design new monitoring well network to include nested monitoring wells with a well couplet, at several locations along the upper Pamet River. New well nests should be located at varying distances and depths from the river to provide maximum range of observed hydraulic head under normal, restored tidal, and overtopping events. New well nests should also be located to form transects perpendicular to the river to provide greater resolution (and increase confidence of

horizontal and vertical groundwater flow direction during average and flooding conditions. The new well nests would also allow groundwater quality sampling during average and flooding conditions.

Hydraulic heads, groundwater and surface water monitoring should begin well before construction of any culvert improvements or changes of the water exchange near Wilder's Dike to develop a robust baseline dataset, and should continue after any construction projects are completed to fully understand the impacts of the projects to drinking water wells or septic systems.

The long-term monitoring program should include objectives to account for impacts of climate change and rising sea levels increasing the dynamic movement and uncertainty of the salt-freshwater interface. This recommendation can serve to correlate with enhanced climate change resiliency per State MA initiatives, including the Town of Truro 2017 Hazard Mitigation Plan (HMP). The Town of Truro HMP initiative specifically emphasizes reduction of long-term risk to human life and property from hazards to enhance resiliency.

New wells should include installation of one or more new deep monitoring wells to find and intersect the fresh-salt water interface approximately ¼-miles upstream of Wilders Dike, to monitor baseline and potential future tide flow restoration impacts to the position of the fresh-saltwater interface. The recommended conceptual location is based on the results of the impacted groundwater level rise predicted by groundwater modeling for the No Tide Gate alternatives reviewed in this study (Alternatives #3 and #4). The monitoring-well design should include a continuous groundwater sample profiling to determine the position of the fresh-salt water interface at time of drilling. Finished monitoring well construction should accommodate installation of a well couplet, with one well screen below and one well screen above the fresh-salt water interface encountered during well drilling.

Selected monitoring wells should be equipped with an automatic data logging and telemetry system that is capable of alerting the Town via cell phone or web-based communication (ie: DPW) that a preset water quality target (ie: elevated conductivity) has been measured, so that increased groundwater and surface water sampling can be performed. This system would serve as an early warning detection system for private drinking wells that may have their water quality adversely impacted either from surface water infiltration of saline floodwaters, or impacts due to future removal of the tide gate and restoration of tidal migration in the upper Pamet.

#### **4.2 Tidal Data**

The existing set of tidal gages provided meaningful data about the impact of the tide gate and culvert on tidal amplitude and water levels when the gages were functioning correctly. It is recommended that data continue to be collected from these gages for several years to ensure a robust dataset. The addition of water quality would be useful to better understand the

movement of salt water up and down the river during tidal variations. The addition of several other tidal gages both upstream and downstream of the existing gages would expand the dataset and provide better calibration data for future modeling projects.

Perform more detailed study to estimate salt wedge (tidal) excursion distance for tide range at Pamet River estuary, ie: the distance that the salt water wedge of tidal water moves upstream. The distance that the salt-water wedge of surface tidal water moves from the Pamet Harbor estuary to the upper Pamet River may be insufficient to create conditions that can establish a salt marsh habitat upstream of Wilder Dike. Recent surface water quality measurements suggest that after the existing tide gate was removed by storm conditions during a nor'easter in March 2018, fresh water conditions were measured immediately downstream and upstream of Wilder Dike on several occasions. Coordinate collection of additional field data with other technical stakeholders including National Park Service, Cape Cod Commission, and Center for Coastal Studies (Provincetown) who has collected surface water data near Wilders Dike as part of the Cape Cod Bay Monitoring Program for a nutrient study.

#### **4.3 Surface Water Data**

Perform vertical profiling of surface water quality down and up-stream of Wilders Dike, and different tidal flow conditions and precipitation conditions, to assess position of the tidal seawater wedge or prism that migrates upstream to the current tide gate at Wilders Dike. Compare results to target water quality required to support objective of salt marsh restoration in the upper Pamet River and assess if this objective is achievable.

#### **4.4 Alternative Implementation Schedule**

It is recommended that data collection begin before implementation of the selected alternative to establish a robust database of baseline conditions, and continue after the implementation of a selected alternative to provide a robust dataset for understanding the impacts of the alternative and for making future adjustments if necessary.



# **Chapter 6**

## **PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**Pamet River Groundwater Model**

**Quantitative Data Analysis**

**(MODFLOW 2000)**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

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## CHAPTER 6

### Pamet River Groundwater Model (MODFLOW 2000)

#### 1.0 INTRODUCTION

The purpose of the Pamet River Investigation is to develop and evaluate options to improve tidal flow upstream of Route 6 and improve river drainage following overtopping events at Ballston Beach. The groundwater model was built to investigate impacts of alternatives to septic systems (groundwater elevation changes) and to drinking water wells (flow direction around the river when it may contain saline water).

Because the Pamet River is primarily groundwater-fed, the groundwater model and the river model were developed in parallel. The groundwater model requires river stage as a boundary condition and uses it to compute interactions between groundwater and surface water. Similarly, the river model requires groundwater head as a boundary condition and uses it to compute interactions between groundwater and surface water. Efforts were made to ensure that the model-computed interactions between groundwater and surface water were similar in each model.

The groundwater model was calibrated to available field data and then four alternatives were developed in coordination with alternatives recommended in the USACE 1998 investigation, construction assessment and planning metrics (see Chapter 1 and Chapter 2). The results were used to make assessments of the impact of each alternative on heads during normal tides, overtop event head changes, the amount of time that high heads would be expected after an overtop event and the velocities, magnitudes and directions around the upper Pamet River.

#### **1.1 Groundwater Model Results Summary.**

The following insert is presented in Section 7.0 Conclusions and Recommendations, page 6-16, and correlates to the Wilder's Dike and Route-6 Culvert Improvement Alternatives and Real-Time Groundwater Well Monitoring & Early-Warning Response Recommendations presented in both the Executive Summary and Chapter 1.

*Movement of saline water from the upper Pamet River towards drinking water wells is of concern from a public health perspective, especially as the river system becomes increasingly dynamic, rising sea levels cause greater sea water inflows / intrusion and more frequent overtop events at Ballston Beach occur.*

*Long term groundwater monitoring at several locations along the upper Pamet River with wells placed at varying distances and depths from the river is strongly recommended to provide the necessary data for future decision-making. This monitoring should begin well before the construction of any culvert improvements or changes to the water exchange near Wilder's Dike and should continue after any construction projects are completed to fully understand the impact of the projects. Continued long-term monitoring will also provide necessary data to prepare for any future impacts to drinking water wells or septic systems.*

## **2.0 MODFLOW DATA SOURCES**

This groundwater model was based on a 2004 USGS model, which covered the whole of Cape Cod region and provided the basis for some decisions made in the development and calibration of this model (Masterson, 2004).

The top elevation of this model (ground surface) was developed from the USGS National Elevation Dataset (NED) 1/3 arc-second Digital Elevation Model (DEM).

Tidal data for the Cape Cod Bay (west) side of the model was set to match the RAS model (see Chapter 7). Tidal data for the Atlantic Ocean (east) side of the model was from data at the NOAA station at Chatham, Lydia Cove (8447435), which is approximately 25 miles south of Pamet River.

## **3.0 MODEL DEVELOPMENT**

The original scope for the investigation called for the use of a density-dependent groundwater model code, SEAWAT, which couples flow computations with transport computations and is used for systems with fresh and saline water. That model may have allowed plots of the freshwater-saltwater interface to be provided for each alternative. However, as the investigation progressed, this plan was revised, for several reasons:

- Variable density can impact flow directions, but the impact is only notable at great depths. The interaction between the Pamet River and the groundwater domain occurs near the ground surface where density variations have little impact.
- There is very little data for defining the current location of the freshwater-saltwater interface. None of the monitoring wells sampled during this study were found to have high salinity unless they were shallow and immediately adjacent to the tidal section of the river. Participation in a USGS pilot of Transient Electromagnetic equipment failed to yield the vertical location of the freshwater-saltwater interface. The reason for this failure could be interference from utilities, excessive depth of the freshwater-saltwater interface beyond the ability of the equipment to sense, or failure of the equipment. Building a SEAWAT model without appropriate salinity data is not recommended and the results would be highly uncertain.
- Computation times for SEAWAT models are significantly longer than for MODFLOW models (which do not include density dependence).

The model was built using MODFLOW 2000 as incorporated into the DoD Groundwater Modeling System (GMS) version 10.3. GMS was used as the pre- and post-processor for the MODFLOW modeling code and solver.

### **3.1 DOMAIN, GRID, GEOLOGY**

The model domain was set such that it would contain the drainage area for the Pamet River (see Figure 1 Attachment D). The north and south boundaries were placed to pass through the highest point of the groundwater lenses in the basins north and south of Pamet River and run perpendicular to the groundwater head contours computed by the Masterson (2004) groundwater model. This placement

allowed the boundaries to be assigned as no-flow boundaries with assumed groundwater flow parallel to the boundaries.

The east and west boundaries of the model were placed offshore at a bathymetric elevation of -10 ft NAVD88. This was approximately one-half mile from the eastern shore and one mile from the western shore.

The upper boundary of the model was the ground surface determined from USGS topographic data. The lower boundary of the model was set low enough to not impact the area of interest at -65 ft NAVD88. Observed groundwater data showed that the impact of tide or flood was not felt by deep wells, so this bottom depth was felt to be sufficient.

MODFLOW computations are made on a regular computational grid with cells arranged in rows, columns and layers. The cells in this grid were given width and length sizes (in plan view) of about 100 ft by 100 ft. The thickness of the top layer varied due to the variation in topography, but the bottom elevation of the top layer was set to -10 ft NAVD88 to ensure top layer cells did not dry out, causing computational difficulties. The second layer thickness was set to 10 ft, with the bottom elevation at -20 ft NAVD88. The lower three layers had thicknesses of 15 ft each.

The geologic history of Cape Cod is glacial deposition. Following the assumptions of the USGS Masterson model (2004), which showed very little geologic variation in the top 100 feet of the model, no geologic layering or variation was applied to this model. All layers were given the same hydraulic conductivity and storage values with the exception of the top layer near the river as described in the boundary condition section below. Monitoring data at two pairs of wells (TRU-5S and TRU-5D; PW-4 and PW-3D) showed very little difference between deep and shallow heads, indicating vertical homogeneity and no confining units in the upper section of the subsurface.

## **3.2 BOUNDARY CONDITIONS**

### **3.2.1 Ocean/Bay Boundaries**

The east and west boundaries of the model on the top layer were specified as a MODFLOW general head boundary condition with the stage set to the tidal levels and a low conductance value. The boundary condition was applied to all top layer cells from the coastline to the model boundary. A general head boundary is, conceptually, a known head that is far from the model boundary. It was used in this model to simulate the expected layering of coastal deposits, including some fine layers with low hydraulic conductivity. The absence of a tidal signature in observation well USACE-1, located a few hundred feet from the shore verified that a separation between the groundwater and the ocean tide exists. The conductance value applied to a general head boundary is the proportionality constant relating head difference to flow. The conductance value assigned in the model was a calibration parameter and was altered until the model computed values were similar to those measured in the field.

For the lower layers (2 through 5), the ocean and bay boundaries were applied only at the edge of the grid as a specified head boundary condition. This simulates the geologic outcrops at the bay or ocean floor.

### **3.2.2 River Boundary**

The Pamet River was incorporated into the model using the MODFLOW river package. The stage was applied based on the results of the HEC-RAS model. For simplicity and because of the coarse resolution

of the grid, stage values were applied from approximately every fifth RAS cross-section and interpolated to cells between those locations. At the same locations, the river bottom elevation was taken from the lowest cross-section elevation in the RAS model. River conductance was applied to each section of the river and was varied during calibration until the model computed heads matched those measured in the field. In general, conductances were higher at the downstream end of the river where sediments would be expected to be thinner due to the more dynamic nature of the river.

In order to take advantage of the options for interpolation of river stage and bottom elevation in GMS, the river was modeled using an arc which applied the river boundary condition to only the model cells intersected by the river arc. In reality, the river is much wider than a single model cell, especially near the downstream end at Cape Cod Bay. To account for this difference, the hydraulic conductivity of the cells within the flood plain of the river were set higher in layer 1 than in deeper layers or in surrounding areas. The conductance was also increased as the river became wider. These adjustments allowed the head changes in the modeled river to be felt immediately across the entire width of the river.

### 3.2.3 Surficial Boundary (Recharge)

A recharge boundary condition was applied to the surficial boundary of the model. This boundary condition was applied to all cells not included in other boundary conditions (river cells or general head boundary cells). For the calibration periods, the applied recharge value was based on the average daily precipitation reported in Truro over the previous 55 days with an assumption that 55% of precipitation recharges the groundwater. The 55% recharge assumption was set to match the assumption used in the Masterson model. The constant precipitation sets the antecedent conditions for each model period. The length of the period for averaging the recharge (55 days) was a calibration parameter which was adjusted until the model-computed heads near the top of the groundwater lenses matched those measured in the field. Table 1 shows the recharge rates applied for each calibration period.

*Table 1: Recharge rates for calibration models*

| CALIBRATION PERIOD     | RECHARGE RATE<br>(FT/D) | RECHARGE RATE<br>(IN/YR) |
|------------------------|-------------------------|--------------------------|
| JANUARY 22-29, 2017    | 0.0050                  | 21.9                     |
| FEBRUARY 6-12, 2017    | 0.0040                  | 17.5                     |
| APRIL 23 – MAY 3, 2017 | 0.0058                  | 25.4                     |

### 3.2.4 Conductance

Both the river boundary condition and the general head boundary condition require the user to supply a conductance value to relate head difference to flow. Conductance can best be understood by deriving it from Darcy's Law:

$$Q = k \frac{\Delta h}{L} A$$

where Q is the volumetric flow rate, k is hydraulic conductivity, Δh is the head difference, L is the length of flow and A is the cross-sectional area of flow.

The equation can be simplified by defining conductance, C, to encompass the characteristics and dimensions of the media through which flow will occur:

$$C = \frac{kA}{L}$$

$$\text{thus, } Q = C\Delta h$$

For the river boundary condition,  $L$ , the length of flow, represents the thickness of the sediments which separate the groundwater regime from the surface water.  $A$ , the cross-sectional area of flow, is the area of the river bed. In GMS, a river boundary condition is applied to an arc in the map module. Because GMS can easily compute the length of the arc which intersects each grid cell, the user enters an abbreviated conductance,

$$C' = \frac{kw}{t}$$

Where  $w$  is the width of the river and  $t$  is the thickness of the sediments. GMS then multiplies the user supplied  $C'$  by the length of the arc intersecting each cell and applies the resulting conductance value to each river cell. As the model solves, it computes the head difference (the difference between the user-supplied river stage and the model-computed groundwater head) in each cell to compute the flow in or out of the river boundary. The model iterates until the flow and head difference are stable and are related by the user-supplied conductance.

For the general head boundary condition,  $L$ , the length of flow, is the distance between the boundary and the source/sink of the boundary condition. Conductance is used to adjust the impact of the general head on the groundwater conditions at the boundary. In GMS, the general head for the ocean or bay boundary was input on a polygon in the map module. Because GMS can easily compute the area of the polygon which intersects each grid cell, the user enters an abbreviated conductance,

$$C' = \frac{k}{L}$$

Where  $L$  is the distance to the source or sink of water. GMS then multiplies the user supplied  $C'$  by the area of the polygon intersecting each cell and applies the resulting conductance value to each cell. As the model solves, it computes the head difference (the difference between the user-supplied ocean stage and the model-computed groundwater head) in each cell to compute the flow in or out of the ocean/bay boundary. The model iterates until the flow and head difference are stable and are related by the user-supplied conductance.

### 3.3 INITIAL CONDITIONS

The calibration models were run in transient mode for a period covering several days. In order to solve the transient flow solution, MODFLOW requires an initial condition, heads at every grid cell at the beginning of the model period. For this model, the initial condition was developed by running each model in steady state mode with all boundary conditions set at an average for the first day of the model period. This provides an approximate condition for the beginning of the model, but is not a perfect option since the system is dynamic and constantly changing due to the continual tidal influence on the lower end of Pamet River. Thus, the first few days of any transient run must be considered a spin-up period as the model adjusts to the conditions. In some areas, the difference between the starting condition and a true equilibrium condition is greater and a trend in the model results is visible throughout the run period.



Because the transient model runs covered a short period of time (6 – 11 days), the precipitation has little impact on the transient solution. Most of the impact of precipitation is on the steady state models used to set initial conditions for the transient models.

## 4.0 CALIBRATION

The MODFLOW model of Pamet River and surrounding areas was calibrated by adjusting input parameters until the output at nine observation points matched the field measured heads for three separate calibration periods. The three calibration periods were selected to cover a wide range of conditions, including:

- January 22-30, 2017,
- February 6-13, 2017, and
- April 23 – May 3, 2017.

More details on the selection of the calibration periods can be found in Chapter 5.

The groundwater calibration points included nine observation wells as shown in the Table 2 and in Figure 2 (Attachment D). TSW-203 is a USGS well monitored once a month (USGS NWIS, 2019). All other wells were monitored by USACE during the data collection period. See Chapter 5 for information on the data collection program. All wells were installed as part of previous projects, except for USACE-1 and USACE-2 which were hand-driven piezometers installed specifically for this project. USACE-1 has since been destroyed or buried by overwash events at Ballston Beach.

*Table 2: Groundwater observation points*

| NAME    | LOCATION DESCRIPTION                              | DEPTH                                    |
|---------|---------------------------------------------------|------------------------------------------|
| C-1     | About 900 ft south of tidal section of river      | 40 ft                                    |
| C-5     | About 4000 ft south of non-tidal section of river | 90 ft                                    |
| PW-4    | About 400 ft south of non-tidal section of river  | Unknown,<br>assume 16 ft                 |
| TRU-5D  | About 350 ft south of non-tidal section of river  | 60 ft                                    |
| TRU-5S  | About 350 ft south of non-tidal section of river  | 20 ft                                    |
| TRU-7   | Near dike, about 25 ft north of river             | 15 ft                                    |
| TSW-203 | About 7000 ft north of river                      | 35 ft                                    |
| USACE-1 | Near head of river                                | Unknown,<br>assume 4 ft<br>(hand-driven) |
| USACE-2 | Near mouth of river                               | Unknown,<br>assume 4 ft<br>(hand-driven) |

Note that data was also collected at PW-3D, which is co-located with PW-4 but screened 150 feet below ground surface. The depth of this well was below the bottom of the model. The heads at PW-3D were very similar to those at PW-4 and showed no indication of significant upward or downward flow.

### 4.1 CALIBRATION PARAMETERS

During the calibration process, the three calibration period models were rerun with varying parameters until the model computed heads matched those measured at each of the observation points. This process also included some iteration with the HEC-RAS model. The river stages computed by RAS were used as boundary conditions in the MODFLOW model. The groundwater heads computed near the river were used as input to the RAS model in computing the groundwater-surface water interaction fluxes. Table 3 shows the major parameters varied in the groundwater model calibration and the final selected parameter values.

*Table 3: Calibrated parameters*

| PARAMETER                                                                                  | CALIBRATED<br>VALUE |
|--------------------------------------------------------------------------------------------|---------------------|
| HYDRAULIC CONDUCTIVITY, LAYERS 2-5 AND LAYER 1 AWAY FROM RIVER (HORIZONTAL/VERTICAL), FT/D | 225/22.5            |
| HYDRAULIC CONDUCTIVITY, LAYER 1, NEAR RIVER (HORIZONTAL/VERTICAL), FT/D                    | 2000/200            |
| CONDUCTANCE, LAYER 1 GENERAL HEAD BOUNDARY (OCEAN), FT <sup>2</sup> /D/FT <sup>2</sup>     | 0.5                 |
| CONDUCTANCE, LAYER 1, RIVER BOUNDARY, FT <sup>2</sup> /D/FT                                | 25 – 56,000         |

Figure 3 (Attachment D) shows the final calibrated hydraulic conductivity for layer 1. Figure 4 (Attachment D) shows the conductance applied to each river cell. Note that GMS converts the general head boundary conductance entered and shown in Table 3 to ft<sup>2</sup>/d as required by Darcy's Law by multiplying the user-supplied value by the area of the cell covered by the boundary polygon. For a cell completely covered by the polygon, the conductance would be about 5000 ft<sup>2</sup>/d. A similar process is followed for the river conductance, except the user-supplied conductance as shown in Table 3 is multiplied by the length of the river arc in each cell.

## 4.2 CALIBRATION RESULTS

Figures 5 and 6 (Attachment D) show maps of groundwater heads at two sample time steps. Figures 7 through 15 (Attachment) show the comparison between model computed heads and field observed heads at each observation point. The large-scale trends in some modeled results which last throughout the model period and are not seen in the observed heads are due to the difficulty in finding an appropriate starting condition for a dynamic system (see Section 3.3).

## 4.3 CALIBRATION ANALYSIS

### 4.3.1 Wells far from Pamet River: C-1, C-5 and TSW-203

Three wells were mostly unaffected by the river boundary condition and only sensitive to the hydraulic conductivity and recharge values applied to the surface of the model. These wells were mostly unaffected by the river boundary condition and only sensitive to the hydraulic conductivity and recharge values applied to the surface of the model.

TSW-203 (Figure 13 Attachment D) is a USGS well which is monitored about once per month. The model closely matches the measured heads at this well with a residual of less than about half a foot in all three calibration periods.

C-1 (Figure 7 Attachment D) is located 900 feet south of the tidal section of the river, but does not have a tidal signature in the head data. The model under-predicts heads at this well by up to about 1 foot during the February and April models. No data was collected in January at this well.

C-5 (Figure 8 Attachment D) is located three-quarters of a mile south of the river and far from the influence of river stages. The model over-predicts heads at this well by 3-4 feet during the February and April models. No data was collected in January at this well. The reason for this large residual could be a significant difference in geology or recharge south of the river as compared to north of the river. There was no data to support the large difference in parameters that would be required for the model to match both this well and TSW-203. It is also possible that the depth or location of the well are not known precisely or an error was made in measuring the depth of the pressure transducer which was used to measure the heads in the well.

#### **4.3.2 Main Section of the River: PW-4, TRU-5S, TRU-5D and TRU-7**

PW-4 (Figure 9 Attachment D) is located about 400 ft south of the non-tidal section of Pamet River. The groundwater model reproduced heads at this well within less than 0.5 ft. The model results show a very small tidal signature which does not appear in the observed data.

TRU-5S (Figure 11 Attachment D) and TRU-5D (Figure 10 Attachment D) are a collocated pair of wells located about 350 ft south of the non-tidal section of Pamet River, between PW-4 and Wilder's Dike. The groundwater model reproduced heads at both these wells within 1 ft. The model results show a very small tidal signature which does not appear in the observed data.

TRU-7 (Figure 12 Attachment D) is a shallow well located near Wilder's Dike. The observed data at this well shows a strong tidal signature with an amplitude of around 1 foot. The groundwater model reproduced the tidal amplitude, but over-predicted heads by about 6 feet. Given that this well is so close to the river where a stage gage measured much higher heads, it is believed that this data is impacted by either a survey error or an error in measurement of the depth of the pressure transducer.

#### **4.3.3 New Wells: USACE-1 and USACE-2**

USACE-1 (Figure 14 Attachment D) was a new hand-driven piezometer installed just over the dune from Ballston Beach, near the head of Pamet River. The data collected at this well showed no tidal influence from either the river or the ocean. The model solution under-predicted the heads at this well by at most 1 foot and showed a very small tidal signature. This well has since been destroyed or buried by overwash events.

USACE-2 (Figure 15 Attachment D) is a new hand-driven piezometer installed at the south bank not far from the mouth of Pamet River. Because it is so close to the tidal section of the river, the groundwater tidal variations at this well are generally 4-5 feet. The groundwater model nicely reproduces these tidal variations and matches heads within a few tenths of a foot during the February and April calibration periods. No data was collected in January at this well.

#### **4.3.4 Summary**

With the exception of C-5 and TRU-7, which are believed to have survey errors or errors in reporting of the depth of the pressure transducers, the model reproduces all observed heads within about one foot. Although the actual heads at TRU-7 are not reproduced by the model, the amplitude of the tidal signature was well matched by the model. Computed heads at wells on the upper, non-tidal section of Pamet River

showed minor tidal variations not matched by the observed data. Because these variations are so small (a few tenths of a foot at most), they are within the expected error of the model and not expected to impact the results of the alternatives analysis. The model is considered to be sufficiently calibrated for the alternatives analysis.

## **5.0 ALTERNATIVE ANALYSIS**

The calibrated model was used to run four separate alternative analysis. The calibrated parameters (hydraulic conductivity, river conductance and ocean conductance) were unchanged in the alternative runs.

The recharge was set to 0.0058 ft/d or 25.4 in/yr matching the April/May calibration run. The calibration process showed that recharge affected the upland portions of the model and had little impact on wells near the river. For the alternative analysis, the specific recharge value selected would not have a significant impact on the results as long as the value was within the range used in calibration

Each alternative was run with a normal tidal signature based on the predicted tides for the period June 10, 2019 and June 17, 2019 and an overtop event based on the conditions between February 28, 2018 and March 13, 2018. See Chapter 7 for additional information on the selection of the two run periods. The river stages were set based on the HEC-RAS model results as before. The bay (western boundary) general heads matched the downstream river stage for both run periods, while the ocean (eastern boundary) general heads were set based on the tides measured (for March 2018) or predicted (for June 2019) at the NOAA station at Chatham, Lydia Cove (8447435).

As with the calibration models, the HEC-RAS model and the MODFLOW model iterated back and forth with the HEC-RAS providing stages to MODFLOW and then MODFLOW providing groundwater heads to HEC-RAS until the difference between successive iterations was minimal.

The alternatives are compared using a number of parameters computed from the model results. These parameters were computed for every computational cell in the model and are presented as contour plots.

- The difference between mean higher high water (MHHW) and mean lower low water (MLLW) in the groundwater (termed 'amplitude' in this report) is shown for each normal tide model run to show the impact that the alternatives would have on normal conditions in the upper Pamet River (see Figure 16 Attachment D for a description of the computation)
- The head rise caused by the overtop event to show how the alternatives would impact the groundwater during an overtop event at Ballston Beach. (See Figure 17 Attachment D for a description of the computation.)
- The time (in hours) that the groundwater head remains at least 1 foot above previous high tide levels for that scenario during the overtop event to show how the alternatives would impact the recovery after an overtop event. (See Figure 17 Attachment D for a description of the computation.) Note that some areas do not fully return to pre-overtop conditions by the end of the model simulation, so some times may be under-predicted. However, this is considered to be a reasonable comparison across scenarios.

- The flow direction towards or away from the upper Pamet River and darcy velocities at the peak of the overtop event to show which areas could be impacted by salt water intrusion if the tide gates are removed.

The amplitude, head rise and time of high head during an overtop event are shown in figures (Attachment D) with the approximate locations of septic tanks and leach pits at residences along North and South Pamet Roads to allow gross, relative estimates of where impacts to septic systems from groundwater rise might occur. The depths of most of these features are unknown and there is insufficient data to directly predict impacts at specific locations.

The flow direction figures (Attachment D) are shown with approximate locations of wells at residences along North and South Pamet Roads to allow gross, relative estimates of where salt-water intrusion impacts might be found. The depths of most of these features are unknown. The location of the switch in groundwater flow direction (from towards the river to away from the river) is directly impacted by the size of the zone of higher hydraulic conductivity applied to the calibration models (as noted previously). The uncertainty in the location and size of this high conductivity zone leads to significant uncertainty in the location of the change in flow direction. The figures (Attachment D) are provided only to show that the switch in flow direction occurs, but do not accurately depict the location of the switch. The velocity magnitudes indicated by the vector color do not directly predict travel times for saline groundwater. This model does not model salt movement in the subsurface and the HEC-RAS model did not model salinities in the river water. There is insufficient data to directly predict impacts (salinity levels) at specific locations.

## **5.1 ALTERNATIVE-1: NO ACTION**

### **5.1.1 Brief Description**

Alternative 1 included the existing culverts at both crossings and a tide gate with parameters like that in existence during March 2018. This scenario approximates existing conditions but does not attempt to simulate the conditions with the new tide gate installed after the old one failed in 2018. A more detailed description of the scenario is provided in Chapter 1.

### **5.1.2 Summary of Results**

Results from this alternative are shown in Figures 18 through 22 (Attachment D). Under normal conditions, there is very little tidal variation in the upper Pamet River due to the tide gate which prevents high tides from passing west of its location (Figure 18 Attachment D). During the overtop event, the groundwater heads rise significantly, up to about 2.7 feet and the impact can be felt about a third of a mile from the river (Figure 19 Attachment D). Of particular concern with this alternative is that high heads remain for a wide swath (0.2 mi) on either side of the upper Pamet River for more than 200 hours, or about 8 days (Figure 20 Attachment D). Many septic systems are estimated to be within the impact area for overtop events. Depths of these systems are largely unknown so specific impacts cannot be accurately predicted.

During normal high tide, the flows in the vicinity are towards the river from both sides (Figure 21 Attachment D). These flow directions along with the tide gate which would prevent high tide from moving salt water into the upper Pamet River, indicate little concern for saltwater intrusion to the groundwater during normal conditions. During an overtop event (Figure 22 Attachment D), the trapped high heads in the groundwater result in flow away from the river towards numerous drinking water wells.

Darcy velocities are mostly less than 15 ft/d, so it is unlikely that short-term overtop events would impact most of the wells. A few, which are very close to the river may be in danger of salinity increases if overtop events become more frequent and long-lasting.

Note that transport velocities can be estimated by dividing Darcy velocity by porosity (generally around 0.3). The size and shape of the zone where flow is away from the river in Figure 22 (Attachment D) matches the zone where higher hydraulic conductivities were used in the top layer of the model (see Figure 3 Attachment D and Section 3.2.2 of this Chapter). Because that shape and size is uncertain, these results cannot be used to quantify impacts to specific wells.

## **5.2 ALTERNATIVE-2: ALL CULVERTS WITH TIDE GATE**

### **5.2.1 Brief Description**

Alternative 2 includes new, larger culverts with a tide gate. This allows faster release of high stages after an overtop event, but still prevents high tide salt water from reaching the upper Pamet River. Additional details on this alternative are presented in Chapter 1.

### **5.2.2 Summary of Results**

Results from this alternative are shown in Figures 23 through 27 (Attachment D).

Tidal amplitudes for this alternative are slightly higher than for Alternative 1 despite the inclusion of a tide gate (Figure 23 Attachment D). This may be due to lower low tides since water is able to escape more easily once the tide gate opens. The head rise caused by the overtop event is slightly lower than for Alternative 1 due to the easier escape of high water in the river. The area of impact is also slightly smaller (Figure 24 Attachment D). The time that groundwater heads are more than 1 foot higher than previous high tide is also much lower than for Alternative 1, with a maximum around 80 hours (about 3 days), less than half of the result from Alternative 1. Many septic systems are estimated to be within the impact area for overtop events. Depths of these systems are largely unknown so specific impacts cannot be accurately predicted.

As with Alternative 1, normal high tides result in most flows being towards the river (Figure 26 Attachment D), but after an overtop event (Figure 27 Attachment), the flow direction reverses for a small zone around the river, including several drinking water wells. Darcy velocities are mostly less than 15 ft/d, so it is unlikely that short-term overtop events would impact most of the wells. A few, which are very close to the river may be in danger of salinity increases if overtop events become more frequent and long-lasting.

Note that transport velocities can be estimated by dividing Darcy velocity by porosity (generally around 0.3). The size and shape of the zone where flow is away from the river in Figure 27 (Attachment D) matches the zone where higher hydraulic conductivities were used in the top layer of the model (see Figure 3 Attachment D and Section 3.2.2 of this Appendix). Because that shape and size is uncertain, these results cannot be used to quantify danger to specific wells.

## **5.3 ALTERNATIVE-3: ALL CULVERTS, NO TIDE GATE**

### **5.3.1 Brief Description**

Alternative 3 includes the same larger culverts as Alternative 2, but there is no tide gate to prevent high tides and salt water from passing into the upper Pamet River. Additional details on this alternative are presented in Appendix Chapter 1.

### **5.3.2 Summary of Results**

Results from this alternative are shown in Figures 28 through 32 (Attachment D).

As expected, the tidal amplitude for a normal day (Figure 28 Attachment D) above Route 6 is higher than with either of the two previous alternatives due to the absence of the tide gate, up to a maximum of about 0.5 ft. During an overtop event (Figure 29 Attachment D), the groundwater rise is slightly smaller and impacts a slightly narrower area around the river. The time that high heads remain (Figure 30 Attachment D) is much smaller, about 50 hours (2 days), or a little over half of that occurring for Alternative 2 and a quarter of that reported by the Alternative 1 model. It should be noted that the groundwater rise is compared to the pre-overtop high tide for this alternative. Normal groundwater levels before the storm are already higher than the no-action groundwater levels. Many septic systems are estimated to be within the impact area for overtop events. Depths of these systems are largely unknown so specific impacts cannot be accurately predicted.

The area which has flows away from the river during an overtop event (Figure 32 Attachment D) is about the same size as for the previous alternatives and includes several nearby wells. Darcy velocities are mostly less than 15 ft/d, so it is unlikely that short-term overtop events would impact most of the wells. A few, which are very close to the river may be in danger of salinity increases if overtop events become more frequent and long-lasting.

Note that transport velocities can be estimated by dividing Darcy velocity by porosity (generally around 0.3). The size and shape of the zone where flow is away from the river in Figure 32 (Attachment D) matches the zone where higher hydraulic conductivities were used in the top layer of the model (see Figure 3 Attachment D and Section 3.2.2 of this Appendix). Because that shape and size is uncertain, these results cannot be used to quantify danger to specific wells.

## **5.4 ALTERNATIVE-4: ALL-BRIDGES**

### **5.4.1 Brief Description**

Alternative 4 consisted of bridges instead of culverts to carry water beneath the roads. This provides additional conveyance, and, without a tide gate, does not prevent saline water from passing into the upper Pamet River during high tides.

### **5.4.2 Summary of Results**

Results from this alternative are shown in Figures 33 through 37 (Attachment D).

The tidal amplitude for a normal day (Figure 33 Attachment D) in the upper Pamet River for Alternative 4 is similar to Alternative 3 and higher than either Alternative 1 or Alternative 2. The maximum is a little below 0.5 ft. The head rise during an overtop event (Figure 34 Attachment D) and the area of impact is slightly smaller for Alternative 4 compared to other alternatives due to the additional conveyance provided by the bridges. The length of time that high heads remain after an overtop event (Figure 35 Attachment D) is also about the same for Alternative 4 and Alternative 3. It should be noted that the

groundwater rise is compared to the pre-overtop high tide for this alternative. Normal groundwater levels before the storm are already higher than the no-action groundwater levels. Many septic systems are estimated to be within the impact area for overtop events. Depths of these systems are largely unknown so specific impacts cannot be accurately predicted.

The area which has flows away from the river during an overtop event (Figure 37 Attachment D) is about the same size as for the previous alternatives and includes several nearby wells. Darcy velocities are mostly less than 15 ft/d, so it is unlikely that short-term overtop events would impact most of the wells. A few, which are very close to the river may be in danger of salinity increases if overtop events become more frequent and long-lasting.

Note that transport velocities can be estimated by dividing Darcy velocity by porosity (generally around 0.3). The size and shape of the zone where flow is away from the river in Figure 37 (Attachment D) matches the zone where higher hydraulic conductivities were used in the top layer of the model (see Figure 3 Attachment D and Section 3.2.2 of this Appendix). Because that shape and size is uncertain, these results cannot be used to quantify danger to specific wells.

## **5.5 SUMMARY OF FINDINGS**

The model shows that removal of the tide gate will result in higher groundwater head fluctuations in the area immediately around the upper Pamet River for normal days. The model also shows that the additional conveyances provided by the larger culvert and the bridges will slightly reduce the groundwater head rise occurring after an overtop event when compared to pre-overtop groundwater levels for each scenario. The greatest advantage in adding conveyance to the crossings is in the reduction in the amount of time that high water remains after an overtop event. Significant improvements were noted both with the larger culvert and again with the bridges.

Overtopping events also introduce salt water into the upper Pamet River. A check of the flow directions and velocities during the peak of the overtop event showed the flow directions switch such that flow from the river (presumably saline) will flow towards nearby wells at velocities generally below 15 ft/d. The wells that can be impacted by arrival of salt water during a single overtop event depends on the amount of time that the salt water remains trapped in the upper Pamet River. Although velocities do not appreciably drop with Alternatives 3 and 4 (no tide gate), the reduction in the amount of time the water is trapped may protect most wells. If overtop events begin to occur more frequently, the impact of salt water to the wells may be greater.

## **6.0 MODEL LIMITATIONS**

This model, like all models, is limited based on the assumptions and uncertainties inherent in the data, calibration and scenarios. Limitations in this model include the following:

- Very little groundwater data was available for calibration. The majority of it was shallow and close to the river. The calibration can be considered coarse, at best.
- Well and septic system locations were estimated based on maps with variable quality and accuracy. Depths were seldom available.



- These models were run for short term events (8-14 days) and cannot predict long term transport of groundwater or salinity.
- The alternatives were compared to a single overtop event from March 2018. If these events become more frequent in the future, their impact could compound. The impact of multiple or frequent overtop events was not investigated by this modeling project.

Uncertainties and assumptions in the model include the following:

- The model assumed homogeneity for hydraulic conductivity, except for the area immediately around the river.
- The river was simulated on a line of cells which were not as wide as the river. This was accounted for by applying a higher hydraulic conductivity to the area representing the true width of the river.
- The system was assumed to have net-zero losses, i.e. all flows removed from the system by wells were assumed to be added back in septic systems and other infiltration methods. Neither the pumping wells nor the infiltration were modeled.
- Heavy pumping or heavy usage of septic systems may cause localized changes in groundwater flow and change the impact of both high tide and overtop events.
- Recharge to the aquifer was estimated and constant throughout the model simulations.

## 7.0 CONCLUSIONS AND RECOMMENDATIONS

The removal of the tide gate will cause higher salinities and higher tide variations in the groundwater in the upper Pamet River on normal days. The removal of the tide gate and the addition of conveyance through larger culverts or bridges will reduce the impacts of overtop events by slightly reducing the head rise and significantly reducing the time that high heads remain in the groundwater. The model shows that overtop events will reverse the direction of groundwater flow along the upper Pamet River and may cause the transport of saline water towards nearby wells. The current model cannot predict impacts to specific wells but Darcy velocities are generally less than 15 ft/d.

This model did not investigate the movement of salinity. This was largely due to the lack of data. Future studies should measure salinity continuously in both the river and several groundwater locations at varying depths to provide data for future studies.

This model did not investigate travel times from the river to specific well locations. This is largely due to the size of the model and the difficulty of dealing with the large datasets that would result from a tidal model running for several years, or longer. Future studies may consider the use of a smaller, inset model that would take boundary conditions from the larger model and may be able to make estimates of travel times for salt water either for normal tidal variations if the tide gate is removed, or for overtop events if additional conveyance is added to the system.

*Movement of saline water from the upper Pamet River towards drinking water wells is of concern from a public health perspective, especially as the river system becomes increasingly dynamic, rising sea levels cause greater sea water inflows / intrusion and more frequent overtop events at Ballston Beach occur.*

*Long term groundwater monitoring at several locations along the upper Pamet River with wells placed at varying distances and depths from the river is strongly recommended to provide the necessary data for future decision-making. This monitoring should begin well before the construction of any culvert improvements or changes to the water exchange near Wilder's Dike and should continue after any construction projects are completed to fully understand the impact of the projects. Continued long-term monitoring will also provide necessary data to prepare for any future impacts to drinking water wells or septic systems.*

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# **Chapter 7**

## **PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**Pamet River Riverine Model Analysis**

**Quantitative Data Analysis**

**(HEC-RAS)**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

**CHAPTER 7:**  
**Pamet River Riverine Model (HEC-RAS) Analysis**  
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## **1.0 INTRODUCTION**

The purpose of this Pamet River Hydrologic & Hydraulic Assessment is to evaluate potential culvert modifications at Wilder's Dike and Route-6 to improve Ballston Beach overtopping drainage, evaluate the tide exchange potential upstream of Route 6 for salt marsh ecosystem benefits and climate change adaptivity, and coordinate hydraulic boundary conditions with the groundwater investigation, as presented in Chapter 6. An unsteady flow HEC-RAS riverine model was built to investigate the resulting river stage magnitudes and drainage times during high flow events for the proposed alternatives and study objectives.

The Pamet River is primarily groundwater-fed; thus, the groundwater model (MODFLOW) and the river model (HEC-RAS) were developed in parallel. The groundwater model requires river stage as a boundary condition and uses it to compute interactions between groundwater and surface water. Similarly, the river model requires groundwater head as a boundary condition and uses it to compute interactions between groundwater and surface water. Efforts were made to ensure that the model-computed interactions between groundwater and surface water were similar in each model.

Under existing conditions, tidal flows within the Pamet River are unrestricted between Pamet Harbor and Wilders Dike. At the dike, a 3.5 foot diameter culvert with a tide flap-gate attached to downstream end restricts tidal flows upstream of the dike but allows freshwater discharge generated within the upper Pamet River watershed to drain thru the culvert when the freshwater discharge elevation is greater than the downstream tidal elevation, since the pressure-head (water-elevation) exerted against the flap gate controls the flow direction.

During normal (non-storm) conditions, the flap gate is forced closed twice daily prohibiting the Pamet Harbor high tide from flowing upstream of the dike, but allows freshwater flows generated in the upper-Pamet River watershed to discharge through both the 4.0 foot culvert at U.S. Route 6 and the 3.5 foot culvert at Wilders Dike when the Pamet Harbor high tide recedes during low (ebb) tide conditions.

During Ballston Beach overwash conditions, accumulated ocean water accumulates up- against the route-6 embankment until discharged thru the Route-6 and Wilder's Dikes culverts. This condition may extend anywhere from 6-hours to 36-hours (if a Nor'easter stalls over New England pushing storm surge in land, or if multiple Nor'easters occur before overwash drains.)

The HEC-RAS model was calibrated using three tidal stations deployed in Truro, MA by USACE, New England District. Once calibration and validation were completed, four culvert modification alternatives were developed using the HEC-RAS model by evaluating both the potential tidal flow conveyance upstream of Wilder's Dike and discharge downstream of Wilder's Dike. The results were used to assess the impact of each alternative on normal tides and a significant coastal storm event, resembling an observed Nor'easter, overtopping ocean water at Ballston Beach.

## **2.0 DATA SOURCES**

The HEC-RAS model used time-series and geospatial data available online and collected by field survey from the USACE, New England District. All geospatial data was converted and projected to a common horizontal and vertical datum for the model; the North American Datum 1983 Massachusetts Main Land (feet) and the North American Vertical Datum 1988 (feet) (NAVD88), respectively.

The Digital Elevation Model (DEM) used to cut cross-sections of the Pamet River and overbanks for the HEC-RAS model was from the 2016 USGS CoNED topobathymetric model downloaded from <https://coast.noaa.gov/digitalcoast/data/coastallidar.html>. The DEM is based upon LiDAR collected by the

USGS and other agencies spanning from 2014 to 2016 and has a 1-meter grid cell resolution (Figure 1 Attachment E).

The DEM was supplemented by cross-section field surveys of the Pamet River conducted by USACE, New England District in January 2017 at several locations along the river. The survey was used to establish bottom elevations below the waterline of the Pamet River for the HEC-RAS cross-sections. Interpolation of the river's bottom elevations was completed for sections where field surveys were not performed.

The HEC-RAS model was calibrated with observed data collected at three tidal stations deployed and maintained by USACE, New England District staff starting in December 2016. River stages were collected through 2017 and most of 2018. The three tidal stations were located just downstream of the tide gate at Wilders Dike, between Wilders Dike and the U.S. Route 6 culvert, and just upstream of the U.S. Route 6 culvert (Figure 2 Attachment E). They are denoted as Pamet 1, Pamet 2, and Pamet 3, respectively, in the downstream to upstream direction (Figure 4 Attachment E). Data analysis indicated the longest continuous time period of reliable collected tides occurred from January 2017 to May 2017. During that time period, both overtopping and non-overtopping storm events at Ballston Beach occurred. Data collected between May 2017 and December 2017 had some time periods of instrumentation abnormalities that adversely impacted the collected data. Therefore; tidal data collected during the second half of 2017 was not used for calibration of the HEC-RAS model.

Hourly tidal data collected at Boston Harbor by NOAA was obtained online at <https://tidesandcurrents.noaa.gov/stationhome.html?id=8443970>, and was used as the HEC-RAS downstream boundary at Pamet Bay. Data analysis of the tides collected at Boston Harbor, which is located 55 miles northwest of Truro, MA, compared against tides collected at the Pamet 1 station showed relatively good agreement in amplitude and phasing. A 0.95 scale factor was applied to adjust Boston Harbor tides before they were used as the downstream boundary condition for the HEC-RAS model. No temporal adjustments were deemed to be necessary as the time of high/low tides at Boston Harbor coincided closely to the time of high and low tides at Pamet Harbor.

High resolution aerial photography for Massachusetts dated 2013-2014 was utilized in ArcGIS from a USGS web mapping service to verify watershed boundaries as well as to delineate river centerlines and other geographic features needed for the HEC-RAS model. The aerials also were used to verify HEC-RAS Manning's n values along with locating other important geographic features for the model.

In addition to the HEC-RAS model, a HEC-HMS model was developed for the Pamet River watershed. This allows the HEC-RAS model to incorporate surface runoff as a uniform lateral inflow from the watershed into the river. Data needed for the HEC-HMS model included hourly precipitation data collected at the nearby Provincetown Municipal Airport as shown in Figure 3 (Attachment E) and National Land Cover Database 2011 (NLCD) land use and percent imperviousness layers from (<https://viewer.nationalmap.gov/launch/>) to estimate SCS Curve Number loss and transform parameters. ArcGIS with ArcHydro and HEC-GeoHMS 10.4 software were used to pre-process and analyze the data necessary to generate the subbasin boundaries and convert rainfall to runoff within the HEC-HMS model.

The last data source used to development HEC-RAS model consisted of structural elevations surveyed as part of the 1998 UNET Model completed by USACE, New England District. Invert elevations of the existing culverts at Wilders Dike and U.S. Route 6 from that model were used along with Manning's n value estimates.

## **3.0 MODEL DEVELOPMENT**

An unsteady state 1-D HEC-RAS model was developed for the existing conditions of the Pamet River from Ballston Beach in the east to Pamet Harbor the west for a total reach length of 5.1 miles. HEC-RAS version 5.0.5 was used for the final model.

### **3.1 MODEL GEOMETRY**

The model consisted of 117 cross-sections along the 5.1 miles of the Pamet River and adjacent marsh banks as presented in Figure 5 (Attachment E). The average cross-section distance varies between 50-100-ft, specifically located to capture the river profile curvature, overbanks and perpendicular river crossing structures at Wilder's Dike and Route-6; however, a maximum cross-section distance of 750 feet occurs along the western marsh approaching the confluence with Pamet Harbor. Encoded into the HEC-RAS model were two culverts (Wilders Dike and US Route 6), and an inline structure representing Wilders Dike and tide gate. Initial model development for all the geometric elements of the HEC-RAS model was performed in ArcGIS 10.4 using the HEC-GeoRAS 10.4 extension. HEC-GeoRAS was used to spatially define the following elements:

- Stream Centerline
- River Banklines
- Overbank Flowlines
- Cross-Sections
- Ineffective Flow Areas
- Top of Road Crossings (Wilders Dike & US Route 6)
- Culverts (Wilders Dike & US Route 6)

Initially, lateral structures connecting cross-sections to 1-D storage areas representing small tributaries and marsh areas in the floodplain were also encoded in HEC-GeoRAS using the DEM as a guide. Initial runs during the calibration process showed that no flow was entering these storage areas by overtopping the higher elevations along lateral structure alignments, and therefore, they were removed from the HEC-RAS model and deemed as not necessary.

#### **3.1.1 Stream Alignment and Flow Paths**

The HEC-RAS centerline was digitized in ArcGIS 10.4 using the 2013-2014 aerial photography available online for Massachusetts from the USGS (Figure 4 Attachment E). The upstream end of the centerline limit is located at the overwash fan in Ballston Beach and follows the Pamet River centerline in a westerly direction, downstream to the Pamet Harbor Inlet and ultimately into Cape Cod Bay. The model was extended west of the inlet jetties to Cape Cod Bay where deep water tidal conditions are experienced and recorded by NOAA, to accurately depict and calibrate the tidal signal at the Pamet Harbor inlet jetties, which represents the tidal regime along the lower Pamet River between the Harbor and Wilder's Dike. HEC-RAS River banklines and overbank flow lines were also digitized in ArcGIS using the 2013-2014 aerial photography as a guide along with 2 foot contours generated from the DEM for the overbanks.

#### **3.1.2 Cross-Sections**

As introduced previously in section 3.1, HEC-RAS cross-section placements were designated at locations that best characterized the flow carrying capability of the Pamet River and the adjacent floodplain. The cross-sections extended to higher elevations in the overbanks to ensure the entire floodplain was captured. Changes in discharge, slope, and roughness were all considered in cross-section placement.



Cross-sections were clustered closer together near the developed areas at Wilders Dike and U.S. Route 6 and were spaced further apart at the upstream end at Ballston Beach and at the downstream end at Pamet Harbor. Two foot contours generated from the DEM were used to orient cross-sections perpendicular to the flow direction as much as possible in the overbanks. Cross-sections for the HEC-RAS model are shown in Figures 5 thru Figure 10 (Attachment E).

For the Pamet River HEC-RAS Model, initial Manning's n values were assigned based on three primary sources:

- NLCD 2011 Land Use Raster that was resampled to minimize the number of land use categories per cross-section.
- The 2013-14 Massachusetts aerial imagery obtained through the USGS.
- The previous 1998 Pamet River UNET Model.

Prior to calibration, the number of unique land cover categories listed in GIS for the overbanks was compiled (grouped) in order to manage the number of Manning's n values assignments for calibration. The pre-calibration ranges of Manning's n values varied between 0.030 – 0.065 for the channel and between 0.035 – 0.160 for the overbanks and the post-calibration ranges of Manning's n values varied between 0.042 – 0.055 for the channel and between 0.035 – 0.120 for the overbanks.

These Manning's n values were adjusted within reasonable bounds during the calibration phase of model development to accurately simulate the Pamet River system as discussed in the model calibration section 4.0 of this report.

### 3.1.3 Culverts

Both the U.S. Route 6 and Wilders Dike embankments and culverts were added to the geometry. Physical properties of the culverts, such as, pipe material, diameter, length, upstream and downstream invert elevations were taken from field measurements and the input file from the 1998 UNET model and entered into the HEC-RAS culvert data editor for both locations. Initial Manning's n values for both corrugated metal culverts were 0.024 with the Wilder's Dike 'n' value calibrated to a value of 0.019 to represent age and field conditions. Table 1 summarizes the culvert data used in the HEC-RAS model.

**Table 1. HEC-RAS Culvert Data**

| <b>Culvert Parameter</b>                  | <b>Wilders Dike</b> | <b>U.S. Route 6</b> |
|-------------------------------------------|---------------------|---------------------|
| Culvert Shape                             | Circular            | Circular            |
| Diameter (feet)                           | 3.5                 | 4                   |
| Material                                  | Corrugated Metal    | Corrugated Metal    |
| Distance to Upstream Cross-Section (feet) | 15                  | 90                  |
| Culvert Length (feet)                     | 56                  | 360                 |
| Entrance Loss Coefficient                 | 0.5                 | 0.5                 |
| Exit Loss Coefficient                     | 0.7                 | 0.7                 |
| Manning's n value                         | 0.019               | 0.024               |
| Upstream Invert Elev. (ft. NAVD88)        | -1.14               | -1.15               |
| Downstream Invert Elev. (ft. NAVD88)      | -1.33               | -1.63               |
| Upstream Centerline Station (feet)        | 544                 | 152.25              |
| Downstream Centerline Station (feet)      | 215.25              | 311.5               |

### 3.1.4 Wilders Dike Tide Gate

An inline structure with a culvert and gate was encoded into the HEC-RAS model in order to simulate the operation of the Wilders Dike Tide Gate. The opening and closing of the tide gate was replicated using a sluice gate type in the model. Since HEC-RAS does not allow for circular geometric properties to describe a physical gate, the size of the gate over the end of the 3.5 foot diameter culvert was approximated using an equivalent height and width. Coefficients were adjusted as needed during the calibration process of comparing computed water surface elevations against observed elevations collected at the Pamet 2 tide station. Table 2 summarizes the calibrated data used for the tidal gate in the model.

**Table 2. HEC-RAS Wilders Dike Gate Data**

| Gate Parameter                | Wilders Dike Gate |
|-------------------------------|-------------------|
| Gate Type                     | Sluice            |
| Sluice Discharge Coefficient  | 0.3               |
| Orifice Coefficient           | 0.5               |
| Weir Shape                    | Sharp Crested     |
| Weir Coefficient              | 3                 |
| Gate Height (feet)            | 3.5               |
| Gate Width (feet)             | 4                 |
| Invert Elevation (ft. NAVD88) | -1.14             |

Hydraulic operation triggers were evaluated during the calibration process to determine when the tide gate opened and closed. Parameters were adjusted so that computed stages at the Pamet 2 and Pamet 3 tide stations closely as possible matched the three calibration events. The HEC-RAS's Elevation Controlled Gate Boundary Condition in the Unsteady Flow Editor was the modeling feature selected to simulate the operation of the tide gate at Wilders Dike. By using the elevated controlled gate approach, tide gate opening and closing simulation was established as the model computed the difference in stage at a cross-section downstream of the tide gate versus a cross-section upstream of the gate. Input to the HEC-RAS model for this approach included:

- The stage difference at which the gate begins to close and open,
- Gate opening/closing rates,
- The maximum/minimum gate opening, and
- The initial setting of the tide gate.

Table 3 summarizes the calibrated values used for simulating the tide gate operations at Wilders Dike.

Early in March 2018, a coastal storm and surge impacted the area detaching the existing (and aging) tide gate off the culvert at Wilders Dike. Thus, between the dates of March 2018 and early August 2018, there was no tide gate installed onto Wilders Dike and water level tide data collected at Pamet 2 and Pamet 3 after removal of the tide gate showed elevated water levels propagating upstream through the culverts, during both normal tidal conditions and storm conditions. This allowed a comparison of river stages with and without the gate before a replacement flap gate was installed in August 2018.

**Table 3. HEC-RAS Wilders Dike Gate Operation Parameters**

| Gate Parameter                                    | Wilders Dike Gate |
|---------------------------------------------------|-------------------|
| Downstream Reference Cross-Section                | 13621             |
| Upstream Reference Cross-Section                  | 13025             |
| Stage Difference When Gates Start to Open (feet)  | 0.75              |
| Stage Difference When Gates Start to Close (feet) | -0.4              |
| Gate Opening Rate (feet/min)                      | 1                 |
| Gate Closing Rate (feet/min)                      | 1                 |
| Maximum Gate Opening (feet)                       | 3.5               |
| Minimum Gate Opening (feet)                       | 0.4               |
| Initial Gate Opening (feet)                       | 3.5               |

In August 2018, a new lighter and smaller flap gate was installed at Wilder’s Dike by the town of Truro. (Note: this new lighter gate is temporary; this study recommends the Wilder’s Dike modification culvert/gate will be heavier). Data analysis of the collected tides showed that the new (lighter and temporary) gate operates with different water level parameters than the previous (broken) flap gate based upon the tidal signal amplitude propagating upstream. During periods when reliable observed data was collected at Pamet 2 and Pamet 3, it was verified that tidal amplitudes were higher upstream of the dike with the new (lighter and temporary) gate versus previous (broken) flap gate.

The decision was made by the project team to calibrate the HEC-RAS model using gate parameters associated with the previous (broken) gate as opposed to the new (lighter and temporary) gate since the majority of recorded and observed data collected and the development of the groundwater and riverine models was already in the advanced stages. By continuing to use the parameters from the previous (broken) tide gate for the HEC-RAS model, the alternative analysis computations of the duration to drain the upper portion of the Pamet River of flood waters through the U.S. Route 6 culvert and Wilders Dike would be representative of the old (broken) tide gate and not the newly installed one. For an alternative analysis such as this, not incorporating the new gate was deemed to be reasonable.

### **3.1.5 Ineffective Flow Areas**

Ineffective flow areas represent any riverine section or channel where flow momentum and/or energy are not effectively convey downstream (i.e. bridges or other structural features, isolated topographic low spots, sand-bars/sedimentation, etc.)

Ineffective flow areas along the Pamet River were digitized in ArcGIS using the HEC-GeoRAS extension during model development and subsequently adjusted during the calibration process to block riverine flow volume that does not discharge downstream and contribute to the Pamet River overbank, channel and Route-6 and Wilder’s Dike culvert flow discharge. If ineffective flow areas are not included in the model, then the flow volume and resulting HEC-RAS model would be not accurately calibrated and proposed alternatives inaccurately evaluated.

Ineffective flow areas were also defined at the bounding cross-sections upstream and downstream of the Wilders Dike and U.S. Route 6 culverts because the embankments obstruct flow in the overbanks. Typical contraction and expansion coefficients of 0.3 and 0.5 were also used at the bounding cross-sections for Wilders Dike and U.S. Route 6 crossings.

## **3.2 BOUNDARY & INITIAL CONDITIONS**

Four types of external flow boundary conditions were developed for the HEC-RAS model; 1. flow hydrograph at the upstream end at Ballston Beach; 2. a stage hydrograph at the downstream end at Pamet Harbor; 3. two lateral inflow hydrographs representing surface runoff from the watershed; and 4. multiple groundwater interflow stage hydrographs along the entire Pamet River centerline length to represent groundwater heads and baseflow conditions.

### **3.2.1 HEC-RAS's Elevation Controlled Gate Boundary Condition in the Unsteady Flow Editor**

A flow hydrograph was developed at the upstream end of the Pamet River at Ballston Beach representing either no flow for calibration and alternative analysis events that didn't overwash the dunes at Ballston Beach or for the larger storm events simulated where wave overtopping and overwash was observed to occur. The overwash flow hydrograph was developed by computing wave runup heights and overtopping volumes at a shore-perpendicular transect cut from the 2016 DEM. For time steps where wave runup exceeded the dune crest, wave overtopping discharge was calculated using the modified Hedges and Reis (1998) method described in Laudier et al. (2011). Figure 11 (Attachment E) shows the overwash flow hydrographs developed for the January 22-29, 2017 overwash calibration event. Overwash discharge was periodic, with wave runup only exceeding the dune crest and flowing into the Pamet River at higher stages of the tide cycle.

At the downstream boundary at Pamet Harbor, a stage hydrograph was used for the HEC-RAS model. As previously mentioned, the stage hydrograph was taken from recorded water levels during the time period of each calibration event at NOAA's Boston Harbor tidal station with a 0.95 scale factor applied to reduce amplitudes slightly to better represent tidal conditions at Cape Cod Bay just outside of the inlet jetties at Pamet Harbor. Figures 12-14 (Attachment E) show the adjusted stage hydrographs used for the three calibration events.

### **3.2.2 Watershed Runoff Boundary Condition**

A HEC-HMS model of the Pamet River basin was developed to calculate the local precipitation runoff flow hydrographs to be used as a freshwater inflow boundary condition in the HEC-RAS model. The HEC-HMS model was not calibrated due to the lack of any streamflow gages within the Pamet River watershed or any nearby watersheds with similar topographical characteristics.

Calibration of the HEC-HMS model was deemed not necessary early in the investigation since the 7.6 square mile size of the Pamet River watershed runoff, coupled with large tidal surge overtopping storm events with small precipitation that were the focus evaluated in this study, would not be a significant contribution of freshwater flow recharging the Pamet River. (Note: If larger frequency-based storm events, such as the 100-year, were going to be analyzed for flow rates, volumes and subsequent flood mapping, then a more robust HEC-HMS hydrologic model that includes calibration would be warranted).

The contributing drainage area of the Pamet River was determined using the HEC-HMS GIS extension, HEC-GeoHMS to model overland surface flow from the same topographical DEM as was used to develop the HEC-RAS model. The Pamet watershed was divided into six subbasins; two in the freshwater upper Pamet River, and four in the tidally driven lower Pamet River.

Local runoff hydrographs computed from the two upper Pamet River subbasins were imported into the HEC-RAS model. Runoff from the lower portion of the Pamet River was considered negligible for the storm conditions analyzed in proportion to the tidal flows between Pamet Harbor and Wilder's Dike. The tidal boundary at Cape Cod Bay is a much larger driver of flows in the lower portion of the Pamet River than local runoff from these four subbasins. Figure 15 (Attachment E) presents the Pamet River

Watershed drainage areas delineated for the HEC-HMS model. Local runoff flow hydrographs were computed in HEC-HMS using the SCS Method. SCS curve numbers were developed for subbasin losses based upon the land use and percent impervious layers from the National Land Cover Database 2011 (NLCD). Table 4 summarizes the SCS loss method parameters used for the two upper Pamet River subbasins. The SCS Unit Hydrograph Method, with a Delmarva graph type (typically used for coastal locations within a watershed), was used for the subbasin transform method with a lag time calculated in accordance with the standard TR-55 worksheet, as shown in Table 5.

**Table 4. SCS Loss Parameters**

| Subbasin        | Curve Number (CN) | Percent Impervious |
|-----------------|-------------------|--------------------|
| UpperPamet02_SB | 41                | 2.6                |
| UpperPamet01_SB | 51                | 1.2                |

**Table 5. TR-55 Time of Travel**

|                                                  | UpperPamet01_SB        | UpperPamet02_SB        |
|--------------------------------------------------|------------------------|------------------------|
| <b>Sheet Flow Characteristics</b>                |                        |                        |
| Surface Description                              | Woods Light Underbrush | Woods Light Underbrush |
| Manning's n Value                                | 0.4                    | 0.4                    |
| Flow Length (ft.)                                | 100                    | 100                    |
| Two-Year 24-hour Rainfall (in.)                  | 3.18                   | 3.18                   |
| Land Slope (ft. / ft.)                           | 0.009                  | 0.012                  |
| Sheet Flow Tt (hr.)                              | 0.49                   | 0.44                   |
| <b>Shallow Concentrated Flow Characteristics</b> |                        |                        |
| Surface Description                              | Forest                 | Forest                 |
| Flow Length (ft.)                                | 5,030                  | 12,280                 |
| Watercourse Slope (ft. / ft.)                    | 0.039                  | 0.160                  |
| Average Velocity - computed (fps)                | 0.50                   | 0.90                   |
| Shallow Concentrated Flow Tt (hr.)               | 2.79                   | 3.79                   |
| <b>Channel Flow Characteristics</b>              |                        |                        |
| Cross-sectional Flow Area (sq. ft.)              | 385                    | 166                    |
| Wetted Perimeter (ft.)                           | 146                    | 47                     |
| Hydraulic Radius - computed (ft.)                | 2.64                   | 3.53                   |
| Channel Slope (ft. / ft.)                        | 0.00100                | 0.00018                |
| Manning's n Value                                | 0.048                  | 0.048                  |
| Average Velocity - computed (fps)                | 1.87                   | 0.97                   |
| Flow Length (ft.)                                | 4,274                  | 6,517                  |
| Channel Flow Tt (hr.)                            | 0.63                   | 1.87                   |
| Watershed Time of travel (hr.)                   | 3.92                   | 6.10                   |
| Watershed Time of travel (min.)                  | 235.33                 | 366.29                 |
| <b>Estimate of Lag Time (min) (60% of Tc)</b>    | <b>141.20</b>          | <b>219.77</b>          |

The Muskingum-Cunge (M-C-HMS-method), hydrologic-riverine-channel routing method, available in the HEC-HMS model, was used for the upper Pamet River with routing parameters and Manning's n values correlating to the HEC-RAS cross-sections. Specified hyetographs of hourly rainfall for the three calibration events were taken from the nearby Provincetown Municipal Airport gage. Since the HEC-HMS model was not calibrated, a sensitivity analysis of the channel flows generated by M-C-HMS-Method, was performed against the calibrated HEC-RAS model river flows to investigate the sensitivity of the M-C-HMS-Method computed river stages for various runoff volumes and peaks. The contributing drainage area of the upper Pamet River is small at 2.6 square miles. Results indicated that runoff from the upper Pamet subbasins had relatively small peaks and minimal volumes, resulting in minimal increases in river stages. The largest calibration event of February 6-12, 2017 had a peak runoff of 1.6 cfs and a volume of 3.7 acre-feet. Doubling and even tripling the peak and volume did not significantly raise the river stages and was considered negligible. However, the boundary condition was still included in the HEC-RAS model in case larger rainfall events are examined in the future.

### **3.2.3 Groundwater Interflow Boundary Condition**

Groundwater stages computed from the MODFLOW model were entered into the HEC-RAS model as a 'groundwater interflow boundary condition'. Input of this boundary condition in HEC-RAS requires an upstream and downstream cross-section where the boundary condition applies, an hourly time series of groundwater heads, a specific conductance in feet/day, and a thickness or length from the cross-section to the point where the groundwater stage was computed. HEC-RAS converts the groundwater heads to groundwater flows entering or exiting the river applying Darcy's equation where the head is the difference between the river stage at the cross-section and the time series of stages from the MODFLOW model. Depending on the stages of the river versus the groundwater stages, flow can either be entering or exiting the river.

For the Pamet model, cross-sections in groups of five were used for the groundwater interflow. A total of 30 groundwater interflow boundary conditions were used that covered the entire length of the Pamet River from Ballston Beach downstream to Pamet Harbor. Table 6 summarizes the locations of the 30 groundwater interflow boundary conditions.

### **3.2.4 Initial Conditions**

The HEC-RAS model requires an initial river discharge to numerically stabilize the model computations at the start of the simulation. Additionally, all cross-sections in the model must be "wet" at the first time step; thus, low flows or ebb tide resulting in dry conditions will unstabilize the model into error. A value of 6 cfs was selected for all calibration simulations. Lower values caused model instabilities and higher values over-predicted observed stages.

## **3.3 SIMULATION RUN-TIME PARAMETERS**

The same HEC-RAS run-time parameters were used for all calibration and alternative analysis simulations. There were no simulation convergence issues or computational instabilities using a one minute computational time step whereas larger time steps introduced some computational instabilities at the tide gate cross-sections. Default HEC-RAS computation options and tolerances were used for all simulations with the exception of using 0.6 instead of 1.0 for the theta implicit weighting factor. Lowering the factor to 0.6 is typical for tidal simulations with HEC-RAS gate structures function as it leads to slightly more stable solutions. Detailed flow and stage output were produced at each cross-section along with hydrographs at 15-minute intervals in order to produce smooth hydrograph results used for calibration purposes. Runtimes for a 7-10 day simulation were typically under a minute in duration.

Table 6. HEC-RAS Groundwater Interflow Boundary Conditions

| Groundwater Interflow BC | River Station From (feet) | River Station To (feet) | River Length (feet) |
|--------------------------|---------------------------|-------------------------|---------------------|
| 1                        | 27034                     | 26758                   | 276                 |
| 2                        | 26627                     | 25863                   | 764                 |
| 3                        | 25734                     | 25382                   | 352                 |
| 4                        | 25188                     | 24778                   | 410                 |
| 5                        | 24702                     | 24207                   | 495                 |
| 6                        | 24066                     | 23558                   | 508                 |
| 7                        | 23328                     | 22764                   | 564                 |
| 8                        | 22696                     | 21591                   | 1105                |
| 9                        | 21417                     | 20941                   | 476                 |
| 10                       | 20534                     | 19859                   | 675                 |
| 11                       | 19553                     | 18714                   | 839                 |
| 12                       | 18508                     | 17613                   | 895                 |
| 13                       | 17385                     | 16749                   | 636                 |
| 14                       | 16624                     | 15791                   | 833                 |
| 15                       | 15643                     | 14810                   | 833                 |
| 16                       | 14639                     | 14087                   | 552                 |
| 17                       | 14087                     | 13695                   | 392                 |
| 18                       | 13621                     | 13549                   | 72                  |
| 19                       | 13429                     | 13169                   | 260                 |
| 20                       | 13025                     | 12736                   | 289                 |
| 21                       | 12628                     | 12009                   | 619                 |
| 22                       | 11784                     | 11315                   | 469                 |
| 23                       | 11166                     | 10417                   | 749                 |
| 24                       | 10184                     | 8799                    | 1385                |
| 25                       | 8660                      | 8257                    | 403                 |
| 26                       | 7832                      | 7287                    | 545                 |
| 27                       | 6991                      | 6374                    | 617                 |
| 28                       | 6128                      | 5361                    | 767                 |
| 29                       | 5102                      | 3625                    | 1477                |
| 30                       | 3100                      | 1439                    | 1661                |

## **4.0 PAMET RIVER HEC-RAS MODEL CALIBRATION**

### **4.1 Calibration Events**

Three unique events in the first four months of 2017 were selected for calibration of the HEC-RAS model. They were:

- January. 22 – 29, 2017;
- February 6 – 12, 2017; and
- April 23 – May 3, 2017

January 22 - 29, 2017 – A nor'easter struck New England with high winds, heavy rain and coastal flooding with beach erosion. Winds gusting as high as 40-50 mph were measured at Boston's Logan Airport and southern New England. Blizzard conditions were reported in inland areas of eastern Massachusetts on January 23-24, 2017 and a total of 1.8 inches of rain fell at nearby Provincetown Municipal Airport from January 23-25, 2017 coupled with significant coastal storm surge flooding. Storm surge and wave runup were observed overtopping the dunes at Ballston Beach and flowing into the upper portion of the Pamet River. This storm served as the dune overtopping high flow calibration event.

February 6 – 12, 2017 – A less significant storm event occurred where there was no observed overtopping of the Ballston Beach dunes from storm surge or runup. A total of 0.45 inches of rain fell at Provincetown Municipal Airport over a span of three days. This storm served as the low flow calibration event with no dune overtopping.

April 23 – May 3, 2017 – This time period was selected because it represented a spring high tide event. There was no dune overtopping at Ballston Beach but the tides at Pamet Bay exceeded typical normal tidal range by as much as 1.5 feet.

### **4.2 CALIBRATION PROCESS**

Similar to the calibration process for the MODFLOW groundwater model, the three calibration time periods were rerun in HEC-RAS to calibrate field parameters, including, Manning n values, gate operation parameters, runoff from the Pamet watershed, and ineffective flow areas/elevations, which vary within a regulated guide-specification range to account for field conditions.

Initial HEC-RAS calibration were performed without any groundwater interflow boundary conditions until computed stages were lower than observed stages by no greater than 1.0 foot. The reason for this being, that once the groundwater interflow was added to the model after the first set of MODFLOW runs, then the computed stages would rise to levels closer to observed stages.

Next, the calibration process included iterations with the MODFLOW groundwater model. The groundwater heads computed by MODFLOW were added as boundary conditions and the impact of introducing groundwater to the computed river stages was investigated. Additional parameter adjustments to the HEC-RAS model were made at this point until the model's computed stages matched, as closely as possible, to those measured at the Pamet 1, Pamet 2, and Pamet 3 tidal stations. Typically it took four to five iterations of HEC-RAS runs and adjustment of calibration parameters, followed by coordinated MODFLOW runs and adjustments, to achieve convergence and good agreement of computed stages between the two models and observed stages and heads recorded at Pamet 1, Pamet 2, and Pamet 3.



### 4.3 CALIBRATION RESULTS

Summary of the calibration results at the three tidal stations for the three calibration periods are shown in Figures 16-24 (Attachment E).

As presented in Figure 16 (Attachment E), the January 22-29, 2017 overwash calibration event computed very good agreement with the Pamet 1 tide station as shown. Storm peaks matched computed peaks consistently well. At low tide, computed stages slightly over-predicted observed stages by 0.2 to 0.3 feet, which is considered acceptable within field and model tolerance.

There was some missing observed data at Pamet 1 after January 27, 2017 at times of peak tide for a few tidal cycles, but once it started recording again on January 29<sup>th</sup>, the agreement between observed and computed stages continued.

Pamet 2, located upstream of Wilders Dike and the tide gate, computed very good agreement can be seen during the peak of the storm on the 25<sup>th</sup> in Figure 17 (Attachment E). It should be noted that for all three events at Pamet 2, it appears that the tide gate at Wilders Dike does not fully close when the stages are high. This results in a tidal signal propagation upstream that can be seen on all the Pamet 2 and Pamet 3 figures.

For the January 22 – 29, 2017 event, once the peak of the storm passed and the gate opened more; (which lowered stages at Pamet 2) continuation of the good calibrated agreement can be seen in the hydrograph.

The January 2017 calibration event computed stages at Pamet 3, located upstream of the U.S. Route 6 culvert, that aligned well with observed stages as shown in Figure 18 (Attachment E), but not as closely aligned as the computed stages at Pamet 2. The model generally under-predicted during high tides by 0.2 to 0.3 feet and under-predicted at low tide by as much as 0.5 feet after the peak of the storm passed near the end of the simulation. Computed tidal amplitudes exceeded observed amplitudes.

Observed stages recorded during the February 6 – 12, 2017 event continued to align well against the computed stages at Pamet 1 as shown in Figure 19 (Attachment E). At low tide, the model continued to generally over-predict stages by 0.4 to 0.5 feet. At high tide, several peaks matched well against the observed with a few peaks under-predicting observed tides by no greater than 1.0 foot. The under-predicting of high peaks could be from the fact that Boston Harbor tides are being used at the Pamet Harbor downstream boundary. Those higher peaks at Boston Harbor might not exactly reflect tides in Pamet Bay. At Pamet 2, the model over-predicted the tidal signal propagating through Wilders Dike by no more than 0.5 feet as shown in Figure 20 (Attachment E). The observed tidal signal amplitude of approximately 1.0 foot was replicated well with the model. The model over-predicting observed stages by 0.3 to 0.4 feet continued through the U.S. Route 6 culvert to the Pamet 3 tide station (Figure 21- Attachment E).

Computed results from the April 23 – May 3, 2017 spring tide event most closely aligned with recorded data of the three events. At Pamet 1, most observed high water peaks matched well against computed peaks (Figure 22-Attachment E). The larger observed peaks may actually be under-predicted if the Boston Harbor peak tides are actually greater than those that occurred at Pamet Harbor.

The over-predicting computations at Pamet 1 during low tide conditions also occurred for the other two events, but less significant for this time period.

Very close agreement occurs between observed and computed stages at Pamet 2, can presented in Figure 23 (Attachment E), particularly after the first five tidal cycles at the beginning of the model

simulation. This close agreement suggests that the Wilders Dike tide gate operations encoded into the model align with the typical operation of the gate during spring and normal tidal conditions.

Lastly at Pamet 3, as presented on Figure 24 (Attachment E), the computed stages slightly under-predict observed high tide peaks by 0.2 to 0.3 feet. Starting on the 3<sup>rd</sup> day of the simulation, the computed tidal signal amplitude is larger than the observed amplitude at Pamet 3 by approximately 0.5 feet.

#### **4.4 MODEL UNCERTAINTY AND SENSITIVITY ANALYSIS**

Uncertainty is inevitable when developing numeric models. For this HEC-RAS Pamet River model, points of uncertainty are associated with the observed data collected at the three tidal stations for several reasons. Seasonality of the data was collected, the tidal station datum and measurement errors of the recorded data can all impact model calibration.

From experience and, as reported by NOAA, typical datum errors for tide stations can be as high as 0.2 feet. In addition, measurement errors can be as high as 0.05 to 0.10 feet.

Converting the stage measurements to the NAVD88 datum that was used for the model also introduces some error depending on how well known the NAVD88 datum is at the tide stations.

All of these uncertainties are additive and can explain to some degree the discrepancies between the HEC-RAS model and the observed stages.

In addition to recorded data measurement uncertainties, there are variable and hydraulic model parameter uncertainties. Variable uncertainty is related to how accurately variables in the model were calibrated within the allowable guide specification range. The variable uncertainties are typically larger than the actual model uncertainties that are computed by the HEC-RAS model.

Considering all of these uncertainties and because the discrepancies between computed and observed stages are small, the computed stages in the model are within the expected error. The model is considered to be sufficiently calibrated for the alternatives analysis.

Model sensitivity analysis was performed on a limited basis to verify model instabilities, gate operational parameters, and initial conditions. Model instabilities, when they occurred, were mainly associated with operational parameters of the tide gate at Wilders Dike. Tide Gate parameters were adjusted, which increased model stability without sacrificing accuracy to the extent possible.

In addition, a sensitivity analysis was conducted to best select an initial flow condition for the HEC-RAS model to analyze any associated impacts that increasing or decreasing the initial flow value may have on the calibration results. Initial flow values between 1 cfs to 10 cfs were entered into the model. Thru this sensitivity analysis, an initial flow condition 6 cfs often provided the best results while other simulations determined 6 cfs to be too small as simulation time was needed to sufficiently ramp up the model.

The initial water elevation (stage) at Pamet Harbor was also an initial condition analyzed with a sensitivity analysis. Simulations were computed and analyzed when the tidal signal at Pamet Harbor was at low tide, mid tide and at high tide. Calibration results were adversely affected during both low and high tide simulations as starting a simulation at low tide tended to under-predict observed tides and conversely starting at high tide tended to over-predict observed tides.

Prior HEC-RAS model experience in tidally influenced areas supports mid-tide level initial condition time-step to be the most effective due to the more equilibrium energy forces exerted against competing forces and variable parameters.

The sensitivity analysis conducted for this calibrated HEC-RAS Pamet River model was verified for predictive evaluations of alternatives.

## **5.0 ALTERNATIVE ANALYSIS AND CONCLUSIONS**

The calibrated HEC-RAS model was used to run four separate alternative geometries: 1. the first alternative assumed no action in the future and used the existing conditions geometry, 2. and 3. the second and third alternatives replaced the existing culverts at Wilders Dike and U.S. Route 6 with larger concrete box culverts, and 4. the fourth alternative replaced the existing embankments and culverts at Wilders Dike and U.S. Route 6 with open daylighted channels with bridge overpasses.

Other geometric properties from the calibration analysis, such as, Manning's n values, and ineffective flow areas were unchanged in the alternative runs. The only calibration parameter modified for the alternative analysis was the tide gate operational parameters at Wilders Dike for the one alternative that includes a tide gate within the larger box culvert. This had to be done in order to maintain the numerical stability of the unsteady HEC-RAS model. Using the same gate operation parameters from the calibration analysis introduced some model instabilities with the larger box culvert.

Each alternative was run with a normal tidal signature based on the predicted tides for the period June 10, 2019 to June 17, 2019 (in the future at this writing) and the significant Ballston Beach overtopping event that occurred between March 1 – 3, 2018. These events were selected in order to evaluate the alternatives over a wide range of hydrologic conditions.

As previously mentioned, Pamet River flows during the early March 2018 nor'easter storm event that detached the tide gate from the downstream face of Wilders Dike culvert. The nor'easter peaked late on March 2, 2018 with hurricane-force winds with record storm surges observed along the New England coastline including on Cape Cod. On March 2<sup>nd</sup>, the third highest recorded tide of 9.04 ft. NAVD88 at NOAA's Boston Harbor tidal station since 1921 occurred. The time period simulated in the HEC-RAS model included February 28 – March 13, 2018. It was extended before and after the nor'easter in order to ramp up the model from normal initial conditions to the storm conditions and to allow time after the storm passed to return back to normal conditions and to drain the upper portion of the Pamet River.

The June 2019 time period was selected based upon examining predicted tides at the NOAA secondary station at Provincetown, MA and comparing them against the long-term normal tidal conditions, typically experienced on Cape Cod, MA. The predicted tides showed no extraordinary lunar event in June 2019 that would cause larger than normal tidal ranges so a seven day time period was selected for the alternatives analysis.

Similar to the calibration events, the downstream stage hydrograph at Pamet Harbor was based upon the adjusted observed tides at Boston Harbor (Figures 25-26- Attachment E). At Ballston Beach, a no-flow boundary condition was set for the normal tidal event, and an overwash flow hydrograph was estimated for the March 2018 nor'easter based upon the same methodology used for the January 2017 overwash calibration event (Figure 27-Attachment E).

Initial simulations with the HEC-RAS model were conducted before adding the groundwater boundary conditions. These initial results were coordinated with the MODFLOW model to establish the 30 groundwater interflow boundary conditions to enter back into the HEC-RAS model. At this point, the MODFLOW model iterated back and forth with the HEC-RAS computing stages to enter into the MODFLOW model and then MODFLOW computing groundwater heads to enter into the HEC-RAS until the difference between successive iterations was minimal.

Alternatives were compared using computed hydrographs at the HEC-RAS Pamet 1, 2, and 3 tidal stations cross-sections; at a cross-section midway between the Pamet 3 tidal station and Ballston Beach; and at Ballston Beach itself. The HEC-RAS model computed stages and profile plots that were compared for each of the four alternatives. To evaluate each alternative's simulation time required to drain the upper portion of the Pamet River during the March 2018 nor'easter, the tidal elevation drainage durations were compiled.

### **5.1 ALTERNATIVE 1: NO ACTION**

Alternative 1 included the existing culverts at Wilders Dike and U.S. Route 6. The same tide gate operation parameters developed during the calibration process were also used. This alternative approximates existing conditions but does not attempt to simulate the conditions with the new (lighter and temporary) tide gate installed in August 2018. The only difference in the HEC-RAS model between this alternative and the model used for calibration was changing the boundary conditions to the March 2018 nor'easter and the normal tidal conditions.

### **5.2 ALTERNATIVE 2: ALL CULVERTS, WITH TIDE GATE**

Alternative 2 includes two larger 16 ft. x 4 ft. concrete box culverts replacing both the 3.5 ft. corrugated metal Wilders Dike and 4.0 ft. U.S. Route 6 circular culverts. Larger culverts have increased conveyance through them and allow for faster release of high stages after an overtopping event. The 16 ft. x 4 ft. dimensions were based upon the recommended culvert size determined in the 1998 Pamet River Investigation (USACE-NAE, 1998). The culvert lengths remained unchanged but the invert elevations were modified slightly. Table 7 summarizes the physical properties of the culverts used for alternatives 2 and 3.

A conceptual drawing was prepared that compares the cross-sectional area differences between the existing culverts and the proposed 16 ft. x 4 ft. box culverts as shown in Figure 28 (Attachment E).

As mentioned previously, the tide gate operation parameters had to be adjusted when compared to the parameters used for the calibration analysis in order to maintain model stability. Using the same tide gate parameters resulted in convergence errors for the normal tide boundary conditions causing the HEC-RAS model to stop-in-error before completing the simulation. A sensitivity analysis was performed to see what tide gate operation parameters resulted in a stable HEC-RAS simulation. Table 8 summarizes the final tide gate operation parameters used for Alternative 2.

### **5.3 ALTERNATIVE 3: ALL CULVERTS, NO TIDE GATE**

Alternative 3 is the same as Alternative 2 except that there is no tide gate at Wilders Dike. Without a tide gate, high tides and salt water will not be prevented from passing into the upper Pamet River. Increases in river stages in the upper portion of the Pamet River were observed during the period of time between March and August 2018 when there was no tide gate installed at Wilders Dike.

### **5.4 ALTERNATIVE 4: ALL BRIDGES**

Alternative 4 consisted of removing the existing embankments at Wilders Dike and U.S. Route 6 and replacing them with open span bridges and daylighted channels between them as shown in Figure 29 (Attachment E). Typical cross-sections of the bridge structures and daylighted channels between them are summarized in Table 9 and shown in Figure 30 (Attachment E). This alternative provides additional

conveyance, and, without a tide gate, does not prevent salt water from passing into the upper portion of the Pamet River during high tides and storm events. Significant modification to the HEC-RAS geometry had to be made which included the addition of five new cross-sections between the existing cross-sections at river stations 14639 and 14087, two new bridges for North Pamet Rd. and U.S. Route 6, respectively, and replacement of the inline structure at Wilders Dike with a new bridge as shown in Figure 31 (Attachment E).

**Table 7. Alternatives 2 and 3 Culvert Properties**

| Location     | Culvert Dimension (W x H) (ft.) | Culvert Length (ft.) | Upstream Invert Elev. (ft. NAVD88) | Downstream Invert Elev. (ft. NAVD88) |
|--------------|---------------------------------|----------------------|------------------------------------|--------------------------------------|
| Wilders Dike | 16 x 4                          | 58                   | -1.50                              | -1.25                                |
| U.S. Route 6 | 16 x 4                          | 360                  | -1.85                              | -1.10                                |

**Table 8. HEC-RAS Wilders Dike Gate Operation Parameters for Alternative 2**

| Gate Parameter                                    | Wilders Dike Gate |
|---------------------------------------------------|-------------------|
| Downstream Reference Cross-Section                | 13621             |
| Upstream Reference Cross-Section                  | 13025             |
| Stage Difference When Gates Start to Open (feet)  | 0.0               |
| Stage Difference When Gates Start to Close (feet) | -0.4              |
| Gate Opening Rate (ft. / min)                     | 1                 |
| Gate Closing Rate (ft. / min)                     | 1                 |
| Maximum Gate Opening (feet)                       | 4.0               |
| Minimum Gate Opening (feet)                       | 0.1               |
| Initial Gate Opening (feet)                       | 4.0               |

**Table 9. Geometric Properties of Alternative 4 Bridges & Channels**

| Location               | Length (ft.) | Upstream Invert Elev. (ft. NAVD88) | Downstream Invert Elev. (ft. NAVD88) | Dimension A (ft.) | Dimension B (ft.) | Dimension C (ft.) |
|------------------------|--------------|------------------------------------|--------------------------------------|-------------------|-------------------|-------------------|
| Wilders Dike Bridge    | 58           | -1.50                              | -1.25                                | 42                | 2                 | 4                 |
| Daylighted Channel 1   | 35           | -1.85                              | -1.80                                |                   |                   |                   |
| U.S. Route 6 Bridge    | 58           | -1.80                              | -1.65                                | 78                | 4                 | 16                |
| Daylighted Channel 2   | 180          | -1.65                              | -1.35                                |                   |                   |                   |
| North Pamet Rd. Bridge | 95           | -1.35                              | -1.10                                | 42                | 2                 | 4                 |

## 5.5 SUMMARY OF FINDINGS

Figures 32-41 (Attachment E) compare computed river hydrographs at five cross-section locations (Pamet 1, 2, 3, between Pamet 3 and Ballston Beach, and at Ballston Beach) for the March 2018 storm and normal tidal boundary conditions. Figures 42-43 (Attachment E) compare profile plots of the maximum stage for each of the alternatives.

Even though the gate operation parameters are slightly different for Alternative 1 compared to the gate operation parameters for Alternative 2, and that computed stages upstream of the tidal gate at Wilders Dike are sensitive to gate operations, some general trends can be seen in the figures when comparing Alternative 2 against Alternative 1.

The computed maximum stages upstream of U.S. Route 6 are essentially equal to each other for Alternatives 1, 3, and 4 as shown in Figure 42 (Attachment E); however as shown in the hydrographs even though the peak stages may not change significantly; replacing the existing culverts with the larger culverts or bridges reduced stages during the March 2018 storm event as shown in Figures 34-36 (Attachment E). Also, in Figures 34-36 (Attachment E), at Pamet 3 and upstream, Alternatives 3 and 4 start with higher stages than Alternatives 1 and 2 because of the lack of a tide gate in those alternatives. By not having a tide gate installed, it can be expected that under normal conditions the stages would be higher upstream of Pamet 1 than if a tide gate was installed. In these simulations, the increase in stages was approximately 1 to 1.5 feet. This increase was also verified with observed stage data collected at Pamet 2 and Pamet 3 between March 2018 and August 2018 when there was no tide gate at Wilders Dike due to it being detached from the Wilder's Dike culvert during the March 2018 storm. Observed data collected during that time also showed an increase in stages by 1 to 1.5 feet.

At Pamet 2, the larger culverts with no tide gate and the bridges only alternatives (Alternatives 3 and 4) slightly increased the maximum stages at high tide compared to the existing conditions alternative (Alternative 1) as shown in Figure 42 (Attachment E) but increased stages at low tides by a greater magnitude during the peak of the March 2018 storm as shown in Figure 33 (Attachment E). These two alternatives do not reduce stages between Wilders Dike and U.S. Route 6 any better than the existing conditions. Increased conveyance between the larger culverts and bridges means that elevated stages can drain quicker from the upper Pamet River but it also means that it can "fill" quicker too. The larger conveyance is both positive and negative in that sense.

For the normal tidal condition boundary conditions, the larger culverts with the tide gate alternative (Alternative 2) increased the tidal amplitude at Pamet 3 and upstream when compared against the tidal gate operations used for the calibration analysis (Alternative 1) as shown in Figures 39-41 (Attachment E). The most likely reason for this is due to the slight change in gate operation parameters. Some of the general trends in comparing the alternatives under the normal tidal conditions can still be ascertained. It can be represented in the profile plot in Figure 43 (Attachment E) that the maximum stages for both the larger culvert with no tide gate alternative (Alternative 3) and the bridges only alternative (Alternative 4) are larger on average by as much as a foot when compared against the other two alternatives. This is to be expected since there is nothing to prevent the tidal signal from propagating further upstream in Alternatives 3 and 4 compared to the tidal gate that exists in Alternatives 1 and 2.

As was seen for the storm boundary conditions, the increased conveyance between the larger culverts and bridges only alternatives (Alternatives 3 and 4) means that elevated stages can drain quicker from the upper Pamet River but it also means that it can "fill" quicker with no tide gate installed. It is clear from analyzing the results that a tidal gate is effective at reducing stages in the upper fresh water portion of the Pamet River.

For each alternative, the simulation time required to drain the upper Pamet River during the March 2018 nor'easter simulation, computed several tidal elevation thresholds compiled from the stage hydrographs at Pamet 3 and Ballston Beach. Tables 10 and 11 summarize these durations.

As presented in Tables 10 and 11, each alternative reduces the time needed to return the upper Pamet River at Pamet 3 and Ballston Beach to pre-storm conditions.

For example, the +3.0 ft. NAVD88 threshold at Ballston Beach, computed 8.35 days required to drain the March 2018 overwash under existing conditions while only 5.88 days would be required to drain the March 2018 overwash with the larger culverts and tide gate alternative (Alternative 2). That is a time reduction of 2.5 days and a clear benefit of the alternative.

Other alternatives less significantly reduced the time needed to drain the March 2018 overwash. The differences between Alternatives 3 and 4 in reducing durations of elevated stages in the upper Pamet River were negligible compared against each other and only reduced durations slightly when compared against Alternative 1.

Alternative 2 produced the largest reduction in time for the scenarios computed for this analysis at Pamet 3 and Ballston Beach compared to Alternative 1.

**Table 10. Time Needed to Drain Water Levels from March 2018 Storm at Pamet 3**

| Threshold<br>(ft. NAVD88) | Alt. #1<br>(Days) | Alt. #2<br>(Days) | Alt. #3<br>(Days) | Alt. #4<br>(Days) | Largest Reduction<br>in Time (Days) <sup>2</sup> | By Which<br>Alternative |
|---------------------------|-------------------|-------------------|-------------------|-------------------|--------------------------------------------------|-------------------------|
| Below +3.0                | 8.1               | 4.64              | 8.38              | 7.4               | 3.46                                             | Alt. #2                 |
| Below +4.0                | 5.95              | 1.75              | 5.89              | 5.95              | 4.2                                              | Alt. #2                 |
| Below +5.0                | 3.31              | 1.61              | 2.18              | 2.66              | 1.7                                              | Alt. #2                 |
| Below +6.0                | 1.34              | N/A <sup>1</sup>  | 0.73              | 0.69              | 0.65                                             | Alt. #4                 |

<sup>1</sup>N/A – Stages didn't exceed +6.0 ft. NAVD88 during simulation for Alternative 2.

<sup>2</sup>Time reductions compared to Alternative 1 (No Action – Existing Conditions).

**Table 11. Time Needed to Drain Water Levels from March 2018 Storm at Ballston Beach**

| Threshold<br>(ft. NAVD88) | Alt. #1<br>(Days) | Alt. #2<br>(Days) | Alt. #3<br>(Days) | Alt. #4<br>(Days) | Largest Reduction<br>in Time (Days) <sup>1</sup> | By Which<br>Alternative |
|---------------------------|-------------------|-------------------|-------------------|-------------------|--------------------------------------------------|-------------------------|
| Below +3.0                | 8.35              | 5.88              | 7.87              | 7.92              | 2.47                                             | Alt. #2                 |
| Below +4.0                | 6.36              | 3.13              | 5.96              | 6.03              | 3.23                                             | Alt. #2                 |
| Below +5.0                | 3.86              | 2.1               | 2.28              | 2.26              | 1.76                                             | Alt. #2                 |
| Below +6.0                | 1.85              | 0.6               | 1.17              | 1.12              | 1.25                                             | Alt. #2                 |

<sup>1</sup>Time reductions compared to Alternative 1 (No Action – Existing Conditions).

## 6.0 MODEL LIMITATIONS

The HEC-RAS model, like all models, is limited based on the assumptions and uncertainties inherent in the data, calibration and alternatives. Limitations in the model include the following:

- All three deployed tidal stations were clustered close to one another. Tidal stations located further downstream or upstream on the Pamet River closer to Pamet Harbor or Ballston Beach, respectively, were not deployed due to associated costs versus data gained for the purposes of this study. Model calibration was not conducted downstream of the Pamet 1 or upstream of the Pamet 3 tide stations; *however, this is not believed to have compromised the model for the purposes of the alternatives evaluated and recommendations concluded in this study.*
- The quality of the data collected at Pamet 1, 2, and 3 tidal stations appeared to be suspect for portions of their deployed time. This limited the number of storm events available for calibration. Ideally, calibration events should span across weather seasons so that a wider range of antecedent weather and flow conditions could be examined *to improve confidence in the most critical events, specifically for this study, overtopping.* All three events used in the calibration analysis spanned just four months.
- Assumptions were made for channel bottom geometry along the majority of the Pamet River's centerline length due to lack of available survey data of the channel. Only a few channel locations were surveyed and interpolations of bottom geometry had to be made elsewhere.
- Overwash flow hydrographs were estimated indirectly using wave runup and storm surge data that was collected offshore in the Atlantic Ocean. A deployed gage at Ballston Beach would have provided a better estimate of the overwash flow volume that occurred during calibration events when the dunes at Ballston Beach were breached. *However, the dynamic geometry of the dunes, sea level and surge will produce uncertainty in modeling overwash events.*
- Topography used to calculate overwash hydrographs at Ballston Beach derived from cross-sections cut from LiDAR data and did not match actual pre- and post- storm beach profiles for the January 2017 calibration event nor the March 2018 storm used for the alternatives analysis. Beach profile surveys of the dunes and berms at Ballston Beach around the time of those two storms would have led to a more accurate estimate of wave runup and overtopping.
- The alternatives were compared to a single overtop event simulation of the March 2018 Nor'easter. If these events become more frequent in the future, their impact could compound. The impact of multiple or frequent overtop events was not investigated by this modeling project.
- The previous (broken) tide gate at Wilders Dike was used for calibration and the alternative analysis. This tide gate was replaced with a lighter gate in August 2018; thus different operating characteristics and parameters than the old gate did. Since the previous (broken) tide gate was modeled, impacts the new gate have on the computed stages and drainage times can't be quantified if a storm similar to the March 2018 nor'easter were to happen today.



- Frequency-based storm events were not evaluated as part of this analysis such as the 10-, 20-, 50-, and 100-year events. If these large flow events are to be evaluated, the HEC-RAS model geometry should be updated accordingly. Extending cross-sections in the floodplain, adding lateral structures and storage areas could be necessary. Simulating large frequency-based events using the existing model geometry would not be appropriate.
- For these reasons and others, the U.S. Army Corps of Engineers accepts no responsibility for the model results due to any changes made to the model files, or for the application of the results to other projects. It is the responsibility of the user to interpret and explain the consequences of any model application other than its intended purpose or revisions to the model files.

## **7.0 REFERENCES**

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# **Chapter 8**

**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**UPPER PAMET RIVER**

**ECOSYSTEM SURVEY, ASSESSMENT AND DETERMINATION**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

## CHAPTER 8

### ECOSYSTEM SURVEY ASSESSMENT

#### 1.0 PAMET RIVER CORRIDOR ECOSYSTEM ANALYSIS: PRE-ROUTE 6 TO PRESENT

As part of the Pamet River study, the USACE study team was tasked with determining the feasibility of conducting future work in the Pamet River watershed in the form of an aquatic ecosystem restoration study and subsequent project. This analysis investigated the four project alternatives presented in Chapter 1 and their capacity to restore tidal flushing.

An aquatic ecosystem restoration project could potentially be eligible for implementation under Section 206 of the USACE's Continuing Authorities Program. However, a Section 206 aquatic restoration study would only warrant further investigation if the USACE could prove: 1) tidal marsh habitat was lost (e.g., converted to inland/palustrine wetland habitat) as a result of the US Route 6 embankment/culvert restriction, and 2) demonstrate that a proposed project alternative is capable of increasing tidal flushing and salinity levels within the watershed to eradicate the areas of dense *Phragmites australis* (common reed) stands, and revert non-native marsh habitat back to native (e.g, *Spartina spp.*) tidal marsh.

To assess changes to the Pamet River corridor wetland complex over time, the USACE study team conducted an inventory of wetland system cover over the course of an 80-year time period. Specifically, the Cowardin et al (1979) wetland classification system was used to delineate wetland units. The USACE study team sought the earliest aerial photographs available (e.g., 1938) to pre-date the installation of the US Route 6 roadbed and box culvert, and then conducted a post-Route 6 survey in 1971 (approximately 40 years later) and compared it to present-day conditions. The construction of Route 6 through Truro Center in the early 1950s is significant since it is thought to have served as a major hydraulic chokepoint along the Pamet River corridor, thereby limiting tidal exchange to the upper reaches of the watershed.

Utilizing USGS EarthExplorer (an online resource) the team was able to locate 1938 and 1971 aerial imagery that had a flight line covering the 215-ac area of interest. This area spans the bulk of the Pamet River corridor commencing at Ballston Beach, and terminating in the expansive tidal marsh one mile east of Pamet Harbor. Aside from the pre/post Route 6 installation, this sequence of photos was also used in the analysis since they were taken during conditions of low cloud cover, were available in high-resolution, and shared the same scale of 1:24,000. From this imagery, the team made inferences in regards to changes in the amount of tidal wetland habitat loss (i.e., conversion or filling), and documented the spread of invasive reed, *Phragmites australis*, a resilient and aggressive plant known to dominate both freshwater and disturbed tidal marsh ecosystems, particularly when salinity levels do not exceed 15-20 parts per thousand.

The Pamet River, including its immediate floodplain, is confined to a narrow valley ranging from 35 to 2,000 feet wide and approximately 3-miles long. The freshwater river flows in a westerly

direction beginning at Ballston Beach on the Atlantic Ocean side and eventually forming a confluence with Pamet Harbor and then into the larger Cape Cod Bay beyond the harbor's entrance channel. The river valley is comprised of glacial-fluvial stratified sands and gravels overlain by thick muck and peat deposits that have accumulated on the wetland's surface over the course of millennia (NRCS WSS 2019).

In its present-day state, the Pamet River corridor is comprised of a mixture of palustrine, riverine, and estuarine wetland systems, which help to create a diversity of contiguous wetland habitats in the watershed. Starting from the ocean side at Ballston Beach, the corridor is comprised of broad-leaved deciduous tree and shrub wetlands, and emergent marsh communities dominated either by cattails (*typha spp.*) or *Phragmites*. Moving west towards the bay, and between US Route 6 and Truro Center Road, both forested and shrub palustrine wetlands (e.g., swamp) remain; however, due to mixing from tidal waters and salinity conditions falling in the oligohaline class (e.g., 0.5-5 parts per thousand) salt marsh habitat was observed in this mixing zone between the Route 6 impoundment and Wilders Dike/Truro Center Road. Heading west of Wilders Dike and its approx. 48 inch flapgate culvert, the Pamet is directed through what appears to be a ditched/channelized 350-linear foot segment where it is surrounded by uplands on either side with dense stands of *Phragmites* flanking both its north/south banks. From this point, heading towards the bay, the Pamet's channel remains clearly defined but the immediately adjacent wetland habitat opens to native tidal marsh dominated by typical New England species, such as saltmeadow cordgrass (*Spartina patens*) and saltmarsh cordgrass (*Sporobolus alterniflorus*). The channel becomes less clearly defined as it empties into Pamet Harbor at the town pier.

The Pamet River was hydrologically altered by two significant historical events that were anthropogenic in origin: 1) the construction of Wilders Dike in the late 1800s and its approximate 4' wide by 50' long opening, and 2) the construction of the US Route 6 roadbed through the middle of the river and its surrounding floodplain (4' W by 360' L culvert). The analysis presented below seeks to assess how the wetland complex in the Pamet River corridor has changed over time with respect to the installation of US Route 6 and the introduction of *Phragmites* in the 1970s-80s timeframe.

The USACE study team analyzed wetland system changes, or changes in wetland vegetation cover and hydrology, by visually assessing the 1938, 1971, and 2015 aerial imagery. The aerial imagery covered an 80-year span in approximately 40-year increments. The 1938 imagery was obtained since it is the oldest flightline available for the upper Cape peninsula, and it pre-dated both the installation of US Route 6 and the spread of *Phragmites*. (Note, assessment of the Pamet's wetland complex in the 1800s and pre-dating the installation of Wilders Dike is not possible due to the lack of photographic technologies that would not become available until the 1930s.) The 1971 imagery encompassed the area of interest approximately 10-15 years after the US Route 6 installation, thus allowing the site to recover and establish a new equilibrium. The 1938 and 1971 imagery were georeferenced to the 2015 orthophotography available for Massachusetts. A geographic information system (GIS) was used to process and analyze geospatial data for this analysis (ESRI v10.5.1). The 2015 orthophotography is a panchromatic

Worldview Satellite Imagery that was orthorectified by MassGIS and made available online along with other vector data sets used in support of this analysis (MassGIS 2019). Once the historic aeriels were georeferenced, wetland units were classified according to the Cowardin et al. (1979) classification system. A brief description of the classification categories developed for this analysis can be seen in table 1. The various wetland units were heads-up digitized using GIS and mapped at a scale of 1:2,000 with a minimum map unit of 0.10 acre throughout the 215-ac area of interest. Finally, we made qualitative comparisons of changes in wetland cover classes amongst survey years (see table 1).

The results of the aerial photography analysis can be found in figures 1 through 3 and are summarized in table 1. One immediate observation was the small amount of change the river channel's geometry has undergone over the past 80 years. This could potentially be attributed to the low gradient/low energy environment of the Pamet River as the freshwater flows from east to west and eventually backs up against the incoming tide. Thus, features such as bends and oxbows, as currently observed, have remained relatively constant over the past 80+ years.

Native palustrine habitat (grouped as emergent, scrub-shrub, and forested wetlands) showed a loss in cover type among survey years. From 1938 through 1971, there was an approximate 4% decrease, and from 1971-2015 there was another 10% decrease (table 1). The initial loss of palustrine habitat can be attributed to the 1.5(+/-) acres of fill placed at the Truro Center shopping plaza, and another 5 acres for the construction of US Route 6 roadway embankment. The second round of impacts could be explained by the spread of *Phragmites*, 8 acres, and 6 acres of beach overwash, which resulted in a thick deposition of sand behind the barrier beach and into the Pamet's headwaters (table 1).

Native estuarine tidal marsh cover did not change appreciably between 1938 and 1971, aside from the aforementioned 1.5 acres of fill by the downtown business plaza (table 1). However, between 1971 and 2015 there was a notable 28% decrease in tidal marsh habitat (table 1). This loss can be attributed to the spread of *Phragmites*, which resulted in 6 acres of dense monocultures in various regions throughout the Pamet River corridor (more details below). Although the spread of *Phragmites* into both palustrine and estuarine areas were counted as habitat loss, there was a gain of 0.5 ac of tidal marsh in the area between Wilders Dike and the Route 6 embankment. This observation was based on field observations where a salinity level of 7 parts per thousand was recorded on an incoming tide and salt-tolerant species, such as narrowleaf cattail (*typha angustifolia*) and marsh elder (*Iva frutescens*), were commonly observed. Although speculative, it is believed that the restriction caused by the Route 6 culvert backs up the incoming seawater where it lingers in the system for a longer period of time. Dense stands of *Phragmites* also border this location, which is indicative of a low-salinity condition that is not capable of killing the plant (generally, 20 parts per thousand will stress and eradicate *Phragmites* in New England tidal marshes).

The dense stands of *Phragmites* that occur throughout the Pamet River corridor are primarily confined to the backside of Ballston Beach on the ocean side, and within the wetlands surrounding both sides of Wilders Dike on the bayside (Figure 1 [2015]). Between 1938-1971, no

*Phragmites* was observed in the Pamet River corridor. These findings are consistent with those of Saltonstall 2002, who performed an extensive genetics study on *Phragmites* in New England and found that non-native *Phragmites* did not begin to colonize New England tidal marshes until sometime after 1960. In support of these findings, USACE biologists with extensive field experience performing salt marsh restoration work throughout the New England region have similar observations that *Phragmites* did not begin to colonize New England tidal marshes until the 1960s-70s timeframe. Since the upper Cape peninsula is far removed from interior sections of New England, it is possible that the plant took longer to colonize the Pamet River corridor, which would help explain its absence in the 1971 photo interpretation.

Assessing *Phragmites* cover between 1971-present, there was a 7% increase over the 215 acre Pamet River corridor. As mentioned in other sections of this report, in 2018 one of the several early spring nor'easters that pummeled the New England coastline destroyed the 48" flapper gate at Wilders Dike thereby increasing tidal conveyance through the dike. Field observations made by USACE team members did not indicate areas where *Phragmites* was stressed or dying back as a result of increased tidal exchange. Salinity measurements taken in the field following the destruction of the tide gate confirmed low salinity levels upstream of Wilder's Dike.

Figure 4 displays the areas where major shifts in wetland cover class has occurred over the 80-year assessment period (see areas shaded in red). The Corps team attributes the major changes in wetland habitat or classification cover to the following: 1) an increase in both the intensity and frequency of coastal storms expanding the Ballston Beach overwash area (6.0 acres), 2) the introduction and spread of invasive *Phragmites* in the 1970s-80s timeframe (14.4 acres), 3) increase of tidal marsh habitat between Wilders Dike and US Route 6 (0.6 ac) due to the box culvert constriction, and wetland fill (e.g., conversion to upland: 6.7 ac) caused by the construction of Route 6 and development of the Truro Center shopping plaza.

| Habitat                                                        | 1938  | 1971  | change | 1971  | 2015 | change |
|----------------------------------------------------------------|-------|-------|--------|-------|------|--------|
| Uplands, wetland fill, beach overwash, other                   | 3.8   | 11    | 7.2    | 11    | 16.4 | 5.4    |
| River channel, ponds, salt pannes, tidal creeks                | 18    | 19    | 1      | 19    | 20.8 | 1.8    |
| Inland, freshwater (palustrine) wetland systems                | 166.4 | 160.7 | -5.7   | 160.7 | 144  | -16.7  |
| Tidal water (estuarine) wetland systems: native high/low marsh | 26    | 24.8  | -1.2   | 24.8  | 19.4 | -5.4   |
| <i>Phragmites</i> -dominated marsh (tidal & non-tidal)         | 0     | 0     | 0      | 0     | 14.4 | 14.4   |

**Table 1.** Change in wetland vegetative community cover class over time (units = acres).

### 1.1 Assumptions and Data Discrepancies

There are slight discrepancies in the data presented in table 1 that are inherent in this type of photo-interpretation analysis. For instance, orthophotography can have errors resulting from airplane tilt when photos are taken, whereas the georeferenced photos can have alignment errors from the georeferencing process where an RMS value of 0.0 ("perfect" fit) is not humanly possible to achieve.

The slight discrepancies in open water features, such as salt pannes, tidal creeks, or other ponded areas can be attributed to differences in tidal conditions amongst the survey years. Also, climatic conditions such as seasonal rainfall patterns would influence ponding on the marsh surface and swelling channels. There is a slight trend in these data showing approximately a 2.8-acre increase in open water, but we do not suspect this reflects a change of conditions on the ground surface. Also, in the field, stands of *Phragmites* were observed in narrow/dense bands. These features are not possible to map using most available orthophotography and at a scale as large as 1:2,000. Thus, it should be assumed *Phragmites* is slightly underestimated in this analysis.

## **2.0 ECOSYSTEM ASSESSMENT CONCLUSIONS**

The theory that tidal marsh habitat was lost, or converted to palustrine wetlands post-Route 6 establishment, cannot be confirmed based upon close examination of historic aerial photography. Based on available data, it appears that the Pamet River corridor contained a large span of palustrine habitat prior to the construction of US Route 6. Development of Palustrine habitat in the upper Pamet was likely influenced by the construction of Wilder's Dike in the late 1800s.

Considering the feasibility of performing a large-scale habitat restoration project (e.g., converting inland wetlands to tidal and/or eradicating *Phragmites* stands beyond Route 6) using one of the proposed alternatives, Alternative #4 (e.g., replacement of existing culverts with bridge spans at Wilders Dike, Route 6 and North Pamet Road and a day-lighted open channel between them.) would be the best model. Alternative #4 provides the greatest potential increase in restoring natural tidal conveyance within the watershed.

Based on the tidal prism of Pamet Harbor, the location of the salt wedge in the channel before Wilders Dike, and amount of freshwater in the Pamet River system, it is not believed that the salt wedge would be pushed far enough upstream to convert existing inland wetlands to tidal marsh. Also, achieving the target salinity of 20 parts per thousand to eradicate *Phragmites* beyond Route 6 does not seem practicable based on salinity data collected in the field. In support of these findings, the March 2018 nor'easter that removed the Wilders Dike flapgate allowed for nearly unrestricted flow in the marsh for six months, or through late summer. During this time period, salinity levels were not high enough to stress existing communities of *Phragmites* as observed by the USACE field team.

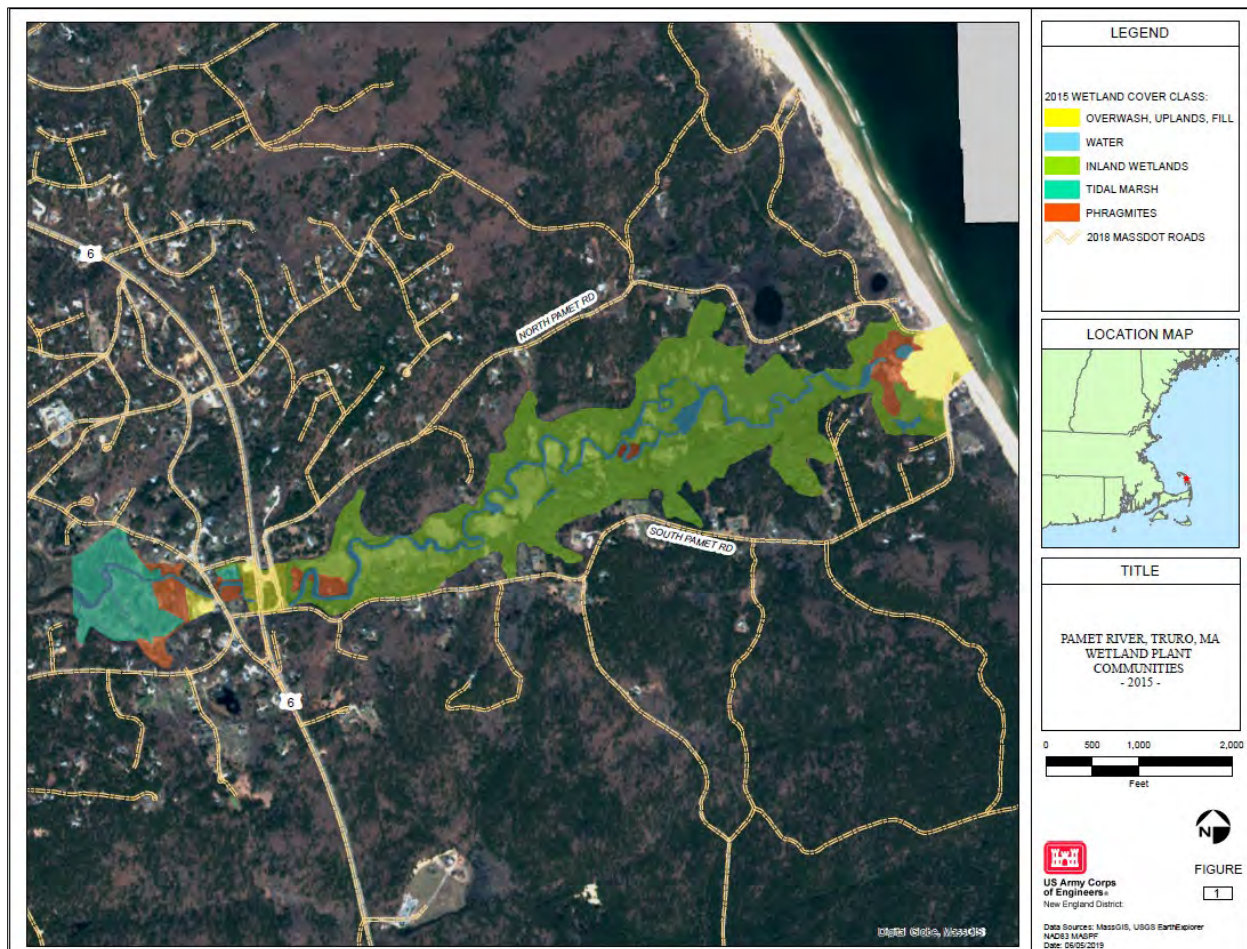
### 3.0 ASSOCIATED FIGURES & MAPS

3.1 Figure 1: Present-day: 2015

3.2 Figure 2: Route 6, post-construction: 1971

3.3 Figure 3: Pre-Route 6: 1938

3.4 Figure 4: Change



**Figure 1** - Present-day (2015) marsh conditions



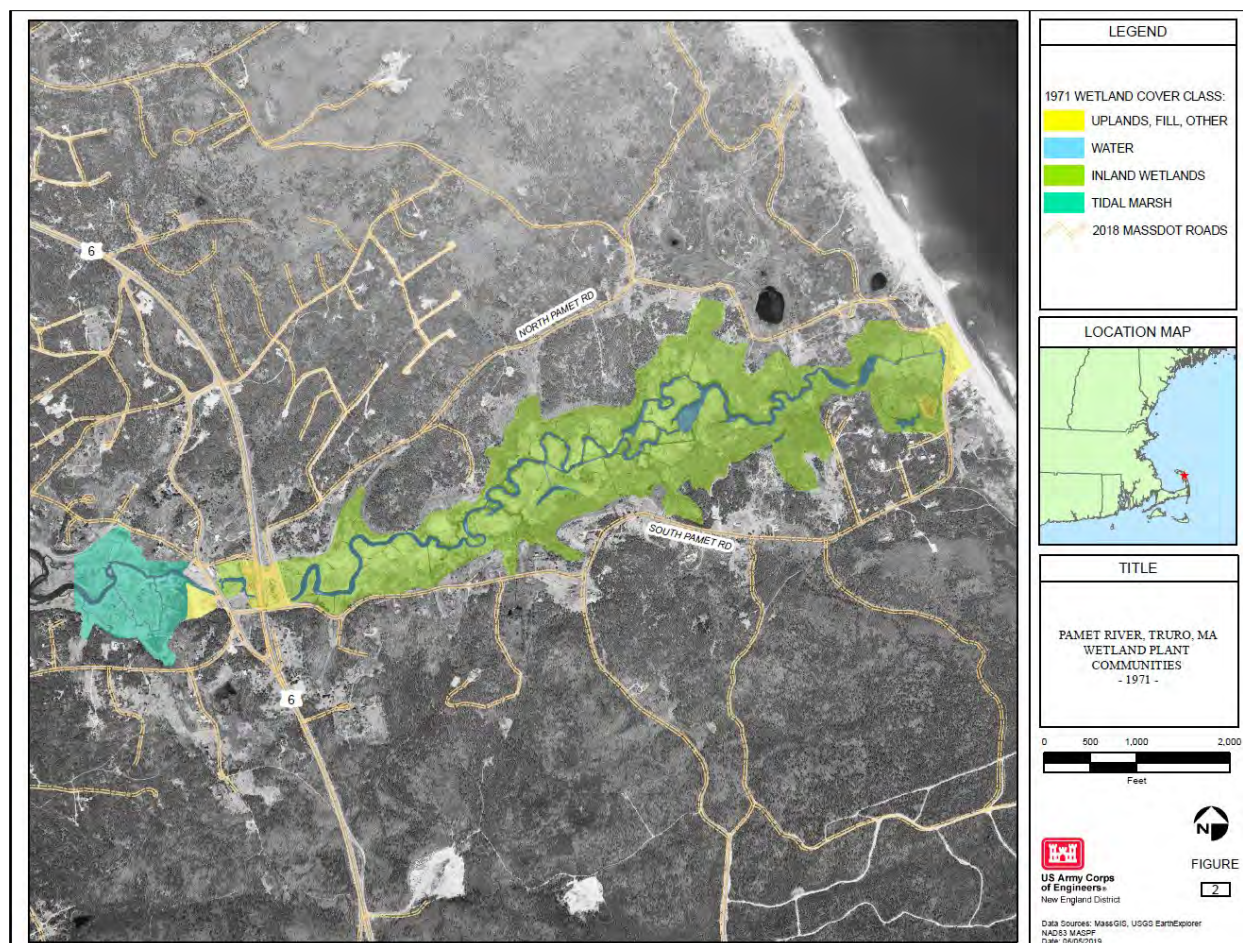


Figure 2 - 1971 (post Route 6) conditions

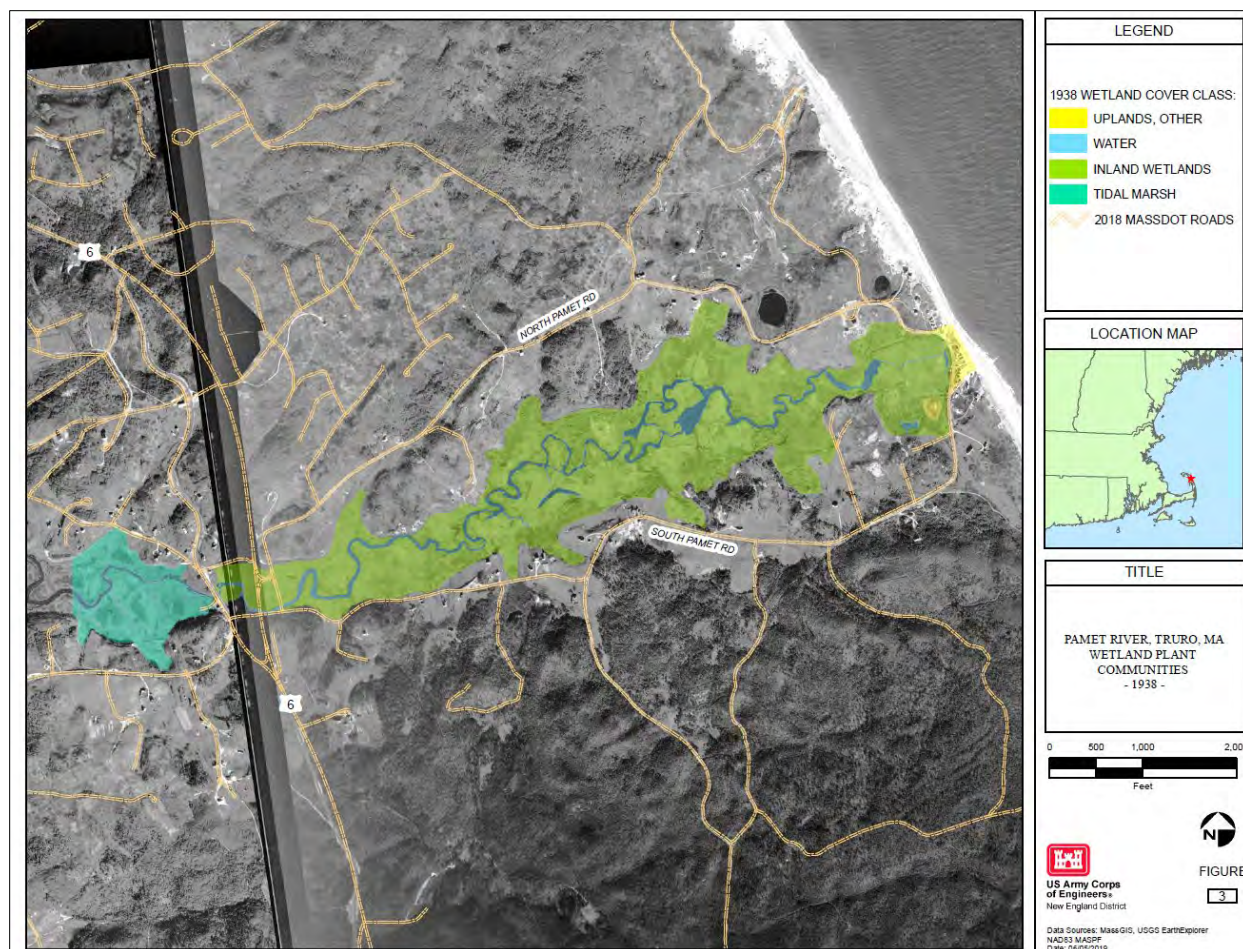
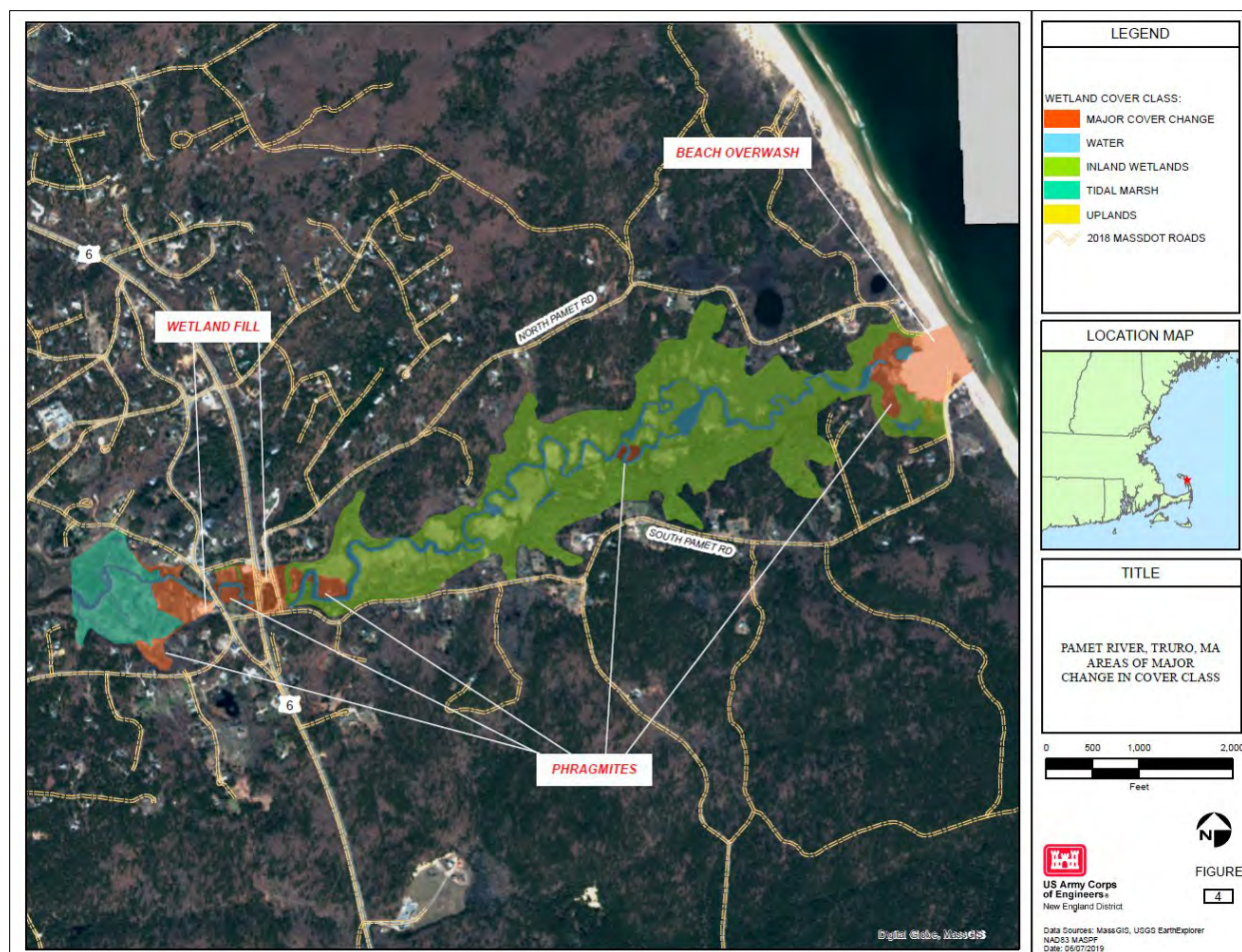


Figure 3 - 1938 (pre-Route 6) conditions





**Figure 4** – Areas where major changes have been detected in wetland cover class: *Phragmites* dominance, wetland fill, Ballston Beach overwash, and inland marsh to tidal (between Rte 6 and Truro Center Rd).

## 4.0 REFERENCES

Cowardin L.M., Carter V., Golet F.C. and LaRoe E.T. 1979. Classification of Wetlands and Deepwater Habitats of the United States. FWS/OBS-79/31. United States Fish and Wildlife Service, Washington, DC, USA.

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Saltonstall, K. Cryptic invasion by a non-native genotype of the common reed, *Phragmites australis*, into North America. 2002. Proceedings of the National Academy of Sciences 99(4):2445-2449.

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**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT A**

**CULVERT MODIFICATION ALTERNATIVE**

**DESIGN PLANS**

**FIGURES A-102 to A-105**

**REFERENCED FROM: CHAPTER 1**

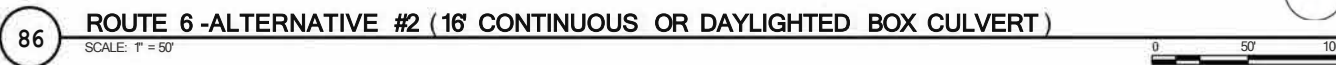
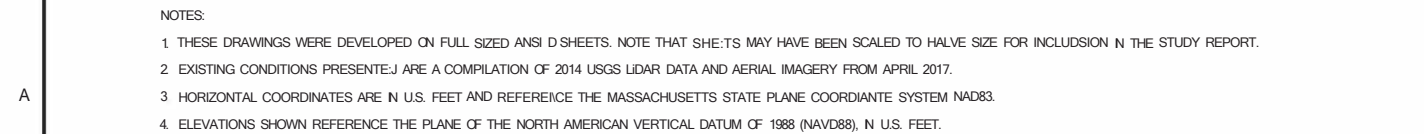
**ANALYSIS OF CULVERT MODIFICATION ALTERNATIVES AT  
WILDER'S DIKE AND ROUTE-6**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**



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NEW ENGLAND DISTRICT  
696 VIRGINIA ROAD  
CONCORD, MA 01742-2751

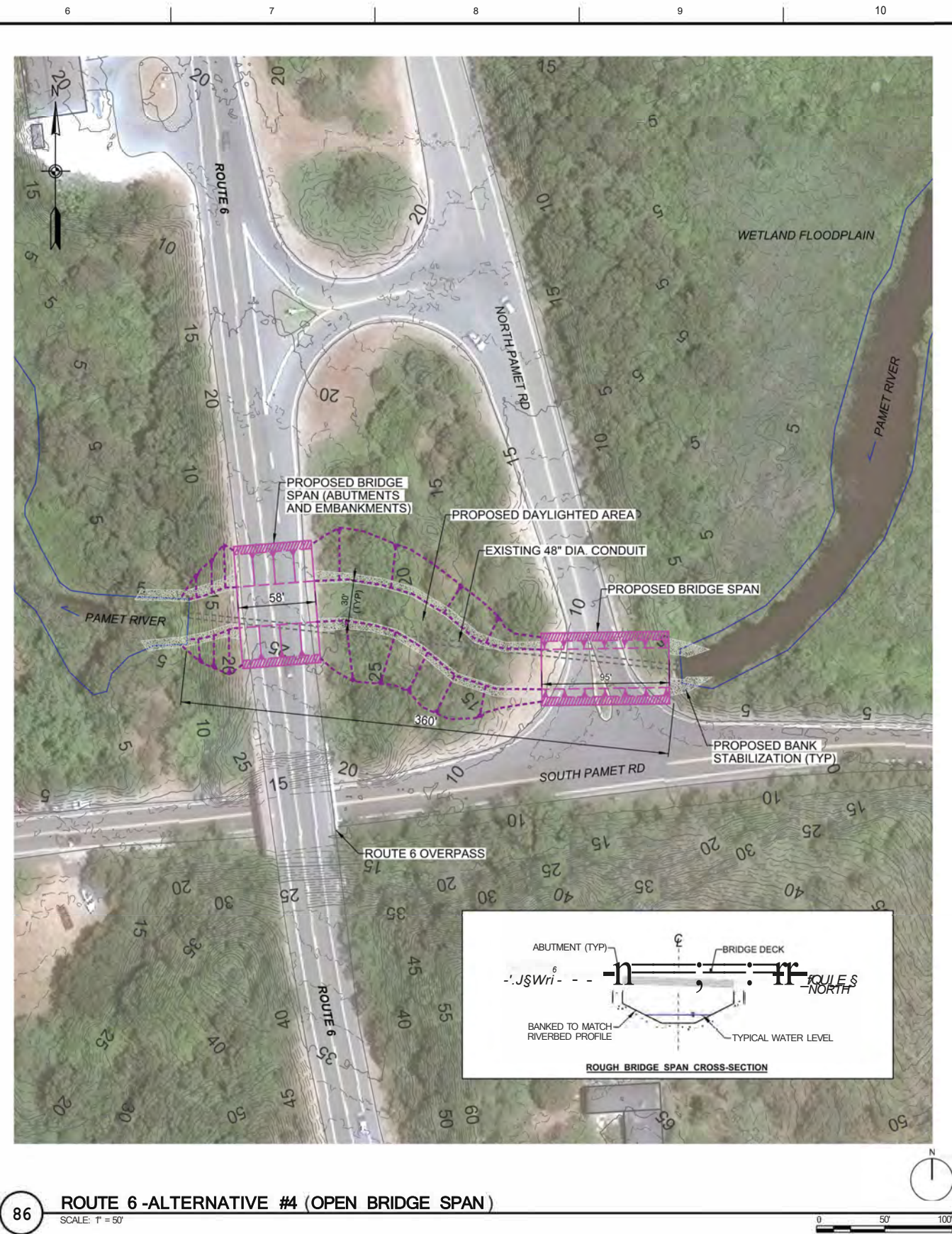
ECOSYSTEM RESTORATION PROJECT  
PAMET RIVER  
TRURO, MASSACHUSETTS

SHEET ID  
**A-102**









US Army Corps of Engineers

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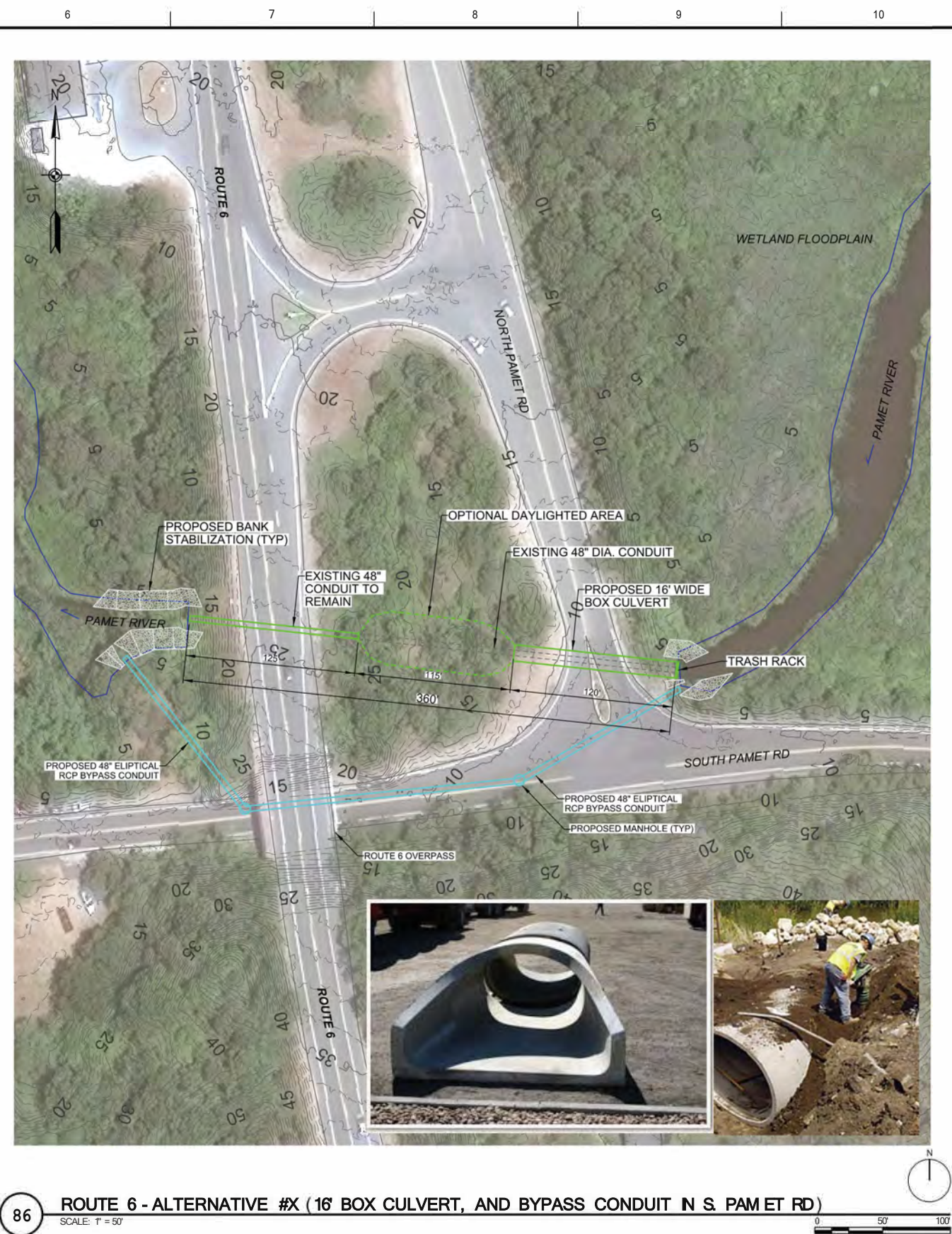
ECOSYSTEM RESTORATION PROJECT  
PAMET RIVER  
TRURO, MASSACHUSETTS

CONFEYANCE ALTERNATIVE

SHEET ID

**A-104**





SHEET ID  
**A-105**



**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT B: FIELD DATA FIGURES**

**TIDAL MONITORING STATIONS (Fig. B-1 to B-4)**

**SALINITY GRAB SAMPLE STATIONS (Fig. B-5 to B-6)**

**WELL INSTRUMENTATION STATIONS (Fig. B-7 to B-18)**

**REFERENCED FROM: CHAPTER 5**

**(2016-18 PAMET RIVER FIELD DATA INSTRUMENTATION, COLLECTION,  
VALIDATION AND *QUALITATIVE ANALYSIS*)**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT B: FIELD DATA FIGURES**  
**TIDAL MONITORING STATIONS**  
**FIGURES B-1 to B-4**

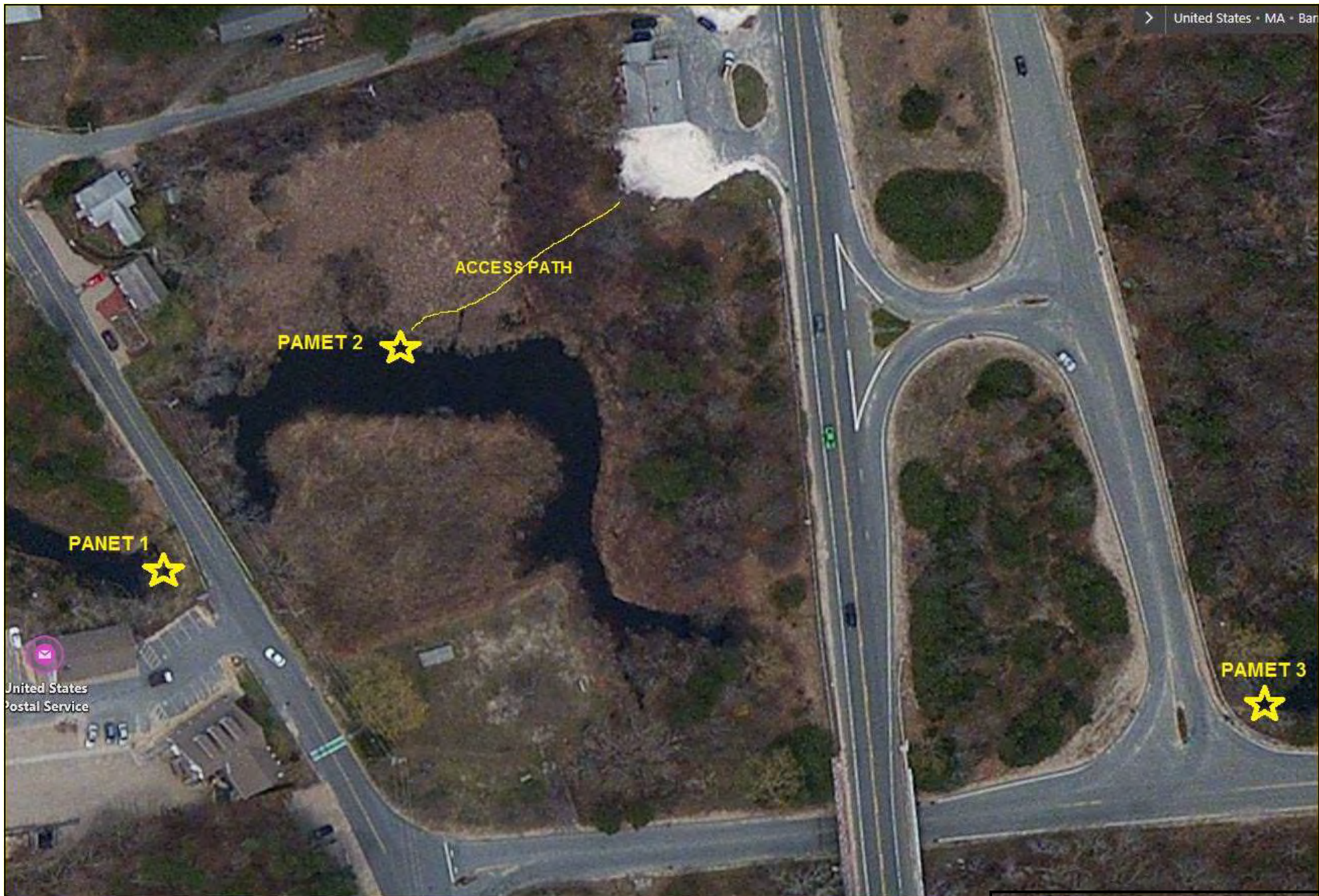
**REFERENCED FROM: CHAPTER 5**

**(2016-18 PAMET RIVER FIELD DATA INSTRUMENTATION, COLLECTION,  
VALIDATION AND QUALITATIVE ANALYSIS)**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**



Tide Gage Locations

Figure B-1





Pamet 1 Tide Gage (Photo December 2016)

Figure B-2





Pamet 2 Tide Gage (Photo December 2016)

Figure B-3





Pamet 3 Tide Gage (Photo December 2016)

Figure B-4



**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT B**

**SALINITY MONITORING STATIONS**

**AND**

**LABORATORY DATA**

**FIGURES B-5 to B-6**

**REFERENCED FROM: CHAPTER 5**

**(2016-18 PAMET RIVER FIELD DATA INSTRUMENTATION, COLLECTION,  
VALIDATION AND *QUALITATIVE ANALYSIS*)**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**



# Pamet River

Sample Locations Sep-26-2018

## Legend

- 3Harbors Realty
- A Will O' the Wisp
- Blackfish
- Clearing @ 65+00
- Clearing along Toe
- Clearing by Power Company
- First
- Krueger Associates Architects
- Pamet
- Pamet Valley Package Inc
- Truro
- Truro
- Truro Historical Society
- US Post Office
- truro town hall

Pamet 3 - Monitoring Station & Sample Location

Pamet 2 - Monitoring Station & Sample Location

Pamet1 - Monitoring Station & Sample Location

Pamet Downstream 1 (Sample Location)

Pamet Downstream 2. (Sample Location)

Google earth

© 2018 Google

FIGURE B-5: SALINITY STATION  
LOCATION MAP

500 ft







# Barnstable County Health Laboratory

## ANALYTICAL REPORT FOR US Army Corp Engineers

### Report Prepared for:

US Army Corp Engineers  
Christopher Kilbridge  
696 Virginia Road  
Concord, MA 01742-2751

Order #: G18110371  
No. of Samples: 5  
Date Received: 9/26/2018

SALINITY LAB DATA REPORT  
FIGURE B-6 Page 1 of 8



# CERTIFICATE OF ANALYSIS

## Barnstable County Health Laboratory (M-MA009)

**Recipient:** Christopher Kilbridge  
US Army Corp Engineers  
696 Virginia Road  
Concord, MA 01742-2751

**Order No.:** G18110371  
**Report Dated:** 10/17/2018  
**Submitter:** Christopher Kilbridge  
**Description:** Lab Analysis

### Laborator ID# 18110371-01

**Sample#:**  
**Collection Address:** PAMET 1  
**Sample Location:**

**Matrix:** Water - Surface Water  
**Sampled:** 09/26/2018 13:30 **By:** Chris Scabia  
**Received:** 09/26/2018 16:29 **By:** PalmerP  
**Turn Around:** Standard

#### Test Parameters

| ITEM                   | RESULT | UNITS    | RL  | MCL | METHOD#   | ANALYST | TESTED     | TIME  |
|------------------------|--------|----------|-----|-----|-----------|---------|------------|-------|
| Chlorides              | 12,000 | mg/L     | 500 |     | EPA 300.0 | LAP     | 10/03/2018 |       |
| Total Dissolved Solids | 23,000 | mg/L     | 7.0 |     | SM 2540C  | LAP     | 10/01/2018 | 10:00 |
| Sodium (Dissolved)     | 6,800  | mg/L     | 100 |     | SM 3111B  | LAP     | 10/23/2018 |       |
| Sodium (Total)         | 6,400  | mg/L     | 100 |     | SM3111B   | LAP     | 10/23/2018 |       |
| Conductance            | 54,000 | umohs/cm | 2.0 |     | EPA120.1  | DCB     | 09/27/2018 | 13:51 |

### Laborator ID# 18110371-02

**Sample#:**  
**Collection Address:** PAMET2  
**Sample Location:**

**Matrix:** Water - Surface Water  
**Sampled:** 09/26/2018 15:00 **By:** Chris Scabia  
**Received:** 09/26/2018 16:29 **By:** PalmerP  
**Turn Around:** Standard

#### Test Parameters

| ITEM                   | RESULT | UNITS    | RL  | MCL | METHOD#   | ANALYST | TESTED     | TIME  |
|------------------------|--------|----------|-----|-----|-----------|---------|------------|-------|
| Chlorides              | 650    | mg/L     | 25  |     | EPA 300.0 | LAP     | 10/03/2018 |       |
| Total Dissolved Solids | 2,500  | mg/L     | 7.0 |     | SM 2540C  | LAP     | 10/01/2018 | 10:01 |
| Sodium (Dissolved)     | 1,200  | mg/L     | 20  |     | SM 3111B  | LAP     | 10/23/2018 |       |
| Sodium (Total)         | 1,100  | mg/L     | 25  |     | SM 3111B  | LAP     | 10/23/2018 |       |
| Conductance            | 3,100  | umohs/cm | 2.0 |     | EPA120.1  | DCB     | 09/27/2018 | 13:51 |

### Laborator ID# 18110371-03

**Sample#:**  
**Collection Address:** PAMET3  
**Sample Location:**

**Matrix:** Water - Surface Water  
**Sampled:** 09/26/2018 12:00 **By:** Chris Scabia  
**Received:** 09/26/2018 16:29 **By:** PalmerP  
**Turn Around:** Standard

#### Test Parameters

| ITEM                   | RESULT | UNITS    | RL  | MCL | METHOD#   | ANALYST | TESTED     | TIME  |
|------------------------|--------|----------|-----|-----|-----------|---------|------------|-------|
| Chlorides              | 590    | mg/L     | 25  |     | EPA 300.0 | LAP     | 10/03/2018 |       |
| Total Dissolved Solids | 1,300  | mg/L     | 7.0 |     | SM 2540C  | LAP     | 10/01/2018 | 10:01 |
| Sodium (Dissolved)     | 320    | mg/L     | 10  |     | SM 3111B  | LAP     | 10/23/2018 |       |
| Sodium (Total)         | 350    | mg/L     | 25  |     | SM 3111B  | LAP     | 10/23/2018 |       |
| Conductance            | 2,700  | umohs/cm | 2.0 |     | EPA120.1  | DCB     | 09/27/2018 | 13:52 |

ND = None Detected

RL = Reporting Limit

MCL = Maximum Contaminant Level



# CERTIFICATE OF ANALYSIS

## Barnstable County Health Laboratory (M-MA009)

**Recipient:** Christopher Kilbridge  
US Army Corp Engineers  
696 Virginia Road  
Concord, MA 01742-2751

**Order No.:** G18110371  
**Report Dated:** 10/17/2018  
**Submitter:** Christopher Kilbridge  
**Description:** Lab Analysis

**Laborator)I ID#: 18110371-04**

**Sample#:**  
**Collection Address:** PAMET DOWNSTREAM 1  
**Sample Location:**

**Matrix:** Water - Surface Water  
**Sampled:** 09/26/2018 14:00 **By:** Chris Scabia  
**Received:** 09/26/2018 16:29 **By:** PalmerP  
**Turn Around:** Standard

**Test Parameters**

| ITEM                   | RESULT | UNITS    | RL  | MCL | METHOD#   | ANALYST | TESTED     | TIME  |
|------------------------|--------|----------|-----|-----|-----------|---------|------------|-------|
| Chlorides              | 14,000 | mg/L     | 500 |     | EPA 300.0 | LAP     | 10/03/2018 | 13:53 |
| Total Dissolved Solids | 20,000 | mg/L     | 7.0 |     | SM 2540C  | LAP     | 10/02/2018 | 10:35 |
| Sodium (Dissolved)     | 3,900  | mg/L     | 100 |     | SM3111B   | LAP     | 10/23/2018 |       |
| Sodium (Total)         | 4,000  | mg/L     | 100 |     | SM 31118  | LAP     | 10/23/2018 |       |
| Conductance            | 49,000 | umohs/cm | 2.0 |     | EPA120.1  | DCB     | 09/27/2018 | 13:53 |

**Laborator)I ID#: 18110371-05**

**Sample#:**  
**Collection Address:** PAMET DOWNSTREAM 2  
**Sample Location:**

**Matrix:** Water - Surface Water  
**Sampled:** 09/26/2018 14:15 **By:** Chris Scabia  
**Received:** 09/26/2018 16:29 **By:** PalmerP  
**Turn Around:** Standard

**Test Parameters**

| ITEM                   | RESULT | UNITS    | RL  | MCL | METHOD#   | ANALYST | TESTED     | TIME  |
|------------------------|--------|----------|-----|-----|-----------|---------|------------|-------|
| Chlorides              | 12,000 | mg/L     | 500 |     | EPA 300.0 | LAP     | 10/03/2018 |       |
| Total Dissolved Solids | 25,000 | mg/L     | 7.0 |     | SM 2540C  | LAP     | 10/02/2018 | 10:35 |
| Sodium (Dissolved)     | 6,700  | mg/L     | 100 |     | SM 3111B  | LAP     | 10/23/2018 |       |
| Sodium (Total)         | 6,400  | mg/L     | 100 |     | SM 3111B  | LAP     | 10/23/2018 |       |
| Conductance            | 57,000 | umohs/cm | 2.0 |     | EPA120.1  | DCB     | 09/27/2018 | 13:53 |

Attached please find the laboratory certified parameter list.

**Approved By:**  
(Lab Manager)

J o2.C?/D/ 'g



## CHAIN OF CUSTODY

BARNSTABLE COUNTY DEPARTMENT OF HEALTH & ENVIRONMENT  
WATER QUALITY LABORATORY

3195 Main Street/PO Box 427, Barnstable, MA 02630

Phone: 508-375-6805; Fax: 508-362-7103

PAGE\_\_ OF\_\_

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| ATTENTION: BtR6/J /<yfP |                                                                    |            |              |  |                                   | ATTENTION: Y10,hn,P..PY./D Dlv1.slan               |                             |  |      |                     |        |      |  | PWSID:                                         |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
| COMPANY NAME:           |                                                                    |            |              |  |                                   | COMPANY NAME: Lt: Zm... : (Zm.../u...+'rno-;nee>"S |                             |  |      |                     |        |      |  | PWS NAME:                                      |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
| ADDRESS:                |                                                                    |            |              |  |                                   | ADDRESS:&, 6, Vjr,v;11a ;5og d                     |                             |  |      |                     |        |      |  | PWS CLASS:                                     |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
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| E-MAIL:                 |                                                                    |            |              |  |                                   | E-MAIL: {:/2r/So,Rher. , S!,a/Q.@//s4ce. :(,2/mg.  |                             |  |      |                     |        |      |  | RUSH (days): One _ Two _ Three _ Four _ Five _ |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
| PHONE:                  |                                                                    |            | FAX:         |  |                                   | PHONE:                                             |                             |  | FAX: |                     |        | 11/r |  |                                                | REPORT DELIVERY |                                                    | Fax__ e-mail__ Hardcopy__ |                       |  |  |         |  |  |  |  |
| LAB ID                  | SAMPLE LOCATION/ IDENTIFICATION<br>(Street Address + City + State) | COLLECTION |              |  | MA DEP LOCATION ID or MAP +PARCEL | SAMPLE TYPE                                        |                             |  |      |                     |        |      |  |                                                | MATRIX          | POLYMER                                            | ANALYSIS                  |                       |  |  | COMMENT |  |  |  |  |
|                         |                                                                    | DATE       | TIME         |  |                                   |                                                    |                             |  |      |                     |        |      |  |                                                |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
| 1                       | I fp. i:T 1                                                        | 9-Zb -1    | 130 PM       |  |                                   |                                                    |                             |  |      |                     |        |      |  |                                                |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
| 2.                      | PAtJ\ET ;}                                                         | 9-26-18    | 3PM          |  |                                   |                                                    |                             |  |      |                     |        |      |  |                                                |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
| 3                       | PAME T 3                                                           | 9-26-18    | 2PM (NOON)   |  |                                   |                                                    |                             |  |      |                     |        |      |  |                                                |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
| 4                       | P Mt:T DOWNSTREAM1                                                 | 9/26/18    | 2PM          |  |                                   |                                                    |                             |  |      |                     |        |      |  |                                                |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
| 5                       | IPAME, Oow>"J9 TREAM2                                              | 9/26/18    | 2PM          |  |                                   |                                                    |                             |  |      |                     |        |      |  |                                                |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
| Relinquished By:        |                                                                    | Date/Time  | Received By: |  |                                   | Date/Time                                          | Container Type <sup>3</sup> |  |      | p                   | IP, GV |      |  |                                                |                 | Temp (°C)                                          |                           |                       |  |  |         |  |  |  |  |
| Christopher Scalera     |                                                                    | 9/26/18    |              |  |                                   | 11/1k,i                                            | Preservative                |  |      | HCl                 | V      |      |  |                                                |                 | See reverse side for Routine sampling instruction. |                           |                       |  |  |         |  |  |  |  |
|                         |                                                                    | 420        |              |  |                                   | j TL.)                                             |                             |  |      | HNO <sub>3</sub>    | V      | V    |  |                                                |                 |                                                    |                           |                       |  |  |         |  |  |  |  |
|                         |                                                                    |            |              |  |                                   |                                                    |                             |  |      | Others <sup>4</sup> | S      | S    |  |                                                |                 |                                                    |                           |                       |  |  |         |  |  |  |  |

<sup>1</sup> Routine includes *pH*, *Nitrate*, *Total Coliform*, *Sodium*, *Copper*, *Iron*, *Conductance*.

<sup>3</sup> Container Type: P = Plastics; CG = Clear Glass; AG = Amber Glass; GV = Glass Vial

<sup>2</sup> Routine+VOC (Real Estate Kit). VOC=Volatile Organic Compounds

<sup>4</sup> H = H<sub>2</sub>SO<sub>4</sub>; T = Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub> (THIO); S = Sterile; N = NaOH





# CUSTOMER INVOICE

Barnstable County Health Laboratory

Invoice Date: 10/17/2018

US Army Corps of Engineers, New England District

Engineering Division

696 Virginia Road

Concord, MA 01742-2751

Invoice#: G18110371

PO#:

Total Paid: \$0.00

Amount Due: \$385.00

Payment Terms: Upon Receipt

| Service      | Procedure Description  | Date Completed | QTY | Price   | Invoice Amount |
|--------------|------------------------|----------------|-----|---------|----------------|
| Laboratory   | Chlorides              | 10/17/2018     | 5   | \$12.00 | \$60.00        |
|              | Conductance            | 10/17/2018     | 5   | \$10.00 | \$50.00        |
|              | Sodium (Dissolved)     | 10/17/2018     | 5   | \$15.00 | \$75.00        |
|              | Sodium (Total)         | 10/17/2018     | 5   | \$20.00 | \$100.00       |
|              | Total Dissolved Solids | 10/17/2018     | 5   | \$20.00 | \$100.00       |
| Grand Total: |                        |                |     |         | \$385.00       |



# CERTIFICATE OF ANALYSIS

## Barnstable County Health Laboratory (M-MA009)

**Recipient:** Christopher Kilbridge  
US Army Corp Engineers  
696 Virginia Road  
Concord, MA 01742-2751

**Order No.:** G18110880  
**Report Dated:** 11/16/2018  
**Submitter:** Christopher Kilbridge  
**Description:** Lab Analysis

### **Laboratory ID#: 18110880-01**

**Sample #:**  
**Collection Address:** Pamet 1-Upper  
**Sample Location:**

**Matrix:** Water  
**Sampled:** 11/08/2018 **By:** C.S.  
**Received:** 11/09/2018 10:15 **By:** Ellie  
**Turn Around:** Standard

### **Test Parameters**

| <u>ITEM</u>            | <u>RESULT</u> | <u>UNITS</u> | <u>RL</u> | <u>MCL</u> | <u>METHOD #</u> | <u>ANALYST</u> | <u>TESTED</u> | <u>TIME</u> |
|------------------------|---------------|--------------|-----------|------------|-----------------|----------------|---------------|-------------|
| Chlorides              | 780           | mg/L         | 10        |            | EPA 300.0       | LAP            | 11/09/2018    |             |
| Total Dissolved Solids | 1,200         | mg/L         | 7.0       |            | SM 2540C        | LAP            | 11/09/2018    |             |
| Sodium (Dissolved)     | 520 'J'       | mg/L         | 10        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Sodium (Total)         | 520           | mg/L         | 10        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Conductance            | 2,800         | umohs/cm     | 2.0       |            | EPA 120.1       | DCB            | 11/09/2018    | 14:51       |

*'J' Values are for samples that were filtered after the sampling date for Dissolved Sodium.*

### **Laboratory ID#: 18110880-02**

**Sample #:**  
**Collection Address:** Pamet 1-Lower  
**Sample Location:**

**Matrix:** Water  
**Sampled:** 11/08/2018 **By:** C.S.  
**Received:** 11/09/2018 10:15 **By:** Ellie  
**Turn Around:** Standard

### **Test Parameters**

| <u>ITEM</u>            | <u>RESULT</u> | <u>UNITS</u> | <u>RL</u> | <u>MCL</u> | <u>METHOD #</u> | <u>ANALYST</u> | <u>TESTED</u> | <u>TIME</u> |
|------------------------|---------------|--------------|-----------|------------|-----------------|----------------|---------------|-------------|
| Chlorides              | 710           | mg/L         | 10        |            | EPA 300.0       | LAP            | 11/09/2018    |             |
| Total Dissolved Solids | 1,200         | mg/L         | 7.0       |            | SM 2540C        | LAP            | 11/09/2018    |             |
| Sodium (Dissolved)     | 480 'J'       | mg/L         | 10        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Sodium (Total)         | 500           | mg/L         | 10        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Conductance            | 2,600         | umohs/cm     | 2.0       |            | EPA 120.1       | DCB            | 11/09/2018    | 14:51       |

*'J' Values are for samples that were filtered after the sampling date for Dissolved Sodium.*

### **Laboratory ID#: 18110880-03**

**Sample #:**  
**Collection Address:** Pamet 2  
**Sample Location:**

**Matrix:** Water  
**Sampled:** 11/08/2018 **By:** C.S.  
**Received:** 11/09/2018 10:15 **By:** Ellie  
**Turn Around:** Standard

### **Test Parameters**

| <u>ITEM</u>            | <u>RESULT</u> | <u>UNITS</u> | <u>RL</u> | <u>MCL</u> | <u>METHOD #</u> | <u>ANALYST</u> | <u>TESTED</u> | <u>TIME</u> |
|------------------------|---------------|--------------|-----------|------------|-----------------|----------------|---------------|-------------|
| Chlorides              | 730           | mg/L         | 10        |            | EPA 300.0       | LAP            | 11/09/2018    |             |
| Total Dissolved Solids | 920           | mg/L         | 7.0       |            | SM 2540C        | LAP            | 11/09/2018    |             |
| Sodium (Dissolved)     | 500 'J'       | mg/L         | 10        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Sodium (Total)         | 490           | mg/L         | 10        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Conductance            | 2,500         | umohs/cm     | 2.0       |            | EPA 120.1       | DCB            | 11/09/2018    | 14:51       |

*'J' Values are for samples that were filtered after the sampling date for Dissolved Sodium.*



# CERTIFICATE OF ANALYSIS

## Barnstable County Health Laboratory (M-MA009)

**Recipient:** Christopher Kilbridge  
US Army Corp Engineers  
696 Virginia Road  
Concord, MA 01742-2751

**Order No.:** G18110880  
**Report Dated:** 11/16/2018  
**Submitter:** Christopher Kilbridge  
**Description:** Lab Analysis

### **Laboratory ID#: 18110880-04**

**Sample #:**  
**Collection Address:** Pamet 3  
**Sample Location:**

**Matrix:** Water  
**Sampled:** 11/08/2018 **By:** C.S.  
**Received:** 11/09/2018 10:15 **By:** Ellie  
**Turn Around:** Standard

### **Test Parameters**

| <u>ITEM</u>            | <u>RESULT</u> | <u>UNITS</u> | <u>RL</u> | <u>MCL</u> | <u>METHOD #</u> | <u>ANALYST</u> | <u>TESTED</u> | <u>TIME</u> |
|------------------------|---------------|--------------|-----------|------------|-----------------|----------------|---------------|-------------|
| Chlorides              | 700           | mg/L         | 10        |            | EPA 300.0       | LAP            | 11/09/2018    |             |
| Total Dissolved Solids | 1,000         | mg/L         | 7.0       |            | SM 2540C        | LAP            | 11/09/2018    |             |
| Sodium (Dissolved)     | 480 'J'       | mg/L         | 10        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Sodium (Total)         | 520           | mg/L         | 10        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Conductance            | 2,600         | umohs/cm     | 2.0       |            | EPA 120.1       | DCB            | 11/09/2018    | 14:52       |

*'J' Values are for samples that were filtered after the sampling date for Dissolved Sodium.*

### **Laboratory ID#: 18110880-05**

**Sample #:**  
**Collection Address:** Pamet Down Stream 1  
**Sample Location:**

**Matrix:** Water  
**Sampled:** 11/08/2018 **By:** C.S.  
**Received:** 11/09/2018 10:15 **By:** Ellie  
**Turn Around:** Standard

### **Test Parameters**

| <u>ITEM</u>            | <u>RESULT</u> | <u>UNITS</u> | <u>RL</u> | <u>MCL</u> | <u>METHOD #</u> | <u>ANALYST</u> | <u>TESTED</u> | <u>TIME</u> |
|------------------------|---------------|--------------|-----------|------------|-----------------|----------------|---------------|-------------|
| Chlorides              | 1,000         | mg/L         | 10        |            | EPA 300.0       | LAP            | 11/09/2018    |             |
| Total Dissolved Solids | 1,500         | mg/L         | 7.0       |            | SM 2540C        | LAP            | 11/09/2018    |             |
| Sodium (Dissolved)     | 880 'J'       | mg/L         | 10        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Sodium (Total)         | 830           | mg/L         | 10        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Conductance            | 3,700         | umohs/cm     | 2.0       |            | EPA 120.1       | DCB            | 11/09/2018    | 14:52       |

*'J' Values are for samples that were filtered after the sampling date for Dissolved Sodium.*

### **Laboratory ID#: 18110880-06**

**Sample #:**  
**Collection Address:** Pamet Down Stream 2  
**Sample Location:**

**Matrix:** Water  
**Sampled:** 11/08/2018 **By:** C.S.  
**Received:** 11/09/2018 10:15 **By:** Ellie  
**Turn Around:** Standard

### **Test Parameters**

| <u>ITEM</u>            | <u>RESULT</u> | <u>UNITS</u> | <u>RL</u> | <u>MCL</u> | <u>METHOD #</u> | <u>ANALYST</u> | <u>TESTED</u> | <u>TIME</u> |
|------------------------|---------------|--------------|-----------|------------|-----------------|----------------|---------------|-------------|
| Chlorides              | 1,300         | mg/L         | 20        |            | EPA 300.0       | LAP            | 11/09/2018    |             |
| Total Dissolved Solids | 1,900         | mg/L         | 7.0       |            | SM 2540C        | LAP            | 11/09/2018    |             |
| Sodium (Dissolved)     | 980 'J'       | mg/L         | 20        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Sodium (Total)         | 950           | mg/L         | 20        |            | SM 3111B        | LAP            | 11/16/2018    | 14:21       |
| Conductance            | 4,700         | umohs/cm     | 2.0       |            | EPA 120.1       | DCB            | 11/09/2018    | 14:52       |

*'J' Values are for samples that were filtered after the sampling date for Dissolved Sodium.*



# CERTIFICATE OF ANALYSIS

## Barnstable County Health Laboratory (M-MA009)

**Recipient:** Christopher Kilbridge  
US Army Corp Engineers  
696 Virginia Road  
Concord, MA 01742-2751

**Order No.:** G18110880  
**Report Dated:** 11/16/2018  
**Submitter:** Christopher Kilbridge  
**Description:** Lab Analysis

Attached please find the laboratory certified parameter list.

**Approved By:**  
(Lab Manager)

A handwritten signature in black ink, appearing to read "Jengmin Lei", is written over a horizontal line.

SALINITY LAB DATA REPORT  
FIGURE B-6 Page 8 of 8

**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT B**  
**GROUNDWATER INSTRUMENTATION**  
**PHOTOS**

**FIGURES B-7 to B-11**

**REFERENCED FROM: CHAPTER 5**

**(2016-18 PAMET RIVER FIELD DATA INSTRUMENTATION, COLLECTION,  
VALIDATION AND *QUALITATIVE ANALYSIS*)**

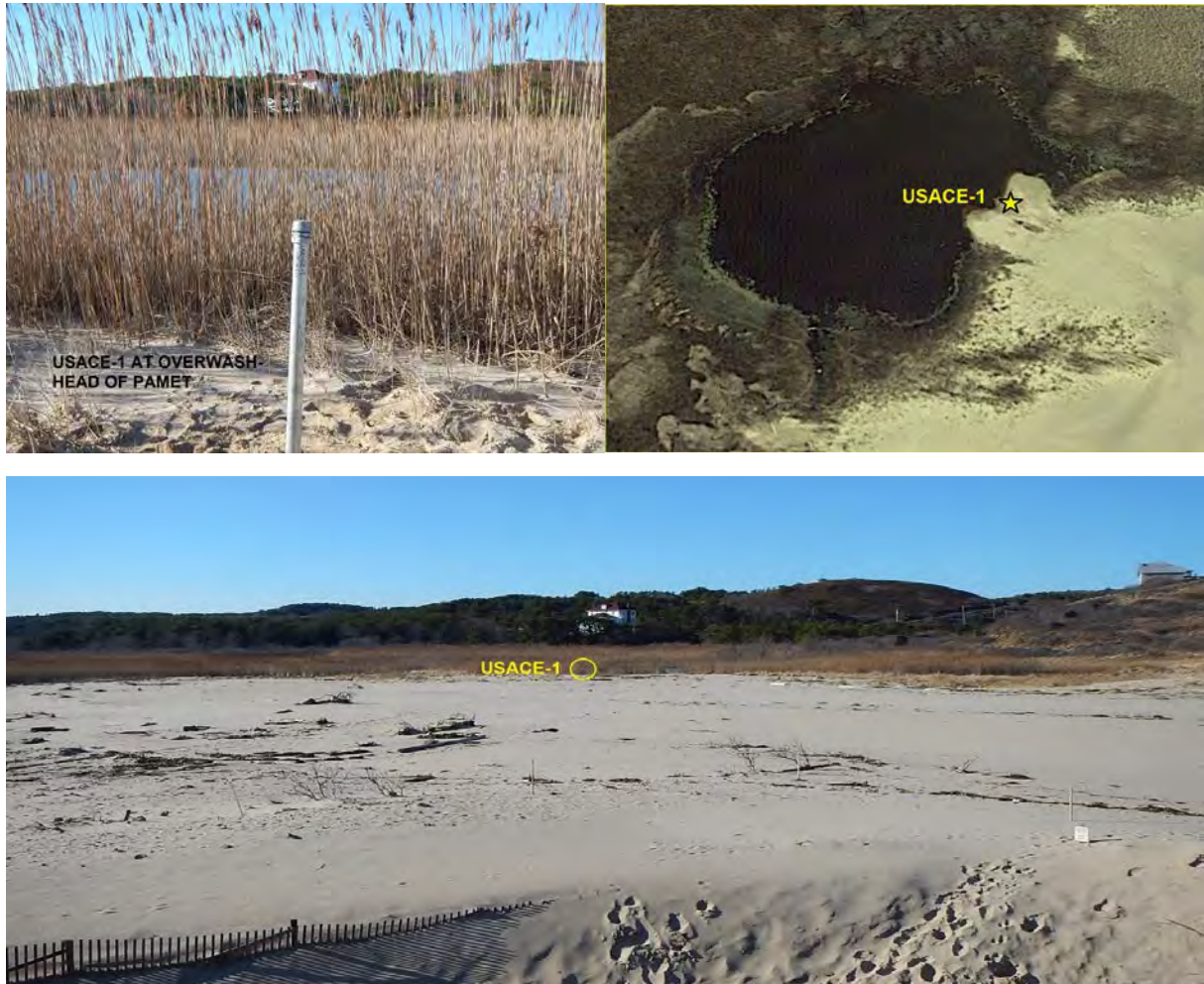
**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

## Pamet River Well Site Locations

**USACE-1** This well is located near the extent of the recent over-wash from Ballston Beach and the head of the Pamet River. It can be recognized as a capped 2 inch diameter galvanized steel pipe protruding about 4 feet above ground. Although originally hand-tightened, the cap may require a pipe wrench to remove it.



Viewed from North Pamet Road Parking Lot Beach Access

FIGURE B-7



USACE-2      This well, also composed of a capped 2 inch diameter galvanized steel pipe, extends about 19.5 feet above ground just sea ward of the Pamet Harbor breakwater. Obviously it can only be accessed at low tide with a ladder.



TRU-7      This well is a 2 inch diameter PVC pipe standing 1.7 ft agl. It sits within the confines of the Wilder Dyke Park on Truro Center Road near the U.S. Post Office.



FIGURE B-8



TLF-005 This well is a 1 inch diameter gray PVC pipe standing just over 1 ft agl. It's located on a curve on the South Pamet Road about 15 ft below the guard rail and next to a stream. A rubber plumbing cap secures the opening with a hose clamp that requires a common blade screwdriver.



TRU-5 These wells are 2 inch diameter PVC pipe in flush-mounted casings. Proceeding along S. Pamet Rd. from TLF-005 they sit on the Kelly property at 31 S. Pamet at the back of the field opposite the house driveway. A white mail box marks the entrance to the field. A ½ socket will be necessary to unbolt the covers.



FIGURE B-9



C-5 This well on Collins Rd., which leads right off of S. Pamet, sits on a curve at the entrance to Fire Rd. #3 in plain sight. At about 1.5 ft agl, it holds a 2 inch diameter PVC pipe in 4 inch diameter steel casing with a key lock.



PW-3/PW-4 Two wells are 2 inch diameter PVC pipe in 4 inch diameter steel casings with key locks; the third is 1 inch dia. PVC with a threaded cap. Further along S. Pamet is the Mooney Farm. The wells are at the back of the field on the left side of the road near the pasture fence.

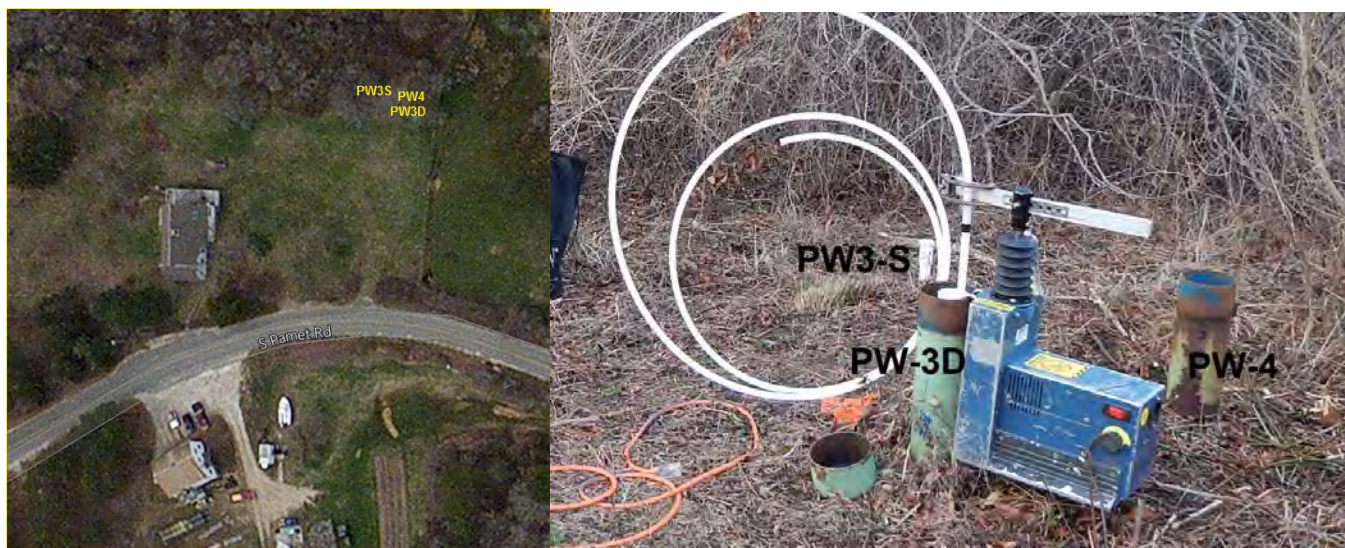


FIGURE B-10

C-1 South of the Post Office, Depot Rd. bears to the right and leads to Pamet Harbor. Stay to the right at the next fork and the well will be on your left at the corner of Depot Rd. and Maria Rosa (Private Path). This is another 2 inch PVC pipe inside a 4 inch dia. 1 ft tall steel casing with a pad lock.



FIGURE B-11

**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT B**

**GROUNDWATER INSTRUMENTATION**

**WELL REDEVELOPMENT DATA**

**FIGURES B-12 to B-18**

**REFERENCED FROM: CHAPTER 5**

**(2016-18 PAMET RIVER FIELD DATA INSTRUMENTATION, COLLECTION,  
VALIDATION AND *QUALITATIVE ANALYSIS*)**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

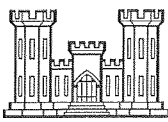


|    | A                                                                                                                                                                | B             | C            | D                                                                                                         | E                       | F                | G            | H        | I                                                                                                                                                                                                                                                                                                                                                                          |
|----|------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|--------------|-----------------------------------------------------------------------------------------------------------|-------------------------|------------------|--------------|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1  |                                                                                                                                                                  |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |
| 2  |                                                                                                                                                                  |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |
| 3  | PRIORITY LIST OF MONITORING WELLS FOR PAMET RIVER MODEL AND STUDY- DRAFT (23/1/2017)                                                                             |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |
| 4  |                                                                                                                                                                  |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |
| 5  | Well Name                                                                                                                                                        | Diameter (in) | Depth (ft)   | Location Description                                                                                      | Data Type               | Transducer Owner | Year Drilled | Well Log | Rationale                                                                                                                                                                                                                                                                                                                                                                  |
| 6  | TRU-7                                                                                                                                                            | 2             | 15           | 100 ft north gate (verbal NPS/CCC)                                                                        | Head and Salinity       | NPS              | ???          | No       | Data here would provide head and salinity data near the gate and help ensure the model correctly reproduces the near impact of the existing tide gate. This is the only well near the river on the north side.                                                                                                                                                             |
| 7  | C5                                                                                                                                                               | 2             | 90           | about 0.85 miles south of river and 0.85 miles west of Ballston Beach                                     | Head only               | USACE            | 2001         | Yes      | Head data here would ensure that the flow northward from the Chequeset flow lens into the groundwater fed Pamet River is correct. The heads probably do not vary significantly, instrumenting could be replaced with frequent (perhaps weekly or biweekly) field measurements if staff and funding is available. Water is expected to be fresh; no need for salinity data. |
| 8  | PW-3s                                                                                                                                                            | 2             | 7 (or 50 ??) | 0.1 miles south of river on edge of lowland area, about 0.75 miles west of Ballston Beach-Mooney Property | Head and Salinity       | NPS              | 1996         | Yes      | This location, about halfway between the gate and Ballston Beach, will help ensure the model is correctly reproducing the impact of the river. Salinity data in the <b>shallow well</b> should be mostly fresh (and not that useful) unless an overtopping event occurs during the monitoring period.                                                                      |
| 9  | PW-3d                                                                                                                                                            | 2             | 150          | 0.1 miles south of river on edge of lowland area, about 0.75 miles west of Ballston Beach-Mooney Property | Head and Salinity       | NPS              | 1996         | Yes      | This location, about halfway between the gate and Ballston Beach, will help ensure the model is correctly reproducing the impact of the river. Salinity data in the <b>deep well</b> will help ensure the saltwater freshwater interface is correctly computed by the model.                                                                                               |
| 10 | USACE-1                                                                                                                                                          | 1.5           | 10           | near Ballston Beach (old PR12 pool area)                                                                  | Head only               | USACE            | NEW          |          | New hand drive well point to measure water table at headwater Pamet River                                                                                                                                                                                                                                                                                                  |
| 11 | TRU-5s                                                                                                                                                           | 2             | 20           | south of river near edge of lowland area, about 0.5 miles upstream of gate                                | Head only (Salinity ??) | USACE            | 1994         | Yes      | Another point along the river where heads could be measured to ensure the model correctly reproduces the interaction between the river and the groundwater. Salinity data may help determine the depth of the mixing zone during an overtopping event.                                                                                                                     |
| 12 | TRU-5d                                                                                                                                                           | 2             | 60           | south of river near edge of lowland area, about 0.5 miles upstream of gate                                | Head and Salinity       | NPS              | 1994         | Yes      | Another point along the river where heads could be measured to ensure the model correctly reproduces the interaction between the river and the groundwater. Salinity data may help determine the depth of the mixing zone during an overtopping event.                                                                                                                     |
| 13 | TLF-005                                                                                                                                                          | 2 or 1" PVC?  | ???          | 0.2 miles upsream of gate, just south of river                                                            | Head and Salinity       | NPS              | 1996 ??      | No       | Head and salinity data just upstream of the gate. Note that depth on this well is unknown.                                                                                                                                                                                                                                                                                 |
| 14 | USACE-2                                                                                                                                                          | 1.5           | 10           | downstream of tide gate and Wilders Dyke                                                                  | Head only               | USACE            | NEW          |          | New hand driven well point to monitor fresh-saltwater interface downstream of tide gate. See possible locations A through D on aerial photo attached. Install near road in right-of-way along edge flood plain to monitor impacts of existing tide.                                                                                                                        |
| 15 | C1                                                                                                                                                               | 2             | 40           | about 0.8 miles east of bay, 0.15 miles south of wetlands edge                                            | Head only (Salinity ??) | USACE            | 2002         | Yes      | Head and salinity at this well would help define the width of the impact of the tide on the water quality in the ungated section of the river. It is not clear if this well is too far away to provide meaningful data.                                                                                                                                                    |
| 16 |                                                                                                                                                                  |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |
| 17 | Notes/Sources:                                                                                                                                                   |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |
| 18 | 1. "Pamet River Investigation, Groundwater Assessment Study, Truro, Massachusetts- Final Report." May, 1997. Cape Cod Commission- Appendix II- Drilled Well Logs |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |
| 19 | 2. Truro Outer Cape 2004 Water Table Map- well logs                                                                                                              |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |
| 20 | 3. USACE-1 and USACE-2 will be new hand driven well points installed by USACE-NAE in January 2017.                                                               |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |
| 21 | 4. = data loggers borrowed from National Park Service (NPS)                                                                                                      |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |
| 22 |                                                                                                                                                                  |               |              |                                                                                                           |                         |                  |              |          |                                                                                                                                                                                                                                                                                                                                                                            |

FIGURE B-12



**Pamet River, Truro, MA**  
**Well Development/Re-Development Record**

|                                                                                   |                                                   |                                         |                                                         |
|-----------------------------------------------------------------------------------|---------------------------------------------------|-----------------------------------------|---------------------------------------------------------|
|  | Development Date <u>1-25-2017</u>                 | PID (PPM) _____                         | Well Name <u>TRU-55</u>                                 |
|                                                                                   | Development Crew <u>A. McAnis</u>                 | Ambient Air <u>43°F</u>                 | Protective Casing Height (ft AGS) <u>0.0' FLUSH Csg</u> |
|                                                                                   | <u>C. Scabia</u>                                  | Before Development @ Well Opening _____ | Measuring Point Height (ft AGS) <u>0.46' BG-5</u>       |
|                                                                                   | After Development @ Well Opening _____            | Well Depth (ft BMP) <u>19.86'</u>       |                                                         |
| Gallons Purged <u>17.5</u>                                                        | Pre-Development Wellhead Photo (Y/N)? <u>(--)</u> |                                         | Casing Diameter (in) <u>2"</u>                          |
| Gallons Added <u>0</u>                                                            | Pre-Development Wellhead Photo (Y/N)? _____       |                                         | Screen/Open Hole Length (ft) <u>5'</u>                  |
| Ft Sediment Removed <u>0</u>                                                      | Post Development Sampling (Y/N)? <u>V</u>         |                                         | DTW, Initial (ft BMP) <u>2.5'</u>                       |
| Hard Bottom (Y/N)? <u>N</u>                                                       |                                                   |                                         | DTS, Initial (ft BMP) <u>19.86</u>                      |

|                                                             |                                                                                                |                                                                                                                                                                            |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Goal _____                                                  | Measurement Criteria _____                                                                     | Field Notes (development method used, changes in water color, sediment size and minerals, sheens, odors, floe, well behavior, equipment or decon issues, IDW disposition): |
| Verify well bottom is not debris or damage                  | Cased and screened welis - weighted sounder.                                                   | <u>2" PVC AL 1/8 11/16 EL 0W</u><br><u>MONITORING WELL COVER.</u><br><u>NO CAS INITIALLY ON 2" PVC.</u><br><u>SAMPLES ANALYZED ON 1/26 AM</u>                              |
| Remove accumulated bottom sediment and/or debris            | total depth is the same as that measured by geophysical logging or verified well construction. |                                                                                                                                                                            |
| Remove stagnant water and other materials from the well     | Field water quality parameter changes become less than 10% between 3 successive measurements.  |                                                                                                                                                                            |
| Water is representative of the aquifer                      | Field water quality parameter changes become less than 10% between 3 successive measurements.  |                                                                                                                                                                            |
| Re-establish a good hydraulic connection with the formation | Specific capacity/recovery rate measurements are <10% between 3 successive measurements.       |                                                                                                                                                                            |

| 2013 Dev-Final Results         |               |               |                                      |                         |                             |                                |                  |            |             |            |                      |                                  |                                  |
|--------------------------------|---------------|---------------|--------------------------------------|-------------------------|-----------------------------|--------------------------------|------------------|------------|-------------|------------|----------------------|----------------------------------|----------------------------------|
| Date/Time<br>dd-mmm-yy / 00:00 | DTW<br>ft BMP | DTS<br>ft BMP | Make-Up<br>Water<br>Added<br>gallons | Purge Rate<br>or ml/min | Volume<br>Purged<br>gallons | Total Vol<br>Purged<br>gallons | Turbidity<br>NTU | Temp<br>°C | pH<br>units | DO<br>mg/L | Field<br>RedOx<br>mV | Specific<br>Conductance<br>mS/cm | Recovery<br>Rate<br>ft/min or hr |
| 3-1' {                         | 5:06 PM       | 2.5           | —                                    | PUMP START              |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                | 5:10 PM       | 2.5           | —                                    | PUMP STOP 0.5           | 2.5                         | 2.5                            | 1011.54          | 9.88       | 5.94        | 13.57      | 160.49               | 102                              |                                  |
| 1-2' {                         | 5:23 PM       | 2.46          | —                                    | START                   |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                | 5:25 PM       | 2.45          | —                                    | STOP 0.6                | 1.25                        | 3.75                           |                  |            |             |            |                      | 166.11                           |                                  |
| 3-4' {                         | 5:31 PM       | 2.45          | —                                    | START                   |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                | 5:33 PM       | 2.45          | —                                    | STOP 0.5                | 1                           | 4.75                           |                  |            |             |            |                      |                                  |                                  |
| 2-3' {                         | 5:42 PM       | 2.45          | —                                    | START                   |                             |                                | 1325.33          | 10.07      | 5.95        | 10.99      | 157.37               | 166.11                           |                                  |
|                                | 5:46 PM       | 2.45          | —                                    | STOP 0.5                | 2                           | 6.75                           |                  |            |             |            |                      |                                  |                                  |
| 1-2' {                         | 5:50 PM       | 2.45          | —                                    | START                   |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                |               | 2.45          | —                                    | STOP 0.5                | 2                           | 8.75                           |                  |            |             |            |                      |                                  |                                  |
| 3-4' {                         | 6:00          | 2.45          | —                                    | START                   |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                | 6:08          | 2.45          | 20.04                                | STOP 0.625              | 5                           | 13.75                          | 604.03           | 10.04      | 5.90        | 11.80      | 164.02               | 89.17                            |                                  |

PIO Photo Ionization Device  
DTW Depth to Water  
DTS Depth to Sediment

PPM Parts Per Million  
BMP Below Measuring Point  
AGS Above Ground Surface

ft/min feet per minute  
gal gallons  
ml/min milliliters per minute

Print Date: 1/23/2017

\* f/c TO OF SEDIMENT IN BUCKET BOJIM AFTER ST 5 GAL PURGE

Page\_of\_

Pamet River\_Well Development V2.xlsx

**FIGURE B-13**

PAMET RIVER YSI 650 SONDE WATER QUALITY PARAMETER SAMPLING DURING WELL  
REDEVELOPMENT

|           |           |
|-----------|-----------|
| Filename  | PAMET.dat |
| Model     | 650       |
| ID        | YSI 650   |
| Revision  | 1.20      |
| Site name |           |

| USE THESE !!!!! APRIL-16-2018 UPDATE<br>YSI VALUES WITHOUT SOFTWARE ERROR IN YSI EXPORT (CONDUCTIVITY IS CORRECT) |         |                             |              |               |                 |             |               |              |             |              |               |                |              |
|-------------------------------------------------------------------------------------------------------------------|---------|-----------------------------|--------------|---------------|-----------------|-------------|---------------|--------------|-------------|--------------|---------------|----------------|--------------|
| Well ID                                                                                                           | SiteNum | Date Time M/D/Y<br>HH:MM:SS | Temp C       | Cond<br>Ms/cm | SpCond<br>mS/cm | Sal ppt     | DOsat %       | DO<br>mg/L   | pH          | pH mV        | Orp mV        | Turbid+<br>NTU | Baro psi     |
| TRU-5S                                                                                                            | 1       | 01/26/17 11:34:45           | 9.82         | 0.072         | 0.102           | 0.05        | 121           | 13.71        | 5.95        | 48.8         | 168           | 1018.7         | 14.36        |
| TRU-5S                                                                                                            | 1       | 01/26/17 11:35:00           | 9.85         | 0.072         | 0.102           | 0.05        | 120.4         | 13.64        | 5.95        | 49.1         | 168           | 1018.3         | 14.36        |
| TRU-5S                                                                                                            | 1       | 01/26/17 11:35:15           | 9.86         | 0.072         | 0.102           | 0.05        | 120.1         | 13.59        | 5.94        | 49.4         | 168           | 1016.6         | 14.36        |
| TRU-5S                                                                                                            | 1       | 01/26/17 11:35:30           | 9.88         | 0.072         | 0.102           | 0.05        | 119.8         | 13.56        | 5.94        | 49.6         | 169           | 1013.1         | 14.36        |
| TRU-5S                                                                                                            | 1       | 01/26/17 11:35:45           | 9.9          | 0.072         | 0.102           | 0.05        | 119.5         | 13.52        | 5.94        | 49.6         | 169           | 1009.1         | 14.36        |
| TRU-5S                                                                                                            | 1       | 01/26/17 11:36:00           | 9.91         | 0.073         | 0.102           | 0.05        | 119.3         | 13.49        | 5.93        | 49.8         | 169           | 1004.9         | 14.36        |
| TRU-5S                                                                                                            | 1       | 01/26/17 11:36:15           | 9.93         | 0.073         | 0.102           | 0.05        | 119           | 13.45        | 5.93        | 50.1         | 169           | 1000.1         | 14.36        |
|                                                                                                                   |         | <b>SAMPLE 1 AVERAGE</b>     | <b>9.88</b>  | <b>0.072</b>  | <b>0.102</b>    | <b>0.05</b> | <b>119.87</b> | <b>13.57</b> | <b>5.94</b> | <b>49.49</b> | <b>168.57</b> | <b>1011.54</b> | <b>14.36</b> |
| TRU-5S                                                                                                            | 2       | 01/26/17 11:49:19           | 10.03        | 0.118         | 0.165           | 0.08        | 108.5         | 12.23        | 6           | 46.3         | 156           | 1340.3         | 14.36        |
| TRU-5S                                                                                                            | 2       | 01/26/17 11:49:34           | 10.04        | 0.118         | 0.166           | 0.08        | 103.3         | 11.64        | 5.98        | 47.4         | 157           | 1320.7         | 14.36        |
| TRU-5S                                                                                                            | 2       | 01/26/17 11:49:49           | 10.05        | 0.119         | 0.166           | 0.08        | 100.2         | 11.29        | 5.97        | 47.8         | 157           | 1317.1         | 14.36        |
| TRU-5S                                                                                                            | 2       | 01/26/17 11:50:04           | 10.06        | 0.119         | 0.166           | 0.08        | 97.9          | 11.03        | 5.96        | 48.4         | 157           | 1318.2         | 14.36        |
| TRU-5S                                                                                                            | 2       | 01/26/17 11:50:19           | 10.07        | 0.119         | 0.166           | 0.08        | 96.4          | 10.86        | 5.95        | 49           | 158           | 1320.8         | 14.36        |
| TRU-5S                                                                                                            | 2       | 01/26/17 11:50:34           | 10.08        | 0.119         | 0.166           | 0.08        | 94.7          | 10.67        | 5.94        | 49.5         | 158           | 1323.6         | 14.36        |
| TRU-5S                                                                                                            | 2       | 01/26/17 11:50:49           | 10.09        | 0.119         | 0.166           | 0.08        | 93.2          | 10.5         | 5.93        | 49.8         | 158           | 1326.3         | 14.36        |
| TRU-5S                                                                                                            | 2       | 01/26/17 11:51:04           | 10.09        | 0.119         | 0.167           | 0.08        | 92.3          | 10.39        | 5.92        | 50.3         | 158           | 1329           | 14.36        |
| TRU-5S                                                                                                            | 2       | 01/26/17 11:51:19           | 10.1         | 0.119         | 0.167           | 0.08        | 91.2          | 10.26        | 5.92        | 50.7         | 158           | 1332           | 14.36        |
|                                                                                                                   |         | <b>SAMPLE 2 AVERAGE</b>     | <b>10.07</b> | <b>0.119</b>  | <b>0.166</b>    | <b>0.08</b> | <b>97.52</b>  | <b>10.99</b> | <b>5.95</b> | <b>48.80</b> | <b>157.44</b> | <b>1325.33</b> | <b>14.36</b> |
| TRU-5S                                                                                                            | 3       | 01/26/17 12:00:57           | 10.03        | 0.063         | 0.089           | 0.04        | 112.2         | 12.65        | 5.89        | 52           | 164           | 607.6          | 14.35        |
| TRU-5S                                                                                                            | 3       | 01/26/17 12:01:12           | 10.04        | 0.063         | 0.089           | 0.04        | 107           | 12.06        | 5.9         | 51.7         | 164           | 610.3          | 14.35        |
| TRU-5S                                                                                                            | 3       | 01/26/17 12:01:27           | 10.04        | 0.064         | 0.090           | 0.04        | 104.5         | 11.78        | 5.9         | 51.5         | 164           | 606.5          | 14.35        |
| TRU-5S                                                                                                            | 3       | 01/26/17 12:01:42           | 10.04        | 0.063         | 0.089           | 0.04        | 102.6         | 11.57        | 5.9         | 51.5         | 164           | 602.1          | 14.35        |
| TRU-5S                                                                                                            | 3       | 01/26/17 12:01:57           | 10.04        | 0.063         | 0.089           | 0.04        | 101.5         | 11.45        | 5.9         | 51.6         | 164           | 599.4          | 14.35        |
| TRU-5S                                                                                                            | 3       | 01/26/17 12:02:12           | 10.04        | 0.063         | 0.089           | 0.04        | 100.4         | 11.32        | 5.9         | 51.8         | 164           | 598.3          | 14.35        |
|                                                                                                                   |         | <b>SAMPLE 3 AVERAGE</b>     | <b>10.04</b> | <b>0.063</b>  | <b>0.089</b>    | <b>0.04</b> | <b>104.70</b> | <b>11.81</b> | <b>5.90</b> | <b>51.68</b> | <b>164.00</b> | <b>604.03</b>  | <b>14.35</b> |
| TRU-5D                                                                                                            | 1       | 01/26/17 12:20:27           | 10.65        | 0.045         | 0.062           | 0.03        | 141.5         | 15.73        | 6.49        | 20           | 155           | 1606.5         | 14.33        |
| TRU-5D                                                                                                            | 1       | 01/26/17 12:20:42           | 10.65        | 0.045         | 0.062           | 0.03        | 130           | 14.45        | 6.47        | 21           | 151           | 1606.5         | 14.34        |
| TRU-5D                                                                                                            | 1       | 01/26/17 12:20:57           | 10.66        | 0.045         | 0.062           | 0.03        | 126.7         | 14.08        | 6.46        | 21.7         | 149           | 1606.7         | 14.34        |
| TRU-5D                                                                                                            | 1       | 01/26/17 12:21:12           | 10.65        | 0.045         | 0.062           | 0.03        | 123.1         | 13.69        | 6.44        | 22.4         | 147           | 1606.6         | 14.33        |
| TRU-5D                                                                                                            | 1       | 01/26/17 12:21:27           | 10.65        | 0.045         | 0.062           | 0.03        | 120.4         | 13.38        | 6.43        | 22.9         | 146           | 1606.5         | 14.34        |
| TRU-5D                                                                                                            | 1       | 01/26/17 12:21:42           | 10.64        | 0.045         | 0.063           | 0.03        | 118.2         | 13.14        | 6.43        | 23.2         | 145           | 1606.4         | 14.34        |
|                                                                                                                   |         | <b>SAMPLE 1 AVERAGE</b>     | <b>10.65</b> | <b>0.045</b>  | <b>0.062</b>    | <b>0.03</b> | <b>126.65</b> | <b>14.08</b> | <b>6.45</b> | <b>21.87</b> | <b>148.83</b> | <b>1606.53</b> | <b>14.34</b> |
| TRU-5D                                                                                                            | 2       | 01/26/17 12:27:45           | 10.23        | 0.045         | 0.063           | 0.03        | 151.5         | 17           | 6.51        | 18.9         | 138           | 641.4          | 14.33        |
| TRU-5D                                                                                                            | 2       | 01/26/17 12:28:00           | 10.24        | 0.045         | 0.063           | 0.03        | 141.2         | 15.84        | 6.51        | 18.9         | 139           | 605.8          | 14.33        |
| TRU-5D                                                                                                            | 2       | 01/26/17 12:28:15           | 10.23        | 0.045         | 0.063           | 0.03        | 136.8         | 15.35        | 6.5         | 19.1         | 140           | 589.3          | 14.33        |
| TRU-5D                                                                                                            | 2       | 01/26/17 12:28:30           | 10.23        | 0.045         | 0.063           | 0.03        | 134.2         | 15.07        | 6.49        | 19.6         | 141           | 603            | 14.33        |
| TRU-5D                                                                                                            | 2       | 01/26/17 12:28:45           | 10.23        | 0.045         | 0.063           | 0.03        | 131.6         | 14.77        | 6.49        | 20.1         | 142           | 596.5          | 14.33        |
| TRU-5D                                                                                                            | 2       | 01/26/17 12:29:00           | 10.22        | 0.045         | 0.063           | 0.03        | 129.5         | 14.54        | 6.48        | 20.5         | 143           | 588.3          | 14.33        |
|                                                                                                                   |         | <b>SAMPLE 2 AVERAGE</b>     | <b>10.23</b> | <b>0.045</b>  | <b>0.063</b>    | <b>0.03</b> | <b>137.47</b> | <b>15.43</b> | <b>6.50</b> | <b>19.52</b> | <b>140.50</b> | <b>604.05</b>  | <b>14.33</b> |
| TRU-5D                                                                                                            | 3       | 01/26/17 12:34:53           | 10.21        | 0.085         | 0.118           | 0.06        | 145.9         | 16.39        | 6.53        | 18           | 149           | 1157.2         | 14.33        |
| TRU-5D                                                                                                            | 3       | 01/26/17 12:35:08           | 10.22        | 0.085         | 0.118           | 0.06        | 137.4         | 15.42        | 6.51        | 18.5         | 151           | 1149.9         | 14.33        |
| TRU-5D                                                                                                            | 3       | 01/26/17 12:35:23           | 10.21        | 0.085         | 0.119           | 0.06        | 133.4         | 14.99        | 6.51        | 19           | 151           | 1149.4         | 14.33        |
| TRU-5D                                                                                                            | 3       | 01/26/17 12:35:38           | 10.21        | 0.085         | 0.119           | 0.06        | 131.2         | 14.74        | 6.5         | 19.6         | 152           | 1104           | 14.33        |
| TRU-5D                                                                                                            | 3       | 01/26/17 12:35:53           | 10.22        | 0.085         | 0.119           | 0.06        | 128.9         | 14.47        | 6.48        | 20.2         | 153           | 1083           | 14.33        |
|                                                                                                                   |         | <b>SAMPLE 3 AVERAGE</b>     | <b>10.21</b> | <b>0.085</b>  | <b>0.119</b>    | <b>0.06</b> | <b>135.36</b> | <b>15.20</b> | <b>6.51</b> | <b>19.06</b> | <b>151.20</b> | <b>1128.70</b> | <b>14.33</b> |
| PW-3D                                                                                                             | 1       | 01/27/17 08:36:49           | 5.02         | 4.270         | 6.904           | 3.77        | 207.2         | 25.79        | 5.55        | 68.7         | 96            | 304.7          | 14.4         |
| PW-3D                                                                                                             | 1       | 01/27/17 08:37:04           | 5.01         | 4.271         | 6.909           | 3.77        | 132.4         | 16.48        | 5.36        | 78.9         | 85            | 287.9          | 14.4         |
| PW-3D                                                                                                             | 1       | 01/27/17 08:37:19           | 5            | 4.273         | 6.914           | 3.77        | 122.1         | 15.21        | 5.3         | 82           | 81            | 289.5          | 14.4         |

| USE THESE !!!!! APRIL-16-2018 UPDATE                                      |         |                             |             |               |                 |             |               |              |             |              |               |                |              |
|---------------------------------------------------------------------------|---------|-----------------------------|-------------|---------------|-----------------|-------------|---------------|--------------|-------------|--------------|---------------|----------------|--------------|
| YSI VALUES WITHOUT SOFTWARE ERROR IN YSI EXPORT (CONDUCTIVITY IS CORRECT) |         |                             |             |               |                 |             |               |              |             |              |               |                |              |
| Well ID                                                                   | SiteNum | Date Time M/D/Y<br>HH:MM:SS | Temp C      | Cond<br>Ms/cm | SpCond<br>mS/cm | Sal ppt     | DOsat %       | DO<br>mg/L   | pH          | pH mV        | Orp mV        | Turbid+<br>NTU | Baro psi     |
| PW-3D                                                                     | 1       | 01/27/17 08:37:34           | 5           | 4.274         | 6.917           | 3.77        | 112.3         | 13.99        | 5.26        | 84.1         | 79            | 289.7          | 14.4         |
| PW-3D                                                                     | 1       | 01/27/17 08:37:49           | 5           | 4.276         | 6.919           | 3.77        | 105.1         | 13.09        | 5.23        | 85.9         | 78            | 276.7          | 14.4         |
|                                                                           |         | <b>SAMPLE 1 AVERAGE</b>     | <b>5.01</b> | <b>4.273</b>  | <b>6.913</b>    | <b>3.77</b> | <b>135.82</b> | <b>16.91</b> | <b>5.34</b> | <b>79.92</b> | <b>83.80</b>  | <b>289.70</b>  | <b>14.40</b> |
| PW-3D                                                                     | 2       | 01/27/17 08:43:38           | 5.04        | 3.560         | 5.753           | 3.1         | 197.1         | 24.63        | 5.19        | 87.8         | 114           | 2.9            | 14.4         |
| PW-3D                                                                     | 2       | 01/27/17 08:43:53           | 5.07        | 3.572         | 5.768           | 3.11        | 159.6         | 19.93        | 5.15        | 90           | 112           | 4.1            | 14.4         |
| PW-3D                                                                     | 2       | 01/27/17 08:44:08           | 5.06        | 3.581         | 5.784           | 3.12        | 148.3         | 18.52        | 5.14        | 90.5         | 110           | 3.6            | 14.4         |
| PW-3D                                                                     | 2       | 01/27/17 08:44:23           | 5.06        | 3.585         | 5.792           | 3.12        | 142           | 17.74        | 5.13        | 90.9         | 108           | 2.9            | 14.4         |
|                                                                           |         | <b>SAMPLE 2 AVERAGE</b>     | <b>5.06</b> | <b>3.575</b>  | <b>5.774</b>    | <b>3.11</b> | <b>161.75</b> | <b>20.21</b> | <b>5.15</b> | <b>89.80</b> | <b>111.00</b> | <b>3.38</b>    | <b>14.40</b> |
| PW-3D                                                                     | 3       | 01/27/17 08:49:50           | 5           | 4.877         | 7.891           | 4.34        | 196.3         | 24.35        | 5.28        | 83.4         | 120           | 0.3            | 14.4         |
| PW-3D                                                                     | 3       | 01/27/17 08:50:05           | 5.01        | 4.888         | 7.906           | 4.35        | 148.9         | 18.47        | 5.26        | 84.3         | 117           | -0.3           | 14.4         |
| PW-3D                                                                     | 3       | 01/27/17 08:50:20           | 5.02        | 4.896         | 7.918           | 4.36        | 131           | 16.24        | 5.25        | 84.6         | 115           | -0.2           | 14.4         |
|                                                                           |         | <b>SAMPLE 3 AVERAGE</b>     | <b>5.01</b> | <b>4.887</b>  | <b>7.905</b>    | <b>4.35</b> | <b>158.73</b> | <b>19.69</b> | <b>5.26</b> | <b>84.10</b> | <b>117.33</b> | <b>-0.07</b>   | <b>14.40</b> |
| PW-4                                                                      | 1       | 01/27/17 08:56:18           | 4.86        | 0.063         | 0.103           | 0.05        | 161.7         | 20.72        | 6.65        | 10.8         | 68            | 1530.4         | 14.4         |
| PW-4                                                                      | 1       | 01/27/17 08:56:33           | 4.89        | 0.063         | 0.103           | 0.05        | 142.4         | 18.24        | 6.63        | 12           | 70            | 1530.8         | 14.4         |
| PW-4                                                                      | 1       | 01/27/17 08:56:48           | 4.91        | 0.063         | 0.103           | 0.05        | 134.9         | 17.26        | 6.61        | 12.8         | 71            | 1531           | 14.4         |
| PW-4                                                                      | 1       | 01/27/17 08:57:03           | 4.91        | 0.063         | 0.103           | 0.05        | 129.4         | 16.56        | 6.61        | 13.3         | 72            | 1531           | 14.4         |
|                                                                           |         | <b>SAMPLE 1 AVERAGE</b>     | <b>4.89</b> | <b>0.063</b>  | <b>0.103</b>    | <b>0.05</b> | <b>142.10</b> | <b>18.20</b> | <b>6.63</b> | <b>12.23</b> | <b>70.25</b>  | <b>1530.80</b> | <b>14.40</b> |
| PW-4                                                                      | 2       | 01/27/17 09:02:44           | 5.32        | 0.070         | 0.111           | 0.05        | 161           | 20.39        | 6.69        | 8.6          | 90            | 1536.3         | 14.4         |
| PW-4                                                                      | 2       | 01/27/17 09:02:59           | 5.3         | 0.069         | 0.111           | 0.05        | 143           | 18.11        | 6.68        | 9.3          | 91            | 1536.1         | 14.4         |
| PW-4                                                                      | 2       | 01/27/17 09:03:14           | 5.31        | 0.069         | 0.111           | 0.05        | 136           | 17.23        | 6.67        | 10           | 92            | 1536.1         | 14.4         |
| PW-4                                                                      | 2       | 01/27/17 09:03:29           | 5.32        | 0.069         | 0.111           | 0.05        | 131.2         | 16.61        | 6.66        | 10.3         | 93            | 1536.2         | 14.4         |
|                                                                           |         | <b>SAMPLE 2 AVERAGE</b>     | <b>5.31</b> | <b>0.069</b>  | <b>0.111</b>    | <b>0.05</b> | <b>142.80</b> | <b>18.09</b> | <b>6.68</b> | <b>9.55</b>  | <b>91.50</b>  | <b>1536.18</b> | <b>14.40</b> |
| PW-4                                                                      | 3       | 01/27/17 09:09:31           | 5.23        | 0.070         | 0.112           | 0.05        | 156.9         | 19.92        | 6.71        | 7.6          | 104           | 268            | 14.4         |
| PW-4                                                                      | 3       | 01/27/17 09:09:46           | 5.24        | 0.070         | 0.112           | 0.05        | 135.6         | 17.2         | 6.71        | 7.6          | 105           | 275            | 14.4         |
| PW-4                                                                      | 3       | 01/27/17 09:10:01           | 5.24        | 0.070         | 0.112           | 0.05        | 130.3         | 16.53        | 6.71        | 8            | 105           | 275.4          | 14.4         |
| PW-4                                                                      | 3       | 01/27/17 09:10:16           | 5.24        | 0.070         | 0.112           | 0.05        | 124.7         | 15.83        | 6.7         | 8.5          | 106           | 274.6          | 14.4         |
| PW-4                                                                      | 3       | 01/27/17 09:10:31           | 5.25        | 0.070         | 0.112           | 0.05        | 120.7         | 15.31        | 6.69        | 8.7          | 107           | 272            | 14.4         |
| PW-4                                                                      | 3       | 01/27/17 09:10:46           | 5.26        | 0.070         | 0.112           | 0.05        | 117.6         | 14.92        | 6.69        | 9            | 108           | 268.9          | 14.4         |
|                                                                           |         | <b>SAMPLE 3 AVERAGE</b>     | <b>5.24</b> | <b>0.070</b>  | <b>0.112</b>    | <b>0.05</b> | <b>130.97</b> | <b>16.62</b> | <b>6.70</b> | <b>8.23</b>  | <b>105.83</b> | <b>272.32</b>  | <b>14.40</b> |
| TRU-7                                                                     | 1       | 01/27/17 14:08:33           | 8.19        | 7.817         | 11.514          | 6.56        | 220.6         | 24.92        | 6.25        | 32.5         | 209           | 976.4          | 14.37        |
| TRU-7                                                                     | 1       | 01/27/17 14:08:48           | 8.22        | 7.871         | 11.584          | 6.6         | 158.4         | 17.88        | 6.31        | 29           | 202           | 1421.4         | 14.37        |
| TRU-7                                                                     | 1       | 01/27/17 14:09:03           | 8.22        | 7.891         | 11.612          | 6.62        | 147.9         | 16.69        | 6.33        | 28           | 200           | 1479           | 14.37        |
| TRU-7                                                                     | 1       | 01/27/17 14:09:18           | 8.22        | 7.905         | 11.634          | 6.63        | 137.6         | 15.53        | 6.35        | 27.2         | 198           | 1500.5         | 14.37        |
| TRU-7                                                                     | 1       | 01/27/17 14:09:33           | 8.22        | 7.915         | 11.650          | 6.64        | 129.7         | 14.63        | 6.36        | 26.4         | 196           | 1432.1         | 14.37        |
|                                                                           |         | <b>SAMPLE 1 AVERAGE</b>     | <b>8.21</b> | <b>7.880</b>  | <b>11.599</b>   | <b>6.61</b> | <b>158.84</b> | <b>17.93</b> | <b>6.32</b> | <b>28.62</b> | <b>201.00</b> | <b>1361.88</b> | <b>14.37</b> |
| TRU-7                                                                     | 2       | 01/27/17 14:14:12           | 8.39        | 5.506         | 8.064           | 4.48        | 182           | 20.74        | 6.31        | 29.6         | -11           | 1094.9         | 14.37        |
| TRU-7                                                                     | 2       | 01/27/17 14:14:27           | 8.41        | 5.542         | 8.112           | 4.51        | 138.8         | 15.8         | 6.35        | 27.2         | -18           | 1150.9         | 14.37        |
| TRU-7                                                                     | 2       | 01/27/17 14:14:42           | 8.43        | 5.562         | 8.137           | 4.52        | 121.1         | 13.79        | 6.37        | 26.2         | -21           | 1142.9         | 14.37        |
| TRU-7                                                                     | 2       | 01/27/17 14:14:57           | 8.42        | 5.575         | 8.159           | 4.53        | 110.6         | 12.59        | 6.38        | 25.6         | -22           | 1089.3         | 14.37        |
|                                                                           |         | <b>SAMPLE 2 AVERAGE</b>     | <b>8.41</b> | <b>5.546</b>  | <b>8.118</b>    | <b>4.51</b> | <b>138.13</b> | <b>15.73</b> | <b>6.35</b> | <b>27.15</b> | <b>-18.00</b> | <b>1119.50</b> | <b>14.37</b> |
| TRU-7                                                                     | 3       | 01/27/17 14:22:24           | 8.65        | 6.847         | 9.955           | 5.61        | 190.1         | 21.37        | 6.28        | 30.7         | -28           | 886            | 14.36        |
| TRU-7                                                                     | 3       | 01/27/17 14:22:39           | 8.77        | 6.899         | 9.998           | 5.64        | 126.7         | 14.2         | 6.37        | 26.1         | -37           | 868.2          | 14.36        |
| TRU-7                                                                     | 3       | 01/27/17 14:22:54           | 8.79        | 6.916         | 10.018          | 5.65        | 116.8         | 13.08        | 6.39        | 25           | -40           | 857.4          | 14.36        |
| TRU-7                                                                     | 3       | 01/27/17 14:23:09           | 8.79        | 6.929         | 10.036          | 5.66        | 105.9         | 11.87        | 6.41        | 24.2         | -42           | 848.1          | 14.36        |
|                                                                           |         | <b>SAMPLE 3 AVERAGE</b>     | <b>8.75</b> | <b>6.898</b>  | <b>10.002</b>   | <b>5.64</b> | <b>134.88</b> | <b>15.13</b> | <b>6.36</b> | <b>26.50</b> | <b>-36.75</b> | <b>864.93</b>  | <b>14.36</b> |

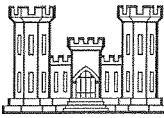
PAMET RIVER YSI 650 SONDE WATER QUALITY PARAMETER SAMPLING DURING WELL  
REDEVELOPMENT

|           |           |
|-----------|-----------|
| Filename  | PAMET.dat |
| Model     | 650       |
| ID        | YSI 650   |
| Revision  | 1.20      |
| Site name |           |

| USE THESE !!!!! APRIL-16-2018 UPDATE                                      |         |                             |           |               |                 |         |         |         |      |        |        |                |             |
|---------------------------------------------------------------------------|---------|-----------------------------|-----------|---------------|-----------------|---------|---------|---------|------|--------|--------|----------------|-------------|
| YSI VALUES WITHOUT SOFTWARE ERROR IN YSI EXPORT (CONDUCTIVITY IS CORRECT) |         |                             |           |               |                 |         |         |         |      |        |        |                |             |
| WELL ID                                                                   | SiteNum | Date Time M/D/Y<br>HH:MM:SS | Temp<br>C | Cond<br>Ms/cm | SpCond<br>mS/cm | Sal ppt | DOsat % | DO mg/L | pH   | pH mV  | Orp mV | Turbid+<br>NTU | Baro<br>psi |
| C-1                                                                       | 1       | 02/02/17 15:21:23           | 8.84      | 0.171         | 0.247           | 0.12    | 199.6   | 23.15   | 7    | -7.1   | 128    | 1583.5         | 14.62       |
| C-1                                                                       | 1       | 02/02/17 15:21:38           | 8.86      | 0.171         | 0.247           | 0.12    | 147.5   | 17.1    | 6.9  | 0      | 134    | 1583.7         | 14.62       |
| C-1                                                                       | 1       | 02/02/17 15:21:53           | 8.86      | 0.171         | 0.247           | 0.12    | 142.2   | 16.48   | 6.8  | 3.4    | 136    | 1583.7         | 14.62       |
| C-1                                                                       | 1       | 02/02/17 15:22:08           | 8.86      | 0.171         | 0.247           | 0.12    | 140.8   | 16.32   | 6.8  | 6.1    | 139    | 1583.5         | 14.62       |
| SAMPLE 1 AVERAGE                                                          |         |                             | 8.86      | 0.171         | 0.247           | 0.12    | 157.5   | 18.26   | 6.85 | 0.6    | 134.3  | 1583.6         | 14.6        |
| C-1                                                                       | 2       | 02/02/17 15:31:58           | 10.59     | 0.166         | 0.229           | 0.11    | 173.6   | 19.31   | 6.7  | 10.6   | 162    | 1606.5         | 14.63       |
| C-1                                                                       | 2       | 02/02/17 15:32:13           | 10.61     | 0.167         | 0.231           | 0.11    | 138.4   | 15.4    | 6.6  | 15.3   | 162    | 1606.6         | 14.63       |
| C-1                                                                       | 2       | 02/02/17 15:32:28           | 10.64     | 0.168         | 0.231           | 0.11    | 132.5   | 14.72   | 6.5  | 18.2   | 163    | 1607           | 14.63       |
| C-1                                                                       | 2       | 02/02/17 15:32:43           | 10.61     | 0.168         | 0.232           | 0.11    | 130.5   | 14.52   | 6.5  | 20.4   | 164    | 1606.7         | 14.63       |
| SAMPLE 2 AVERAGE                                                          |         |                             | 10.61     | 0.167         | 0.231           | 0.11    | 143.8   | 15.99   | 6.56 | 16.1   | 162.8  | 1606.7         | 14.6        |
| C-1                                                                       | 3       | 02/02/17 15:39:10           | 9.26      | 0.16          | 0.229           | 0.11    | 167.9   | 19.27   | 6.6  | 15.2   | 167    | 1408.8         | 14.63       |
| C-1                                                                       | 3       | 02/02/17 15:39:25           | 9.32      | 0.16          | 0.229           | 0.11    | 134.8   | 15.45   | 6.5  | 18.8   | 169    | 1402.2         | 14.63       |
| C-1                                                                       | 3       | 02/02/17 15:39:40           | 9.31      | 0.161         | 0.23            | 0.11    | 132.6   | 15.21   | 6.5  | 21.2   | 171    | 1383.1         | 14.63       |
| C-1                                                                       | 3       | 02/02/17 15:39:55           | 9.33      | 0.161         | 0.23            | 0.11    | 130.2   | 14.92   | 6.4  | 23.3   | 172    | 1391.5         | 14.63       |
| SAMPLE 3 AVERAGE                                                          |         |                             | 9.31      | 0.161         | 0.230           | 0.11    | 141.4   | 16.21   | 6.49 | 19.6   | 169.8  | 1396.4         | 14.6        |
| C-5                                                                       | 1       | 02/03/17 14:08:54           | 3.08      | 0.298         | 0.513           | 0.25    | 108.6   | 14.56   | 6.8  | 2.8    | 162    | 1508.8         | 14.61       |
| C-5                                                                       | 1       | 02/03/17 14:09:09           | 3.1       | 0.303         | 0.521           | 0.25    | 98.6    | 13.22   | 6.6  | 11.6   | 176    | 1508.7         | 14.61       |
| C-5                                                                       | 1       | 02/03/17 14:09:24           | 3.1       | 0.304         | 0.523           | 0.25    | 97.1    | 13.02   | 6.6  | 15.5   | 181    | 1508.7         | 14.61       |
| C-5                                                                       | 1       | 02/03/17 14:09:39           | 3.14      | 0.305         | 0.523           | 0.25    | 96.6    | 12.93   | 6.5  | 19.9   | 186    | 1509.1         | 14.61       |
| SAMPLE 1 AVERAGE                                                          |         |                             | 3.11      | 0.303         | 0.520           | 0.25    | 100.2   | 13.43   | 6.62 | 12.5   | 176.3  | 1508.8         | 14.6        |
| C-5                                                                       | 2       | 02/03/17 14:14:48           | 3.42      | 0.086         | 0.147           | 0.07    | 85.1    | 11.33   | 6.7  | 7.7    | 179    | 1512.8         | 14.61       |
| C-5                                                                       | 2       | 02/03/17 14:15:03           | 3.41      | 0.086         | 0.147           | 0.07    | 74.9    | 9.97    | 6.7  | 10.2   | 182    | 1512.5         | 14.61       |
| C-5                                                                       | 2       | 02/03/17 14:15:18           | 3.41      | 0.086         | 0.147           | 0.07    | 73.1    | 9.74    | 6.6  | 12.2   | 184    | 1512.4         | 14.61       |
| C-5                                                                       | 2       | 02/03/17 14:15:33           | 3.41      | 0.086         | 0.147           | 0.07    | 72.3    | 9.62    | 6.6  | 13.1   | 186    | 1512.4         | 14.61       |
| SAMPLE 2 AVERAGE                                                          |         |                             | 3.41      | 0.09          | 0.15            | 0.07    | 76.35   | 10.17   | 6.65 | 10.80  | 182.75 | 1512.53        | 14.61       |
| C-5                                                                       | 3       | 02/03/17 14:20:05           | 3.25      | 0.086         | 0.146           | 0.07    | 88.8    | 11.86   | 6.6  | 11.5   | 183    | 1510.4         | 14.61       |
| C-5                                                                       | 3       | 02/03/17 14:20:20           | 3.25      | 0.086         | 0.147           | 0.07    | 79      | 10.55   | 6.6  | 13.7   | 186    | 1510.2         | 14.61       |
| C-5                                                                       | 3       | 02/03/17 14:20:35           | 3.24      | 0.086         | 0.147           | 0.07    | 78.1    | 10.44   | 6.6  | 15.3   | 188    | 1510           | 14.61       |
| C-5                                                                       | 3       | 02/03/17 14:20:50           | 3.23      | 0.086         | 0.147           | 0.07    | 77.6    | 10.38   | 6.5  | 16.8   | 189    | 1509.9         | 14.61       |
| SAMPLE 3 AVERAGE                                                          |         |                             | 3.24      | 0.086         | 0.147           | 0.07    | 80.9    | 10.81   | 6.59 | 14.3   | 186.5  | 1510.1         | 14.6        |
| TLF-005                                                                   | 1       | 02/03/17 14:28:04           | 5.02      | 1.598         | 2.584           | 1.33    | 19.1    | 2.41    | 7.2  | -17.2  | -220   | 38.6           | 14.61       |
| TLF-005                                                                   | 1       | 02/03/17 14:28:19           | 5.01      | 1.598         | 2.585           | 1.33    | 15.5    | 1.97    | 7.2  | -18    | -228   | 39.3           | 14.61       |
| TLF-005                                                                   | 1       | 02/03/17 14:28:34           | 4.99      | 1.598         | 2.586           | 1.33    | 13.9    | 1.77    | 7.2  | -18.3  | -232   | 40.3           | 14.61       |
| TLF-005                                                                   | 1       | 02/03/17 14:28:49           | 4.98      | 1.597         | 2.587           | 1.33    | 12.9    | 1.64    | 7.2  | -18.5  | -236   | 42             | 14.61       |
| SAMPLE 1 AVERAGE                                                          |         |                             | 5.00      | 1.598         | 2.586           | 1.33    | 15.4    | 1.95    | 7.20 | -18.0  | -229.0 | 40.1           | 14.6        |
| TLF-005                                                                   | 2       | 02/03/17 14:33:35           | 3.76      | 0.273         | 0.459           | 0.22    | 55.7    | 7.34    | 7.8  | -49.3  | -142   | 761.2          | 14.61       |
| TLF-005                                                                   | 2       | 02/03/17 14:33:50           | 3.77      | 0.273         | 0.46            | 0.22    | 52.7    | 6.94    | 7.8  | -50.8  | -141   | 764.6          | 14.61       |
| TLF-005                                                                   | 2       | 02/03/17 14:34:05           | 3.77      | 0.273         | 0.46            | 0.22    | 52.3    | 6.88    | 7.8  | -51.4  | -140   | 724.2          | 14.61       |
| TLF-005                                                                   | 2       | 02/03/17 14:34:20           | 3.76      | 0.274         | 0.46            | 0.22    | 51.8    | 6.82    | 7.8  | -51.8  | -139   | 733.9          | 14.61       |
| SAMPLE 2 AVERAGE                                                          |         |                             | 3.77      | 0.273         | 0.460           | 0.22    | 53.1    | 7.00    | 7.83 | -50.8  | -140.5 | 746.0          | 14.6        |
| USACE-2                                                                   | 1       | 02/03/17 14:46:51           | 2.33      | 23.896        | 42.15           | 26.22   | 12.8    | 1.46    | 7.7  | -44.7  | -58    | 931.9          | 14.61       |
| USACE-2                                                                   | 1       | 02/03/17 14:47:06           | 2.36      | 24.162        | 42.569          | 26.51   | 9.8     | 1.12    | 8    | -59.5  | -67    | 1385.5         | 14.61       |
| USACE-2                                                                   | 1       | 02/03/17 14:47:21           | 2.38      | 24.274        | 42.74           | 26.63   | 8.5     | 0.97    | 8.1  | -64.9  | -71    | 1441.8         | 14.61       |
| USACE-2                                                                   | 1       | 02/03/17 14:47:36           | 2.39      | 24.348        | 42.859          | 26.71   | 7       | 0.79    | 8.2  | -69.1  | -75    | 1477.2         | 14.61       |
| SAMPLE 1 AVERAGE                                                          |         |                             | 2.37      | 24.17         | 42.58           | 26.52   | 9.53    | 1.09    | 8.00 | -59.55 | -67.75 | 1309.10        | 14.61       |

| USE THESE !!!!! APRIL-16-2018 UPDATE                                      |         |                             |           |               |                 |         |         |         |      |       |        |                |             |
|---------------------------------------------------------------------------|---------|-----------------------------|-----------|---------------|-----------------|---------|---------|---------|------|-------|--------|----------------|-------------|
| YSI VALUES WITHOUT SOFTWARE ERROR IN YSI EXPORT (CONDUCTIVITY IS CORRECT) |         |                             |           |               |                 |         |         |         |      |       |        |                |             |
| WELL ID                                                                   | SiteNum | Date Time M/D/Y<br>HH:MM:SS | Temp<br>C | Cond<br>Ms/cm | SpCond<br>mS/cm | Sal ppt | DOsat % | DO mg/L | pH   | pH mV | Orp mV | Turbid+<br>NTU | Baro<br>psi |
| USACE-2                                                                   | 2       | 02/03/17 14:53:26           | 2.12      | 24.417        | 43.364          | 27.02   | 6.3     | 0.73    | 8    | -61.5 | -28    | 1478.9         | 14.61       |
| USACE-2                                                                   | 2       | 02/03/17 14:53:41           | 2.11      | 24.611        | 43.725          | 27.26   | 9.5     | 1.08    | 8.2  | -68.4 | -35    | 1457.8         | 14.61       |
| USACE-2                                                                   | 2       | 02/03/17 14:53:56           | 2.11      | 24.667        | 43.822          | 27.33   | 9.8     | 1.12    | 8.2  | -72.1 | -38    | 1456.1         | 14.61       |
| USACE-2                                                                   | 2       | 02/03/17 14:54:11           | 2.13      | 24.703        | 43.855          | 27.36   | 9.8     | 1.12    | 8.3  | -75.1 | -41    | 1451.1         | 14.61       |
| <b>SAMPLE 2 AVERAGE</b>                                                   |         |                             | 2.12      | 24.600        | 43.692          | 27.24   | 8.9     | 1.01    | 8.18 | -69.3 | -35.5  | 1461.0         | 14.6        |

**Pamet River, Truro, MA**  
**Well Development/Re-Development Record**

|                                                                                   |                                                |                                                   |                                                         |
|-----------------------------------------------------------------------------------|------------------------------------------------|---------------------------------------------------|---------------------------------------------------------|
|  | Development Date <u>1-25-2017</u>              | PID (PPM) <u>438</u>                              | Well Name <u>TRU-55</u>                                 |
|                                                                                   | Development Crew <u>C. Scabia</u>              | Ambient Air <u>438</u>                            | Protective Casing Height (ft AGS) <u>0.0' FLUSH Csg</u> |
| Before Development @ Well Opening _____                                           |                                                | Measuring Point Height (ft AGS) <u>0.46' BG-5</u> |                                                         |
| After Development @ Well Opening _____                                            |                                                | Well Depth (ft BMP) <u>19.86'</u>                 |                                                         |
| Gallons Purged <u>17.5</u>                                                        | Pre-Development Wellhead Photo <u>(Y/N)? -</u> | Casing Diameter (in) <u>2" --- F</u>              |                                                         |
| Gallons Added <u>0</u>                                                            | Pre-Development Wellhead Photo <u>(Y/N)? -</u> | Screen/Open Hole Length (ft) <u>5'</u>            |                                                         |
| Ft Sediment Removed <u>0</u>                                                      | Post Development Sampling <u>(Y/N)? V</u>      | DTW, Initial (ft BMP) <u>2.5'</u>                 |                                                         |
| Hard Bottom (Y/N)? <u>N</u>                                                       |                                                | DTS, Initial (ft BMP) <u>19.86</u>                |                                                         |

|                                                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                                                                |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Goal _____<br>Verify well bottom is not debris or damage<br>Remove accumulated bottom sediment and/or debris<br>Remove stagnant water and other materials from the well<br>Water is representative of the aquifer<br>Re-establish a good hydraulic connection with the formation | Measurement and Criteria<br>Cased and screened wells - weighted sounder.<br>Total depth is the same as that measured by geophysical logging or verified well construction.<br>Field water quality parameter changes become less than 10% between 3 successive measurements.<br>Field water quality parameter changes become less than 10% between 3 successive measurements.<br>Specific capacity/recovery rate measurements are <10% between 3 successive measurements | Field Notes (development method used, changes in water color, sediment size and minerals, sheens, odors, flow, well behavior, equipment or decon issues, IDW disposition):<br><u>2" PVC AL 1/8" ID, 16' EL OW</u><br><u>MONITORING WELL COVER.</u><br><u>NO CAP INITIALLY ON 2" PVC.</u><br><u>SAMPLES ANALYZED ON 1/26 AM</u> |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

| 2013 Dev. Final Results     |               |               |                                |                   |                          |                              |                  |            |             |            |                   |                               |                               |
|-----------------------------|---------------|---------------|--------------------------------|-------------------|--------------------------|------------------------------|------------------|------------|-------------|------------|-------------------|-------------------------------|-------------------------------|
| Date/Time<br>dd-mm-yy/00:00 | DTW<br>ft BMP | DTS<br>ft BMP | Make-Up Water Added<br>gallons | Purge Rate<br>gpm | Volume Purged<br>gallons | Total Vol. Purged<br>gallons | Turbidity<br>NTU | Temp<br>°C | pH<br>units | DO<br>mg/L | Field RedOx<br>mV | Specific Conductance<br>mS/cm | Recovery Rate<br>ft/min or hr |
| 5:06 PM                     | 2.5           |               | —                              | PUMP START        |                          |                              |                  |            |             |            |                   |                               |                               |
| 5:10 PM                     | 2.5           |               | —                              | PUMP STOP 0.5     | 2.5                      | 2.5                          | 1011.54          | 9.88       | 5.94        | 13.57      | 168.49            | 102                           |                               |
| 5:23 PM                     | 2.46          |               | —                              | START             |                          |                              |                  |            |             |            |                   |                               |                               |
| 5:25 PM                     | 2.45          |               | —                              | STOP 0.6          | 1.25                     | 3.75                         |                  |            |             |            |                   |                               |                               |
| 5:31 PM                     | 2.45          |               | —                              | START             |                          |                              |                  |            |             |            |                   |                               |                               |
| 5:33 PM                     | 2.45          |               | —                              | STOP 0.5          | 1                        | 4.75                         |                  |            |             |            |                   |                               |                               |
| 5:42 PM                     | 2.45          |               | —                              | START             |                          |                              | 1325.33          | 10.07      | 5.95        | 10.99      | 157.37            | 166.11                        |                               |
| 5:46 PM                     | 2.45          |               | —                              | STOP 0.5          | 2                        | 6.75                         |                  |            |             |            |                   |                               |                               |
| 5:50 PM                     | 2.45          |               | —                              | START             |                          |                              |                  |            |             |            |                   |                               |                               |
|                             | 2.45          |               | —                              | STOP 0.5          | 2                        | 8.75                         |                  |            |             |            |                   |                               |                               |
| 6:00                        | 2.45          |               | —                              | START             |                          |                              |                  |            |             |            |                   |                               |                               |
| 6:08                        | 2.45          | 20.04         | —                              | STOP 0.625        | 5                        | 13.75                        | 604.03           | 10.04      | 5.90        | 11.80      | 164.02            | 89.17                         |                               |

PIO Photo Ionization Device  
 DTW Depth to Water  
 DTS Depth to Sediment

PPM Parts Per Million  
 BMP Below Measuring Point  
 AGS Above Ground Surface

ft/min feet per minute  
 gal gallons  
 ml/min milliliters per minute

Print Date: 1/23/2017

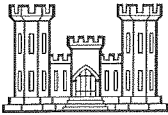
Page\_of\_

Pamet River Well Development V2.xlsx



Pamet River, Truro, MA  
Well Development/Re-Development Record

PURGE GALLON VOL  
= 3 VOLUMES @ 57.25'  
X 1.63 GAL/10' X 5.752 = 18.66 GAL

|                                                                                   |                  |                                       |                                   |      |                                   |                |
|-----------------------------------------------------------------------------------|------------------|---------------------------------------|-----------------------------------|------|-----------------------------------|----------------|
|  | Development Date | 1-26-2017                             | PID (PPM)                         |      | Well Name                         | TRU-5D         |
|                                                                                   | Development Crew | A. McAVOY<br>C. SCABIA                | Ambient Air                       | 40°F | Protective Casing Height (ft AGS) | 0.0' FLUSH Csg |
|                                                                                   |                  |                                       | Before Development @ Well Opening |      | Measuring Point Height (ft AGS)   | 0.33' BG-S     |
|                                                                                   |                  |                                       | After Development @ Well Opening  |      | Well Depth (ft BMP)               | 59.63'         |
| Gallons Purged                                                                    | 20.33            | Pre-Development Wellhead Photo (Y/N)? | ✓                                 |      | Casing Diameter (in)              | 2" PVC         |
| Gallons Added                                                                     | 0.0              | Pre-Development Wellhead Photo (Y/N)? |                                   |      | Screen/Open Hole Length (ft)      | 5'             |
| Ft Sediment Removed                                                               | 0.05             | Post Development Sampling (Y/N)?      | Y                                 |      | DTW, Initial (ft BMP)             | 2.38'          |
| Hard Bottom (Y/N)?                                                                | N                |                                       |                                   |      | DTS, Initial (ft BMP)             | 59.63          |

| Redevelopment Goal                                          | Measurements and Criteria                                                                      | Achieved? | Field Notes (development method used, changes in water color, sediment size and minerals, sheens, odors, floc, well behavior, equipment or decon issues, IDW disposition): |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Verify well bottom is not debris or damage                  | Cased and screened wells – weighted sounder.                                                   | Y         | 2" PVC WELL IS 0.33' BELOW MONITORING WELL COVER.<br>NO INITIAL CAP ON PVC                                                                                                 |
| Remove accumulated bottom sediment and/or debris            | Total depth is the same as that measured by geophysical logging or verified well construction. |           |                                                                                                                                                                            |
| Remove stagnant water and other materials from the well     | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Water is representative of the aquifer                      | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Re-establish a good hydraulic connection with the formation | Specific capacity/recovery rate measurements are <10% between 3 successive measurements.       |           |                                                                                                                                                                            |

| 2013 Dev-Final Results          |               |               |                                      |                              |                             |                                |                                                                                                                                   |            |             |            |                      |                                  |                                  |
|---------------------------------|---------------|---------------|--------------------------------------|------------------------------|-----------------------------|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|------------|-------------|------------|----------------------|----------------------------------|----------------------------------|
| Date / Time<br>dd-mm-yy / 00:00 | DTW<br>ft BMP | DTS<br>ft BMP | Make-Up<br>Water<br>Added<br>gallons | Purge Rate<br>gallons ml/min | Volume<br>Purged<br>gallons | Total Vol<br>Purged<br>gallons | Turbidity<br>NTU                                                                                                                  | Temp<br>°C | pH<br>units | DO<br>mg/L | Field<br>RedOx<br>mV | Specific<br>Conductance<br>mS/cm | Recovery<br>Rate<br>ft/min or hr |
| 9:01 AM                         | 2.38          |               | —                                    | PUMP START                   | ✓                           | ✓                              | 1604.53                                                                                                                           | 10.45      | 6.45        | 14.08      | 148.7                | 62.17                            |                                  |
| 9:04 AM                         | 2.38          |               |                                      | STOP 0.11                    | 0.33                        | 0.33                           | CLEAR BUT WATER STOPPED FLOWING. REMOVED SEDIMENT PLUG IN FOOT VALVE & BOTTOM 10' OF TUBING. START NEXT PUMPING HIGHER IN SCREEN. |            |             |            |                      |                                  |                                  |
| 9:42 AM                         | 2.38          |               | —                                    | PUMP START                   | ✓                           | ✓                              | 604.05                                                                                                                            | 10.45      | 6.5         | 15.43      | 140.7                | 63.0                             |                                  |
| 9:54 AM                         | 2.38          |               | —                                    | STOP 0.833                   | 10.0                        | 10.33                          | 604.05                                                                                                                            | 10.25      | 6.5         | 15.43      | 140.45               | 63.0                             |                                  |
| 10:10 AM                        | 2.38          |               | —                                    | PUMP START                   |                             |                                |                                                                                                                                   |            |             |            |                      |                                  |                                  |
| 10:20                           | 2.38          | 59.68         | —                                    | STOP 0.833                   | 10                          | 20.33                          | 1128.7                                                                                                                            | 10.21      | 6.51        | 15.2       | 151.4                | 118.6                            |                                  |

PID Photo Ionization Device  
DTW Depth to Water  
DTS Depth to Sediment

PPM Parts Per Million  
BMP Below Measuring Point  
AGS Above Ground Surface

ft/min feet per minute  
gal gallons  
mL/min milliliters per minute

Pamet River, Truro, MA  
Well Development/Re-Development Record

PURGE VOLUME NEEDED FOR 3 VOLS  
@ 150'-151' COLUMN =  
1.63 GAL/10FT \* (5) 10' = 24.45  
GALS

|                                                                                   |                  |                                       |                                   |                              |                                   |         |
|-----------------------------------------------------------------------------------|------------------|---------------------------------------|-----------------------------------|------------------------------|-----------------------------------|---------|
|  | Development Date | 1-26-2017                             | PID (PPM)                         |                              | Well Name                         | PW-3D   |
|                                                                                   | Development Crew | A. McAVOY<br>C. SCABIA                | Ambient Air                       | 43                           | Protective Casing Height (ft AGS) |         |
|                                                                                   |                  |                                       | Before Development @ Well Opening |                              | Measuring Point Height (ft AGS)   |         |
|                                                                                   |                  |                                       | After Development @ Well Opening  |                              | Well Depth (ft BMP)               | 153.15' |
| Gallons Purged                                                                    | 25 (1 VOLUME)    | Pre-Development Wellhead Photo (Y/N)? | Y                                 | Casing Diameter (in)         | 2" PVC, 4" CSG                    |         |
| Gallons Added                                                                     | 0                | Pre-Development Wellhead Photo (Y/N)? | Y                                 | Screen/Open Hole Length (ft) | 5'                                |         |
| Ft Sediment Removed                                                               | 0                | Post Development Sampling (Y/N)?      | Y                                 | DTW, Initial (ft BMP)        | 2.63'                             |         |
| Hard Bottom (Y/N)?                                                                | N                |                                       |                                   | DTS, Initial (ft BMP)        |                                   |         |

GALS  
x 3  
= 75  
GALS

| Redevelopment Goal                                          | Measurements and Criteria                                                                      | Achieved? | Field Notes (development method used, changes in water color, sediment size and minerals, sheens, odors, floc, well behavior, equipment or decon issues, IDW disposition): |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Verify well bottom is not debris or damage                  | Cased and screened wells - weighted sounder.                                                   | Y         | Samples taken 1/26 were analyzed on 1/27 @ 0843-08:50                                                                                                                      |
| Remove accumulated bottom sediment and/or debris            | Total depth is the same as that measured by geophysical logging or verified well construction. | Y         |                                                                                                                                                                            |
| Remove stagnant water and other materials from the well     | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Water is representative of the aquifer                      | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Re-establish a good hydraulic connection with the formation | Specific capacity/recovery rate measurements are <10% between 3 successive measurements.       |           |                                                                                                                                                                            |

| 2013 Dev-Final Results             |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|------------------------------------|---------------|---------------|--------------------------------------|-------------------------------|-----------------------------|--------------------------------|------------------|------------|-------------|------------|----------------------|----------------------------------|----------------------------------|
| Date / Time<br>dd-mm-yy / 00:00    | DTW<br>ft BMP | DTS<br>ft BMP | Make-Up<br>Water<br>Added<br>gallons | Purge Rate<br>(gal) or ml/min | Volume<br>Purged<br>gallons | Total Vol<br>Purged<br>gallons | Turbidity<br>NTU | Temp<br>°C | pH<br>units | DO<br>mg/L | Field<br>RedOx<br>mV | Specific<br>Conductance<br>mS/cm | Recovery<br>Rate<br>ft/min or hr |
| 4:23PM                             | 2.63          |               | /                                    | PUMP<br>START                 | /                           | /                              | 289.7            | 5.01       | 5.34        | 16.91      | 83.92                |                                  | ⑦                                |
| 4:34                               | 2.63          |               | /                                    | STOP<br>1.04                  | 12.5                        | 12.5                           |                  |            |             |            |                      |                                  | ②                                |
| NOTE SAMPLE #2 MUCH CLEARER        |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
| 4:38                               | 2.63          | /             | /                                    | PUMP<br>START                 | /                           | /                              | 3.37             | 5.06       | 5.19        | 20.2       | 116.07               |                                  | ③                                |
| 4:50                               | 2.63          | /             | /                                    | STOP<br>1.04                  | 12.5                        | 25                             | -0.07            | 5.01       | 5.26        | 19.69      | 117.53               |                                  |                                  |
| SAMPLE #3 VERY CLEAR               |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
| NOTE ALSO PRE & POST DTW WERE SAME |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                    |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |

SAMPLE #

PID Photo Ionization Device  
DTW Depth to Water  
DTS Depth to Sediment

PPM Parts Per Million  
BMP Below Measuring Point  
AGS Above Ground Surface

ft/min feet per minute  
gal gallons  
mL/min milliliters per minute

Pamet River, Truro, MA  
Well Development/Re-Development Record

|                                                                                                                                                          |                  |           |                                   |           |                                   |        |
|----------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|-----------|-----------------------------------|-----------|-----------------------------------|--------|
|                                                                         | Development Date | 1-26-2017 | PID (PPM)                         | Well Name | PW-4                              |        |
|                                                                                                                                                          | Development Crew | A. McRae  | Ambient Air                       | 40°F      | Protective Casing Height (ft AGS) |        |
|                                                                                                                                                          |                  | C. SCASIA | Before Development @ Well Opening |           | Measuring Point Height (ft AGS)   | 38.56' |
|                                                                                                                                                          |                  |           | After Development @ Well Opening  |           | Well Depth (ft BMP)               |        |
| Gallons Purged <u>18.5</u><br>Gallons Added <u>0.0</u><br>Ft Sediment Removed <u>1.14'</u><br>Hard Bottom (Y/N)? <u>N</u>                                |                  |           |                                   |           |                                   |        |
| Pre-Development Wellhead Photo (Y/N)? <u>Y</u><br>Pre-Development Wellhead Photo (Y/N)? <u>Y</u><br>Post Development Sampling (Y/N)? <u>Y</u>            |                  |           |                                   |           |                                   |        |
| Casing Diameter (in) <u>2" PVC</u><br>Screen/Open Hole Length (ft) <u>5'</u><br>DTW, Initial (ft BMP) <u>2.44</u><br>DTS, Initial (ft BMP) <u>38.56'</u> |                  |           |                                   |           |                                   |        |

| Redevelopment Goal                                          | Measurements and Criteria                                                                      | Achieved? | Field Notes (development method used, changes in water color, sediment size and minerals, sheens, odors, floc, well behavior, equipment or decon issues, IDW disposition): |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Verify well bottom is not debris or damage                  | Cased and screened wells – weighted sounder.                                                   |           | <u>4" OUTER CASING,</u><br><u>2" PVC WELL</u><br><u>PURGE VOLUME FOR</u><br><u>36-37' WATER COLUMN =</u><br><u>1.67' GAL/10' x 3.7 x 3 VOL = 186 GAL</u>                   |
| Remove accumulated bottom sediment and/or debris            | Total depth is the same as that measured by geophysical logging or verified well construction. |           |                                                                                                                                                                            |
| Remove stagnant water and other materials from the well     | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Water is representative of the aquifer                      | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Re-establish a good hydraulic connection with the formation | Specific capacity/recovery rate measurements are <10% between 3 successive measurements.       |           |                                                                                                                                                                            |

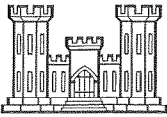
| 2013 Dev-Final Results                        |               |               |                                      |                             |                             |                                |                  |            |             |            |                      |                                  |                                  |
|-----------------------------------------------|---------------|---------------|--------------------------------------|-----------------------------|-----------------------------|--------------------------------|------------------|------------|-------------|------------|----------------------|----------------------------------|----------------------------------|
| Date / Time<br>dd-mm-yy / 00:00               | DTW<br>ft BMP | DTS<br>ft BMP | Make-Up<br>Water<br>Added<br>gallons | Purge Rate<br>gal or ml/min | Volume<br>Purged<br>gallons | Total Vol<br>Purged<br>gallons | Turbidity<br>NTU | Temp<br>°C | pH<br>units | DO<br>mg/L | Field<br>RedOx<br>mV | Specific<br>Conductance<br>mS/cm | Recovery<br>Rate<br>ft/min or hr |
| 5:00 PM                                       | 2.44'         | —             | —                                    | PUMP START                  | —                           | —                              |                  |            |             |            |                      |                                  |                                  |
| 5:10 PM                                       | 7.24'         | —             | —                                    | STOP                        | 3                           | 3                              |                  |            |             |            |                      |                                  |                                  |
| NOTE SURGE BLOCK AT 14.5' DEPTH INADVERTENTLY |               |               |                                      |                             |                             |                                |                  |            |             |            |                      |                                  |                                  |
| 5:15 PM                                       | 6.04'         | —             | —                                    | PUMP START                  | —                           | —                              |                  |            |             |            |                      |                                  |                                  |
| 5:22 PM                                       | 13.2'         | —             | —                                    | STOP                        | 2                           | 5                              |                  |            |             |            |                      |                                  |                                  |
| NOTE SURGE BLOCK AT 14.5' DEPTH INADVERTENTLY |               |               |                                      |                             |                             |                                |                  |            |             |            |                      |                                  |                                  |
| 5:50 PM                                       | 3.36'         | —             | —                                    | PUMP START                  | —                           | —                              |                  |            |             |            |                      |                                  |                                  |
| 5:52 PM                                       | 10.44'        | —             | —                                    | STOP                        | 1.5                         | 6.5                            | 1530.8           | 4.89       | 6.42        | 18.19      | 70.3                 |                                  |                                  |
| FLOW STOPPED, FOOT VALVE PLUGGED, CLEARED     |               |               |                                      |                             |                             |                                |                  |            |             |            |                      |                                  |                                  |
| 6:02 PM                                       | 6.10'         | —             | —                                    | PUMP START                  | —                           | —                              |                  |            |             |            |                      |                                  |                                  |
| 6:07 PM                                       | N/A           | —             | —                                    | STOP                        | 2                           | 8.5                            | 1536.17          | 5.31       | 9.55        | 18.08      | 91.57                |                                  |                                  |
| FLOW STOPPED, FOOT VALVE PLUGGED, CLEARED     |               |               |                                      |                             |                             |                                |                  |            |             |            |                      |                                  |                                  |
| 6:19 PM                                       | 6.28'         | —             | —                                    | PUMP START                  | —                           | —                              |                  |            |             |            |                      |                                  |                                  |
| 6:49 PM                                       | 9.88'         | 39.7'         | —                                    | STOP                        | 10                          | 18.5                           | 272.32           | 5.24       | 6.70        | 16.62      | 105.87               |                                  |                                  |

PID Photo Ionization Device  
DTW Depth to Water  
DTS Depth to Sediment

PPM Parts Per Million  
BMP Below Measuring Point  
AGS Above Ground Surface

ft/min feet per minute  
gal gallons  
mL/min milliliters per minute

Pamet River, Truro, MA  
Well Development/Re-Development Record

|                                                                                   |                                   |                        |                                       |                                 |                                   |       |        |
|-----------------------------------------------------------------------------------|-----------------------------------|------------------------|---------------------------------------|---------------------------------|-----------------------------------|-------|--------|
|  | Development Date                  | 1-27-2017              | PID (PPM)                             |                                 | Well Name                         | TRU-7 |        |
|                                                                                   | Development Crew                  | A. McAvoy<br>C. Scasia | Ambient Air                           | 45F                             | Protective Casing Height (ft AGS) | 1.7'  |        |
|                                                                                   | Before Development @ Well Opening |                        |                                       | Measuring Point Height (ft AGS) |                                   |       | 1.7'   |
|                                                                                   | After Development @ Well Opening  |                        |                                       | Well Depth (ft BMP)             |                                   |       | 14.95' |
| Gallons Purged                                                                    |                                   | 12.5                   | Pre-Development Wellhead Photo (Y/N)? |                                 | Y                                 |       |        |
| Gallons Added                                                                     |                                   | 0.0                    | Pre-Development Wellhead Photo (Y/N)? |                                 | Y                                 |       |        |
| Ft Sediment Removed                                                               |                                   | 0.06                   | Post Development Sampling (Y/N)?      |                                 | Y                                 |       |        |
| Hard Bottom (Y/N)?                                                                |                                   | N                      |                                       |                                 |                                   |       |        |

| Redevelopment Goal                                          | Measurements and Criteria                                                                      | Achieved? | Field Notes (development method used, changes in water color, sediment size and minerals, sheens, odors, floc, well behavior, equipment or decon issues, IDW disposition): |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Verify well bottom is not debris or damage                  | Cased and screened wells – weighted sounder.                                                   |           | <p>2" PVC WELL, NO METAL CASING.</p> <p>PURGE VOLUME = 3 X</p> <p>8.32' COLUMN X 1.63 GAL/10' = 4.07 GAL</p>                                                               |
| Remove accumulated bottom sediment and/or debris            | Total depth is the same as that measured by geophysical logging or verified well construction. |           |                                                                                                                                                                            |
| Remove stagnant water and other materials from the well     | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Water is representative of the aquifer                      | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Re-establish a good hydraulic connection with the formation | Specific capacity/recovery rate measurements are <10% between 3 successive measurements.       |           |                                                                                                                                                                            |

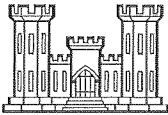
| 2013 Dev-Final Results                      |               |               |                                      |                                      |                             |                                |                  |            |             |            |                      |                                  |                                                  |
|---------------------------------------------|---------------|---------------|--------------------------------------|--------------------------------------|-----------------------------|--------------------------------|------------------|------------|-------------|------------|----------------------|----------------------------------|--------------------------------------------------|
| Date / Time<br>dd-mm-yy / 00:00             | DTW<br>ft BMP | DTS<br>ft BMP | Make-Up<br>Water<br>Added<br>gallons | Purge Rate<br>gal or ml/min          | Volume<br>Purged<br>gallons | Total Vol<br>Purged<br>gallons | Turbidity<br>NTU | Temp<br>°C | pH<br>units | DO<br>mg/L | Field<br>RedOx<br>mV | Specific<br>Conductance<br>mS/cm | Recovery<br>Rate<br>ft/min or hr                 |
| 1:20 PM                                     | 6.63          |               | —                                    | PUMP START                           | —                           | —                              | 1341.86          | 8.21       | 6.32        | 17.93      | 201.11               | 11598.8                          | 175 GAL                                          |
| NOTE: SAMPLE ① TAKEN AT 0.75 GAL            |               |               |                                      |                                      |                             |                                |                  |            |             |            |                      |                                  |                                                  |
| 1:29 PM                                     |               |               | —                                    | CONTINUOUS<br>0.271 AVG<br>GPM       | 2.5                         | 2.5                            | 1119.5           | 8.41       | 6.35        | 15.73      | 17.87                | 8118.0                           | 175 GAL                                          |
| NOTE: SAMPLE ② TAKEN AT 2.5 GAL             |               |               |                                      |                                      |                             |                                |                  |            |             |            |                      |                                  |                                                  |
| 1:39 PM                                     | 8.75'         |               | —                                    | CONTINUOUS<br>0.2631 AVG             | 5                           | 5                              |                  |            |             |            |                      |                                  | NO SAMPLE, VERY BROWN & SANDY SO EXTRA 5 GALLONS |
| 1:53 PM                                     | 8.40'         | 15.0'         | —                                    | STOP-DONE<br>0.378<br>GPM TOTAL AVG. | 7.5                         | 12.5                           | 844.92           | 8.75       | 6.36        | 15.13      | -36.62               | 10001.75                         | 175 GAL                                          |
| NOTE: SAMPLE ③ TAKEN AT 12.5 GALLONS PURGED |               |               |                                      |                                      |                             |                                |                  |            |             |            |                      |                                  |                                                  |
|                                             |               |               |                                      |                                      |                             |                                |                  |            |             |            |                      |                                  |                                                  |
|                                             |               |               |                                      |                                      |                             |                                |                  |            |             |            |                      |                                  |                                                  |
|                                             |               |               |                                      |                                      |                             |                                |                  |            |             |            |                      |                                  |                                                  |
|                                             |               |               |                                      |                                      |                             |                                |                  |            |             |            |                      |                                  |                                                  |
|                                             |               |               |                                      |                                      |                             |                                |                  |            |             |            |                      |                                  |                                                  |
|                                             |               |               |                                      |                                      |                             |                                |                  |            |             |            |                      |                                  |                                                  |

PID Photo Ionization Device  
DTW Depth to Water  
DTS Depth to Sediment

PPM Parts Per Million  
BMP Below Measuring Point  
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ft/min feet per minute  
gal gallons  
mL/min milliliters per minute

Pamet River, Truro, MA  
Well Development/Re-Development Record

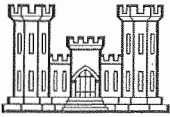
|                                                                                   |                                                |                                           |                                                    |
|-----------------------------------------------------------------------------------|------------------------------------------------|-------------------------------------------|----------------------------------------------------|
|  | Development Date <u>2-2-2017</u>               | PID (PPM)                                 | Well Name <u>USACE-2</u>                           |
|                                                                                   | Development Crew <u>C. SCABIA</u>              | Ambient Air <u>26°F</u>                   | Protective Casing Height (ft AGS) <u>10'</u>       |
|                                                                                   | <u>A. McAVOY</u>                               | Before Development @ Well Opening _____   | Measuring Point Height (ft AGS) <u>Pipe Collar</u> |
|                                                                                   | After Development @ Well Opening _____         | Well Depth (ft BMP) <u>19.80'</u>         |                                                    |
| Gallons Purged _____                                                              | Pre-Development Wellhead Photo (Y/N)? <u>Y</u> | Casing Diameter (in) <u>2" galv. stl.</u> | Screen/Open Hole Length (ft) <u>3'</u>             |
| Gallons Added _____                                                               | Pre-Development Wellhead Photo (Y/N)? _____    | DTW, Initial (ft BMP) <u>13.55'</u>       | DTS, Initial (ft BMP) _____                        |
| Ft Sediment Removed _____                                                         | Post Development Sampling (Y/N)? <u>Y</u>      |                                           |                                                    |
| Hard Bottom (Y/N)? <u>Y</u>                                                       |                                                |                                           |                                                    |

| Redevelopment Goal                                          | Measurements and Criteria                                                                      | Achieved? | Field Notes (development method used, changes in water color, sediment size and minerals, sheens, odors, floc, well behavior, equipment or decon issues, IDW disposition):                                                                                       |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Verify well bottom is not debris or damage                  | Cased and screened wells – weighted sounder.                                                   |           | <u>19.5' pipe (3' st. stl. tip w/ 16' 8 1/2' pcs.)</u><br><u>Driven into sand in intertidal zone</u><br><u>w/ 9.5' below gnd. Lvl. on 2-1-2017</u><br><u>SAUNDER to 19.80' tip to cap collar.</u><br><u>Instrumentation Deployed @ 11:58</u><br><u>on 2-2-17</u> |
| Remove accumulated bottom sediment and/or debris            | Total depth is the same as that measured by geophysical logging or verified well construction. |           |                                                                                                                                                                                                                                                                  |
| Remove stagnant water and other materials from the well     | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                                                                                                                  |
| Water is representative of the aquifer                      | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                                                                                                                  |
| Re-establish a good hydraulic connection with the formation | Specific capacity/recovery rate measurements are <10% between 3 successive measurements.       |           |                                                                                                                                                                                                                                                                  |

| 2013 Dev-Final Results          |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|---------------------------------|---------------|---------------|--------------------------------------|-----------------------------|-----------------------------|--------------------------------|------------------|-------------|-------------|-------------|----------------------|----------------------------------|----------------------------------|
| Date / Time<br>dd-mm-yy / 00:00 | DTW<br>ft BMP | DTS<br>ft BMP | Make-Up<br>Water<br>Added<br>gallons | Purge Rate<br>gal or ml/min | Volume<br>Purged<br>gallons | Total Vol<br>Purged<br>gallons | Turbidity<br>NTU | Temp<br>°C  | pH<br>units | DO<br>mg/L  | Field<br>RedOx<br>mV | Specific<br>Conductance<br>mS/cm | Recovery<br>Rate<br>ft/min or hr |
| <u>2-2-17 / 11:40</u>           | <u>13.55'</u> |               |                                      |                             |                             |                                | <u>1309.1</u>    | <u>2.36</u> | <u>7.99</u> | <u>1.08</u> | <u>-67.87</u>        | <u>42.58</u>                     |                                  |
| <u>2-2-17 / 11:45</u>           |               |               |                                      |                             |                             |                                | <u>1460.97</u>   | <u>2.12</u> | <u>8.18</u> | <u>1.01</u> | <u>-35.55</u>        | <u>43.69</u>                     |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |

|                             |                           |                               |
|-----------------------------|---------------------------|-------------------------------|
| PID Photo Ionization Device | PPM Parts Per Million     | ft/min feet per minute        |
| DTW Depth to Water          | BMP Below Measuring Point | gal gallons                   |
| DTS Depth to Sediment       | AGS Above Ground Surface  | ml/min milliliters per minute |

Pamet River, Truro, MA  
Well Development/Re-Development Record

|                                                                                   |                                             |                                   |                                               |
|-----------------------------------------------------------------------------------|---------------------------------------------|-----------------------------------|-----------------------------------------------|
|  | Development Date <b>2-2-17</b>              | PID (PPM)                         | Well Name <b>C-1</b>                          |
|                                                                                   | Development Crew <b>A. McAVOY</b>           | Ambient Air <b>35°F</b>           | Protective Casing Height (ft AGS) <b>0.9'</b> |
|                                                                                   | <b>C. SCABIA</b>                            | Before Development @ Well Opening | Measuring Point Height (ft AGS) <b>0.7'</b>   |
|                                                                                   | After Development @ Well Opening            | Well Depth (ft BMP) <b>40.23'</b> |                                               |
| Gallons Purged _____                                                              |                                             |                                   | Casing Diameter (in) <b>4" STEEL</b>          |
| Gallons Added _____                                                               | Pre-Development Wellhead Photo (Y/N)? _____ |                                   | Screen/Open Hole Length (ft) <b>5'</b>        |
| Ft Sediment Removed _____                                                         | Pre-Development Wellhead Photo (Y/N)? _____ |                                   | DTW, Initial (ft BMP) <b>29.80'</b>           |
| Hard Bottom (Y/N)? <b>N</b>                                                       | Post Development Sampling (Y/N)? _____      |                                   | DTS, Initial (ft BMP) <b>40.23'</b>           |

| Redevelopment Goal                                          | Measurements and Criteria                                                                      | Achieved? | Field Notes (development method used, changes in water color, sediment size and minerals, sheens, odors, floc, well behavior, equipment or decon issues, IDW disposition): |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Verify well bottom is not debris or damage                  | Cased and screened wells -- weighted sounder.                                                  |           | <b>2" DIA WELL</b><br><b>PURGE VOL = 3 x (40.23 - 29.80) / 1.63 GAL/PER 10' = 5.1 GALLONS TOTAL</b>                                                                        |
| Remove accumulated bottom sediment and/or debris            | Total depth is the same as that measured by geophysical logging or verified well construction. |           |                                                                                                                                                                            |
| Remove stagnant water and other materials from the well     | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Water is representative of the aquifer                      | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Re-establish a good hydraulic connection with the formation | Specific capacity/recovery rate measurements are <10% between 3 successive measurements.       |           |                                                                                                                                                                            |

| 2013 Dev-Final Results                |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|---------------------------------------|---------------|---------------|--------------------------------------|-------------------------------|-----------------------------|--------------------------------|------------------|------------|-------------|------------|----------------------|----------------------------------|----------------------------------|
| Date / Time<br>dd-mmm-yy / 00:00      | DTW<br>ft BMP | DTS<br>ft BMP | Make-Up<br>Water<br>Added<br>gallons | Purge Rate<br>(gal/or ml/min) | Volume<br>Purged<br>gallons | Total Vol<br>Purged<br>gallons | Turbidity<br>NTU | Temp<br>°C | pH<br>units | DO<br>mg/L | Field<br>RedOx<br>mV | Specific<br>Conductance<br>mS/cm | Recovery<br>Rate<br>ft/min or hr |
| <b>SAMPLE ① AFTER 0.5 GAL PURGE ①</b> |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
| 2:40 PM                               | 29.80'        | 40.23'        | —                                    | PUMP START                    | —                           | —                              | 1583.6           | 8.85       | 6.85        | 18.26      | 134.05               | 0.25                             |                                  |
| 2:47 PM                               |               |               |                                      | STOP 0.71                     | 5                           | 5                              |                  |            |             |            |                      |                                  |                                  |
| <b>SAMPLE ② AFTER 5 GAL PURGE ②</b>   |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
| 2:48 PM                               |               |               |                                      | PUMP START                    | —                           | —                              | 1606.7           | 10.61      | 6.56        | 15.99      | 162.7                | 0.23                             |                                  |
| 2:53 PM                               | 29.82'        | 40.21'        | —                                    | STOP 1.0                      | 5                           | 10                             |                  |            |             |            |                      |                                  |                                  |
| <b>SAMPLE ③ AFTER 10 GAL PURGE ③</b>  |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                       |               |               |                                      |                               |                             |                                | 1396.4           | 9.30       | 6.49        | 16.21      | 169.72               | 0.23                             |                                  |
|                                       |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                       |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                       |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                       |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                       |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                       |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                       |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                       |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                       |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |
|                                       |               |               |                                      |                               |                             |                                |                  |            |             |            |                      |                                  |                                  |

SURGE  
BLOCK SET  
SCREEN  
INTERVAL

2-3'

2-3'

SAMPLE  
#

①

②

③

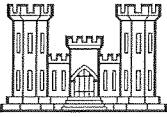
PID Photo Ionization Device  
DTW Depth to Water  
DTS Depth to Sediment

PPM Parts Per Million  
BMP Below Measuring Point  
AGS Above Ground Surface

ft/min feet per minute  
gal gallons  
mL/min milliliters per minute



Pamet River, Truro, MA  
Well Development/Re-Development Record

|                                                                                   |                                                |                                   |                                                    |
|-----------------------------------------------------------------------------------|------------------------------------------------|-----------------------------------|----------------------------------------------------|
|  | Development Date <u>2-3-2017</u>               | PID (PPM)                         | Well Name <u>C-5</u>                               |
|                                                                                   | Development Crew <u>A. McAvoy</u>              | Ambient Air <u>26°F</u>           | Protective Casing Height (ft AGS) <u>1.68' AGS</u> |
|                                                                                   | <u>C. SCASIA</u>                               | Before Development @ Well Opening | Measuring Point Height (ft AGS) <u>1.51' AGS</u>   |
|                                                                                   |                                                | After Development @ Well Opening  | Well Depth (ft BMP) <u>90.27'</u>                  |
| Gallons Purged _____                                                              |                                                |                                   | Casing Diameter (in) <u>2" PVC</u>                 |
| Gallons Added _____                                                               | Pre-Development Wellhead Photo (Y/N)? <u>Y</u> |                                   | Screen/Open Hole Length (ft) <u>5'</u>             |
| Ft Sediment Removed _____                                                         | Pre-Development Wellhead Photo (Y/N)? _____    |                                   | DTW, Initial (ft BMP) <u>77.45'</u>                |
| Hard Bottom (Y/N)? _____                                                          | Post Development Sampling (Y/N)? <u>Y</u>      |                                   | DTS, Initial (ft BMP) <u>88.05'</u>                |

| Redevelopment Goal                                          | Measurements and Criteria                                                                      | Achieved? | Field Notes (development method used, changes in water color, sediment size and minerals, sheens, odors, floc, well behavior, equipment or decon issues, IDW disposition): |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Verify well bottom is not debris or damage                  | Cased and screened wells – weighted sounder.                                                   |           | <u>4" Ø STEEL OUTER CASING</u><br><u>PURGE Vol = 3 x (90.27 - 77.45)</u><br><u>x 1.63 GAL / 10'</u><br><u>= 6.42 GAL</u>                                                   |
| Remove accumulated bottom sediment and/or debris            | Total depth is the same as that measured by geophysical logging or verified well construction. |           |                                                                                                                                                                            |
| Remove stagnant water and other materials from the well     | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Water is representative of the aquifer                      | Field water quality parameter changes become less than 10% between 3 successive measurements.  |           |                                                                                                                                                                            |
| Re-establish a good hydraulic connection with the formation | Specific capacity/recovery rate measurements are <10% between 3 successive measurements.       |           |                                                                                                                                                                            |

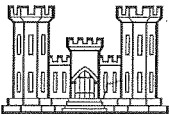
| 2013 Dev-Final Results          |               |               |                                      |                             |                             |                                |                  |             |             |              |                      |                                  |                                  |
|---------------------------------|---------------|---------------|--------------------------------------|-----------------------------|-----------------------------|--------------------------------|------------------|-------------|-------------|--------------|----------------------|----------------------------------|----------------------------------|
| Date / Time<br>dd-mm-yy / 00:00 | DTW<br>ft BMP | DTS<br>ft BMP | Make-Up<br>Water<br>Added<br>gallons | Purge Rate<br>gal or ml/min | Volume<br>Purged<br>gallons | Total Vol<br>Purged<br>gallons | Turbidity<br>NTU | Temp<br>°C  | pH<br>units | DO<br>mg/L   | Field<br>RedOx<br>mV | Specific<br>Conductance<br>mS/cm | Recovery<br>Rate<br>ft/min or hr |
| <u>8:40 AM</u>                  | <u>77.45</u>  | <u>88.05</u>  | <u>—</u>                             | <u>PUMP START</u>           | <u>—</u>                    | <u>—</u>                       |                  |             |             |              |                      |                                  |                                  |
|                                 |               | <u>NO GO</u>  |                                      |                             |                             |                                |                  |             |             |              |                      |                                  |                                  |
| <u>9:30 AM</u>                  | <u>77.45</u>  | <u>—</u>      | <u>—</u>                             | <u>PUMP START</u>           | <u>—</u>                    | <u>—</u>                       | <u>1508.82</u>   | <u>3.10</u> | <u>6.62</u> | <u>13.43</u> | <u>176.27</u>        | <u>0.52</u>                      |                                  |
| <u>9:37 AM</u>                  |               | <u>—</u>      | <u>—</u>                             | <u>STOP</u>                 | <u>5</u>                    | <u>5</u>                       |                  |             |             |              |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |              |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                | <u>1512.52</u>   | <u>3.41</u> | <u>6.65</u> | <u>10.16</u> | <u>182.60</u>        | <u>0.15</u>                      |                                  |
| <u>9:40 AM</u>                  | <u>77.45</u>  | <u>—</u>      | <u>—</u>                             | <u>PUMP START</u>           | <u>—</u>                    |                                |                  |             |             |              |                      |                                  |                                  |
| <u>9:47 AM</u>                  | <u>77.43</u>  | <u>88.05</u>  |                                      | <u>STOP</u>                 | <u>5</u>                    | <u>10</u>                      |                  |             |             |              |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |              |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                | <u>1512.52</u>   | <u>3.24</u> | <u>6.58</u> | <u>10.81</u> | <u>186.3</u>         | <u>0.15</u>                      |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |              |                      |                                  |                                  |
|                                 |               |               |                                      |                             |                             |                                |                  |             |             |              |                      |                                  |                                  |

PID Photo Ionization Device  
DTW Depth to Water  
DTS Depth to Sediment

PPM Parts Per Million  
BMP Below Measuring Point  
AGS Above Ground Surface

ft/min feet per minute  
gal gallons  
mL/min milliliters per minute

**Pamet River, Truro, MA**  
**Well Development/Re-Development Record**

|                                                                                   |                                                |                                            |                                                   |
|-----------------------------------------------------------------------------------|------------------------------------------------|--------------------------------------------|---------------------------------------------------|
|  | Development Date <u>2-3-2017</u>               | PID (PPM) _____                            | Well Name <u>TLCF-005</u>                         |
|                                                                                   | Development Crew <u>A. McNulty</u>             | Ambient Air <u>30</u>                      | Protective Casing Height (ft AGS) <u>1.03 AGS</u> |
|                                                                                   | <u>C. SCABIA</u>                               | Before Development @ Well Opening _____    | Measuring Point Height (ft AGS) <u>1.03 AGS</u>   |
| Gallons Purged <u>17</u>                                                          |                                                | Well Depth (ft BMP) <u>9.80'</u>           | Casing Diameter (in) <u>1" PVC NY STEEL</u>       |
| Gallons Added <u>17</u>                                                           | Pre-Development Wellhead Photo (Y/N)? <u>1</u> | Screen/Open Hole Length (ft) <u>EST 2'</u> | DTW, Initial (ft BMP) <u>1.18'</u>                |
| Ft Sediment Removed <u>ULN</u>                                                    | Pre-Development Wellhead Photo (Y/N)? _____    | DTW, Initial (ft BMP) <u>9.80'</u>         |                                                   |
| Hard Bottom (Y/N)? <u>(-)-</u>                                                    | Post Development Sampling (Y/N)? <u>Y</u>      |                                            |                                                   |

| Redevelopment Goal                                          | Measurements and Criteria                                                                      | Achieved | Field Notes (development method used, changes in water color, sediment size and minerals, sheens, odors, floe, well behavior, equipment or decon issues, IDW disposition):                                                      |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Verify well bottom is not debris or damage                  | Cased and screened wells - weighted sounder.                                                   |          | <u>1" PVC, force Vol = 11 ft x 3 Vols</u><br>$\text{Vol.} = (-3) \times \pi \left(\frac{1}{12}\right)^2 \times \left(\frac{144}{144}\right) \times (9.80 - 1.18) \times 7.48 \frac{\text{GAL}}{\text{ft}^3} = 1.05 \text{ GAL}$ |
| Remove accumulated bottom sediment and/or debris            | Total depth is the same as that measured by geophysical logging or verified well construction. |          |                                                                                                                                                                                                                                 |
| Remove stagnant water and other materials from the well     | Field water quality parameter changes become less than 10% between 3 successive measurements.  |          |                                                                                                                                                                                                                                 |
| Water-s-representative aquifer                              | Field water quality parameter changes become less than 10% between 3 successive measurements.  |          |                                                                                                                                                                                                                                 |
| Re-establish a good hydraulic connection with the formation | Specific capacity/recovery rate measurements are <10% between 3 successive measurements.       |          |                                                                                                                                                                                                                                 |

| 2013 Dev-Final Results                         |                      |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
|------------------------------------------------|----------------------|---------------|--------------------------------------|-----------------------------|-----------------------------|--------------------------------|------------------|-------------|-------------|-------------|----------------------|----------------------------------|----------------------------------|
| Date /Time<br>dd-mm-yy / oo:00                 | DTW<br>ft BMP        | DTS<br>ft BMP | Make-Up<br>Water<br>Added<br>gallons | Purge Rate<br>gal or ml/min | Volume<br>Purged<br>gallons | Total Vol<br>Purged<br>gallons | Turbidity<br>NTU | Temp<br>°C  | pH<br>units | DO<br>mg/L  | Field<br>RedOx<br>mV | Specific<br>Conductance<br>mS/cm | Recovery<br>Rate<br>ft/min or hr |
| <u>11:30 AM</u>                                | <u>1.18</u>          |               |                                      | <u>HAND PUMP START</u>      | <u>0.33</u>                 | <u>0.33</u>                    | <u>40.05</u>     | <u>5.0</u>  | <u>7.20</u> | <u>1.95</u> | <u>-228.8</u>        | <u>2.59</u>                      |                                  |
| <u>11:33 AM</u>                                | <u>9.55</u>          |               |                                      | <u>STOP</u>                 | <u>0.11</u>                 |                                |                  |             |             |             |                      |                                  |                                  |
| <u>11:47 AM</u>                                | <u>5.10</u>          |               | <u>0.5</u>                           | <u>HAND PUMP START</u>      |                             |                                |                  |             |             |             |                      |                                  |                                  |
| <u>11:49 AM</u>                                | <u>9.8 (dry)</u>     |               |                                      | <u>STOP</u>                 | <u>0.25</u>                 | <u>0.5</u>                     | <u>0.83</u>      |             |             |             |                      |                                  |                                  |
| <u>11:51 AM</u>                                | <u>0.8</u>           |               | <u>0.39</u>                          | <u>HAND PUMP START</u>      |                             |                                |                  |             |             |             |                      |                                  |                                  |
| <u>11:53 AM</u>                                | <u>9.5-9.7 (dry)</u> |               |                                      | <u>STOP</u>                 | <u>0.39</u>                 | <u>1.22</u>                    |                  |             |             |             |                      |                                  |                                  |
| <u>SAMPLE ② TAKEN FROM TOP OF PURGE BUCKET</u> |                      |               |                                      |                             |                             |                                |                  |             |             |             |                      |                                  |                                  |
| <u>12:01 PM</u>                                | <u>0.1'</u>          |               | <u>0.39</u>                          | <u>HAND PUMP START</u>      |                             |                                |                  |             |             |             |                      |                                  |                                  |
| <u>12:04 PM</u>                                | <u>dry</u>           |               |                                      | <u>PUMP STOP</u>            | <u>0.39</u>                 | <u>1.61</u>                    | <u>745.97</u>    | <u>37.6</u> | <u>7.82</u> | <u>6.99</u> | <u>-140.67</u>       | <u>0.46</u>                      |                                  |
| <u>12:08</u>                                   | <u>0.1'</u>          |               | <u>0.39</u>                          | <u>HAND PUMP START</u>      |                             |                                |                  |             |             |             |                      |                                  |                                  |
|                                                | <u>9.53'</u>         |               |                                      | <u>STOP</u>                 | <u>0.39</u>                 | <u>2.00</u>                    |                  |             |             |             |                      |                                  |                                  |

PID Photo Ionization Device  
 DTW Depth to Water  
 DTS Depth to Sediment

PPM Parts Per Million  
 BMP Below Measuring Point  
 AGS Above Ground Surface

ft/min feet per minute  
 gal gallons  
 ml/min milliliters per minute

**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT B**

**GROUNDWATER INSTRUMENTATION**

**WELL LOGGER DATA**

**FIGURES B-17 to B-18**

**REFERENCED FROM: CHAPTER 5**

**(2016-18 PAMET RIVER FIELD DATA INSTRUMENTATION, COLLECTION,  
VALIDATION AND *QUALITATIVE ANALYSIS*)**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

**PAMET RIVER WELL LOGGER DEPLOYMENT SCHEDULE JAN-FEB 2017**

**LEVEL MEASUREMENT**

| WELL ID   | LOGGER SOURCE         | LOGGER NAME/ID              | LOGGER S/N | LOGGER RANGE | MEASUREMENT INTERVAL | DEPLOYMENT DATE | DEPLOYMENT TIME | DEPLOYMENT CABLE LENGTH (B.T.O.R) | RISER EL (NAVD '88) | DEPTH TO WATER (At Deployment) |
|-----------|-----------------------|-----------------------------|------------|--------------|----------------------|-----------------|-----------------|-----------------------------------|---------------------|--------------------------------|
| Barometer | National Park Service | Baro (placed in well TRU-7) | 9738929    | 0-30 FT      | 15 MIN.              | 1/27/2017       | 1415 hrs        | 3.0 ft                            |                     | N/A                            |
| TRU-5D    | National Park Service | TRU-5D (PR-1)               | 10375996   | 0-30 FT      | 15 MIN.              | 1/26/2017       | 1345 hrs        | 25 ft                             |                     | 2.37 ft                        |
| PW-3D     | National Park Service | PW-3D (PR-2)                | 1137045    | 0-30 FT      | 15 MIN.              | 1/27/2017       | 1020 hrs        | 25 ft                             |                     | 2.77 ft                        |
| PW-4      | National Park Service | PW-4 (PR-3)                 | 1146251    | 0-30 FT      | 15 MIN.              | 1/27/2017       | 1025 hrs        | 25 ft                             |                     | 2.43 ft                        |
| TRU-7     | National Park Service | TRU-7 (PR-4)                | 10483672   | 0-30 FT      | 15 MIN.              | 1/27/2017       | 1415 hrs        | 12 ft                             |                     | 8.51 ft                        |
| TLF-005   | National Park Service | TLF-005 (PR-5)              | 1146250    | 0-30 FT      | 15 MIN.              | 2/3/2017        | 1200 hrs        | 9.0 ft                            |                     | 9.53 ft                        |
| TRU-5S    | CORPS                 | TRU-5S                      | 20029117   | 0-13 FT      | 15 MIN.              | 1/26/2017       | 1245 hrs        | 10 ft                             |                     | N/A                            |
| USACE-1   | CORPS                 | USACE-1                     | 20029120   | 0-13 FT      | 15 MIN.              | 1/26/2017       | 1515 hrs        | (12.77< bolt) 13 ft               |                     | (4.71< bolt) 4.94              |
| USACE-2   | CORPS                 | USACE-2                     | 20029118   | 0-13 FT      | 15 MIN.              | 2/2/2017        | 1155 hrs        | 16.5 ft                           |                     | 13.55 ft (1140 hrs)            |
| C-5       | CORPS                 | C-5                         | 20049592   | 0-100 FT     | 15 MIN.              | 2/3/2017        | 1030 hrs        | 85.55 ft                          |                     | 77.43 ft                       |
| C-1       | CORPS                 | ** C-1                      | 20049591   | 0-100 FT     | 15 MIN.              | 2/3/2017        | 1100 hrs        | 35.23 ft                          |                     | 29.82 ft                       |

**CONDUCTANCE MEASUREMENT**

| WELL ID | LOGGER SOURCE         | LOGGER NAME/ID   | LOGGER S/N | LOGGER RANGE | MEASUREMENT INTERVAL | DEPLOYMENT DATE | DEPLOYMENT TIME | DEPLOYMENT CABLE LENGTH (B.T.O.R) | RISER EL (NAVD '88) | DEPTH TO WATER (At Deployment) |
|---------|-----------------------|------------------|------------|--------------|----------------------|-----------------|-----------------|-----------------------------------|---------------------|--------------------------------|
| TRU-5D  | National Park Service | TRU-5D (PR-1)    | 10523361   | 0-100 FT     | 15 MIN.              | 1/26/2017       | 1315 hrs        | 5.68 ft                           |                     | 2.37 ft                        |
| PW-3D   | National Park Service | PW-3D (PR-2)     | 10104813   | 0-100 FT     | 15 MIN.              | 1/27/2017       | 1020 hrs        | 150.15 ft                         |                     | 2.77 ft                        |
| PW-4    | National Park Service | PW-4 (PR-3)      | 10104812   | 0-100 FT     | 15 MIN.              | 1/27/2017       | 1025 hrs        | 35.56 ft                          |                     | 2.43 ft                        |
| TRU-7   | National Park Service | TRU-7 (PR-4)     | 10150102   | 0-100 FT     | 15 MIN.              | 1/27/2017       | 1415 hrs        | 13 ft                             |                     | 8.51 ft                        |
| USACE-2 | National Park Service | * USACE-2 (PR-5) | 10150101   | 0-100 FT     | 15 MIN.              | 2/2/2017        | 1155 hrs        | 17.5 ft (B.T.O.T.)                |                     | 13.55 FT                       |
|         |                       |                  |            |              |                      |                 |                 |                                   |                     |                                |

**NOTES:**

1. Depth Loggers use Red Cord (Corps & NPS)
2. Conductance Loggers use Orange Cord (Just NPS)
3. At 15 MIN., HOBO Loggers have 226 days capacity
4. Conductance Loggers all placed 2 ft or 3 ft Above Screen Bottom, as noted
5. 'B.T.O.T.' = Below Top Of Threads; 'B.T.O.R.' = Below Top Of Riser on 2" Galv. Pipes on USACE-1 & USACE-2
6. \* USACE-2 Shows ONLY 132 days of logging capacity, therefore, retrieve data in 4 months' time
7. \* \* Prior to S/N 20049591 install, NPS Logger PR\_5, S/N 1146250 was placed in C-1 on 2/2/2017(DTW = 29.8 ft), however, it was needed for TLF-005 (small diameter) put into service w/CL 35.23 ft at 1540 hrs.

**FIGURE B-17**



## HOBO® Conductivity Loggers

Conductivity monitoring for freshwater and stable saltwater applications

HOBO Conductivity Loggers are convenient, rugged, and cost-effective data loggers for a variety of freshwater and saltwater monitoring applications.



The HOBO U24-001 model provides high-accuracy conductivity data in freshwater environments, for applications such as environmental impact monitoring, stormwater management, and water quality studies.

The HOBO U24-002-C model is for saltwater environments with relatively small changes in salinity ( $\pm 5,000 \mu\text{S/cm}$ ) such as saltwater bays, or to detect salinity events such as upwelling, rainstorm, and discharge events. This logger can also be used to gather salinity data for salinity compensation of HOBO U26 Dissolved Oxygen logger data. **Note:** This logger is not intended for monitoring salinity levels in waters with widely changing salinities as it can have significant measurement error and drift in those environments.

**Supported Measurements:** Conductivity, Salinity, Temperature

### Key Advantages:

- Non-contact capacitive sensor provides long life
- Easy access to sensor for cleaning and shedding air bubbles
- HOBOWare Pro software provides compensation for fouling using calibration points from the start and end of each deployment
- Optical interface provides high-speed, reliable data offload in wet environments
- Compatible with HOBO Waterproof Shuttle for easy and reliable data retrieval

### Minimum System Requirements:



Software



Base Station\*



Coupler<sup>1</sup>

\*HOBO Base Station or HOBO Waterproof Shuttle required.

<sup>1</sup>Coupler included with HOBO Base Station or HOBO Waterproof Shuttle.

► For complete information and accessories, please visit: [www.onsetcomp.com](http://www.onsetcomp.com)

| Part number                                                                                                   | U24-001 Conductivity                                                                                                                                            | U24-002-C Conductivity/Salinity                                                                                                                                                                                                  |
|---------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Memory                                                                                                        | 18,500 temperature and conductivity measurements when using one conductivity range; 14,400 sets of measurements when using both conductivity ranges (64 kbytes) |                                                                                                                                                                                                                                  |
| Conductivity Calibrated Measurement Ranges                                                                    | Low Range: 0 to 1,000 $\mu\text{S/cm}$<br>Full Range: 0 to 10,000 $\mu\text{S/cm}$                                                                              | Low Range: 100 to 10,000 $\mu\text{S/cm}$<br>High Range: 5,000 to 55,000 $\mu\text{S/cm}$                                                                                                                                        |
| Conductivity Calibrated Range – Temperature Range                                                             | 5° to 35°C (41° to 95°F)                                                                                                                                        |                                                                                                                                                                                                                                  |
| Specific Conductance Accuracy (in Calibrated Range using Conductivity Assistant and Calibration Measurements) | Low Range: 3% of reading, or 5 $\mu\text{S/cm}$<br>Full Range: 3% of reading, or 20 $\mu\text{S/cm}$ , whichever is greater                                     | Low Range: 3% of reading or 50 $\mu\text{S/cm}$ , whichever is greater<br>High Range: 5% of reading, in waters within a range of $\pm 3,000 \mu\text{S/cm}$ ; waters with greater variation can have substantially greater error |
| Conductivity Resolution (typical)                                                                             | 1 $\mu\text{S/cm}$                                                                                                                                              | 2 $\mu\text{S/cm}$                                                                                                                                                                                                               |
| Conductivity Drift                                                                                            | Less than 3% sensor drift per year                                                                                                                              | Up to 12% sensor drift per month. Use monthly start & end-point calibration to compensate                                                                                                                                        |
| Temperature Accuracy (in Calibrated Range)                                                                    | 0.1°C (0.2°F)                                                                                                                                                   |                                                                                                                                                                                                                                  |
| Temperature Resolution                                                                                        | 0.01°C (0.02°F)                                                                                                                                                 |                                                                                                                                                                                                                                  |
| Response Time                                                                                                 | 1 second to 90% of change (in water)                                                                                                                            |                                                                                                                                                                                                                                  |
| Measurement and Operating Range                                                                               | 0° to 36°C (32° to 97°F) -non-freezing                                                                                                                          | -2° to 36°C (28° to 97°F) -non-freezing                                                                                                                                                                                          |
| Sample rate                                                                                                   | 1 second to 18 hrs, fixed or multiple-rate sampling with up to 8 user-defined sampling intervals                                                                |                                                                                                                                                                                                                                  |
| Time Accuracy                                                                                                 | $\pm 1$ minute per month                                                                                                                                        |                                                                                                                                                                                                                                  |
| Battery                                                                                                       | 3.6 Volt lithium battery, life: 3 years (at 1 minute logging), typical                                                                                          |                                                                                                                                                                                                                                  |
| Maximum Depth                                                                                                 | 70 m (225 ft)                                                                                                                                                   |                                                                                                                                                                                                                                  |
| Dimensions                                                                                                    | 3.18 cm diameter x 16.5 cm, with 6.3 mm mounting hole (1.25 in diameter x 6.5", ¼ in hole)                                                                      |                                                                                                                                                                                                                                  |
| CE compliant                                                                                                  | Yes                                                                                                                                                             |                                                                                                                                                                                                                                  |

## Contact Us

Sales (8am to 5pm ET, Monday through Friday)

- Email [sales@onsetcomp.com](mailto:sales@onsetcomp.com)
- Call 1-508-759-9500
- In U.S. toll free 1-800-564-4377
- Fax 1-508-759-9100

Technical Support (8am to 8pm ET, Monday through Friday)

- Contact Product Support [onsetcomp.com/support/contact](http://onsetcomp.com/support/contact)
- Call 1-508-759-9500
- In U.S. toll free 1-877-564-4377

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Bourne, MA 02532



**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT C**  
**RECORDED FIELD DATA FIGURES**  
**GROUNDWATER DATA (FIG. C-1 to C-50)**  
**&**  
**TIDAL DATA (FIG. C-51 to C-65)**

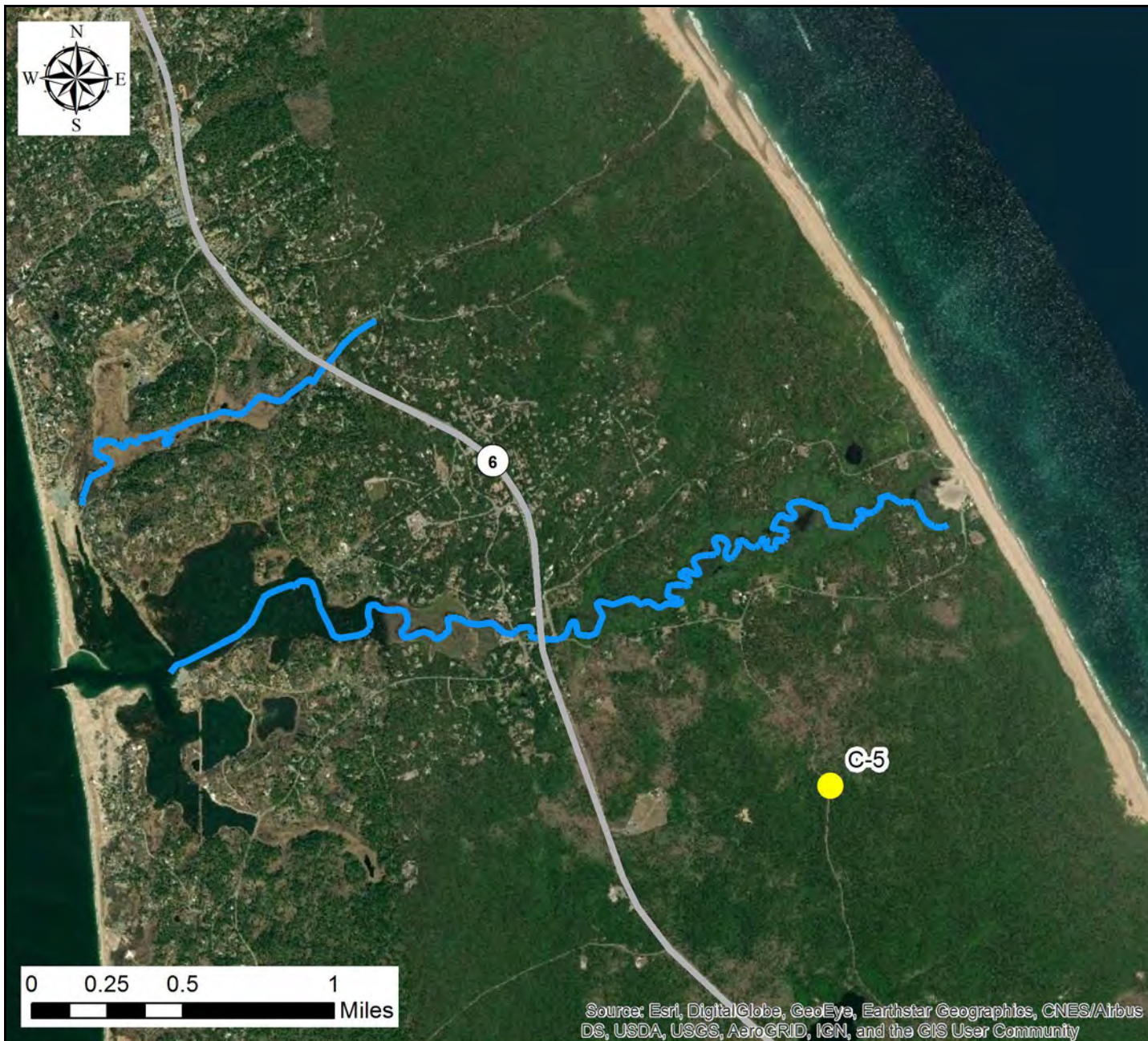
**REFERENCED FROM: CHAPTER 5**

**(2016-18 PAMET RIVER FIELD DATA INSTRUMENTATION, COLLECTION  
VALIDATION AND *QUALITATIVE ANALYSIS*)**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**



**Notes:**

Well C-5 is located about 0.85 miles south of the Pamet River on the ocean side of the Cape Cod Peninsula. The ground surface at this location is approximately 70 ft above NAVD88. The depth of this well is 90 ft.

No survey data was available for this well, so this map shows only the approximate location based on figures in other reports.

**Data Sources:**

ESRI  
USGS National Hydrography Dataset (NHD)  
USGS Small-scale Dataset Major Roads of the United States



WELL C-5 Approximate Location

Figure C-1





**Notes:**

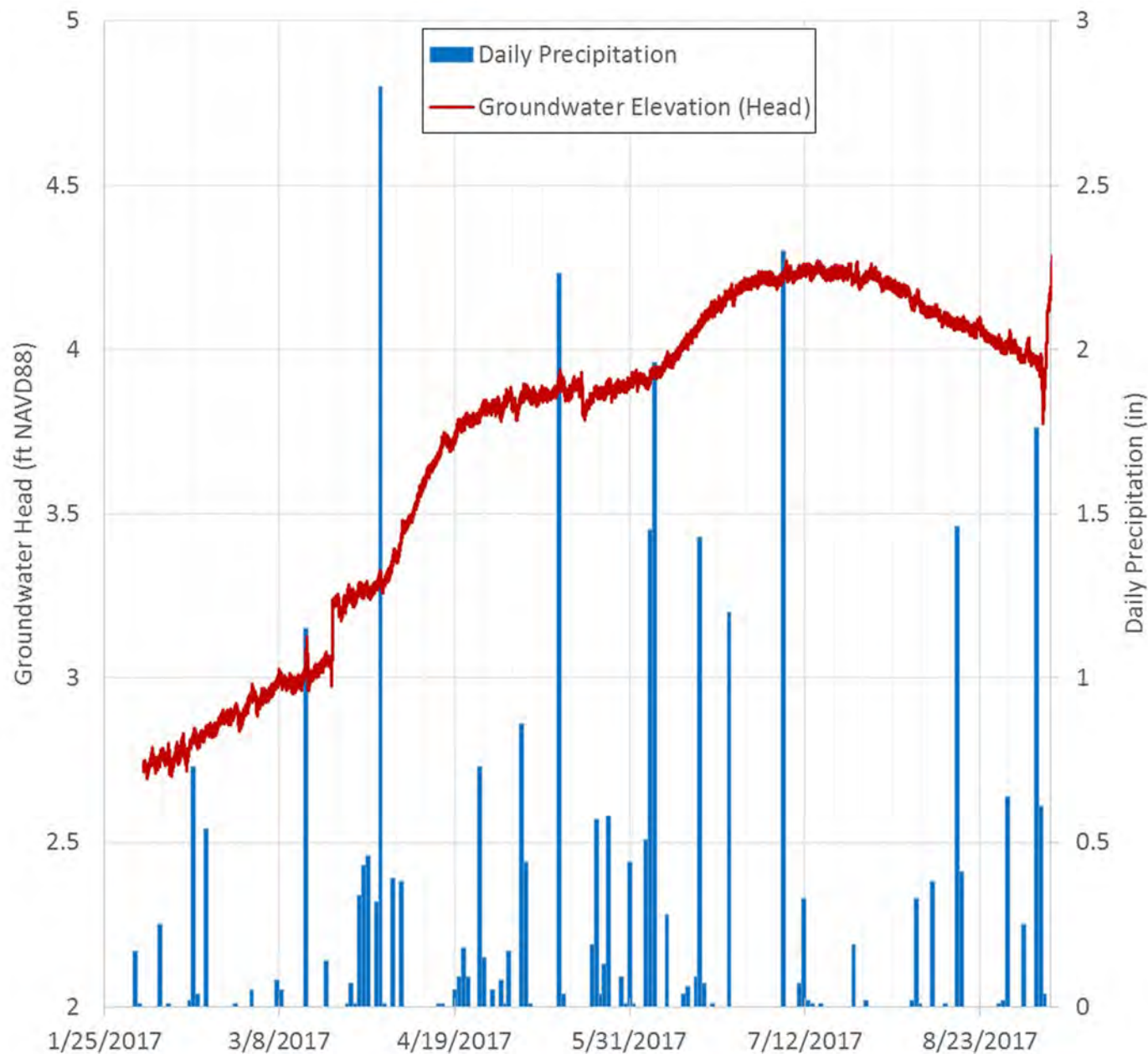
Well C-5 is located about 0.85 miles south of the Pamet River on the ocean side of the Cape Cod Peninsula. The ground surface at this location is approximately 70 ft above NAVD88. The depth of this well is 90 ft.



WELL C-5 Photo (January 2017)

Figure C-2





**Notes:**

The data shows a seasonal rise in water levels during spring rains and snowmelt followed by a drop in water levels during the late summer.

Some precipitation events seem to cause a small, immediate increase in groundwater levels; others cause no change. More likely the impact of precipitation on groundwater at this location is delayed and damped. Some impacts may be masked by the noise in the data.

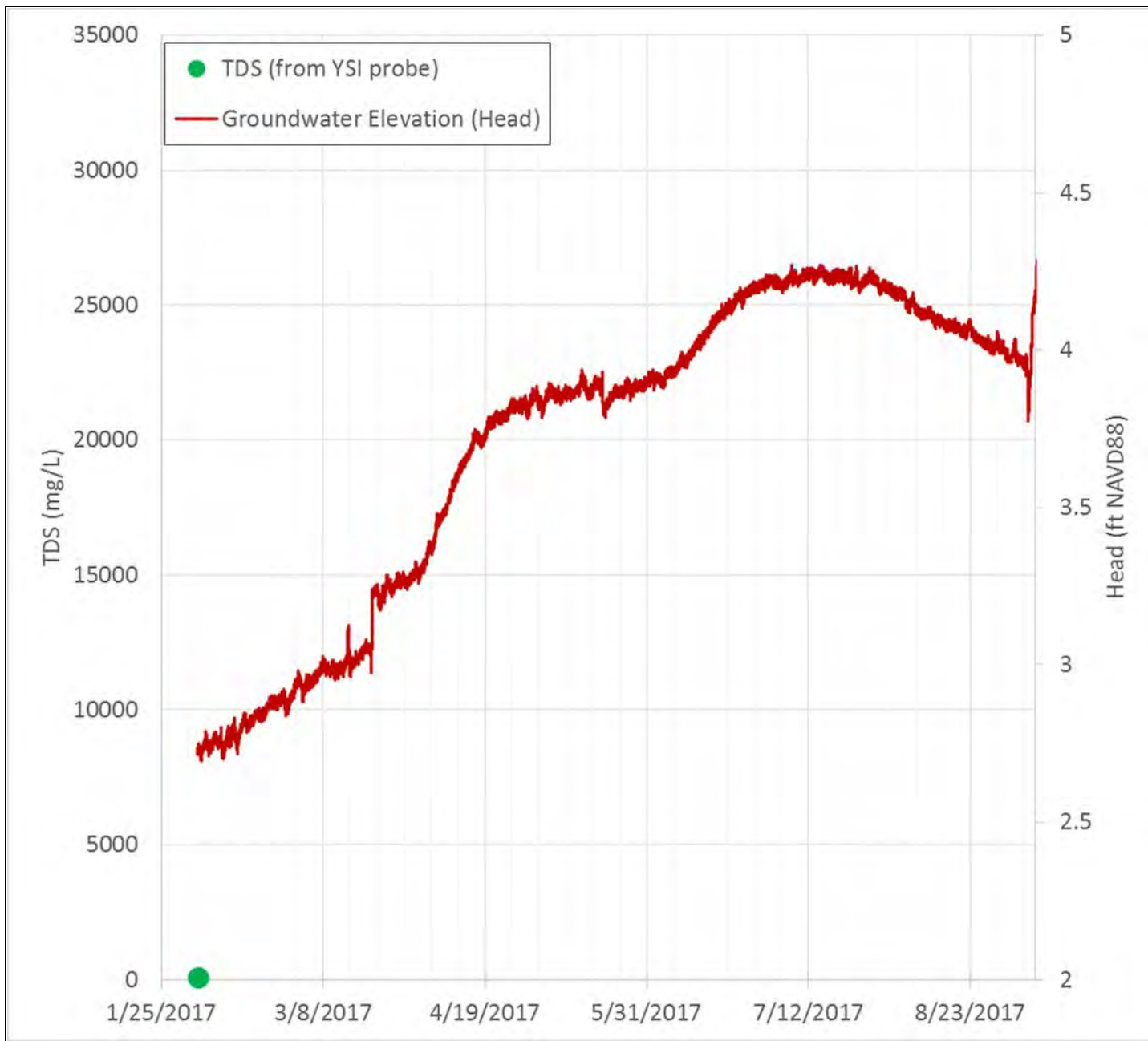
The sudden, 0.2 ft rise in groundwater levels on 3/20/17 was caused by removal of the logger for data download and replacement at a slightly lower elevation.

There is no tidal signature in the data at this well.



WELL C-5 Groundwater Elevation Data

Figure C-3



**Notes:**

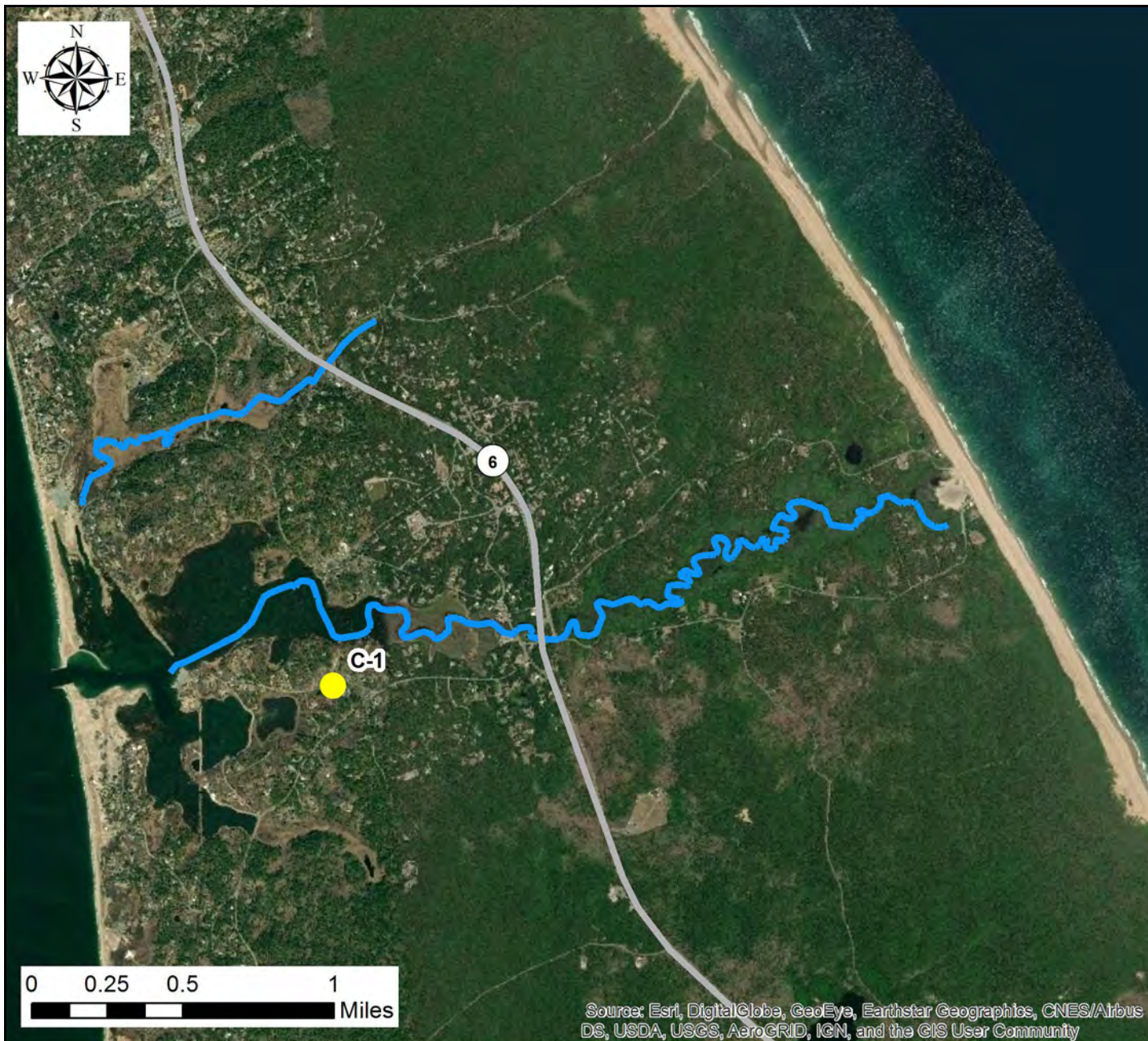
The total dissolved solids (TDS) is very low at this well (96 mg/L), indicating fresh water. This is expected for a well located inland from the coast and only slightly below sea level.



WELL C-5 Groundwater Quality Data

Figure C-4





**Notes:**

Well C-1 is located downstream of Route 6 about 0.15 miles south of Pamet River on a small hill with a casing elevation of 32.8 ft. The depth of the well is 40 ft.

**Data Sources:**

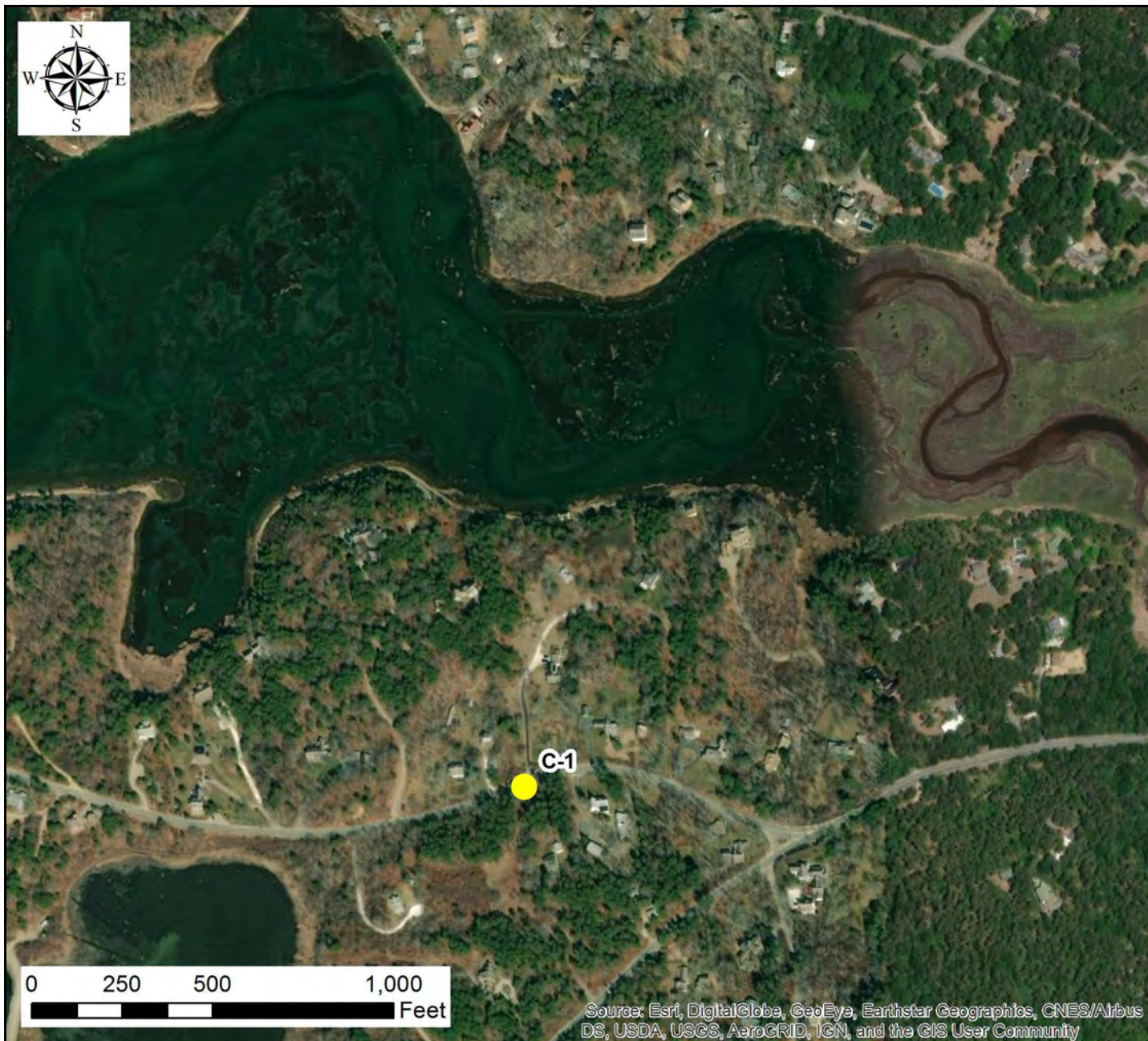
ESRI  
 USGS National Hydrography Dataset (NHD)  
 USGS Small-scale Dataset Major Roads of the United States



WELL C-1 Location

Figure C-5





**Notes:**

Well C-1 is located downstream of Route 6 about 0.15 miles south of Pamet River on a small hill with a casing elevation of 32.8 ft. The depth of the well is 40 ft.



WELL C-1 Location Zoom

Figure C-6





**Notes:**

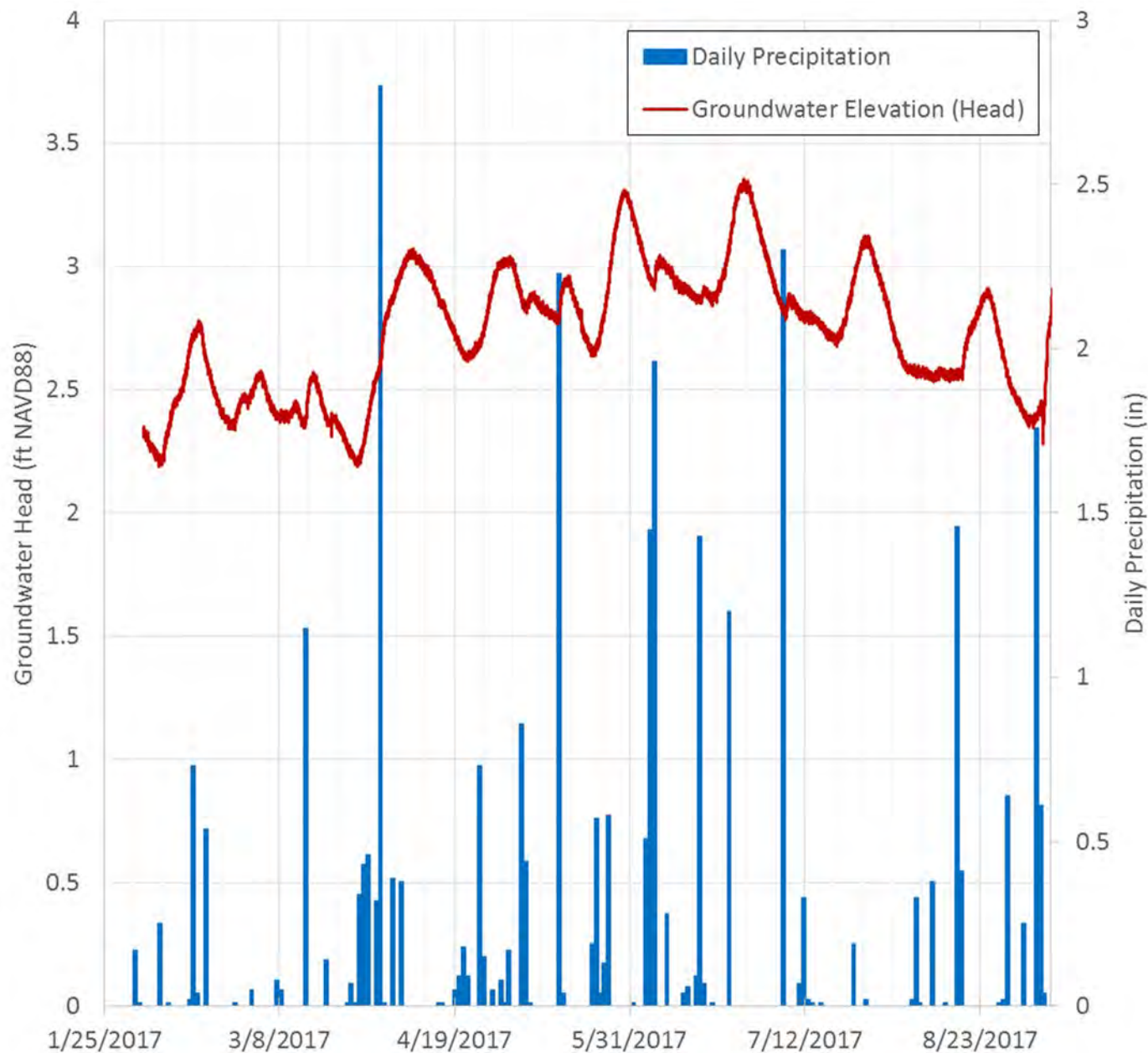
Well C-1 is located downstream of Route 6 about 0.15 miles south of Pamet River on a small hill with a casing elevation of 32.8 ft. The depth of the well is 40 ft.



WELL C-1 Photo (January 2017)

Figure C-7





**Notes:**

There is a clear impact from large (greater than 0.5 inches) precipitation events shown by slope changes or trend changes. The impact is slightly delayed and damped, often occurring 2-5 days after the precipitation event.

There is a small seasonal increase in groundwater elevation over the measurement period due to spring rainfall and snowmelt followed by a small reduction in groundwater levels during the late summer months.

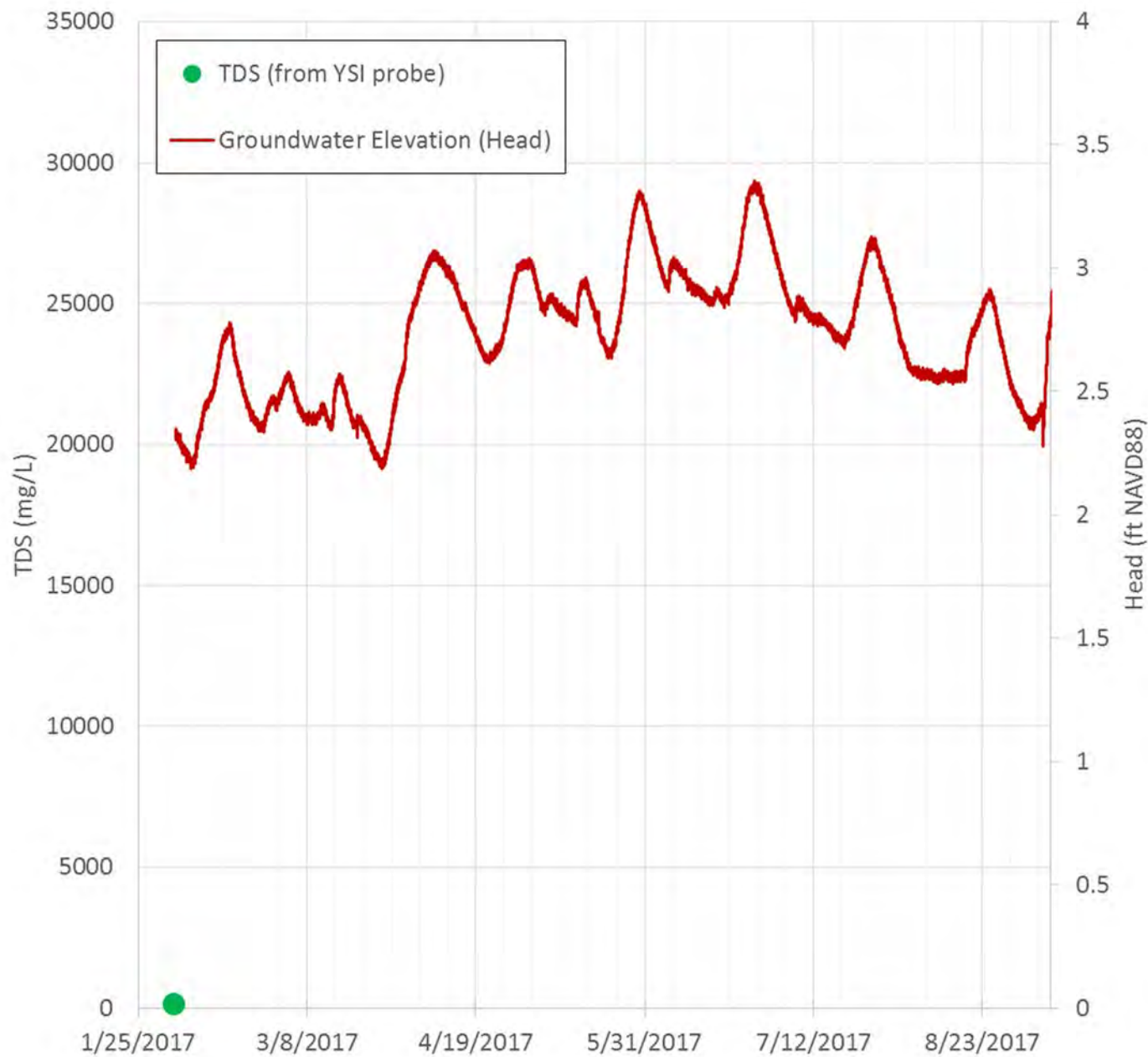
There is no tidal signature in the data at this well.

The dataset shows several unusual peaks lasting 2-3 weeks and involving an increase in water levels of about 0.5 feet. The cause of these variations is unknown.



WELL C-1 Groundwater Elevation Data

Figure C-8



**Notes:**

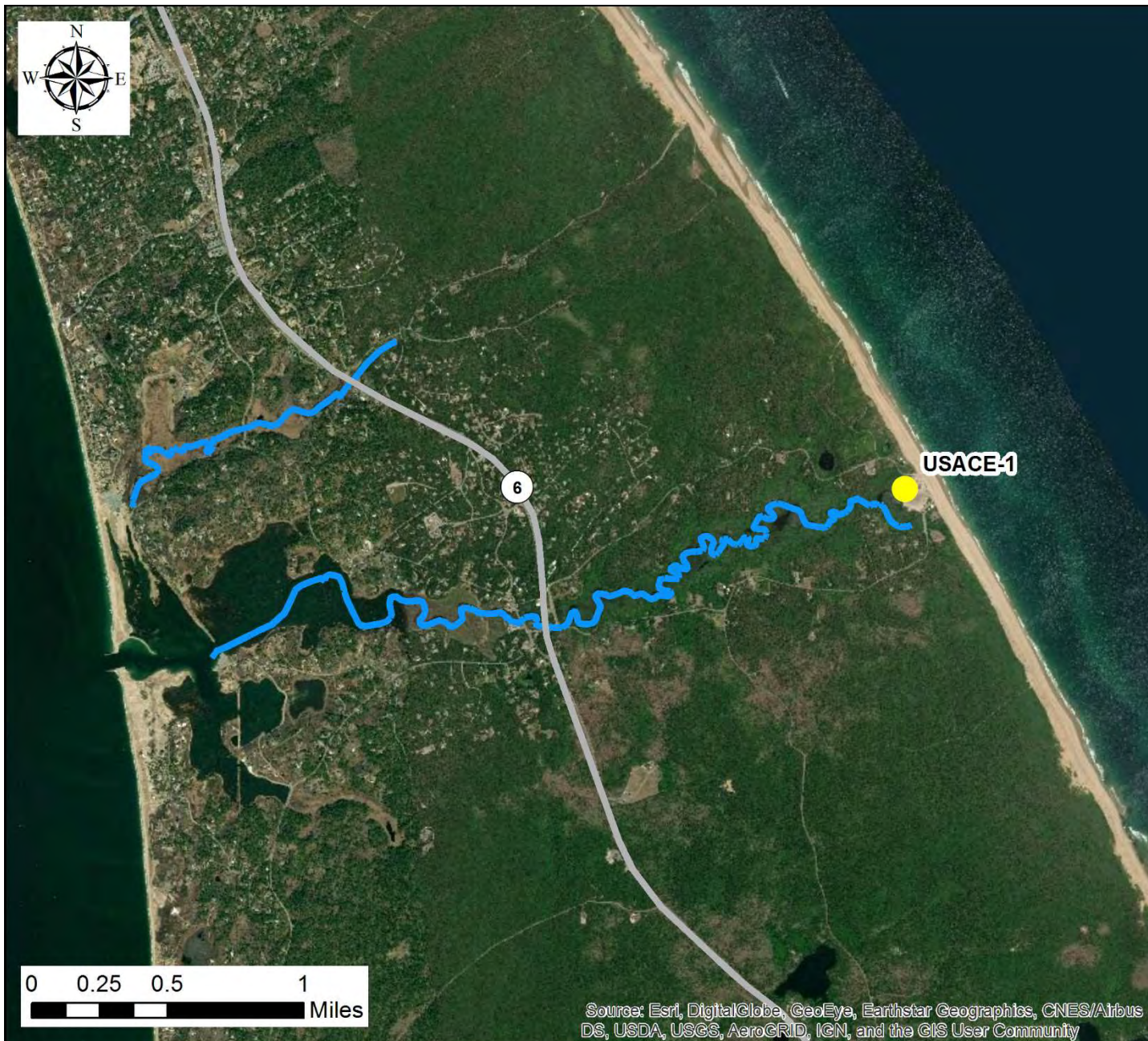
The total dissolved solids (TDS) is very low (149 mg/L) at this well, indicating fresh water. This is expected for a well located inland from the coast and only slightly below sea level.



WELL C-1 Groundwater Quality Data

Figure C-9





**Notes:**

Well USACE-1 is located just inland from Ballston beach near the head of the Pamet River. The casing elevation is 7.5 feet above NAVD88. It was driven by hand about 7 feet into the sand.

**Data Sources:**

ESRI  
USGS National Hydrography Dataset (NHD)  
USGS Small-scale Dataset Major Roads of the United States



WELL USACE-1 Location

Figure C-10





**Notes:**

Well USACE-1 is located just inland from Ballston beach near the head of the Pamet River. The casing elevation is 7.5 feet above NAVD88. It was driven by hand about 7 feet into the sand.



WELL USACE-1 Location Zoom

Figure C-11





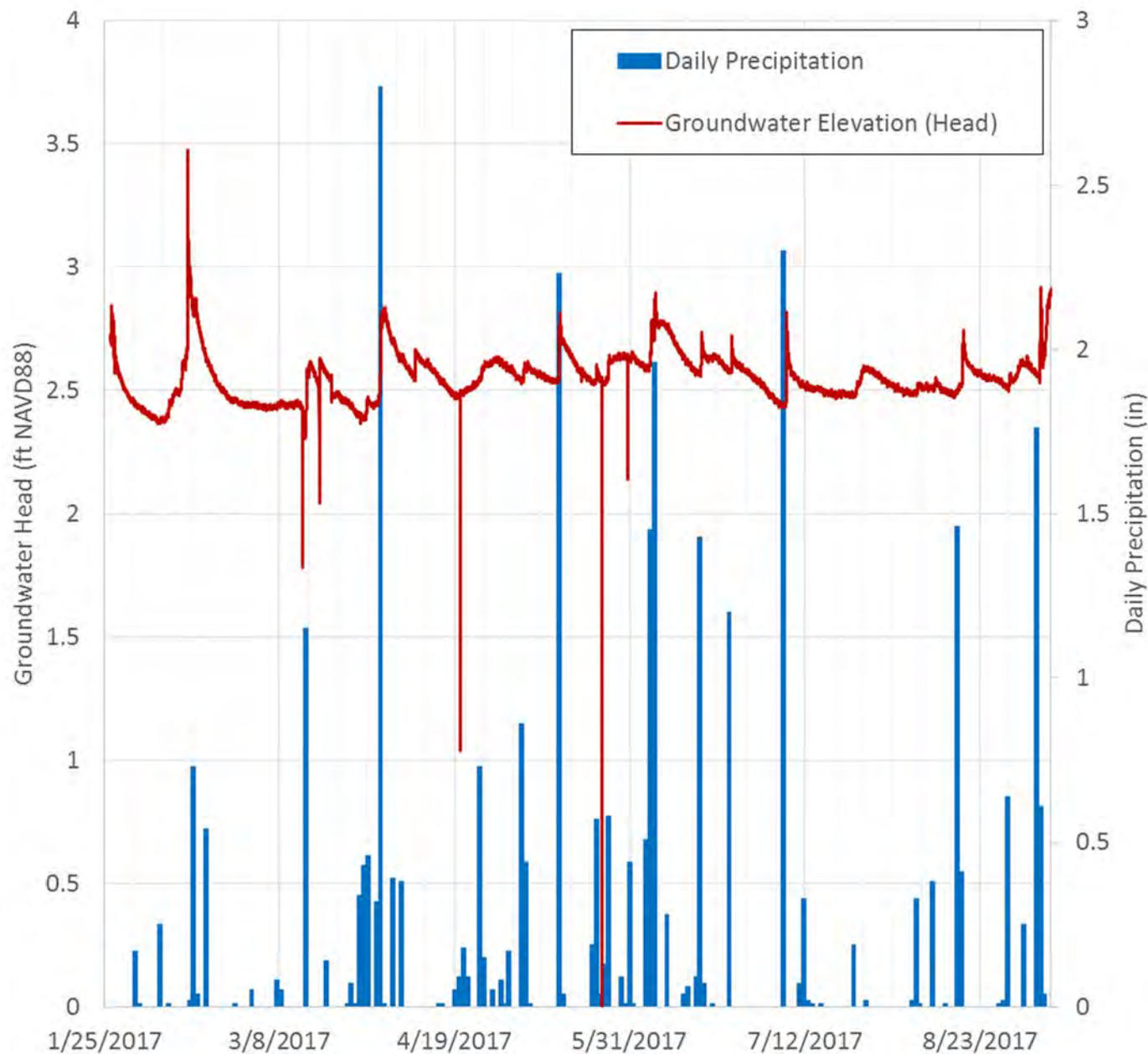
**Notes:**

Well USACE-1 is located just inland from Ballston beach near the head of the Pamet River. The casing elevation is 7.5 feet above NAVD88. It was driven by hand about 7 feet into the sand.



WELL USACE-1 Photo (January 2017)

Figure C-12



**Notes:**

Large and moderate precipitation events result in sudden, immediate groundwater rise because this well is quite shallow and placed in sand. Recovery after a storm is also rapid, usually occurring in 5-7 days.

The February 15, 2017 overtop event is clearly shown in the groundwater heads at this well.

There is no tidal signature at this well. Although it is only about 700 feet from the coast, heads are usually higher than the tide (-2.8 ft to 2.7 ft) so flow would almost always be towards the ocean. The significant infiltration of precipitation is likely overpowering the tidal signature.



WELL USACE-1 Groundwater Elevation Data

Figure C-13





**Notes:**

The total dissolved solids (TDS) for this well is partway between freshwater and seawater. Two options are available for converting the Hobo output to TDS. Because this groundwater is neither fresh nor as saline as seawater, both options are presented. The difference between the results is minimal.

Large, short-lived deviations on 3/17/17, 3/20/17 and 4/20/17 are due to short term removal of the probes for data download.

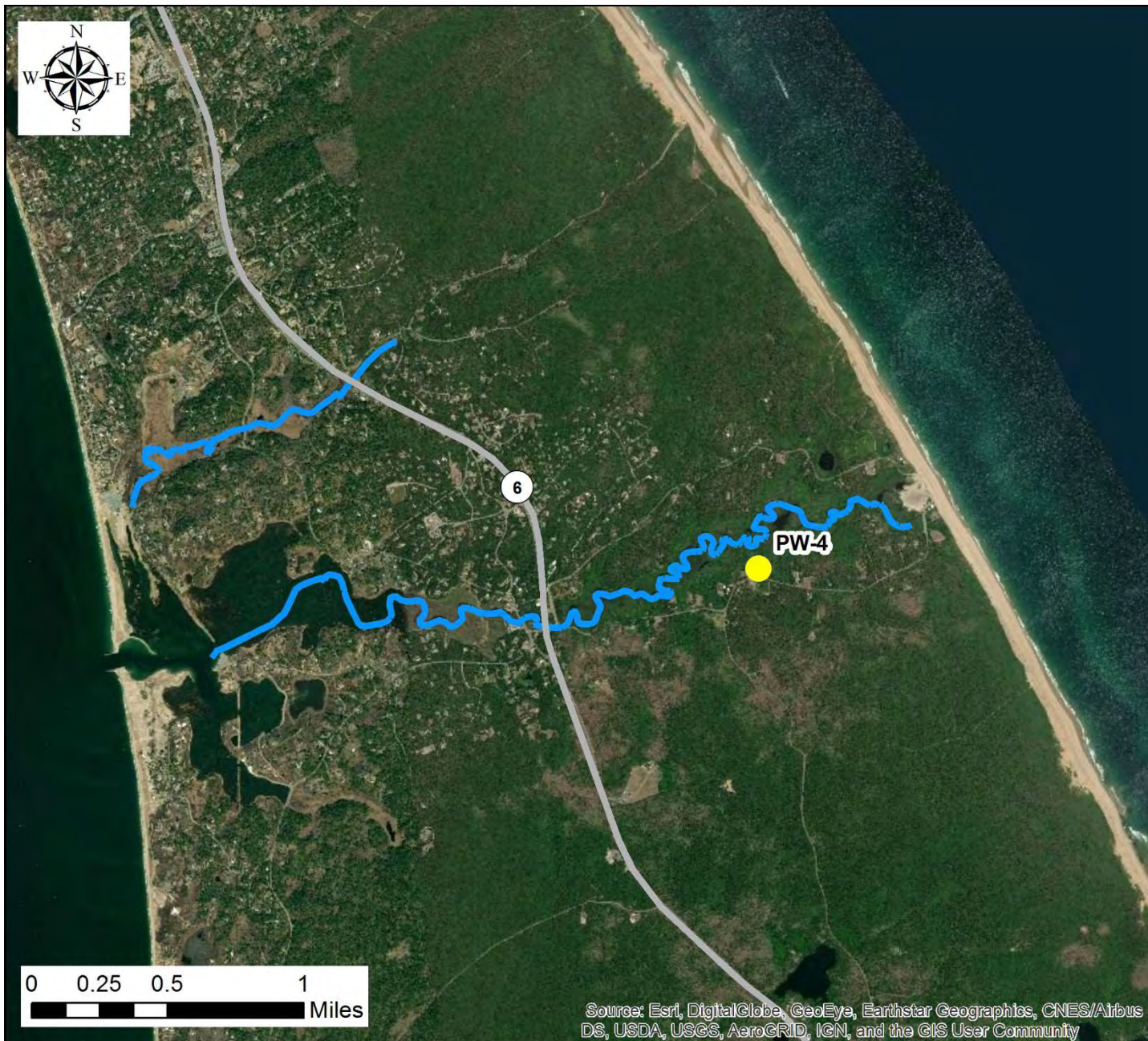
The cause of the TDS anomalies around the end of March and beginning of April is unknown.

The TDS seems to be largely unaffected by groundwater levels, the tide or precipitation events.



WELL USACE-1 Groundwater Quality Data

Figure C-14



**Notes:**

Well PW-4 is located in a low-lying area (ground surface about 1 ft above NAVD88) about 0.1 miles south of the non-tidal section of the Pamet River. The depth of this well is 38.56 ft. This well is co-located with PW-3D.

**Data Sources:**

ESRI  
 USGS National Hydrography Dataset (NHD)  
 USGS Small-scale Dataset Major Roads of the United States



WELL PW-4 Location

Figure C-15





**Notes:**

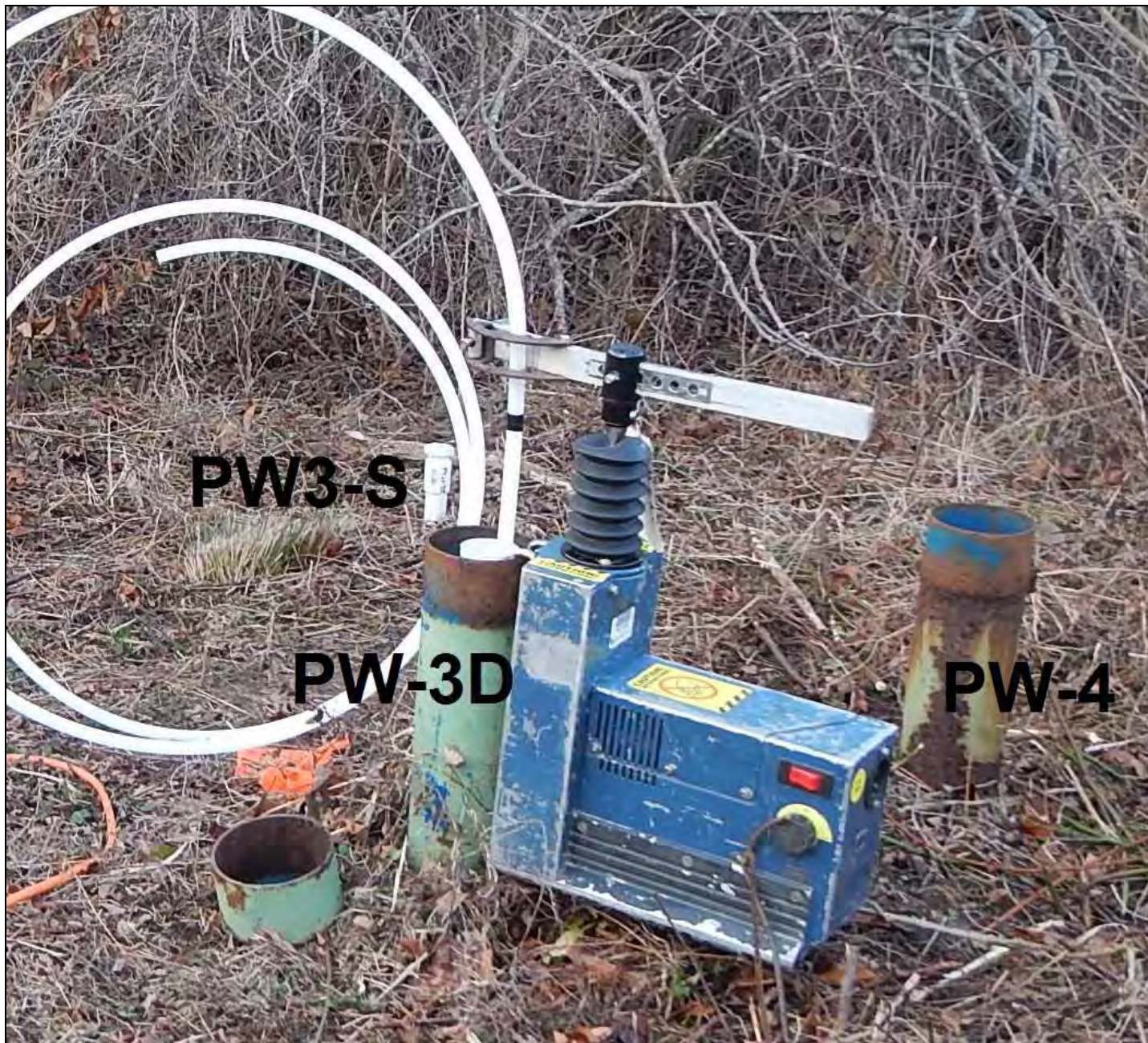
Well PW-4 is located in a low-lying area (ground surface about 1 ft above NAVD88) about 0.1 miles south of the non-tidal section of the Pamet River. The depth of this well is 38.56 ft. This well is co-located with PW-3D.



WELL PW-4 Location Zoom

Figure C-16





**Notes:**

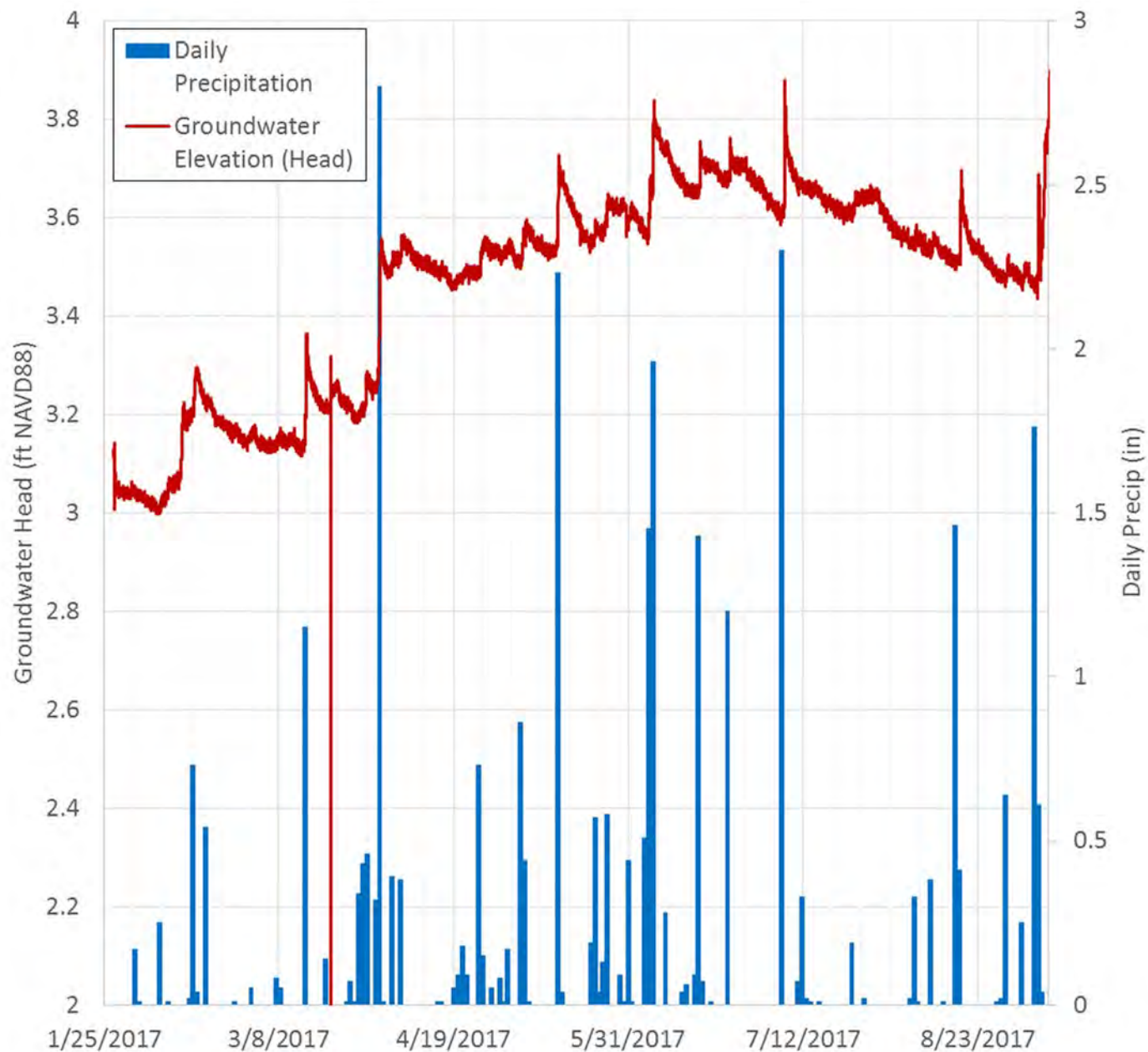
Wells PW-4, PW-3S and PW-3D are located in a low-lying area (ground surface about 1 ft above NAVD88) about 0.1 miles south of the non-tidal section of the Pamet River. The depth of PW-4 is 38.56 ft. The depth of PW-3D is 150 ft. Data was not collected at PW-3S.



WELLS PW-4, PW-3S, PW-3D Photo (January 2017)

Figure C-17





**Notes:**

Large and moderate precipitation events result in sudden, immediate groundwater rise followed by a rapid recovery.

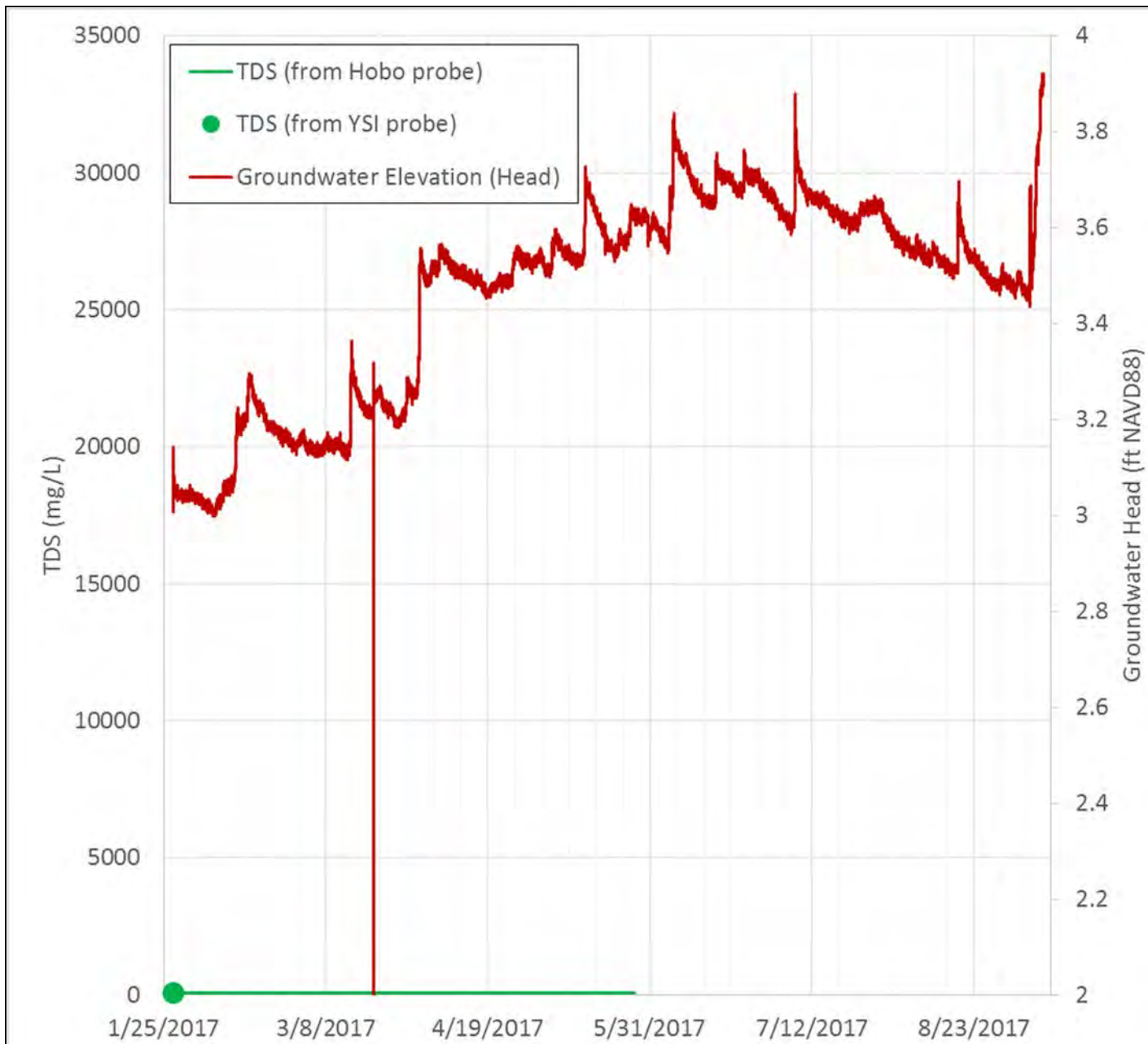
There is a seasonal rise in water levels during the spring followed by a drop in water levels during the late summer.

There is no tidal signature at this well.



WELL PW-4 Groundwater Elevation Data

Figure C-18



**Notes:**

Both the initial instantaneous TDS measurement (73 mg/L) and the long-term continuous measurement shows very fresh water at this site. There is almost no variation in the continuous TDS data; it varies between only 74.23 mg/L and 75.74 mg/L over a period of 4 months. This narrow variation is surprising and may indicate a problem with the probe. However the low TDS is expected with a well which appears to have a direct connection to the surface water sources.



WELL PW-4 Groundwater Quality Data

Figure C-19





**Notes:**

Well PW-3D is located in a low-lying area (ground surface about 1 ft above NAVD88) about 0.1 miles south of the non-tidal section of the Pamet River. The depth of this well is 150 ft, making it the deepest well in the dataset. This well is co-located with PW-4.

**Data Sources:**

ESRI  
USGS National Hydrography Dataset (NHD)  
USGS Small-scale Dataset Major Roads of the United States



WELL PW-3D Location

Figure C-20





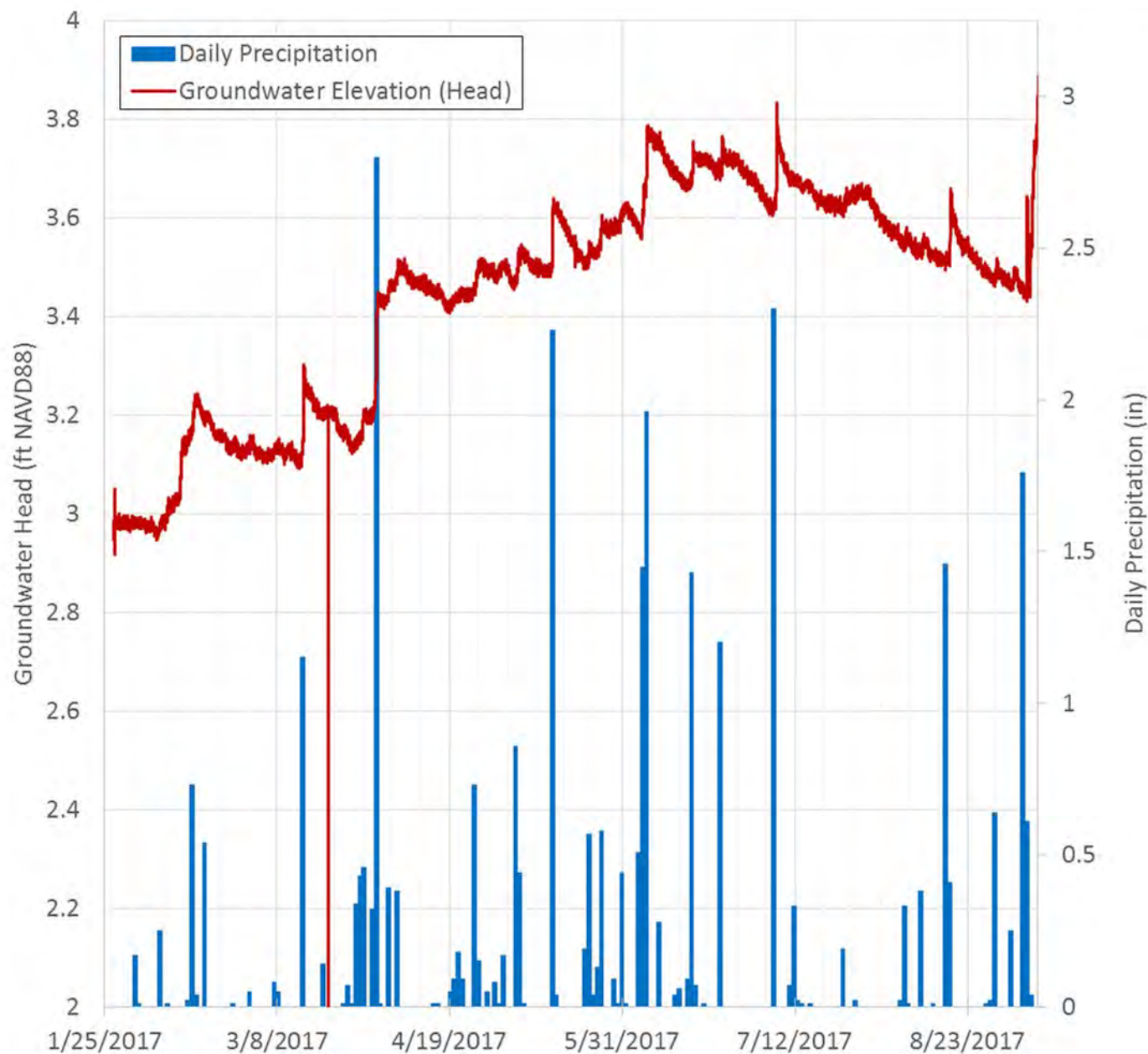
**Notes:**

Well PW-3D is located in a low-lying area (ground surface about 1 ft above NAVD88) about 0.1 miles south of the non-tidal section of the Pamet River. The depth of this well is 150 ft, making it the deepest well in the dataset. This well is co-located with PW-4.



WELL PW-3D Location Zoom

Figure C-21



**Notes:**

Large and moderate precipitation events result in sudden, immediate groundwater rise followed by a rapid recovery. This large, immediate response after precipitation events is unexpected for a well this deep. This may indicate a broken well casing or a coarse, homogeneous sand unit from the surface to the well depth.

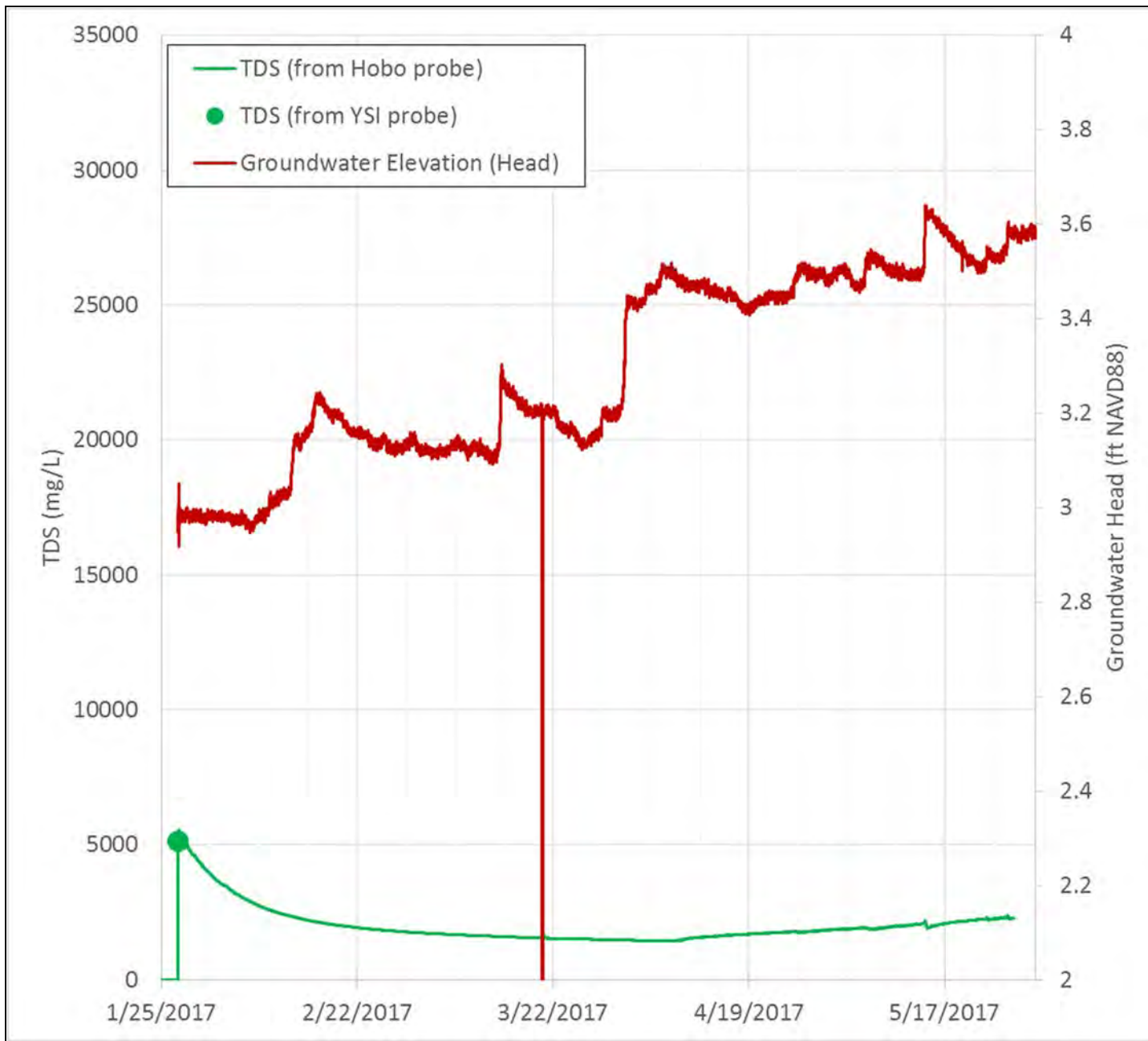
There is a seasonal rise in water levels during the spring followed by a drop in water levels during the late summer.

There is no tidal signature at this well.



WELL PW-3D Groundwater Elevation Data

Figure C-22



**Notes:**

The TDS data at this well shows brackish water with the instantaneous YSI data indicating the TDS was 5100 mg/L. The continuous TDS data shows a smooth, gradual drop in TDS until April 8, 2017 when the nature of the data changes suddenly. After April 8, the data is noisier, seems to be impacted by large storms and begins rising slowly.

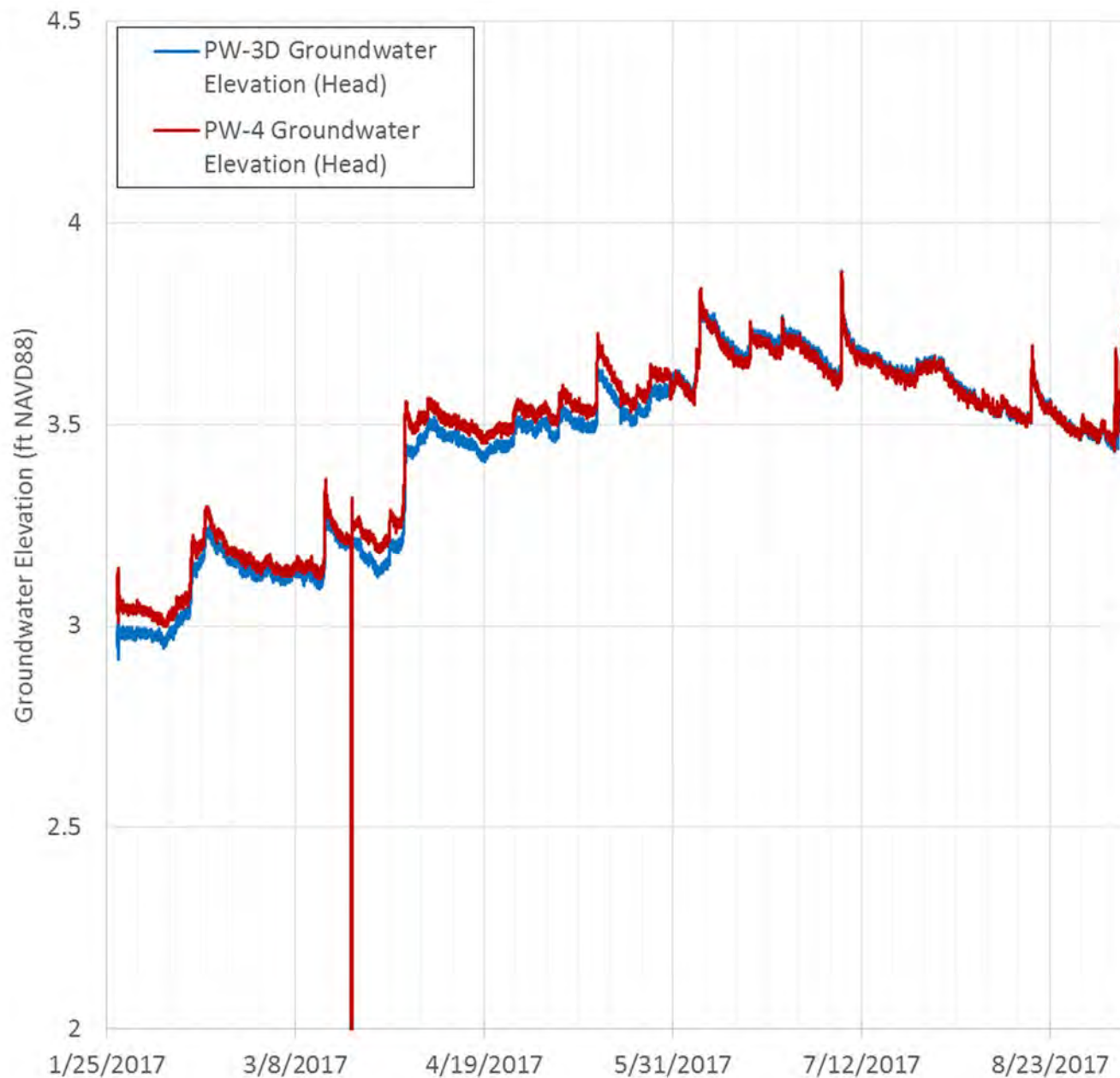
An immediate impact to TDS from precipitation events in a well this deep would not be expected. This may indicate either a broken casing or an unusually coarse, homogenous sand unit from the surface down to the bottom of the well.



WELL PW-3D Groundwater Quality Data

Figure C-23





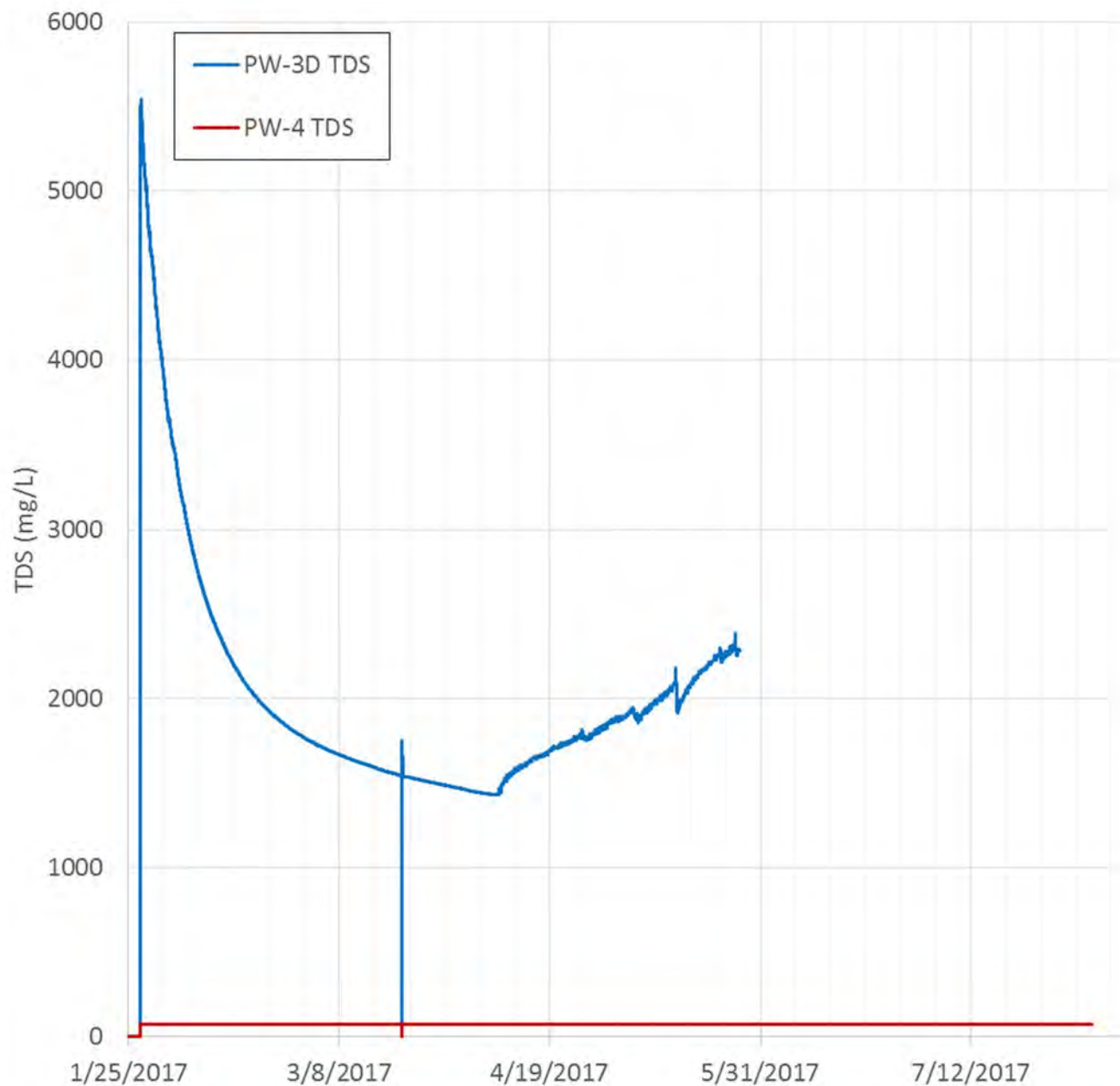
**Notes:**

Assuming PW-4 is less deep than PW-3D, a comparison of the two well head data sets indicates a slight upward gradient through the spring but almost no gradient beginning in June. Both wells have almost identical responses to external stressors, including precipitation. This would indicate that the depths of the wells are similar or they are separated by coarse, homogeneous sand units that transmit flow easily.



Groundwater Elevation Data Comparison: WELLS PW-3D and PW-4

Figure C-24

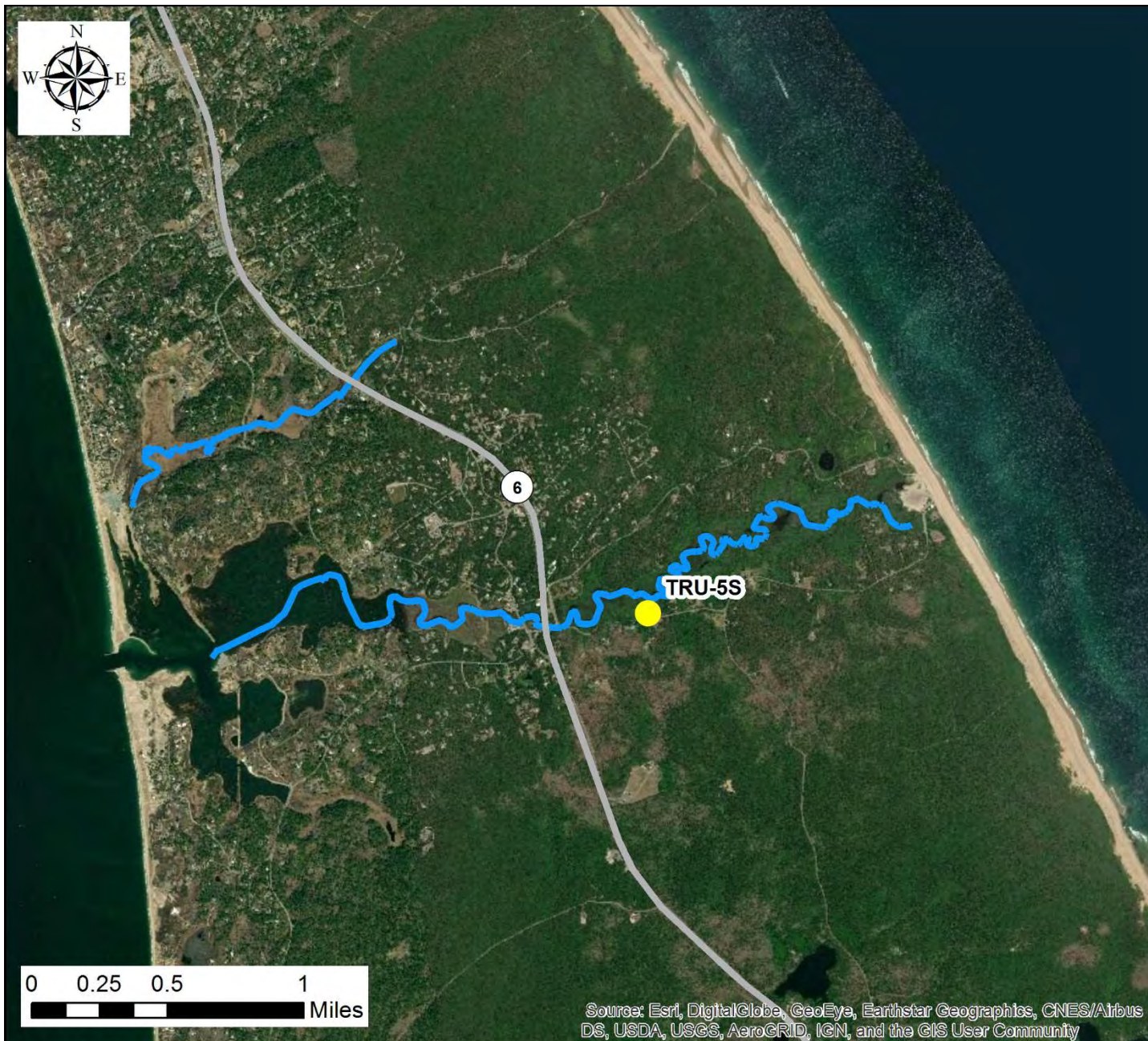


**Notes:**

The significant difference between the TDS at each well would seem to belie the conclusions of the groundwater level data. The groundwater head data seems to indicate the two wells are close in elevation or separated by a coarse, homogenous sand unit. The TDS data, conversely, indicates a separation of the two wells either by elevation differences or by a finer-grained semi-confining or confining unit.







**Notes:**

Well TRU-5S is located about 2500 ft upstream of the dike at the edge of the wetlands south of the Pamet River. The ground surface elevation is about 6 ft above NAVD88 and the depth of the well is 20 ft. This well is co-located with TRU-5D.

**Data Sources:**

ESRI  
USGS National Hydrography Dataset (NHD)  
USGS Small-scale Dataset Major Roads of the United States



WELL TRU-5S Location

Figure C-26





**Notes:**

Well TRU-5S is located about 2500 ft upstream of the dike at the edge of the wetlands south of the Pamet River. The ground surface elevation is about 6 ft above NAVD88 and the depth of the well is 20 ft. This well is co-located with TRU-5D.



WELL TRU-5S Location Zoom

Figure C-27





**Notes:**

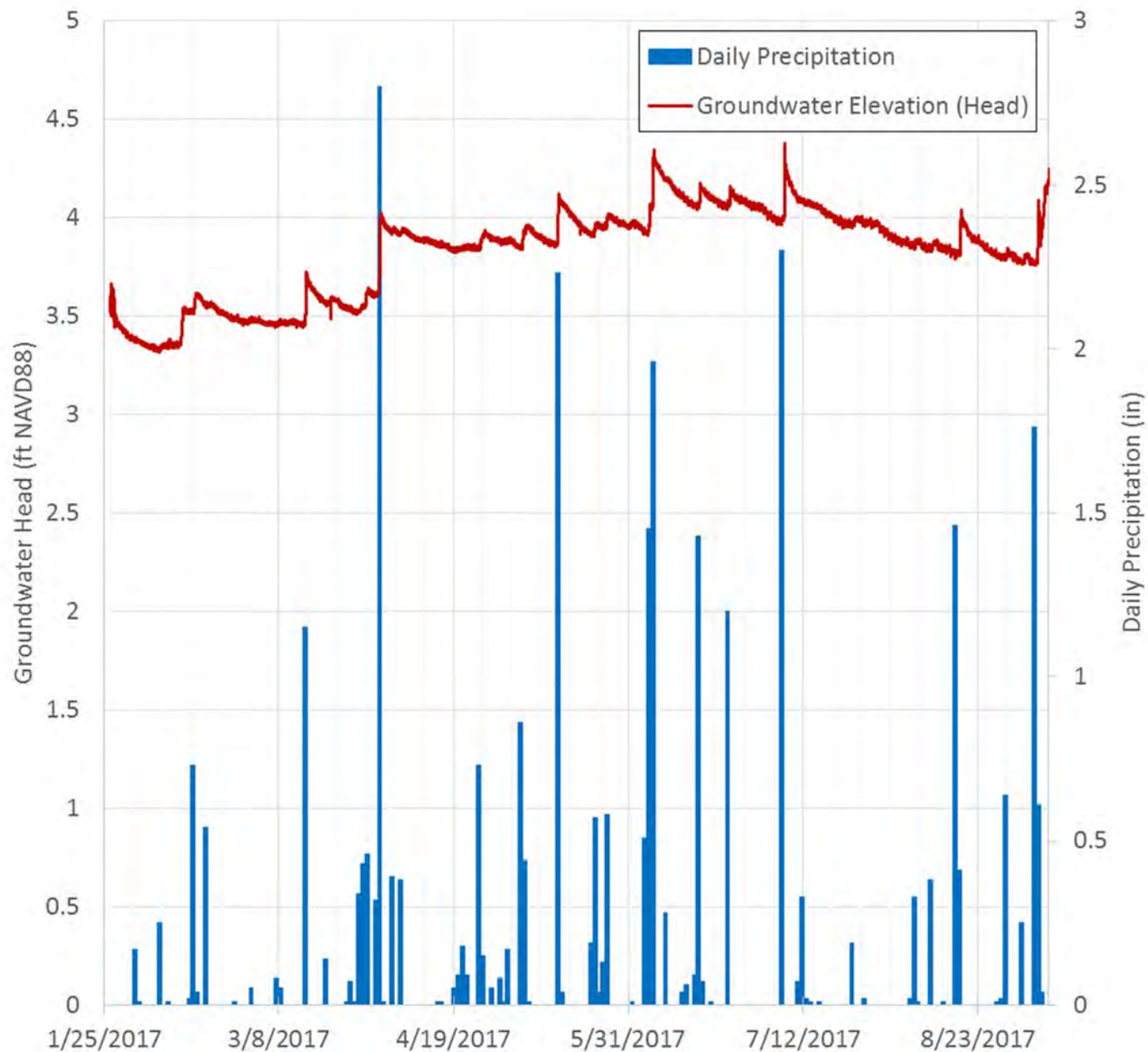
Well TRU-5S is located about 2500 ft upstream of the dike at the edge of the wetlands south of the Pamet River. The ground surface elevation is about 6 ft above NAVD88 and the depth of the well is 20 ft. This well is co-located with TRU-5D.



WELL TRU-5S Photo (January 2017)

Figure C-28





**Notes:**

There is an immediate, significant impact to the groundwater heads at this well after large and medium precipitation events.

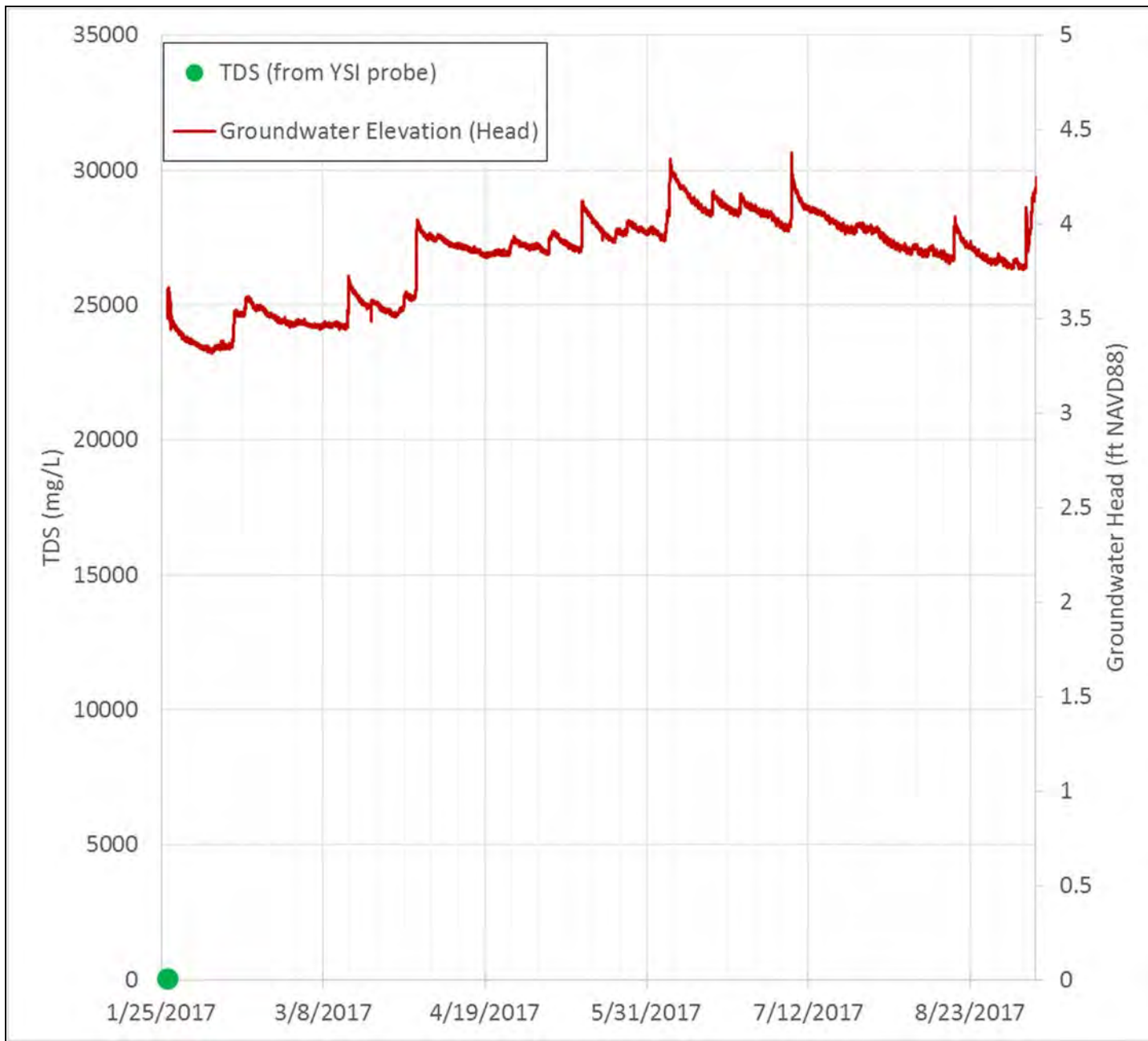
This well shows a slight rise in water levels in response to spring runoff and snowmelt with a slight drop in water levels in the summer.

There is no tidal signature at this well.



WELL TRU-5S Groundwater Elevation Data

Figure C-29



**Notes:**

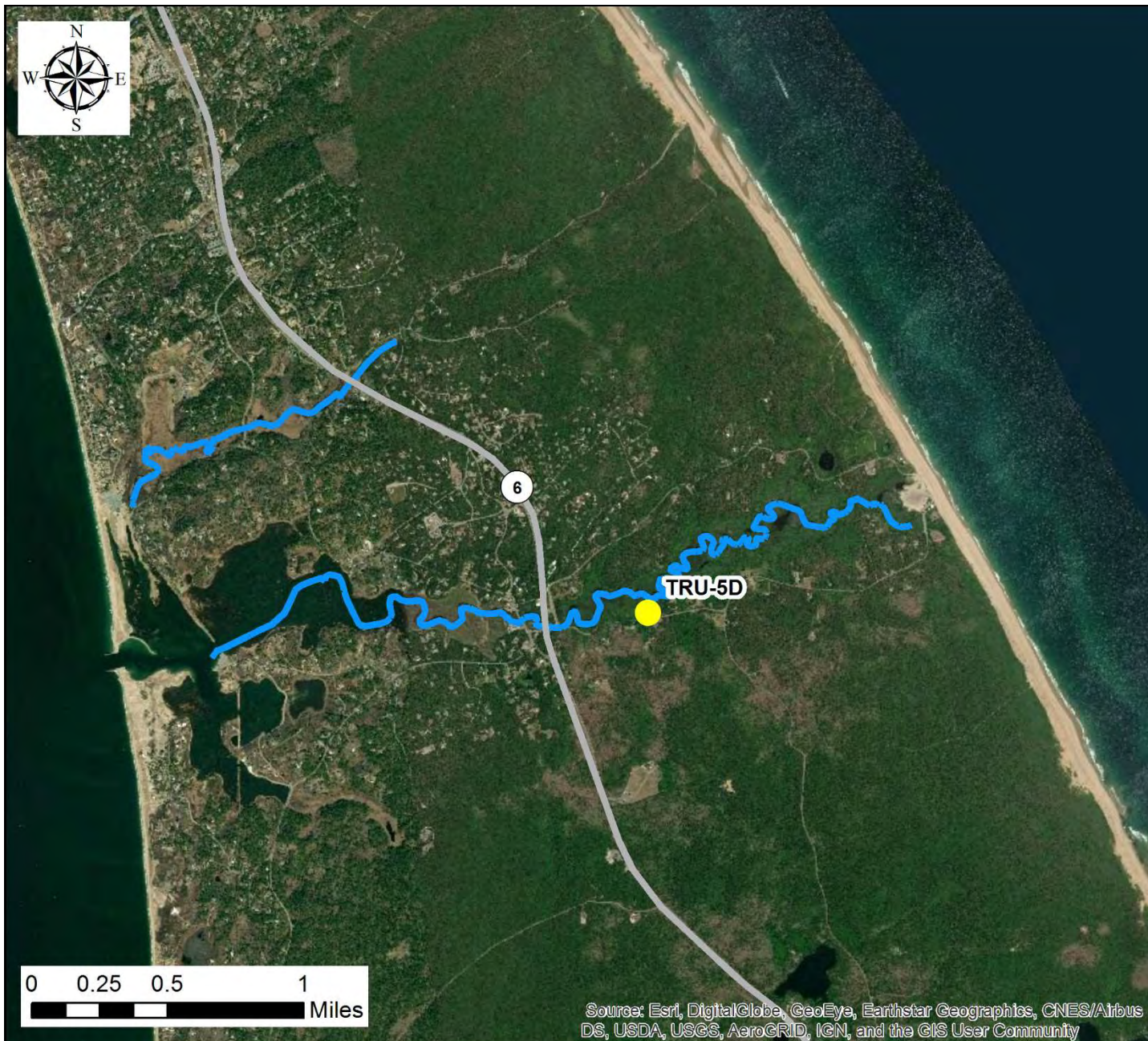
The instantaneous TDS data taken with the YSI meter showed 57 mg/L TDS, well below the threshold for fresh water. Fresh water would be expected at this location, near the non-tidal section of the Pamet River.



WELL TRU-5S Groundwater Quality Data

Figure C-30





**Notes:**

Well TRU-5D is located about 2500 ft upstream of the dike at the edge of the wetlands south of the Pamet River. The ground surface elevation is about 6 ft above NAVD88 and the depth of the well is 60 ft. This well is co-located with TRU-5S.

**Data Sources:**

ESRI  
 USGS National Hydrography Dataset (NHD)  
 USGS Small-scale Dataset Major Roads of the United States



WELL TRU-5D Location

Figure C-31





**Notes:**

Well TRU-5D is located about 2500 ft upstream of the dike at the edge of the wetlands south of the Pamet River. The ground surface elevation is about 6 ft above NAVD88 and the depth of the well is 60 ft. This well is co-located with TRU-5S.



WELL TRU-5D Location Zoom

Figure C-32





**Notes:**

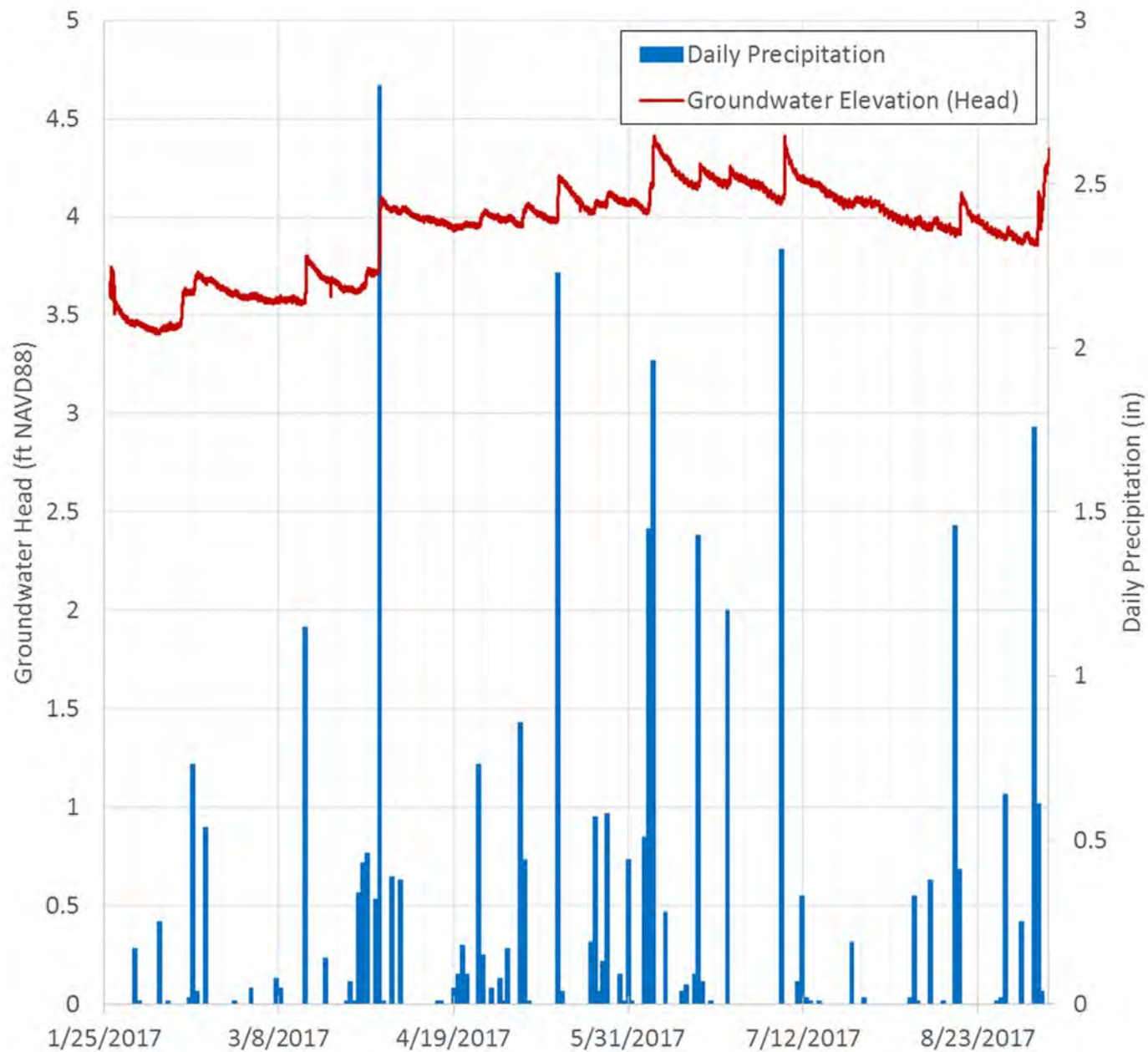
Well TRU-5D is located about 2500 ft upstream of the dike at the edge of the wetlands south of the Pamet River. The ground surface elevation is about 6 ft above NAVD88 and the depth of the well is 60 ft. This well is co-located with TRU-5S.



WELL TRU-5D Photo (January 2017)

Figure C-33





**Notes:**

The water levels in this well are impacted immediately and significantly by large and moderate precipitation events.

This data shows a small rise in water levels during spring runoff and snowmelt followed by a small drop in water levels during the late summer.

There is no tidal signature in this well.



WELL TRU-5D Groundwater Elevation Data

Figure C-34





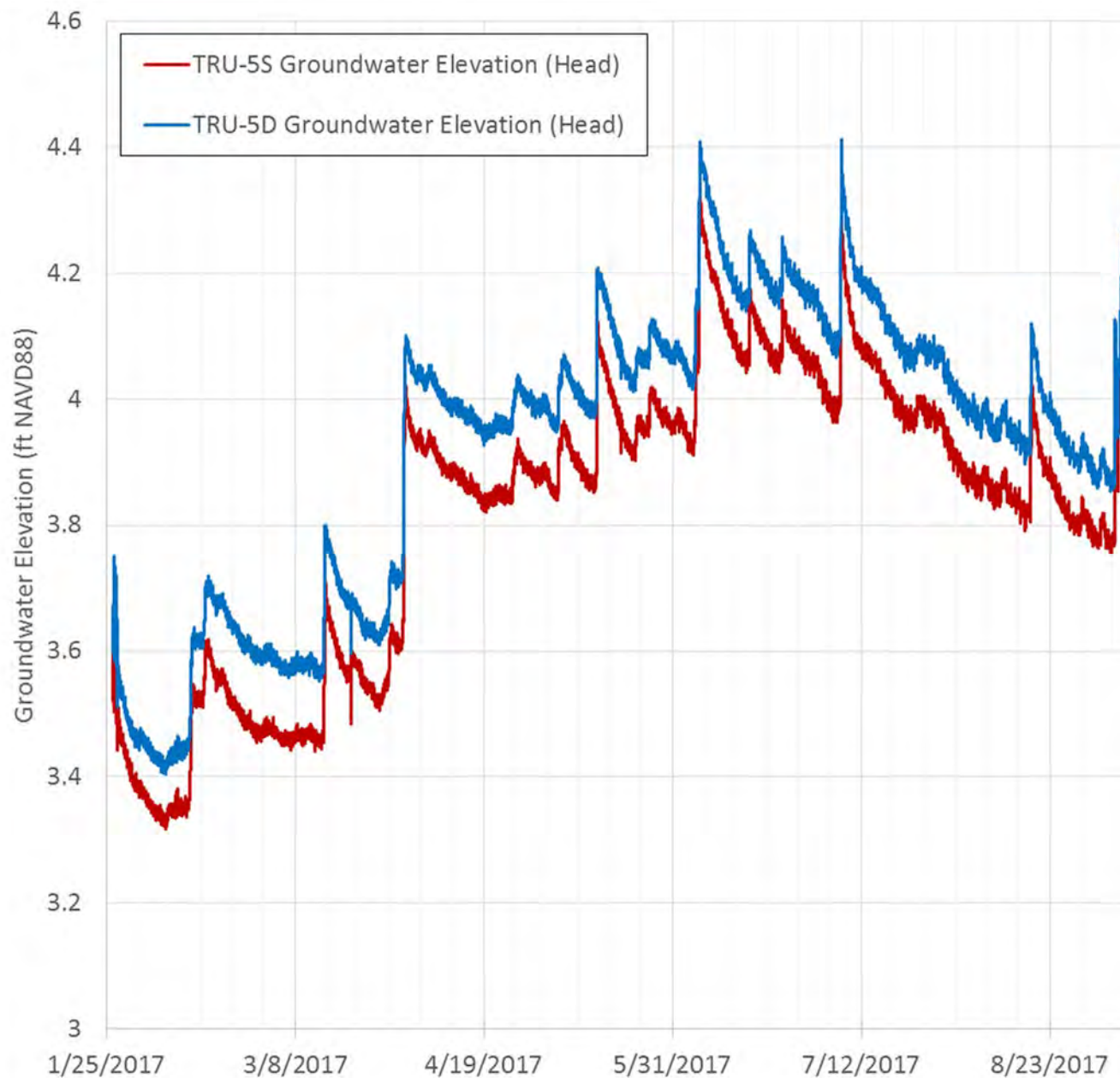
**Notes:**

The instantaneous TDS measurement at this well in January 2017 showed a TDS of 77 mg/L, indicating very fresh water. The continuous TDS data shows a very small variation of TDS, varying only between 75.52 mg/L and 78.95 mg/L over 4 months. The reason for the small variation is unknown but may indicate a problem with the probe.



WELL TRU-5D Groundwater Quality Data

Figure C-35



**Notes:**

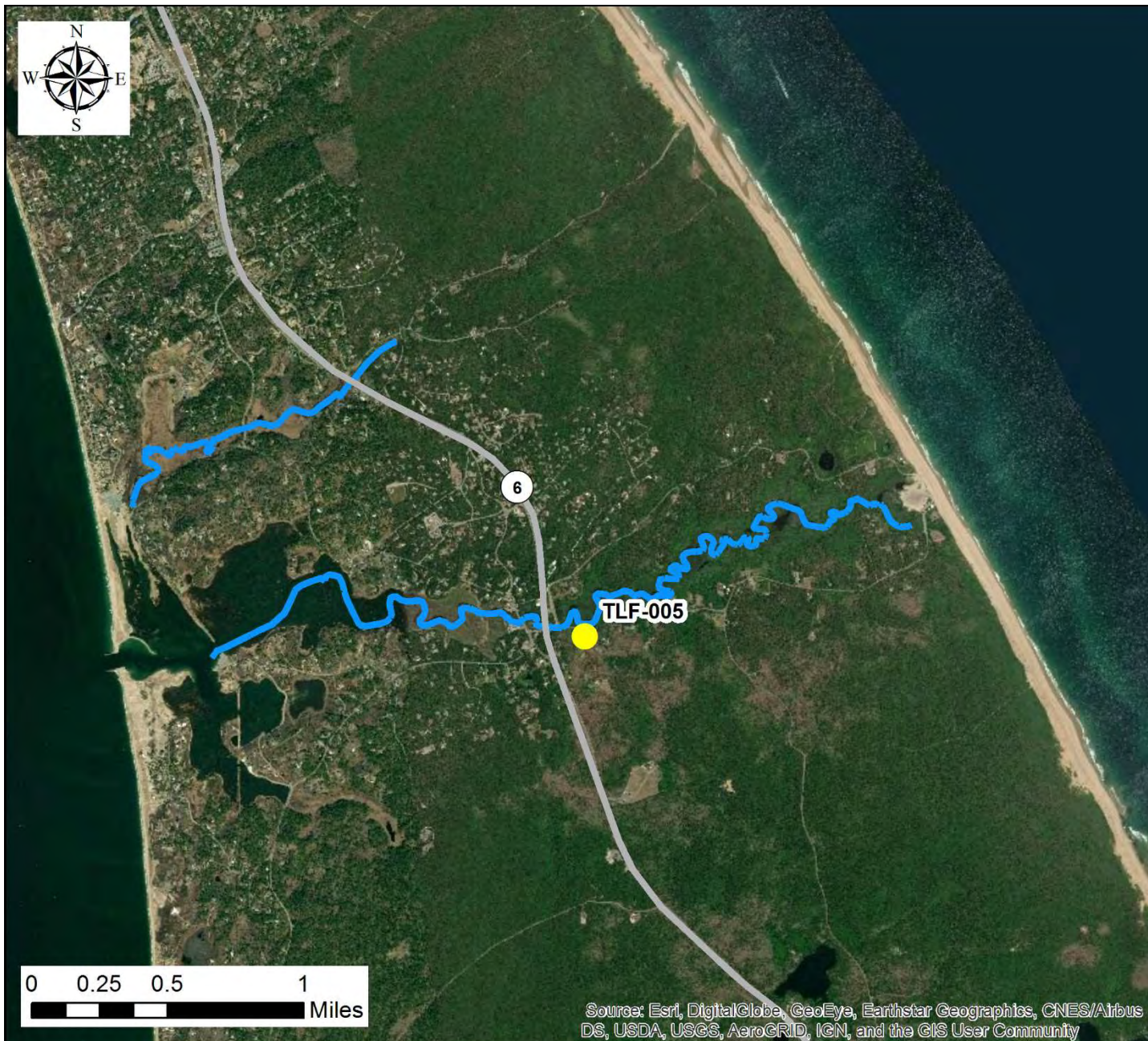
This comparison of the water level data for TRU-5S and TRU-5D shows that both have almost identical responses to precipitation and all external stressors. The water level in TRU-5S (depth = 20 ft) is always about 0.1 ft lower than TRU-5D (depth = 60 ft), indicating an upward gradient of about 0.0025 ft/ft. It is surprising that this gradient remains the same even during large precipitation events.



WELL TRU-5D Groundwater Elevation Data

Figure C-36





**Notes:**

TLF-005 is located just south of the river at the edge of the wetlands and about 0.2 miles upstream of the gate. The ground surface elevation is about 6 ft above NAVD88 and the depth of the well is 14 ft.

**Data Sources:**

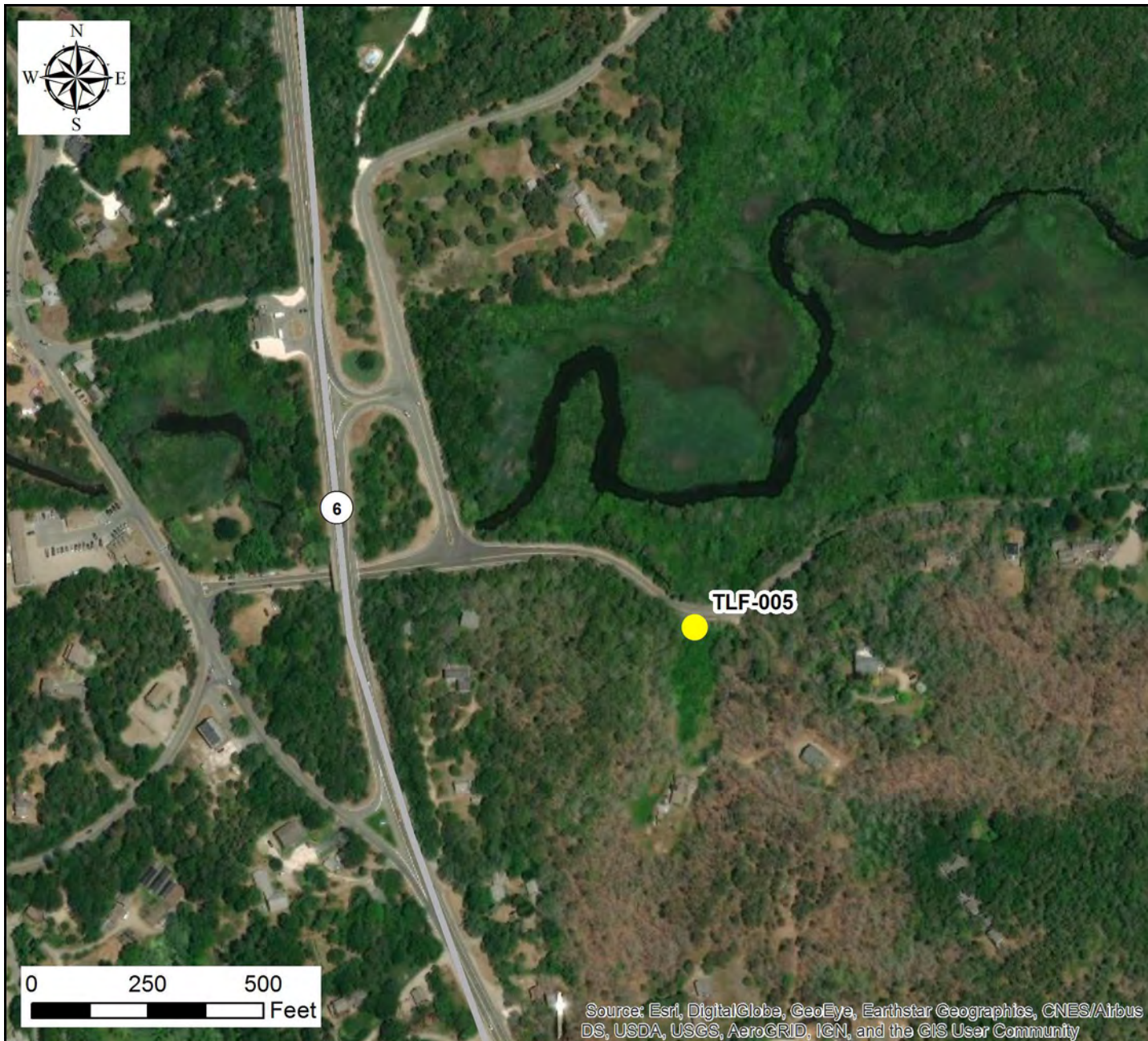
ESRI  
USGS National Hydrography Dataset (NHD)  
USGS Small-scale Dataset Major Roads of the United States



WELL TLF-005 Location

Figure C-37





**Notes:**

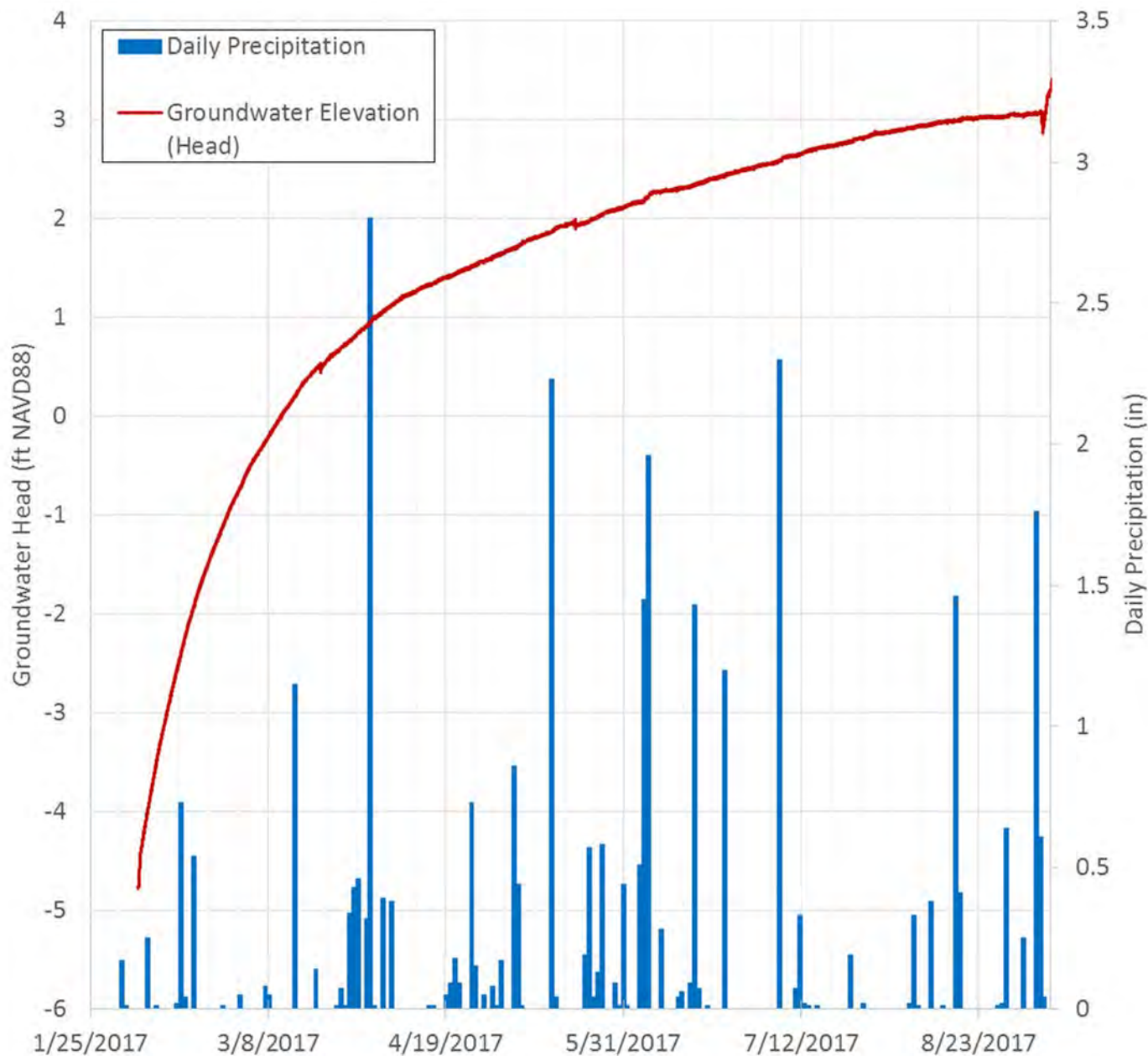
TLF-005 is located just south of the river at the edge of the wetlands and about 0.2 miles upstream of the gate. The ground surface elevation is about 6 ft above NAVD88 and the depth of the well is 14 ft.



WELL TLF-005 Location Zoom

Figure C-38





**Notes:**

The water level data at this well begins very low – much lower than the stage in the river and gradually increases during the 7-month measurement period. The data gradually becomes more noisy, but there is no discernible impact from even large precipitation events.

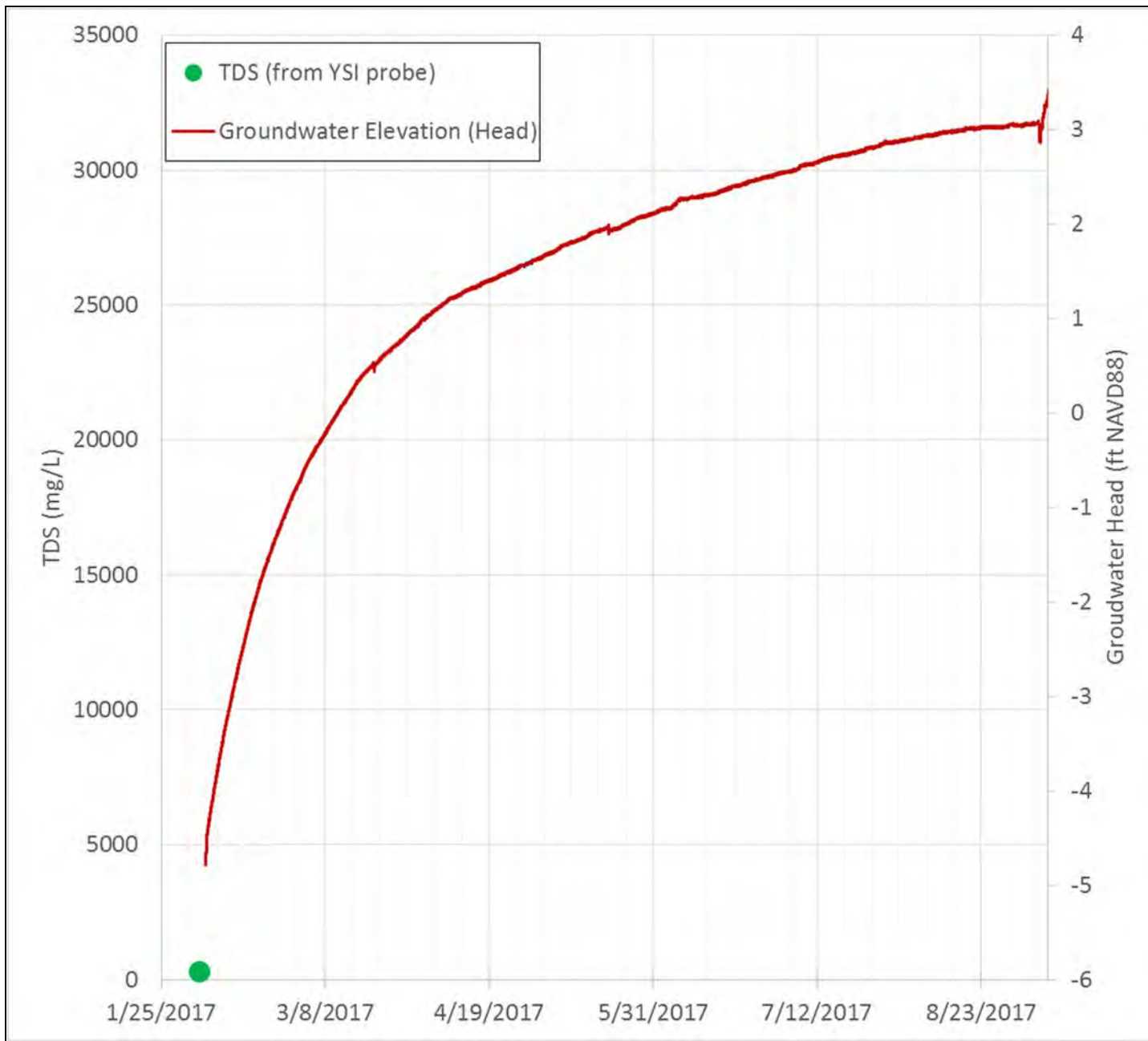
This data indicates that the well is either clogged or is set in a tight section of peat which does not easily transmit water. The initial, low water levels were likely caused by purging and redeveloping the well in preparation for use. The data probably asymptotically approaches the surrounding groundwater level over the measurement period.

This data is of very little use expect where the ambient groundwater level can be extrapolated from the dataset.



WELL TLF-005 Groundwater Elevation Data

Figure C-39



**Notes:**

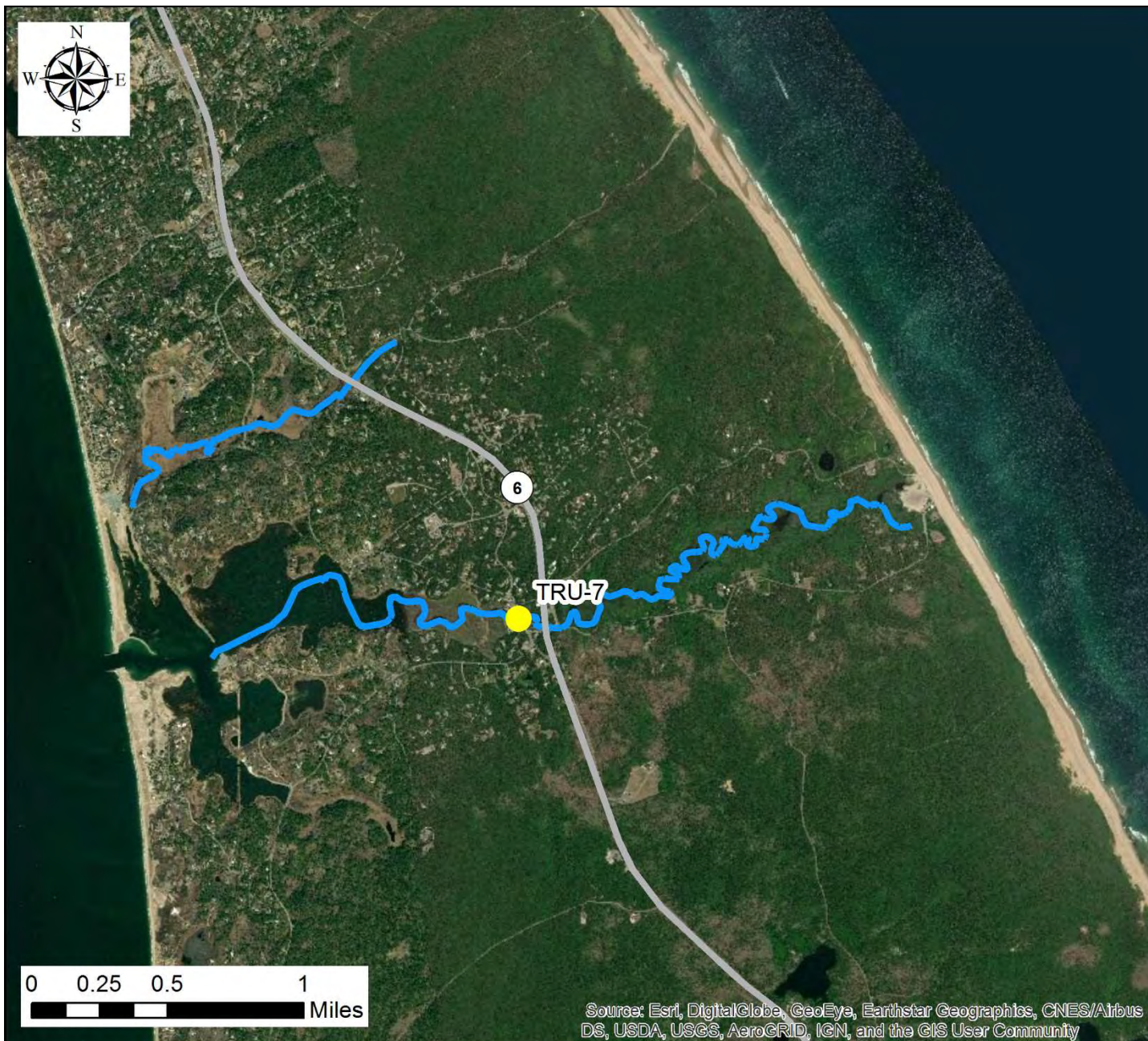
The instantaneous YSI measurement indicated a TDS at this well of 299 mg/L, which is classified as fresh water.



WELL TLF-005 Groundwater Quality Data

Figure C-40





**Notes:**

TRU-7 is located just north of Wilder's Dike and is 15 feet deep. The ground surface elevation at this location is approximately 7 ft above NAVD88.

**Data Sources:**

ESRI  
 USGS National Hydrography Dataset (NHD)  
 USGS Small-scale Dataset Major Roads of the United States



WELL TRU-7 Location

Figure C-41





**Notes:**

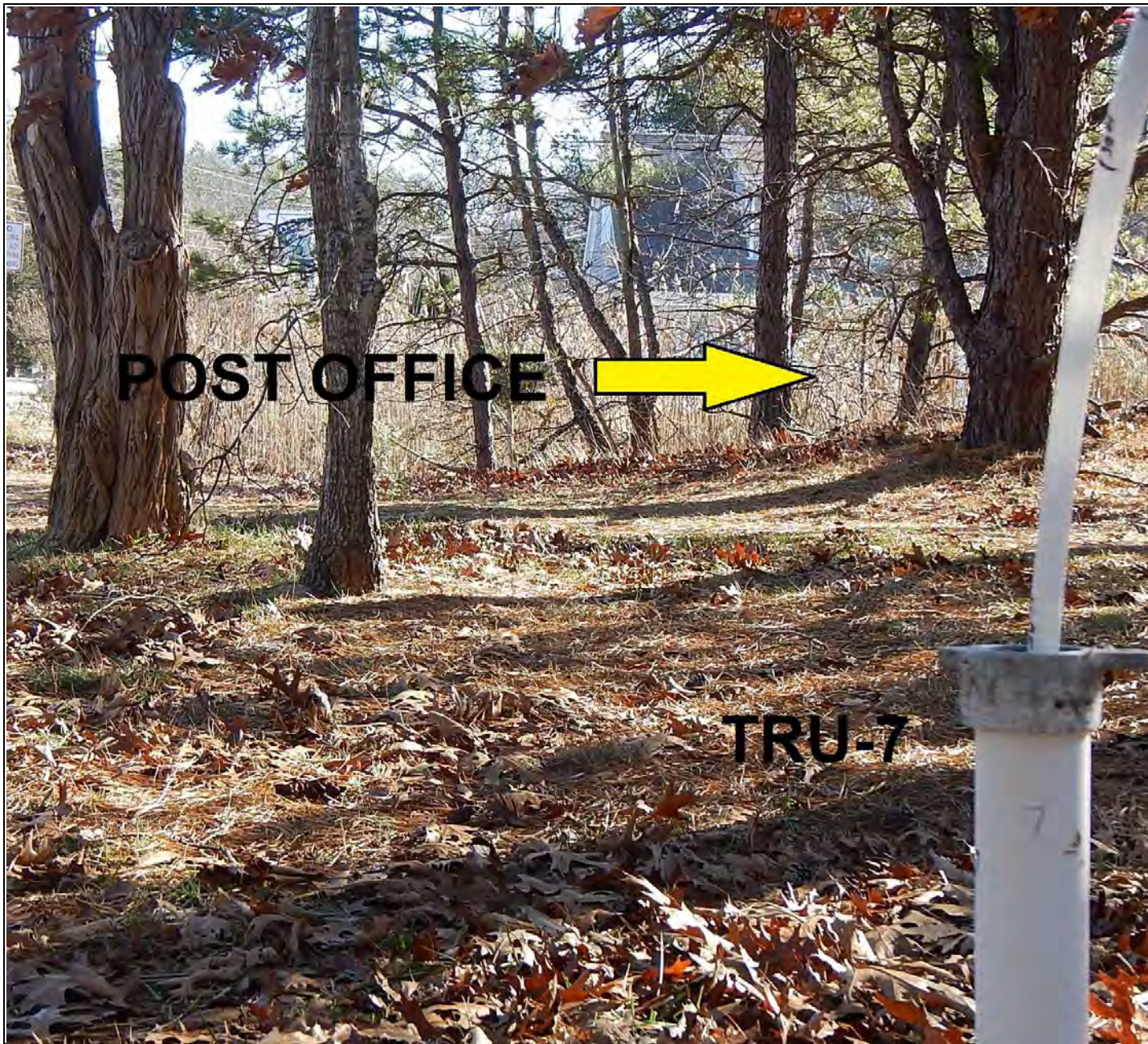
TRU-7 is located just north of Wilder's Dike and is 15 feet deep. The ground surface elevation at this location is approximately 7 ft above NAVD88.



WELL TRU-7 Location Zoom

Figure C-42





**Notes:**

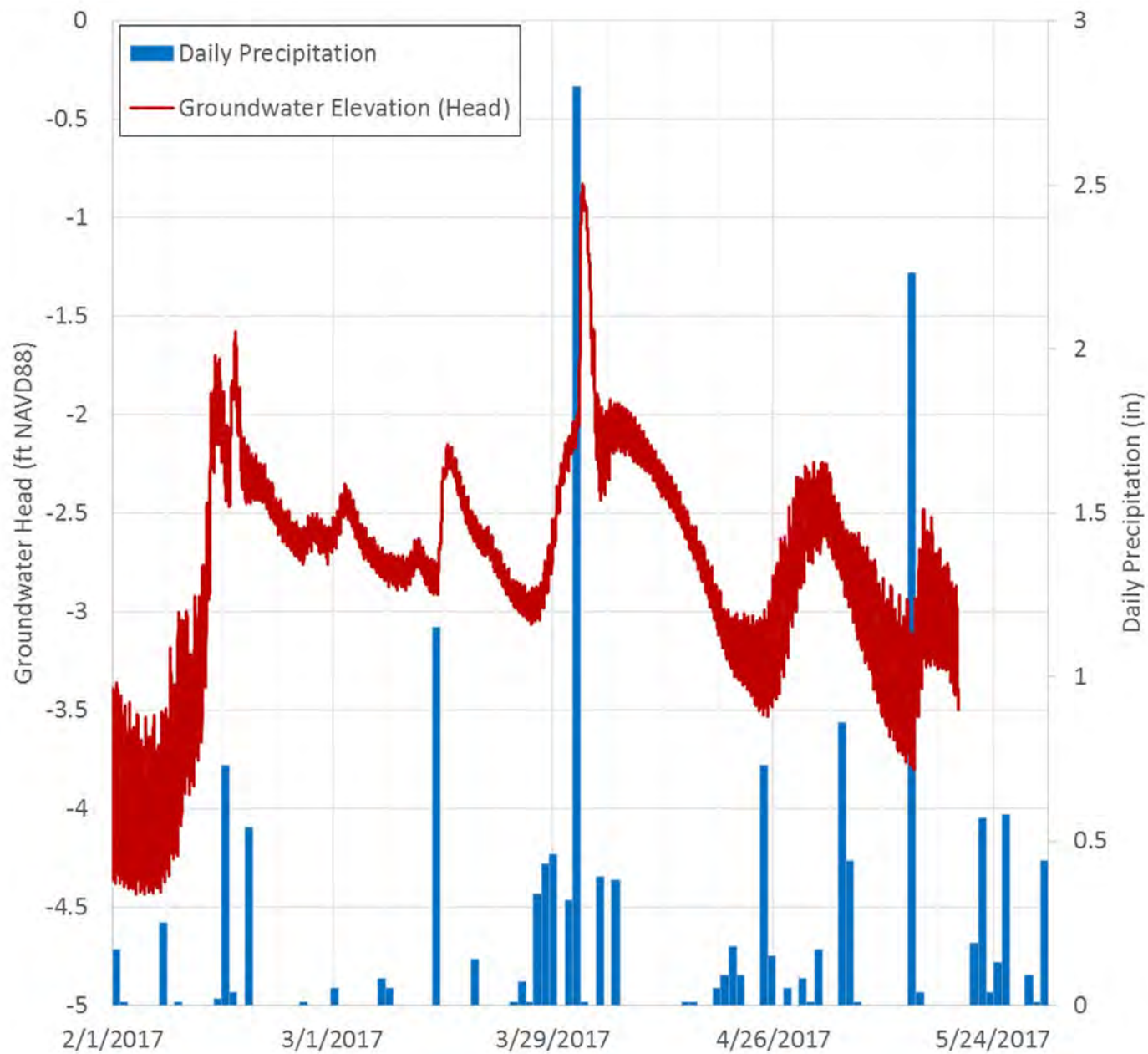
TRU-7 is located just north of Wilder's Dike and is 15 feet deep. The ground surface elevation at this location is approximately 7 ft above NAVD88.



WELL TRU-7 Photo (January 2017)

Figure C-43





**Notes:**

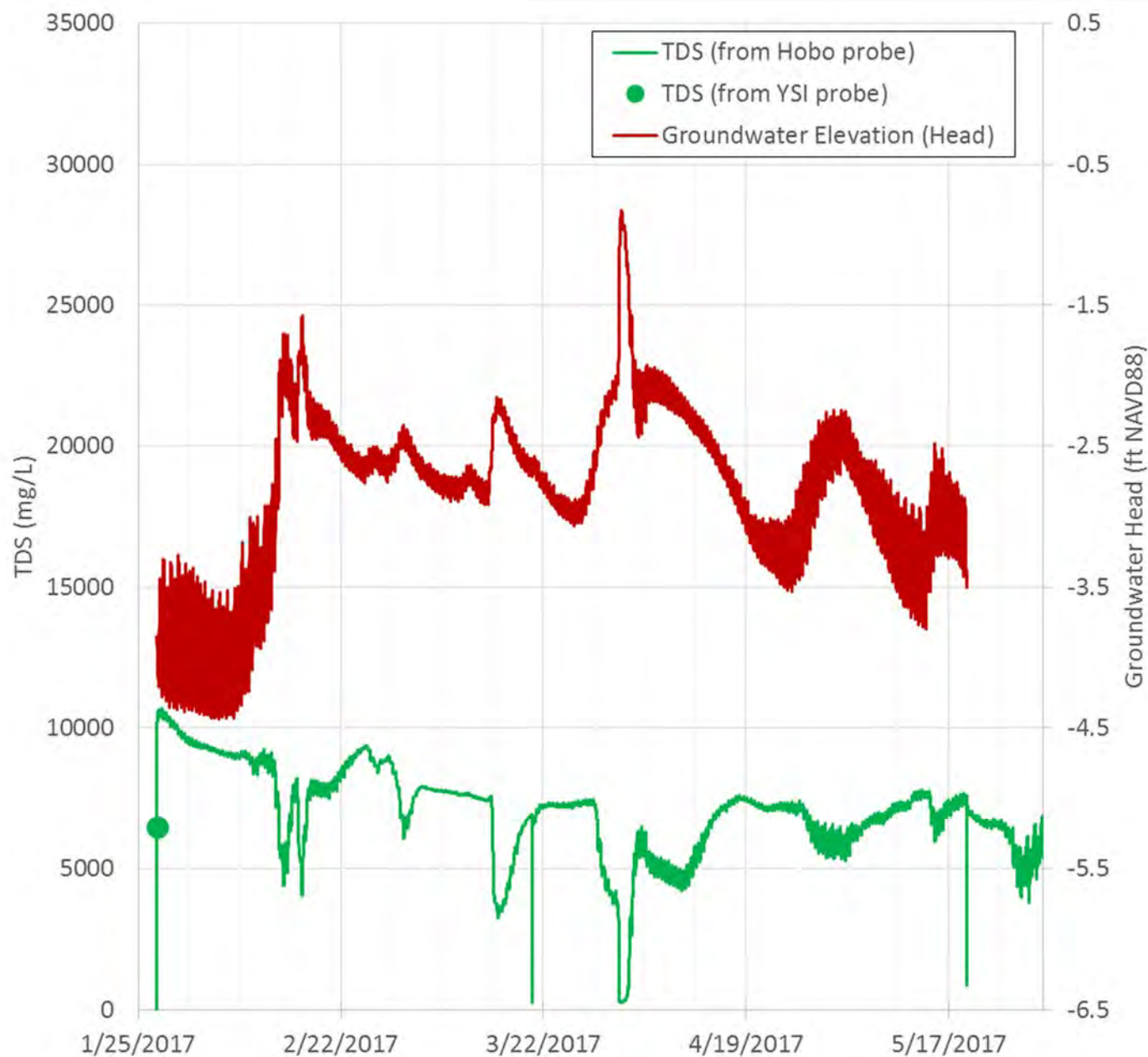
The water levels at TRU-7 are strongly influenced by large precipitation events and by the tide.

The amplitude of the tidal signature is about 1 ft during February but then shrinks to 0.1 to 0.2 feet for most of the spring. Beginning in April, the tidal amplitude begins to grow again, reaching 0.6 ft by the end of the dataset. The reason for this variation in tidal amplitude is unknown.



WELL TRU-7 Groundwater Elevation Data

Figure C-44



**Notes:**

The TDS data at this well indicates brackish water most of the time. During one large precipitation event in the beginning of April, the water quality dropped into the freshwater zone.

Variations in TDS occur in response to large and moderate precipitation events, which increase the head but decrease the TDS by adding additional freshwater to the system.

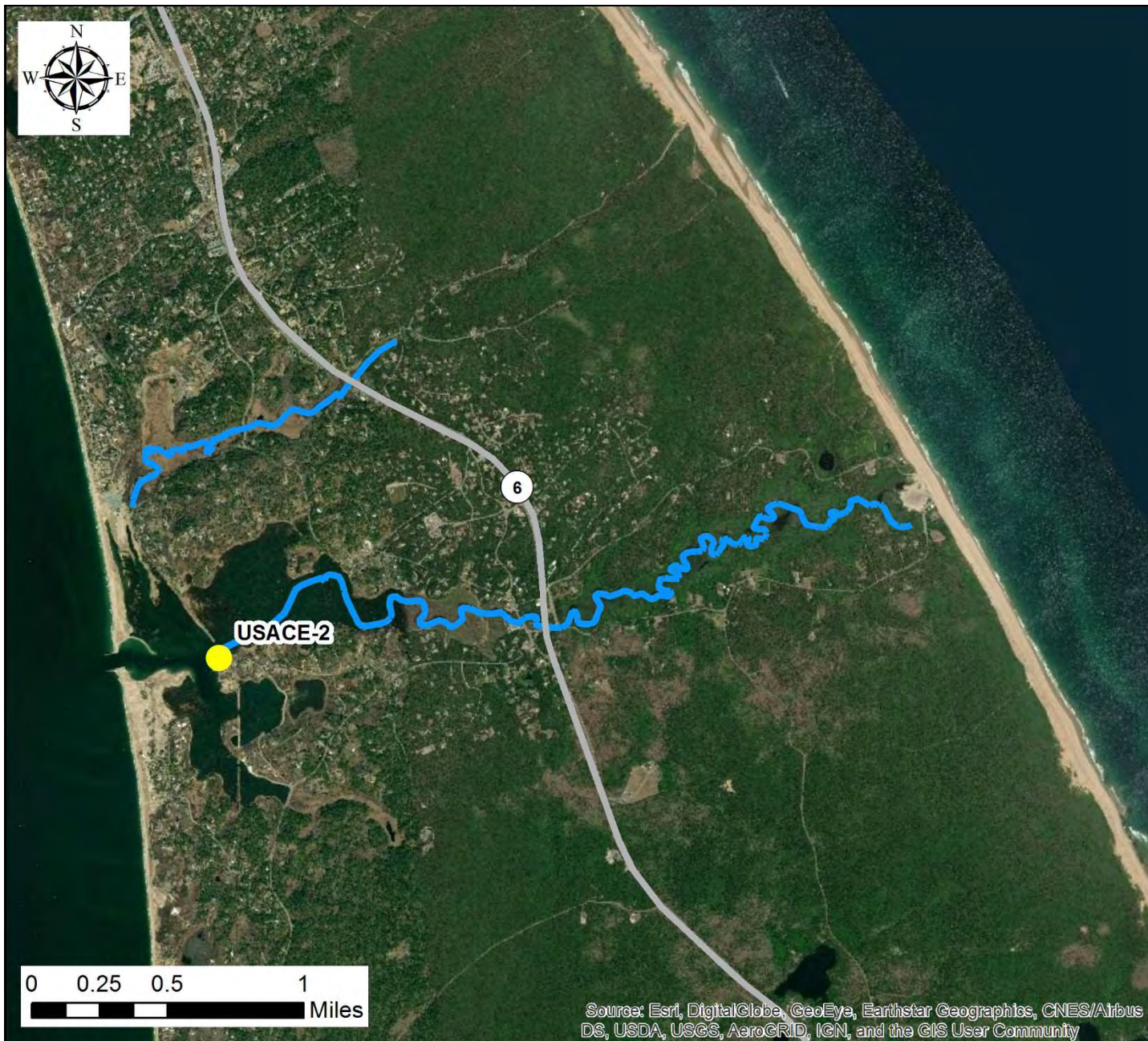
During some periods of the dataset, the TDS data is impacted by the tide as well. The reason that it is not always impacted or that there is significant variation in amplitude is unknown.



WELL TRU-7 Groundwater Quality Data

Figure C-45





**Notes:**

USACE-2 was hand-driven into an area on the south side of Pamet River which was dry during low tide but inundated during high tide. To accommodate the large swings in surface water depth, this well had a large stick up and measured water levels only 9.5 feet below the ground surface.

**Data Sources:**

ESRI  
USGS National Hydrography Dataset (NHD)  
USGS Small-scale Dataset Major Roads of the United States



WELL USACE-2 Location

Figure C-46





**Notes:**

USACE-2 was hand-driven into an area on the south side of Pamet River which was dry during low tide but inundated during high tide. To accommodate the large swings in surface water depth, this well had a large stick up and measured water levels only 9.5 feet below the ground surface.



WELL USACE-2 Location Zoom

Figure C-47





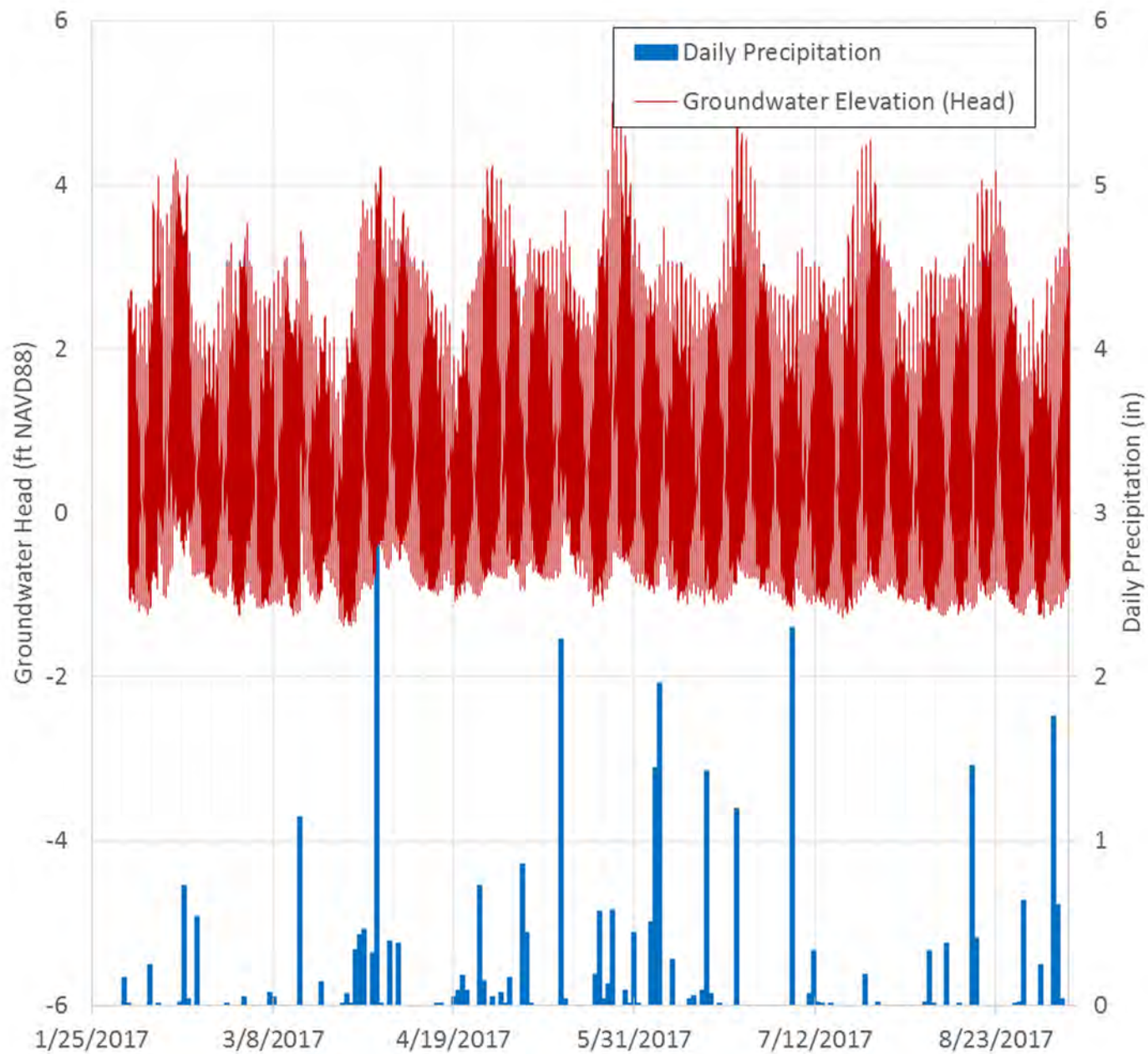
**Notes:**

USACE-2 was hand-driven into an area on the south side of Pamet River which was dry during low tide but inundated during high tide. To accommodate the large swings in surface water depth, this well had a large stick up and measured water levels only 9.5 feet below the ground surface.



WELL USACE-2 Photo (January 2017)

Figure C-48



**Notes:**

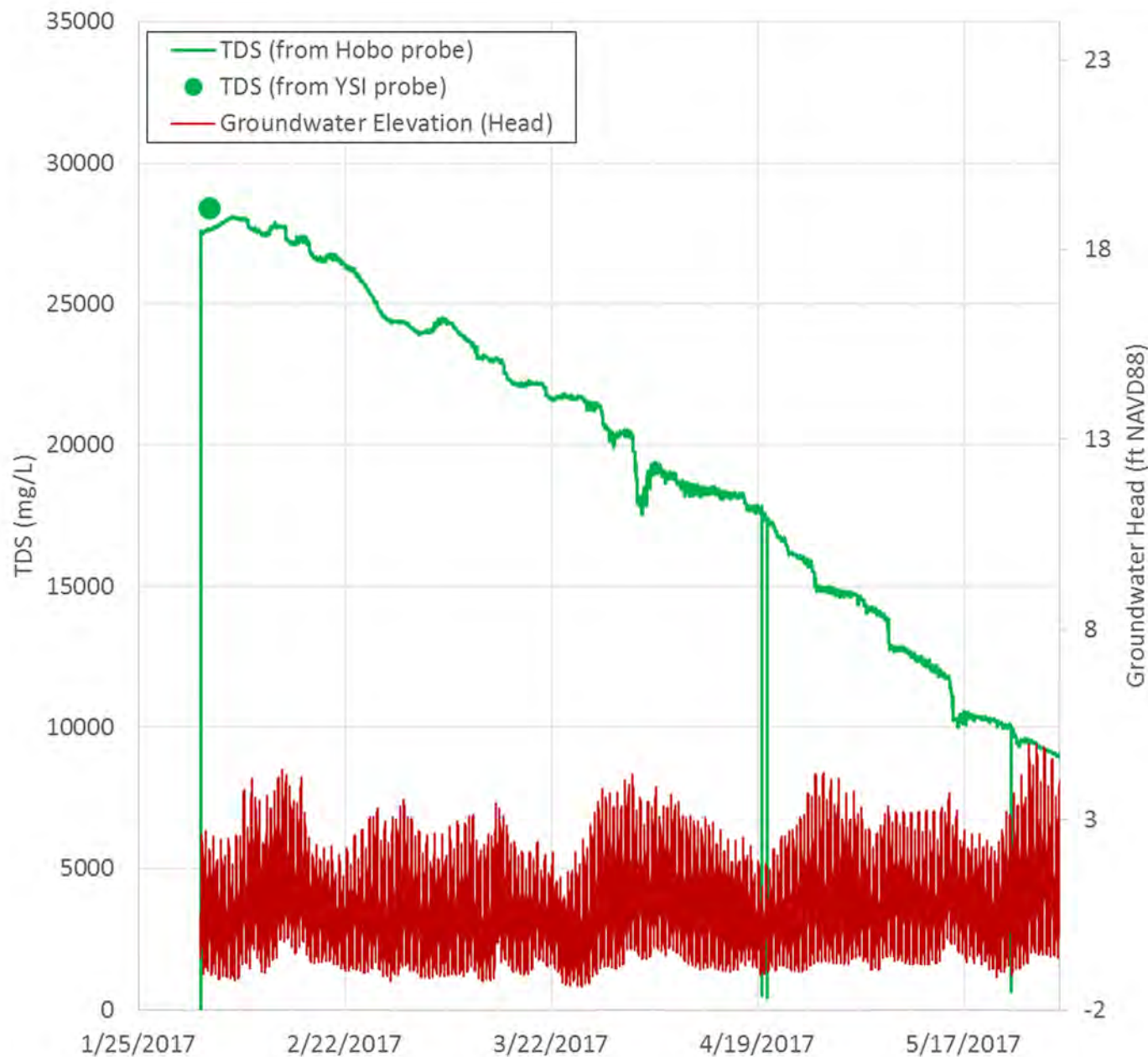
The groundwater levels at this well are clearly strongly influenced by the tidal variations with an amplitude of 4 ft. Impacts from large precipitation events are hard to pick out because of the strong tidal signature.



WELL USACE-2 Groundwater Elevation Data

Figure C-49





**Notes:**

The continuous TDS data at this well indicates a start just below the TDS of seawater (35,000 mg/L) and gradually dropping through the brackish zone to just below 10,000 mg/L. The TDS levels seem to drop noticeably immediately after large or moderate precipitation events, which is reasonable as additional freshwater is added to the system. There is a delay of a few days before the TDS impacts are noted, likely due to the time required to runoff to the river and flow down the river to this point near the bay coast.

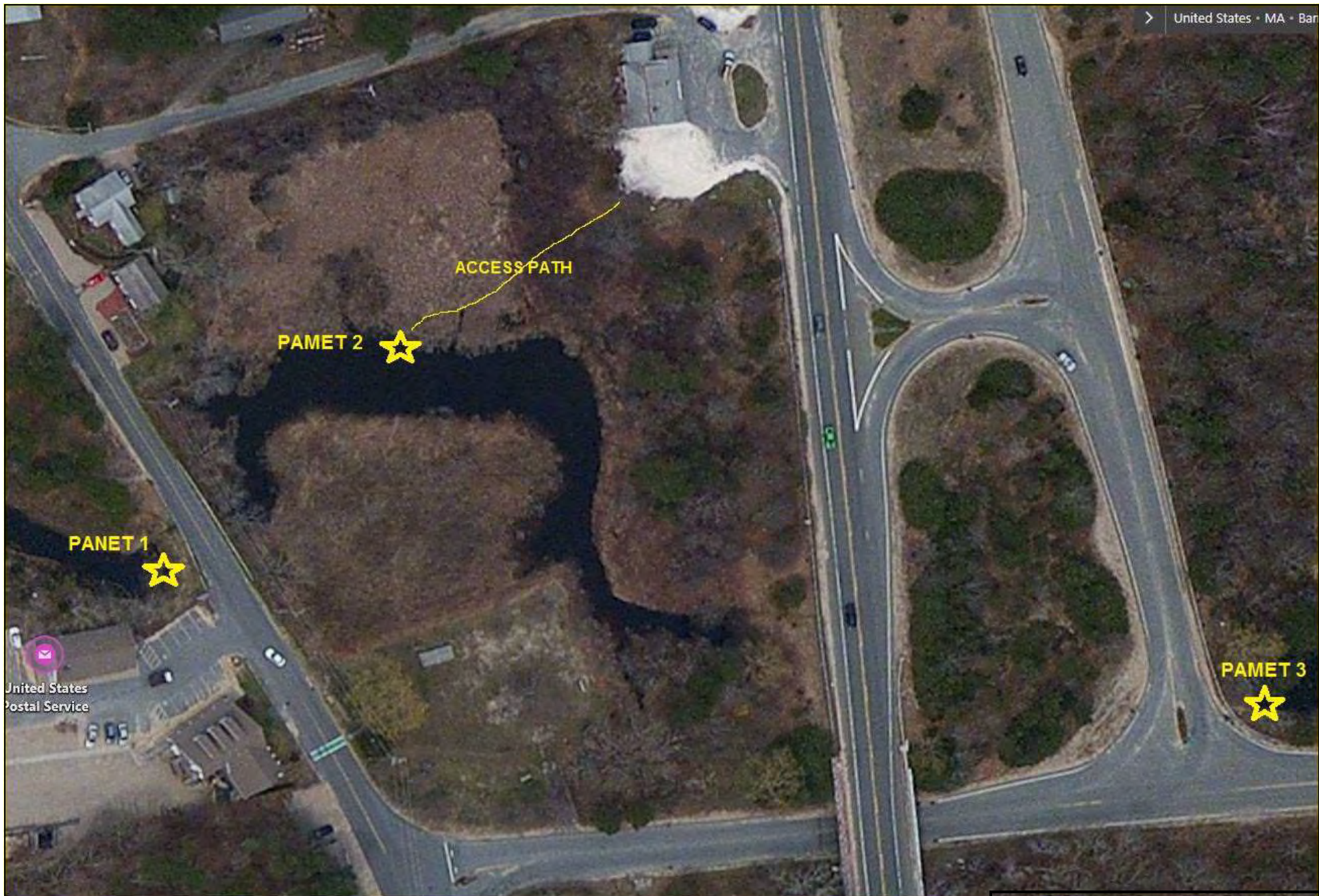
The continuous, significant drop in TDS over the 5-month measurement period is likely due to fouling of the probe and is likely not accurate.



WELL USACE-2 Groundwater Quality Data

Figure C-50





Tide Gage Locations

Figure C-51





Pamet 1 Tide Gage (Photo December 2016)

Figure C-52





Pamet 2 Tide Gage (Photo December 2016)

Figure C-53

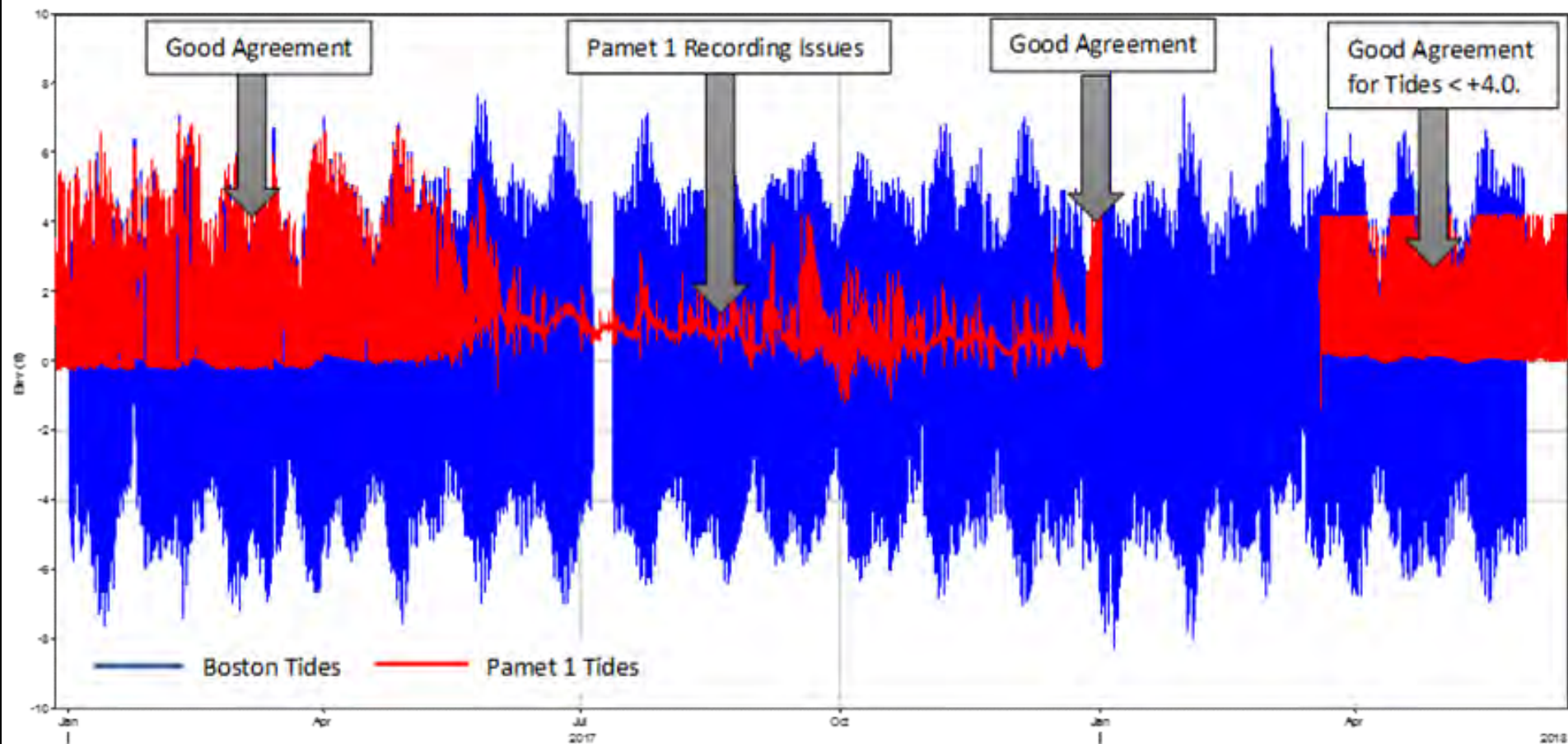




Pamet 3 Tide Gage (Photo December 2016)

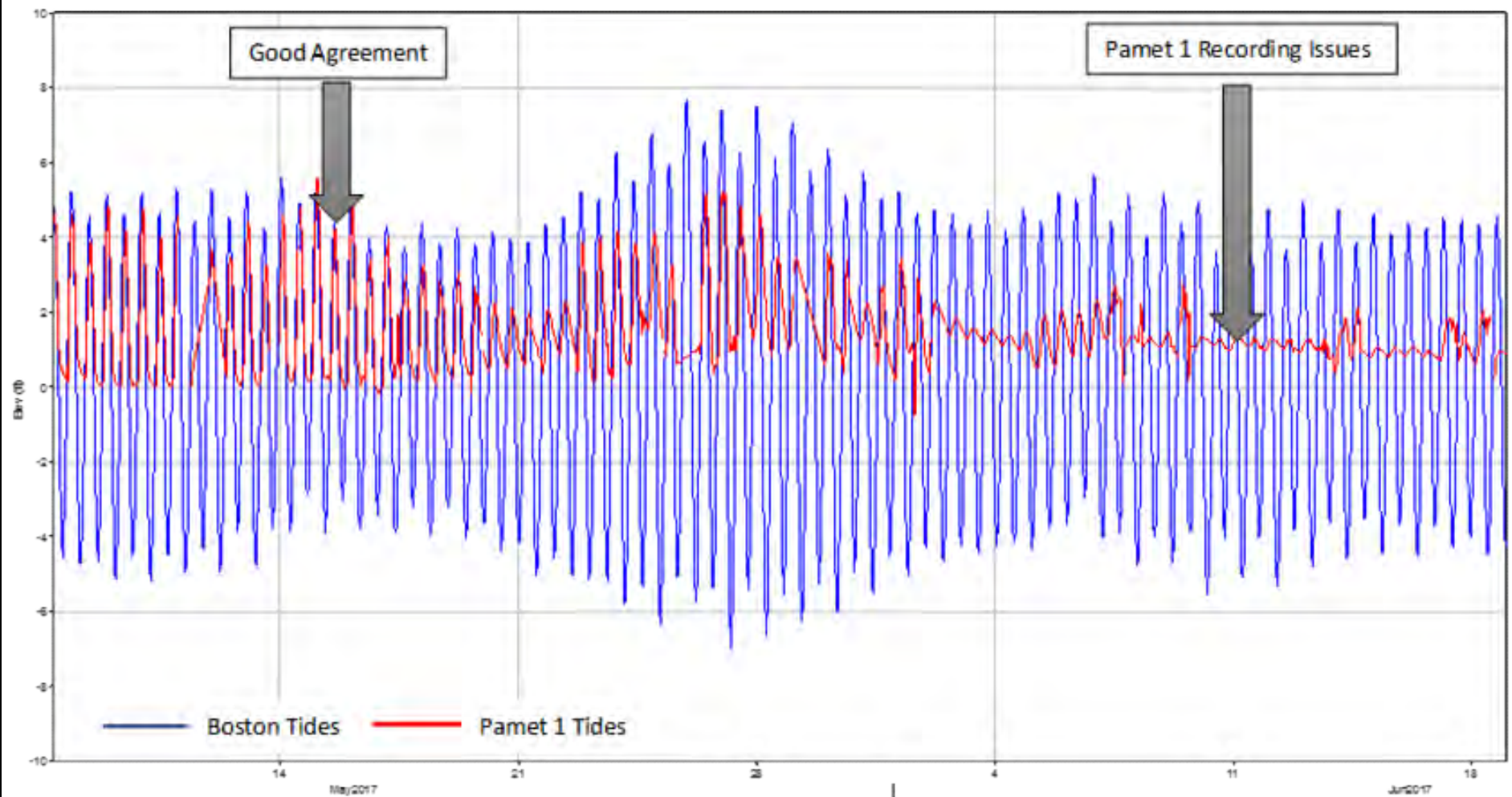
Figure 54





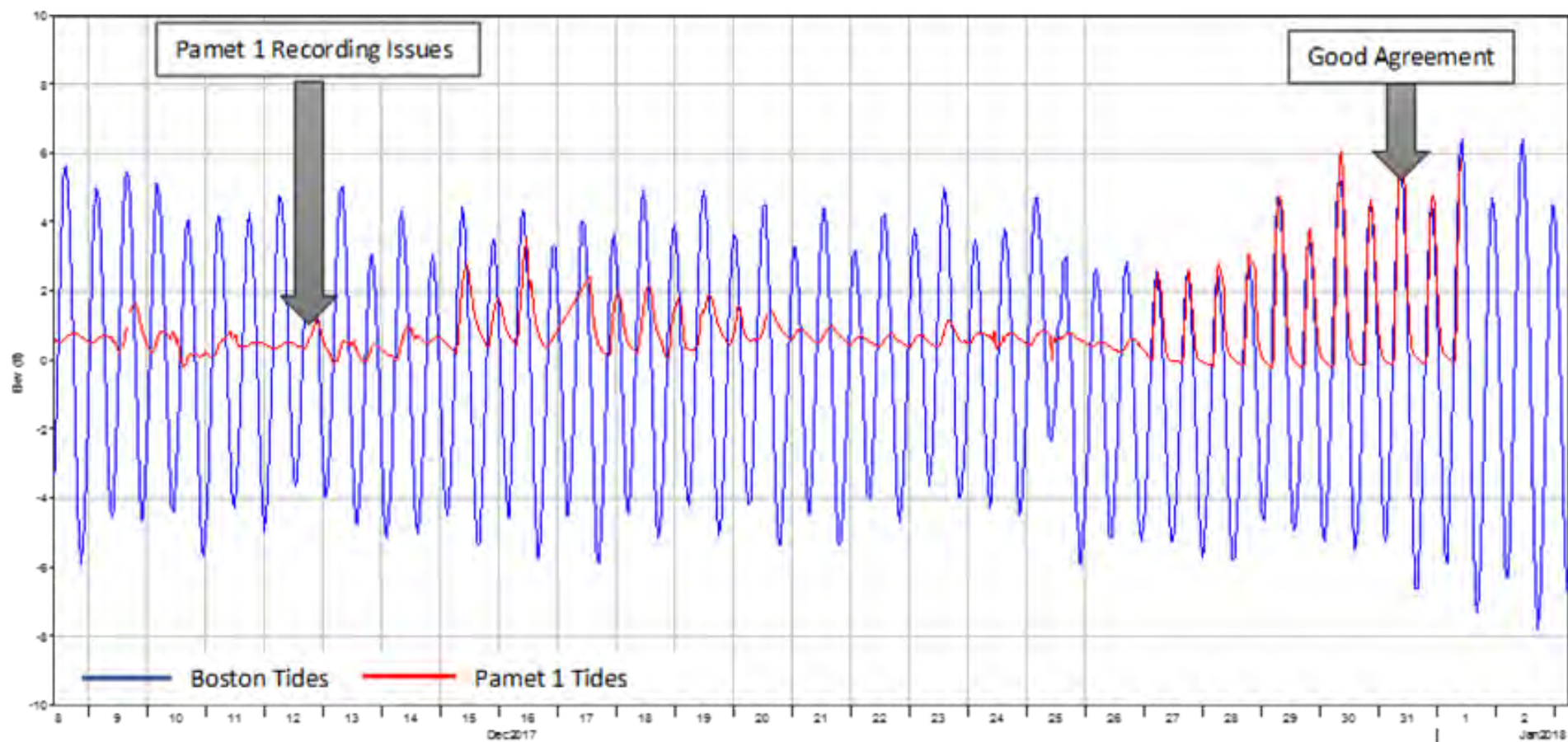
Boston Tides vs Pamet 1 Observed Tides from Dec 27, 2016 to June 15, 2018

Figure 55



Boston Tides vs Pamet 1 Observed Tides from May 7, 2017 to June 18, 2017

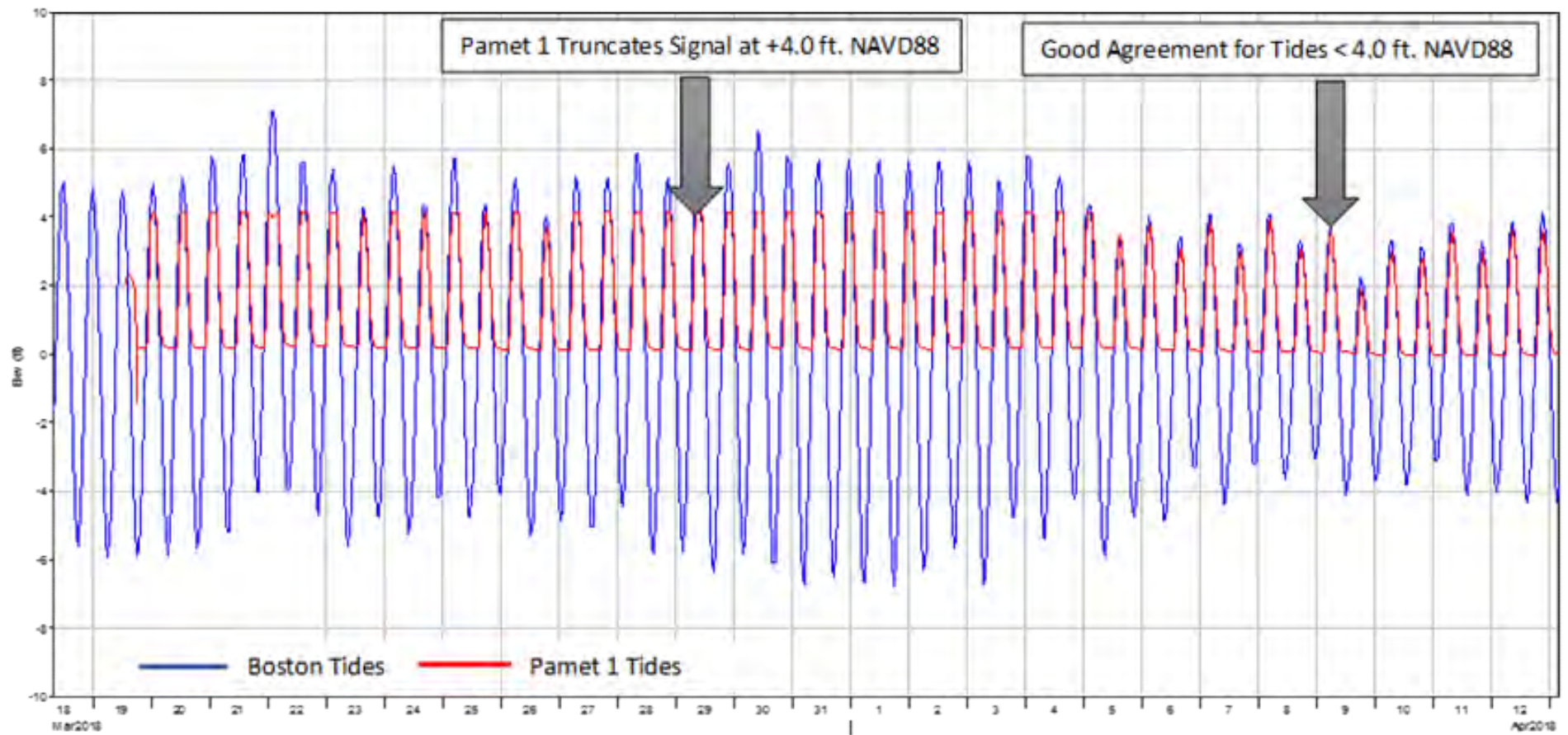
Figure 56



Boston Tides vs Pamet 1 Observed Tides from Dec 8, 2017 to Jan 2, 2018

Figure 57

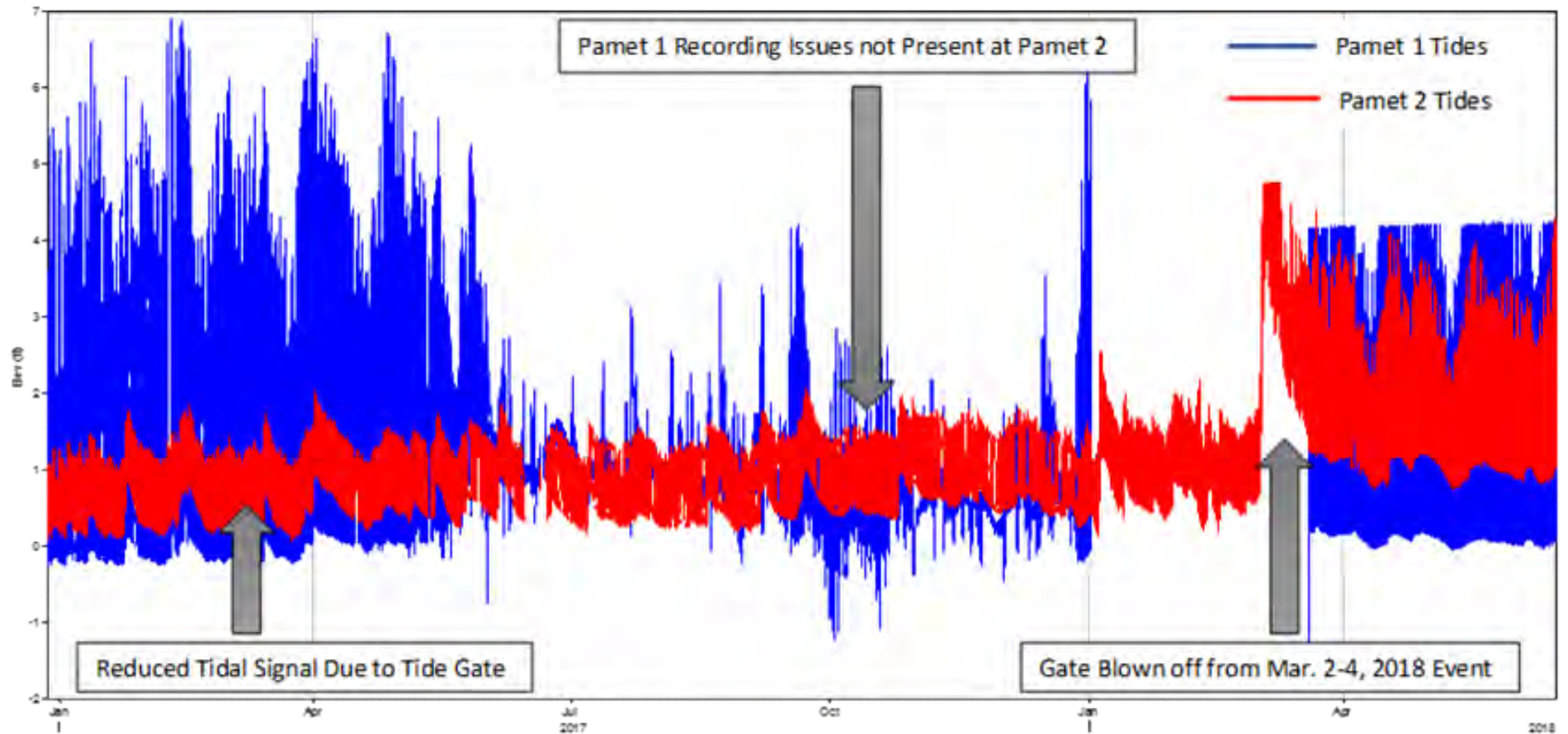




Boston Tides vs Pamet 1 Observed Tides from Mar 18, 2018 to Apr 12, 2018

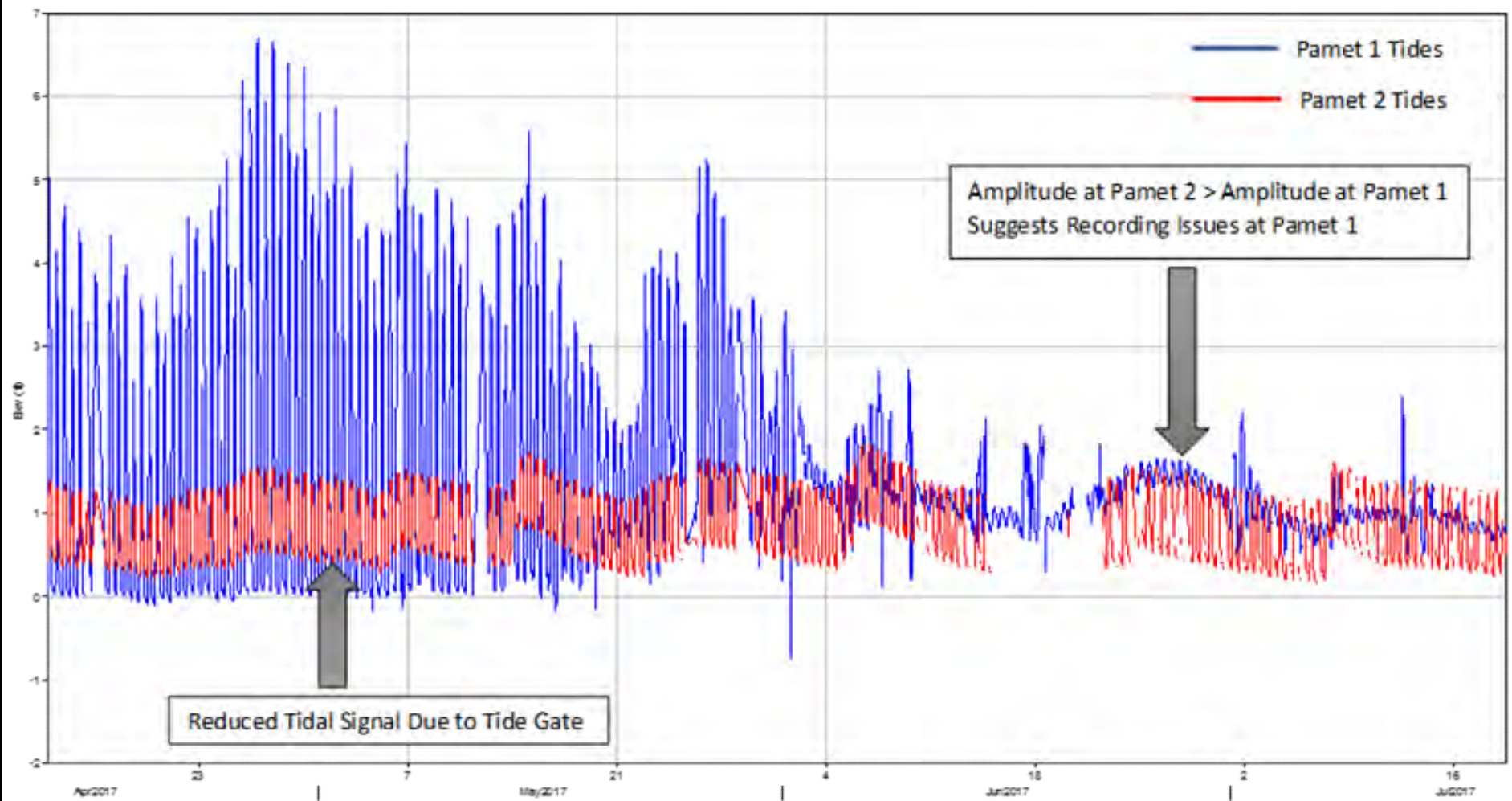
Figure 58





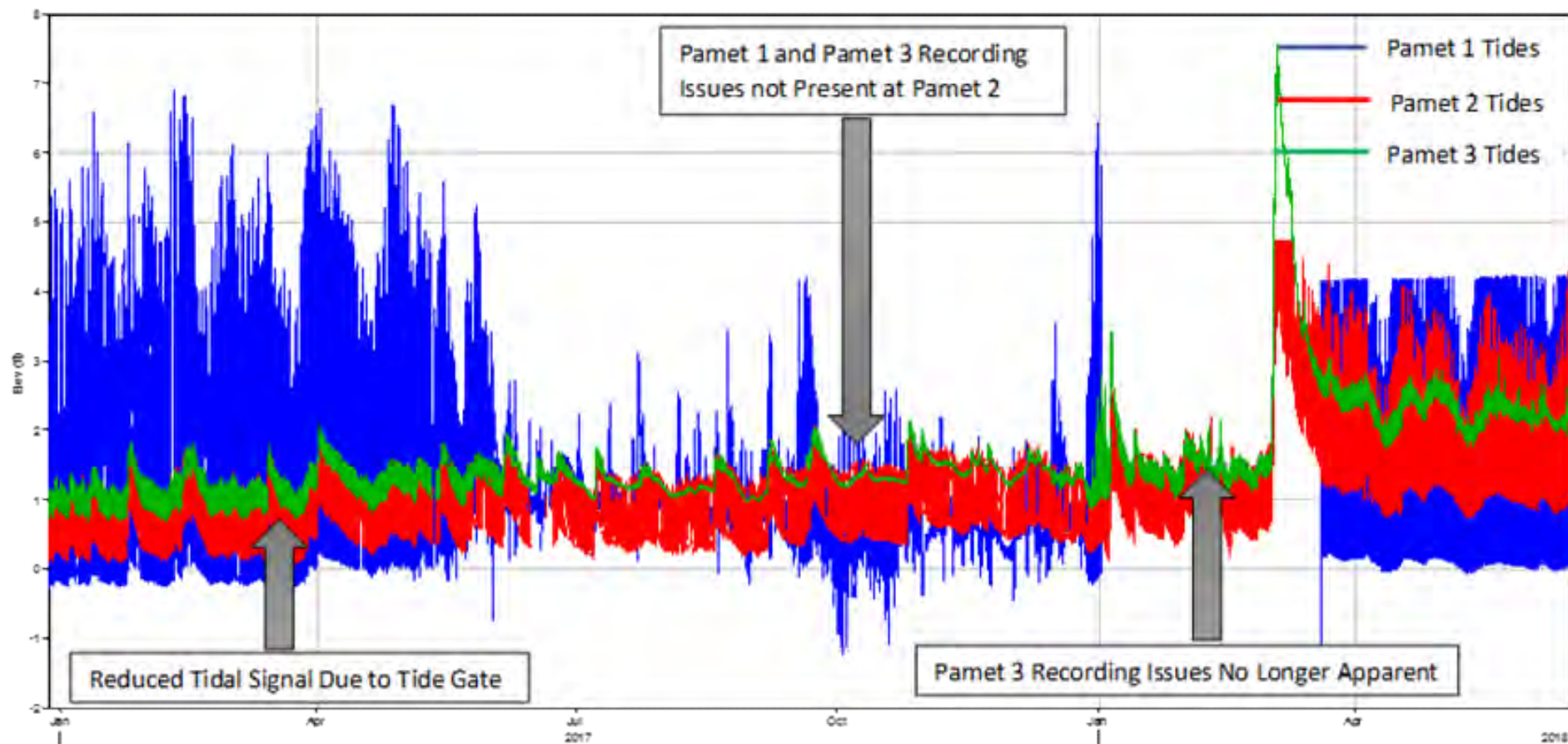
Pamet 1 vs Pamet 2 Observed Tides from Jan 2017 to Jul 2018

Figure 59



Pamet 1 vs Pamet 2 Observed Tides from Apr 2017 to Jul 2017

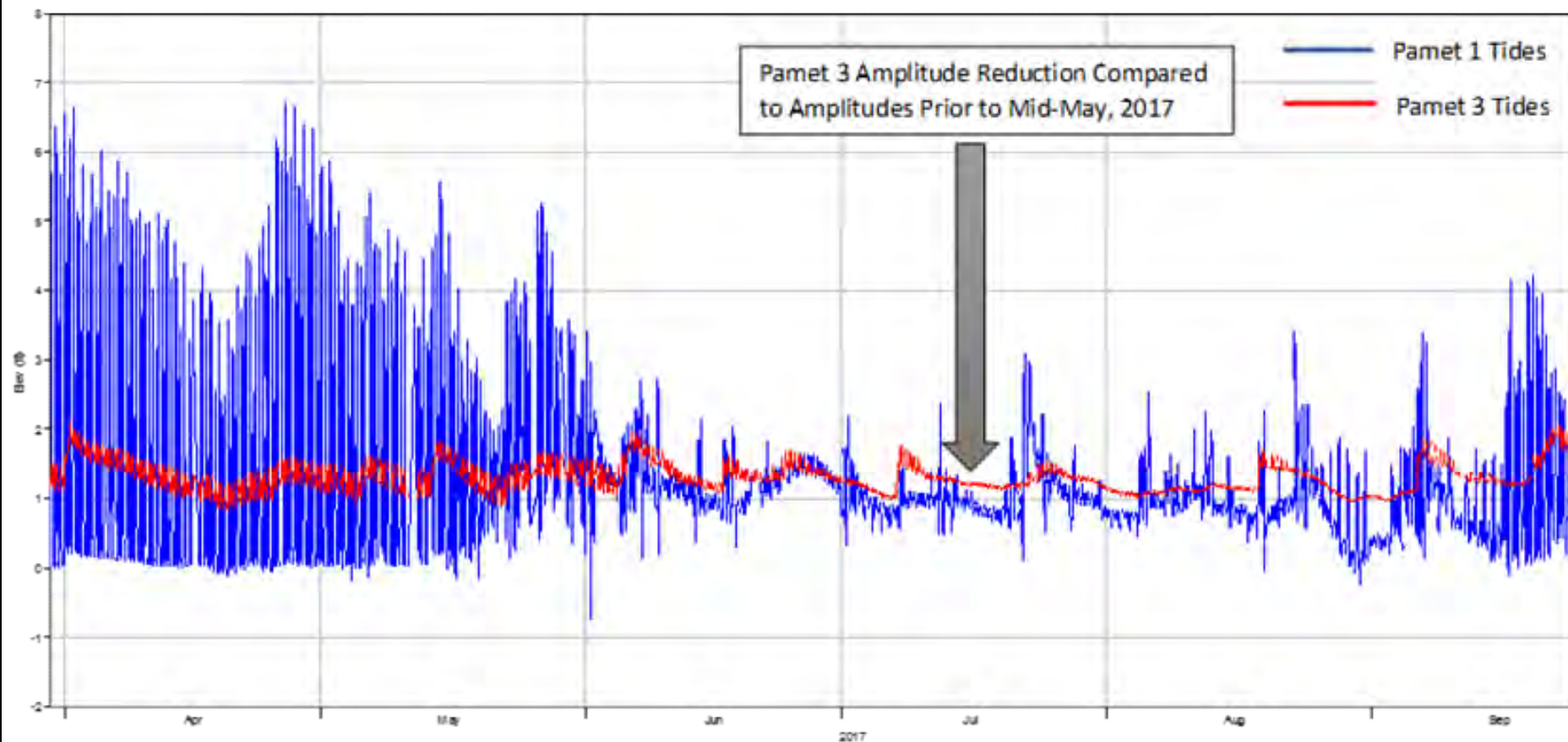
Figure 60



Pamet 1 vs Pamet 2 vs Pamet 3 Observed Tides from Dec 2016 to Jul 2018

Figure 61

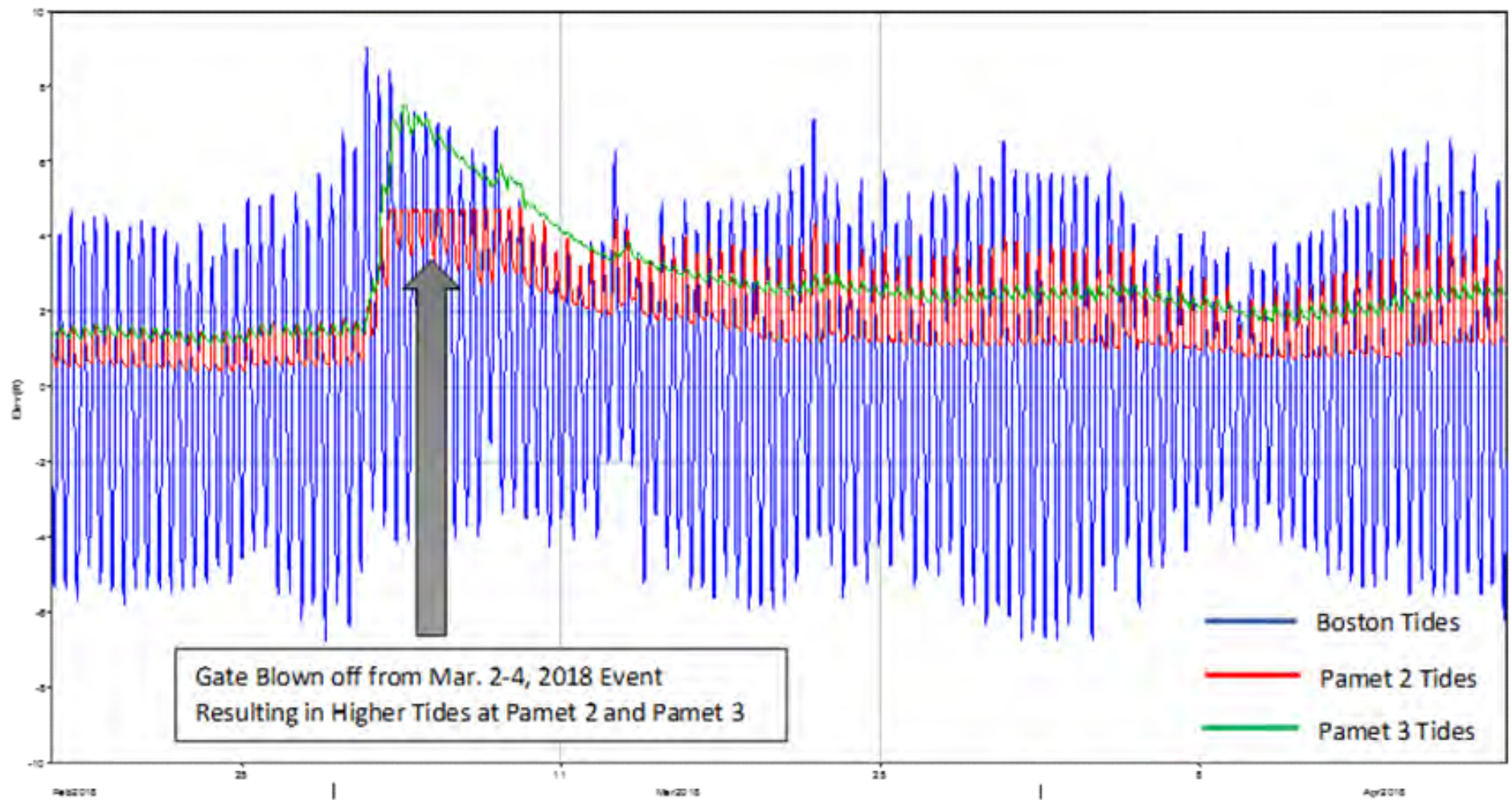




Pamet 1 vs Pamet 3 Observed Tides from Apr 2017 to Sep 2017

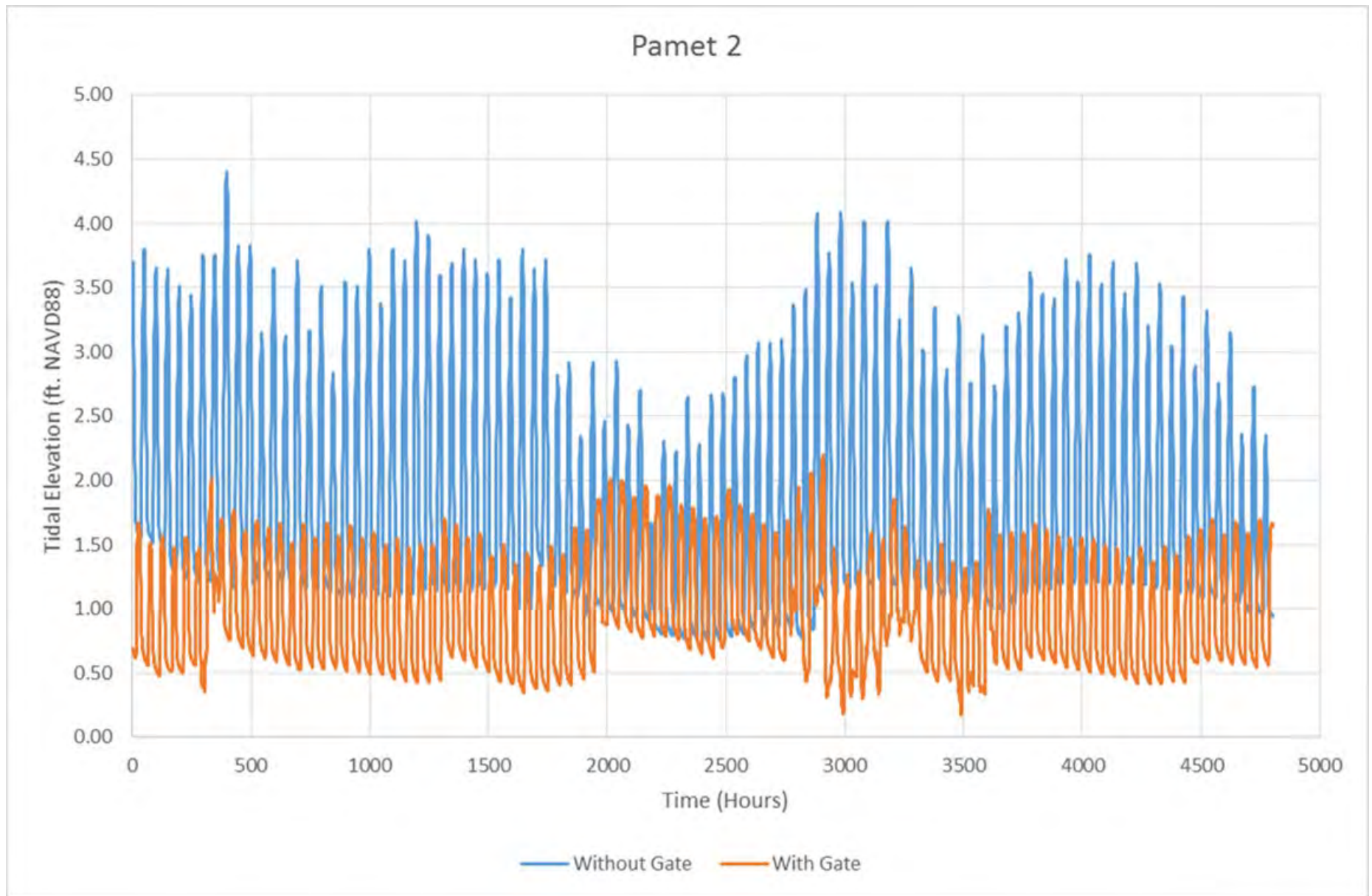
Figure 62





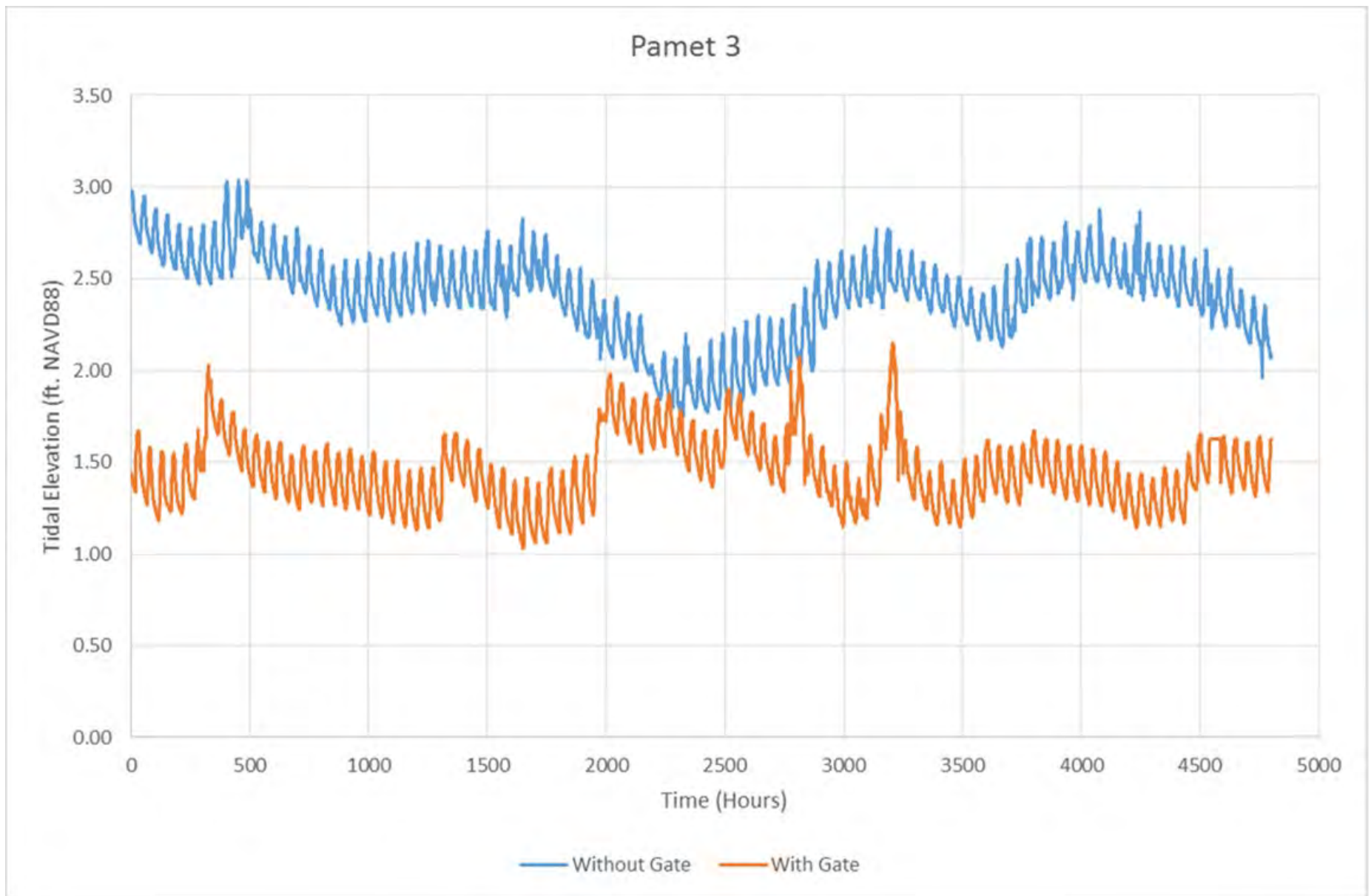
Pamet 1 vs Pamet 2 vs Pamet 3 Observed Tides from Feb 2018 to Apr 2018

Figure 63



Pamet 2 Comparison With Gate (Jan 10 – Feb 28) and Without Gate (Mar 18 – May 6)

Figure 64



Pamet 3 Comparison With Gate (Jan 10 – Feb 28) and Without Gate  
(Mar 18 – May 6)

Figure 65

**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT D**  
**GROUNDWATER MODEL ANALYSIS**  
**FIGURES D-1 to D-37**

**REFERENCED FROM: CHAPTER 6**

Pamet River Groundwater Model - *Quantitative Data Analysis*  
(MODFLOW 2000)

**C.A.P. SECTION 22**  
**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**





#### Notes:

Figure shows boundaries of model (red boundary) and Pamet river (blue line).

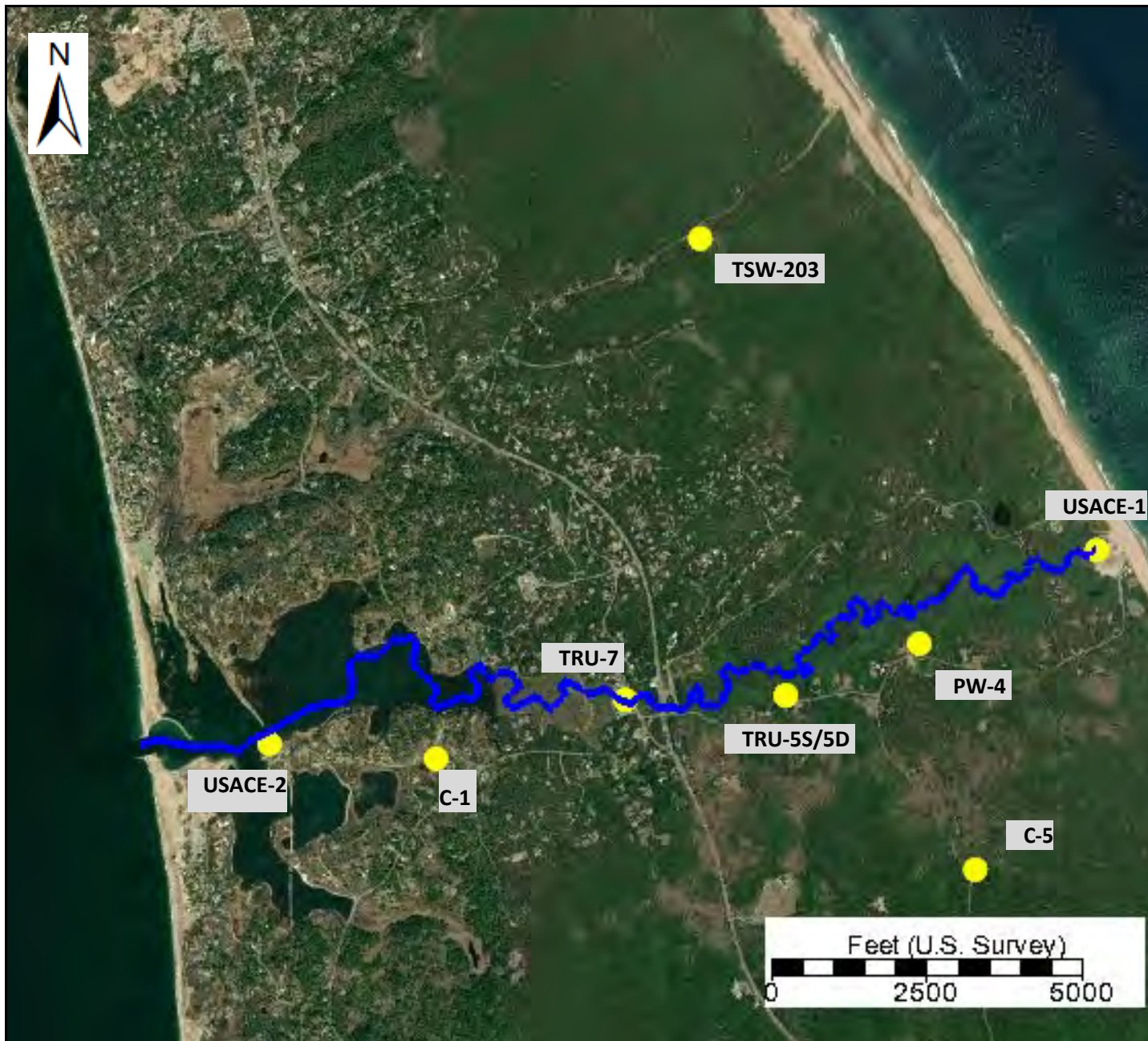
North and south boundaries are placed at the highest head in the groundwater lenses north and south of Pamet River and arranged to be perpendicular to groundwater head contour lines as drawn in Masterson, 2004. This placement allows the assumption that flow is parallel to the boundaries and the use of a no-flow boundary condition.

East and west boundaries are set off-shore such that they have little impact on the heads in the area of interest.



Model Boundaries

Figure D-1



**Notes:**

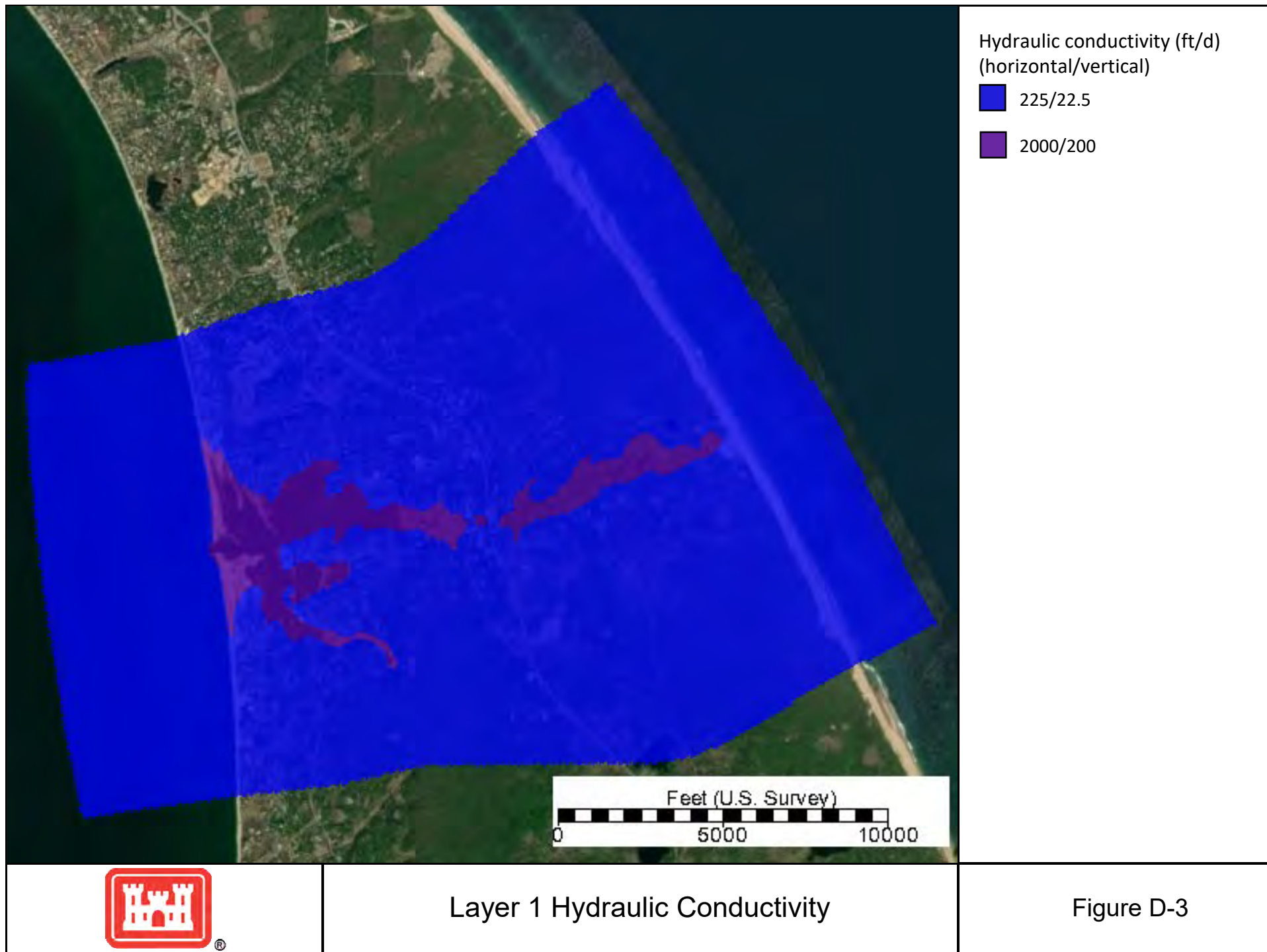
See Table 2 for observation well depths.

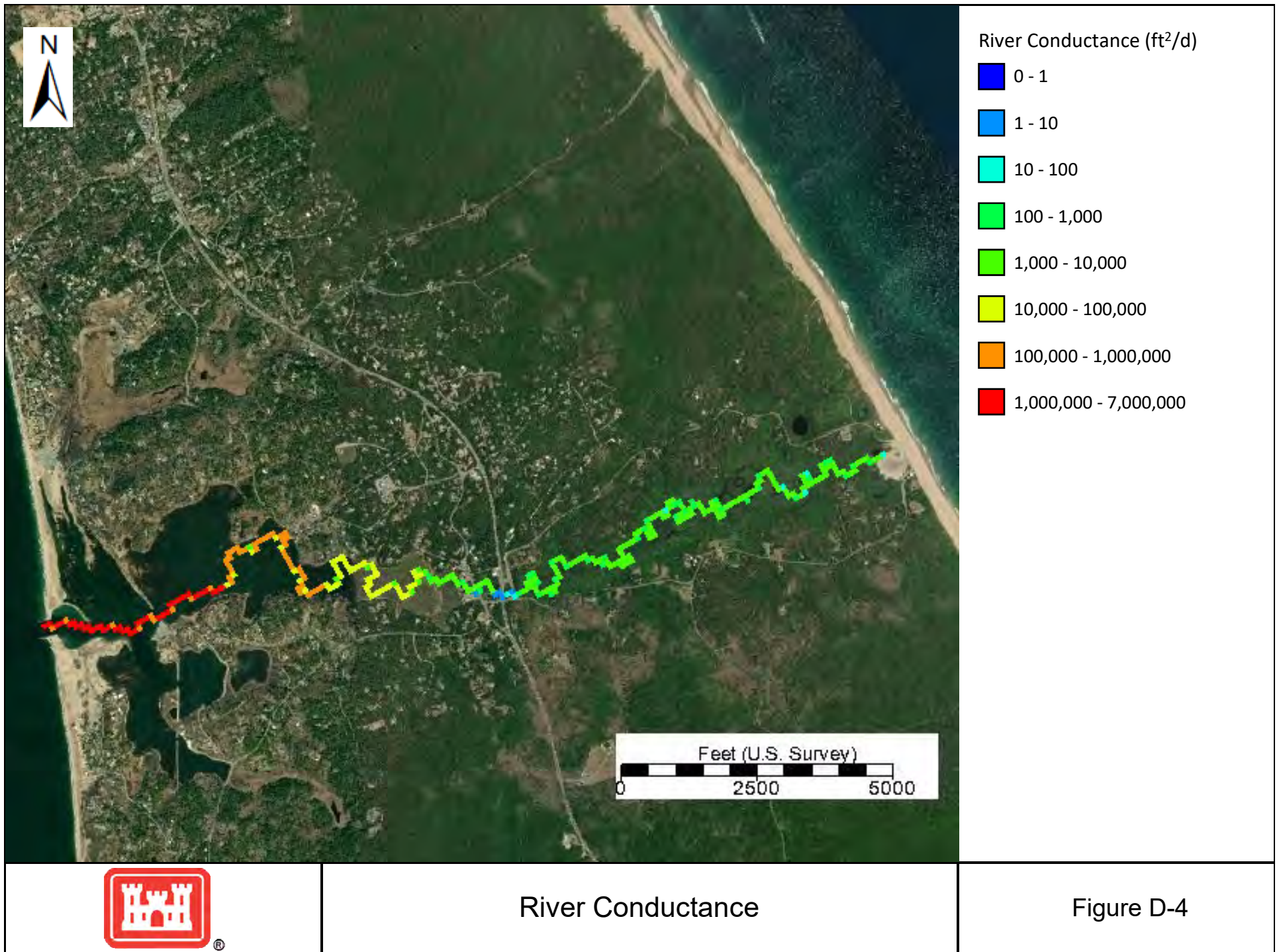


Groundwater Observation Point Locations

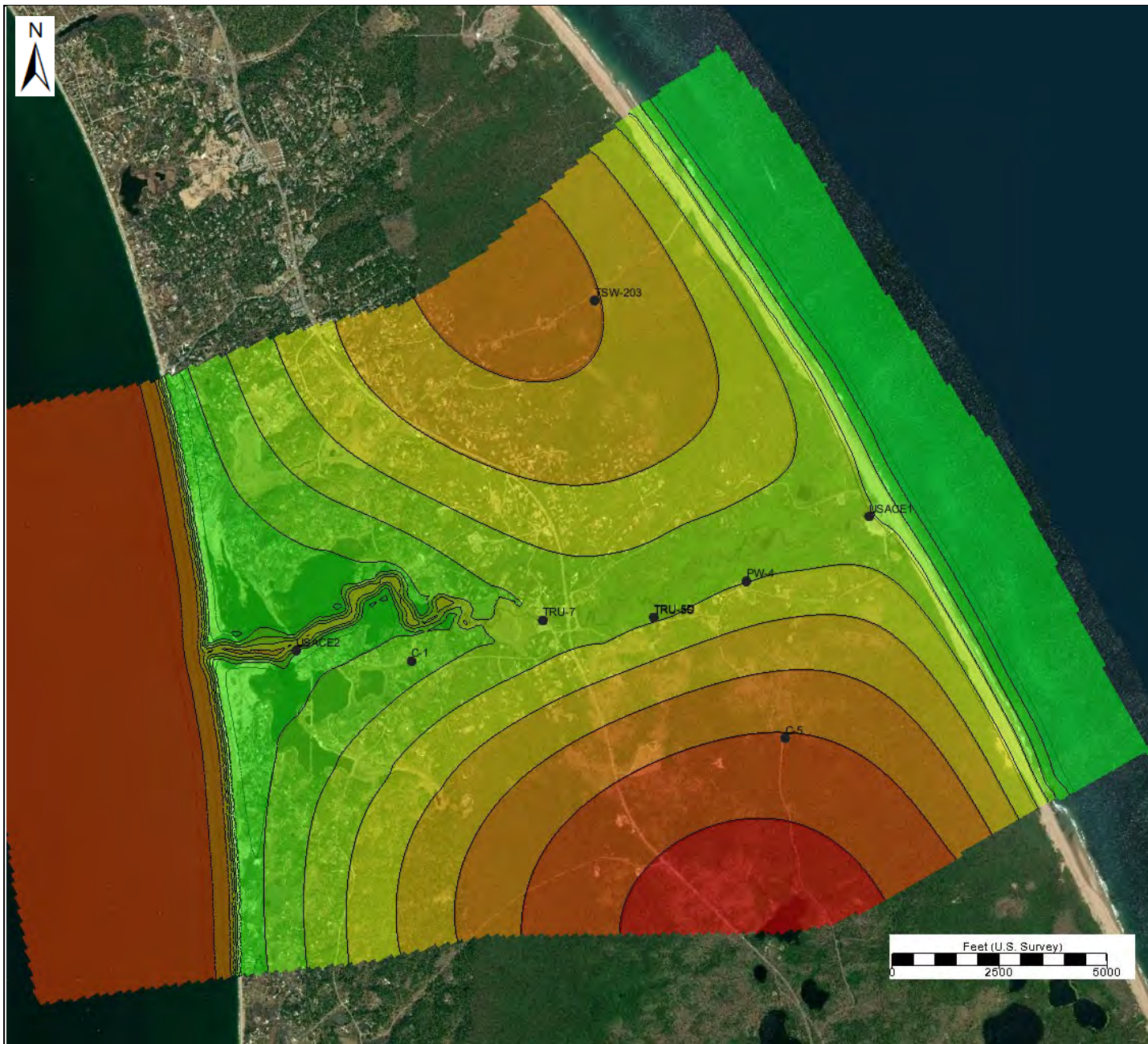
Figure D-2



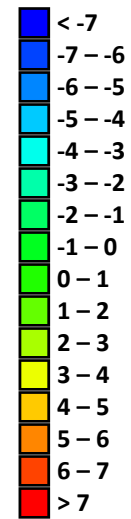








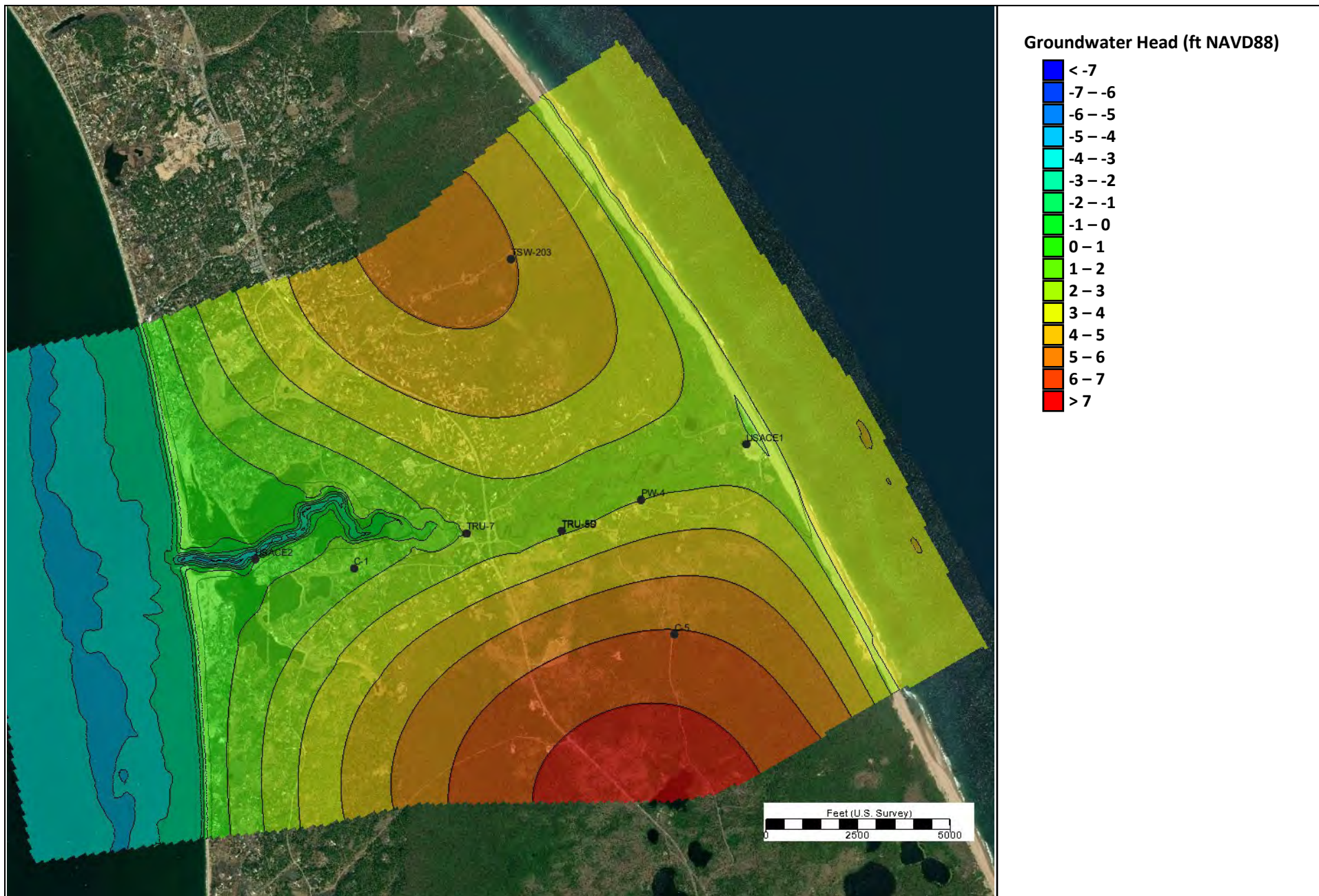
Groundwater Head (ft NAVD88)



Model Results:  
Groundwater Head (2/12/2017 11:00 AM)

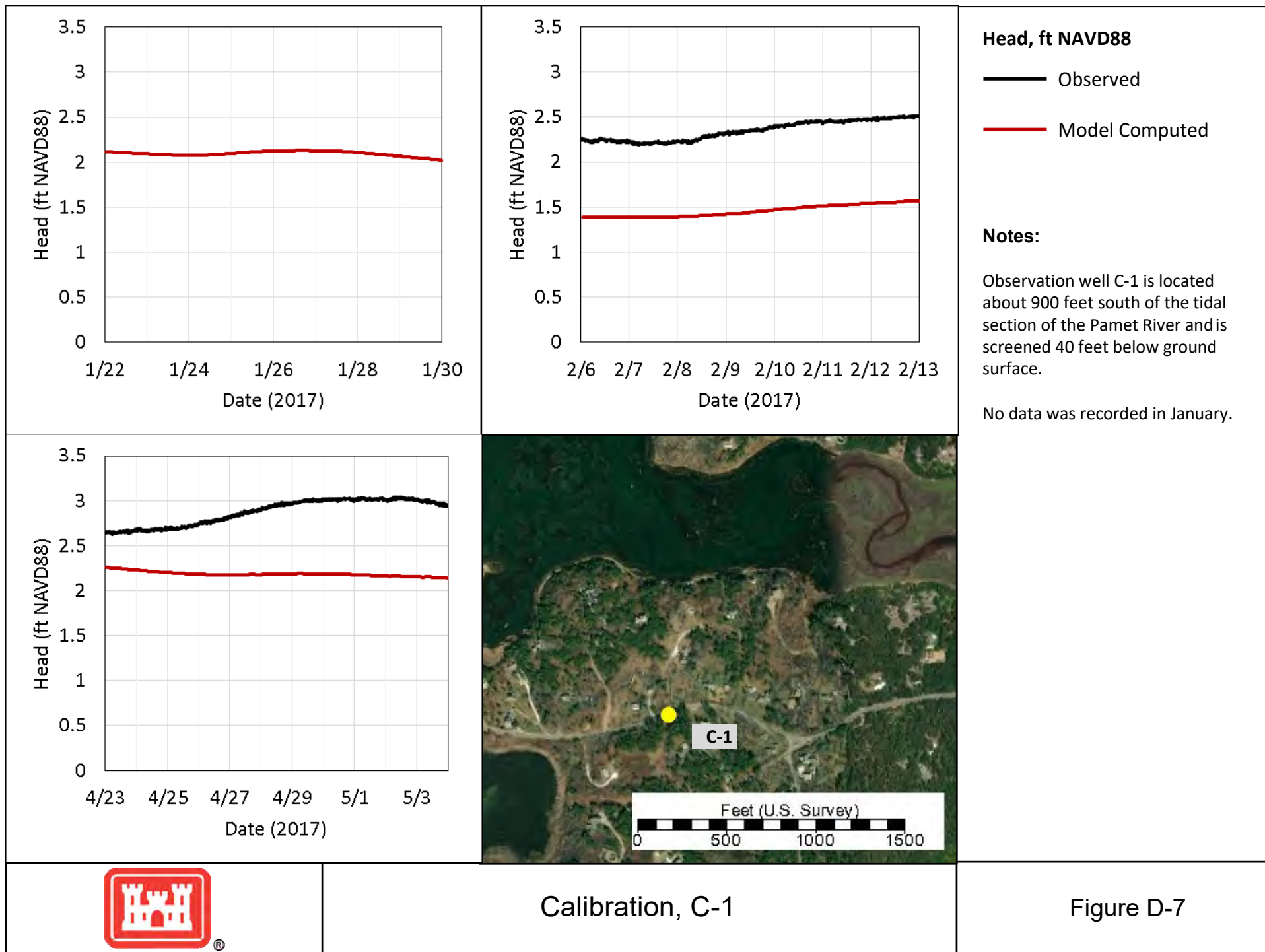
Figure D-5

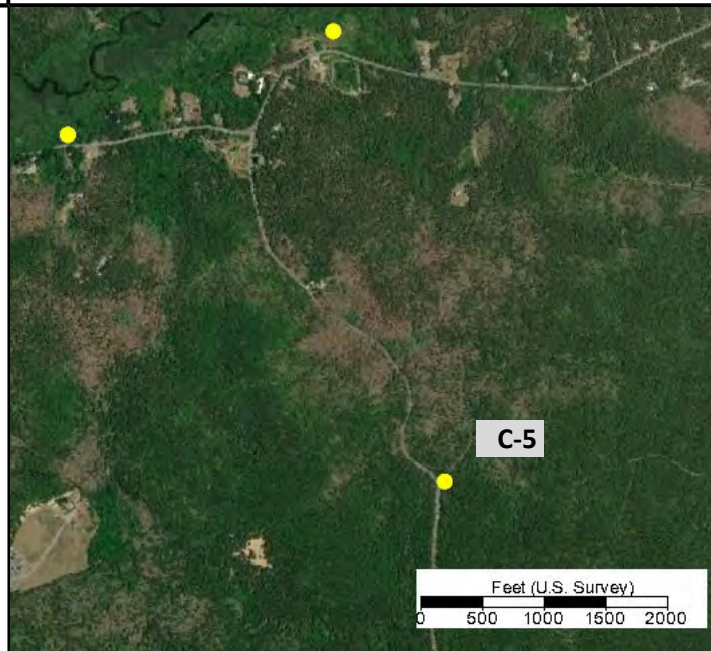
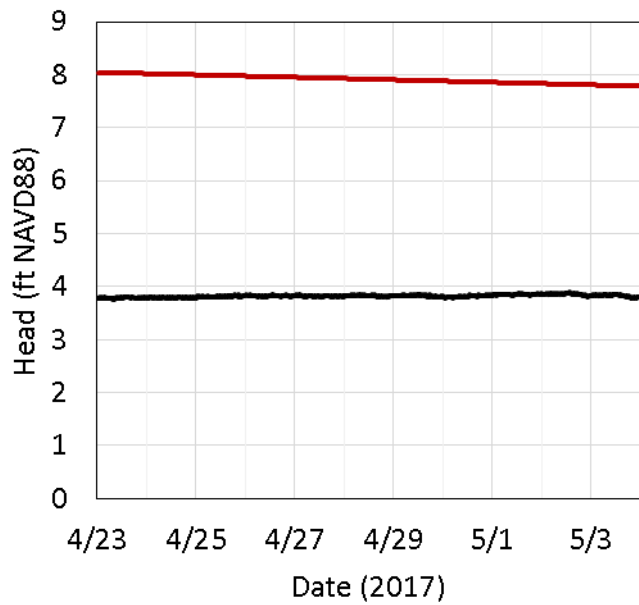
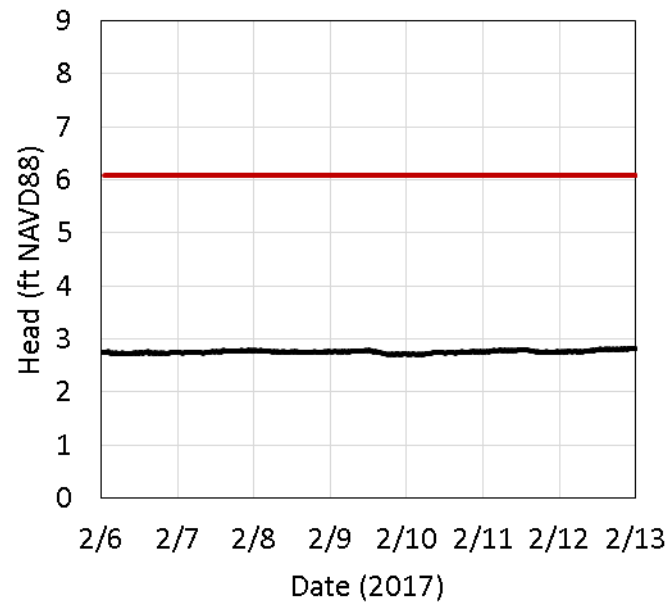
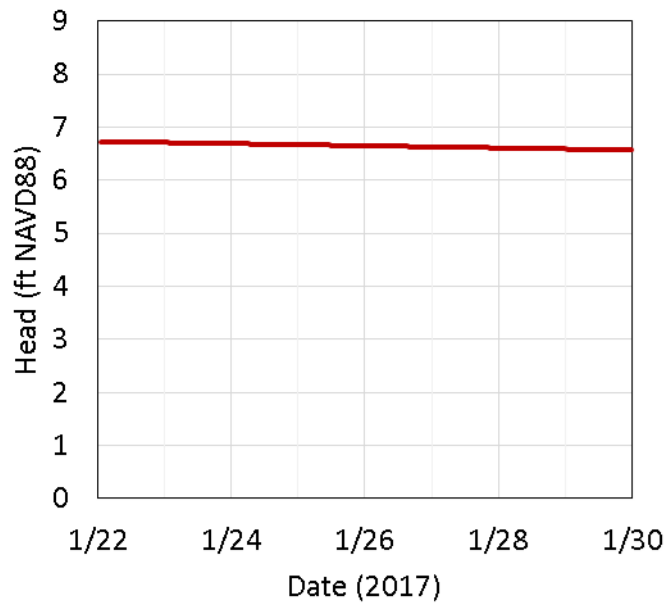




Model Results:  
Groundwater Head (2/12/2017 7:00 PM)

Figure D-6





#### Head, ft NAVD88

— Observed

— Model Computed

#### Notes:

Observation well C-5 is located about 4,000 feet south of the Pamet River and is screened 90 feet below ground surface.

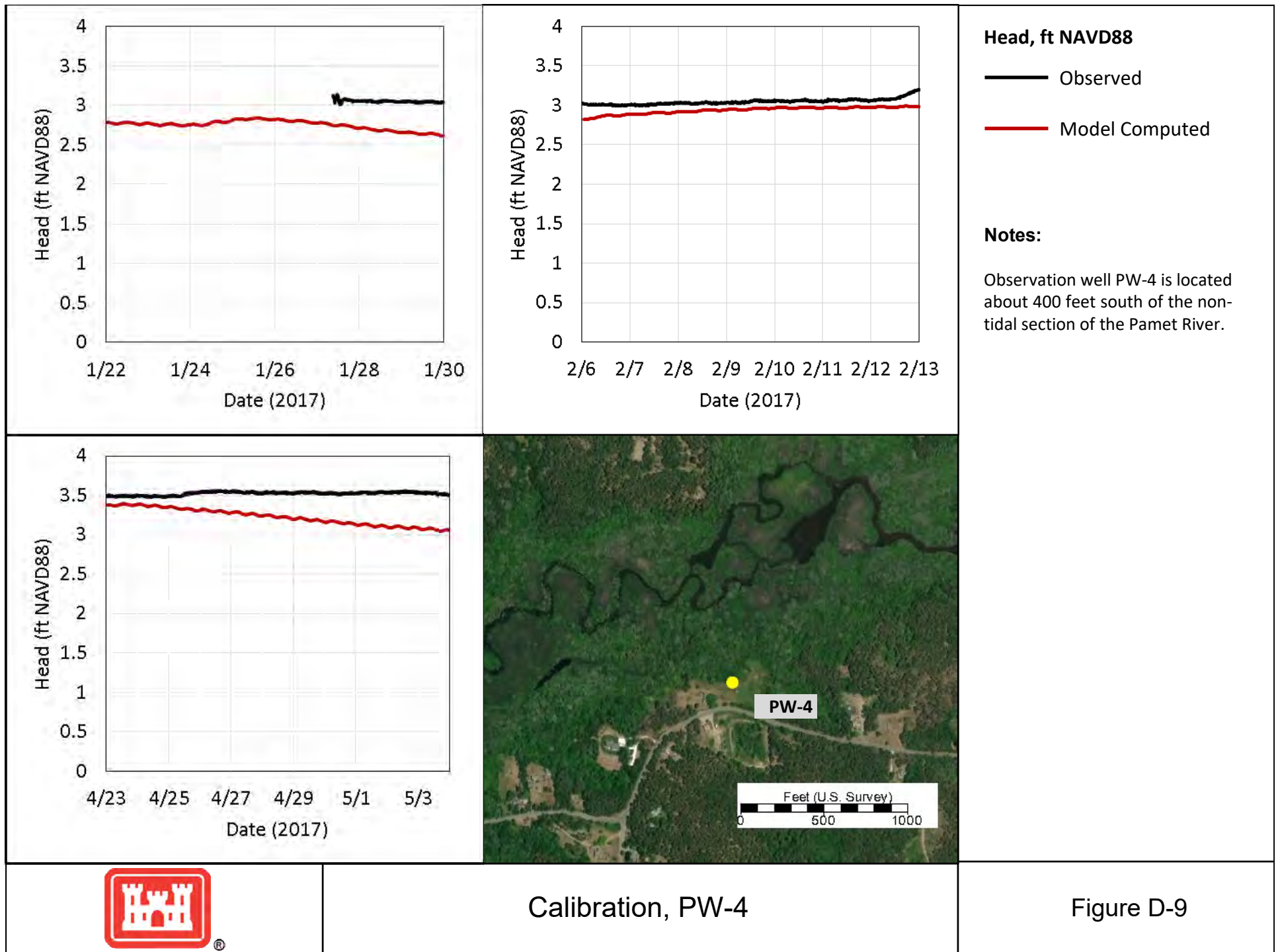
No data was recorded in January.

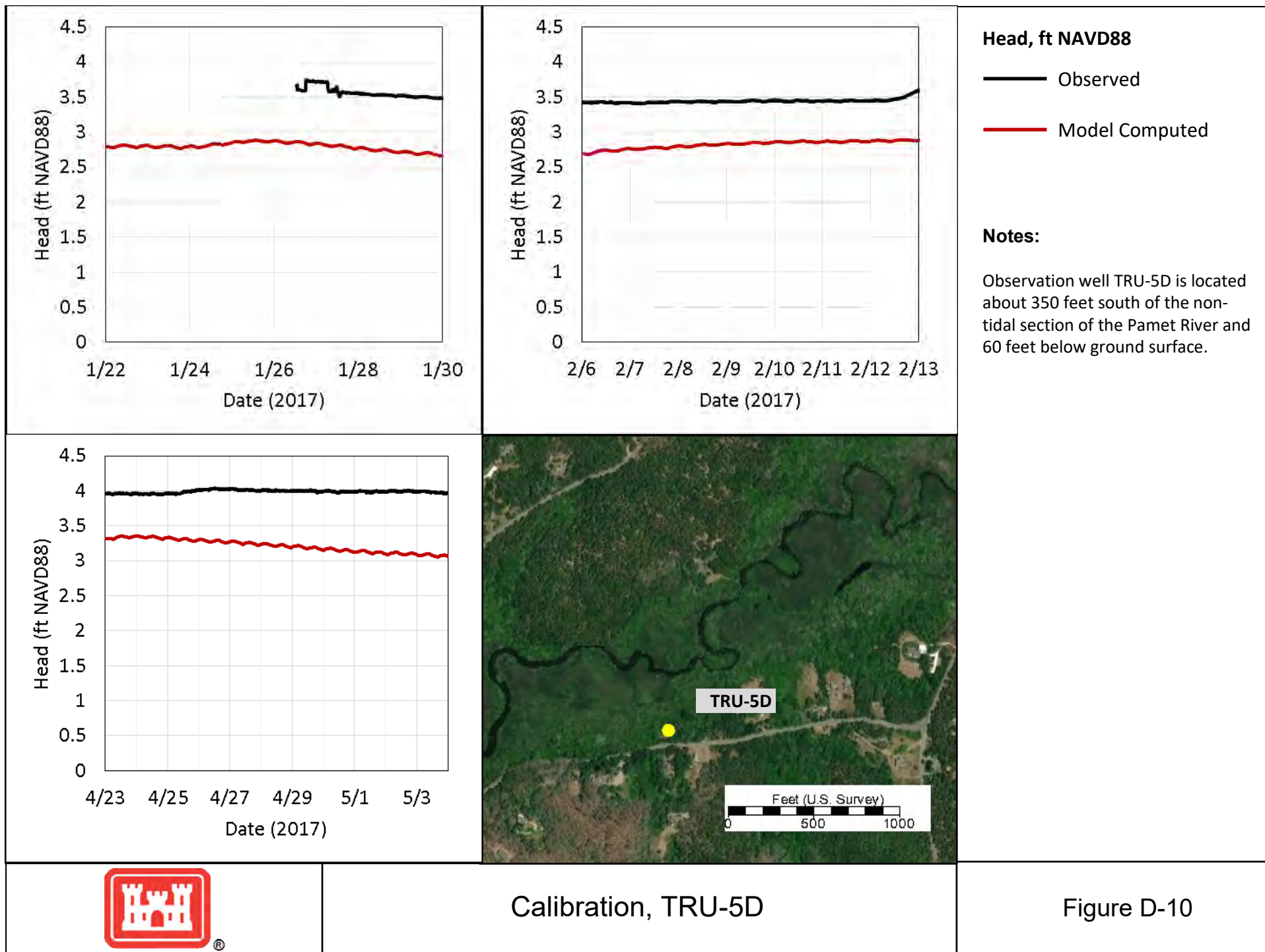


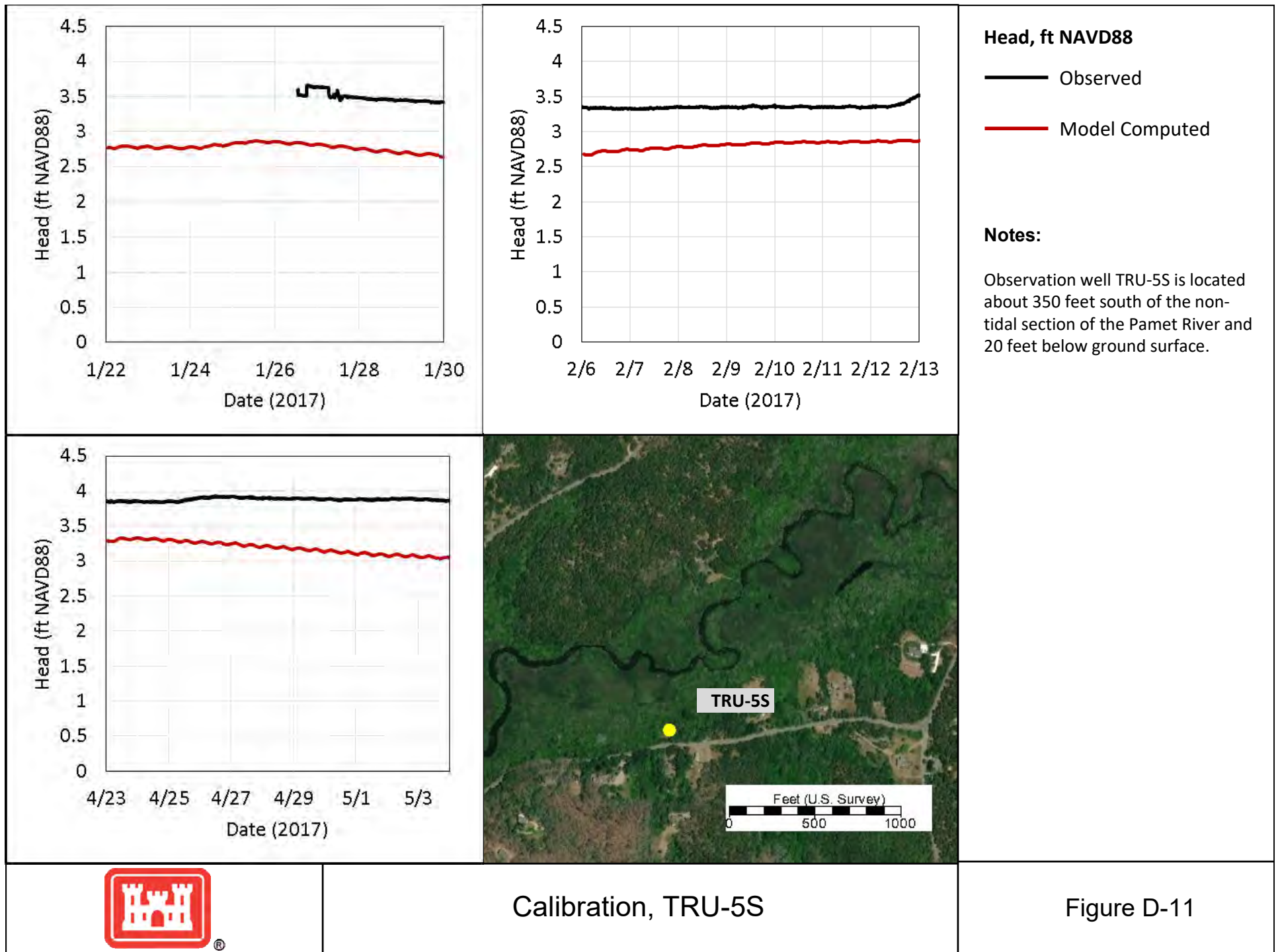
Calibration, C-5

Figure D-8

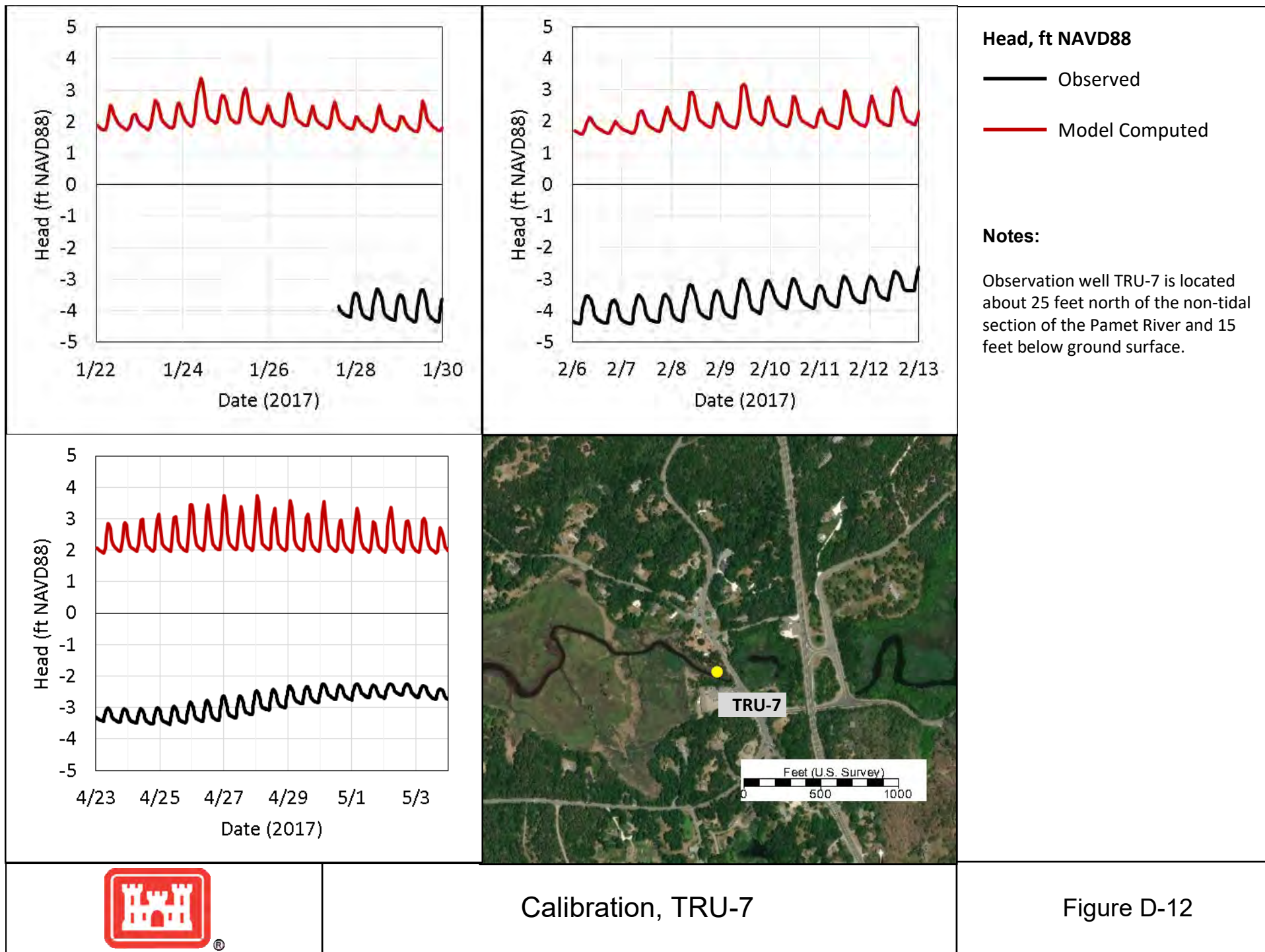




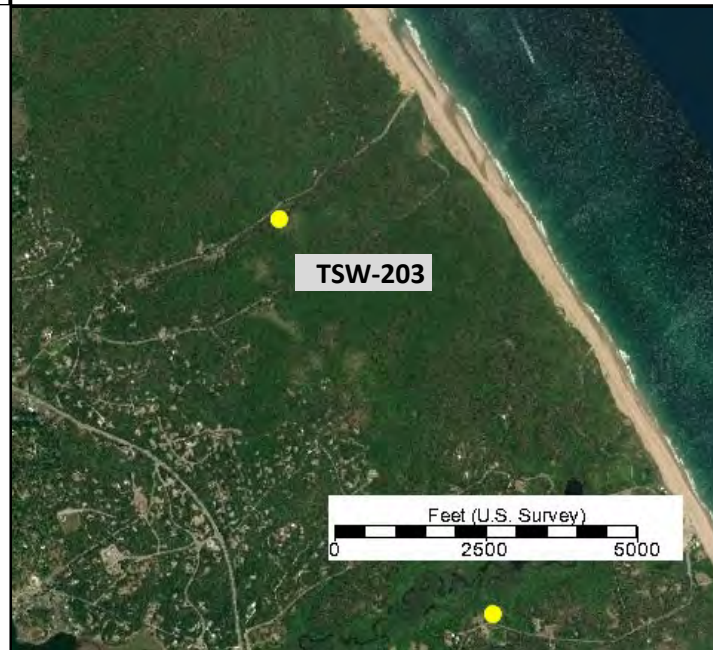
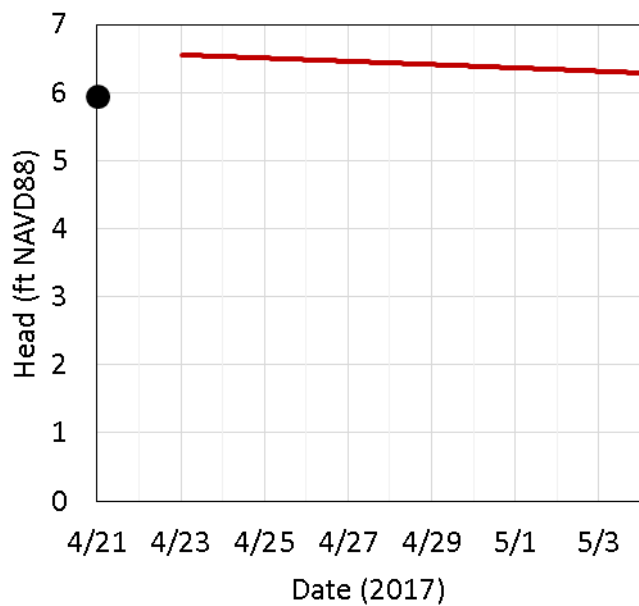
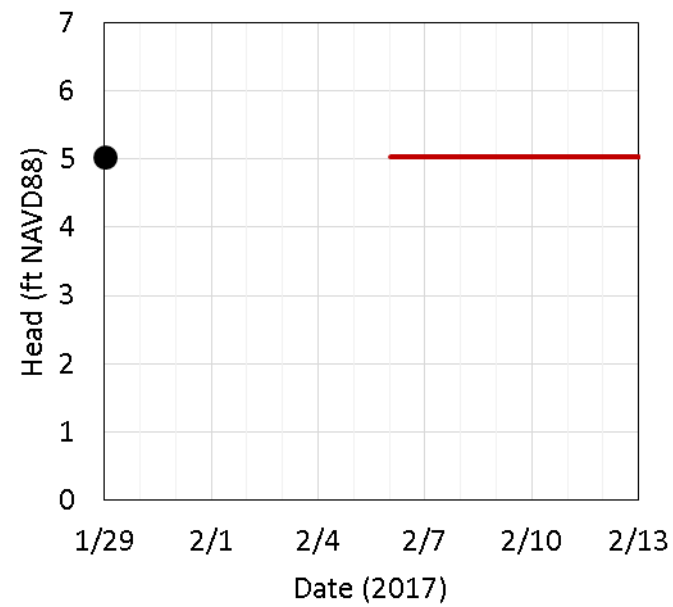
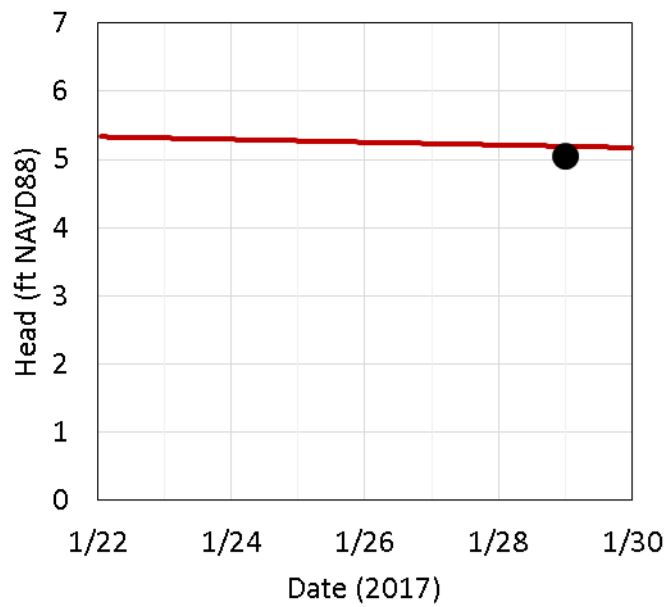












#### Head, ft NAVD88

— Observed

— Model Computed

#### Notes:

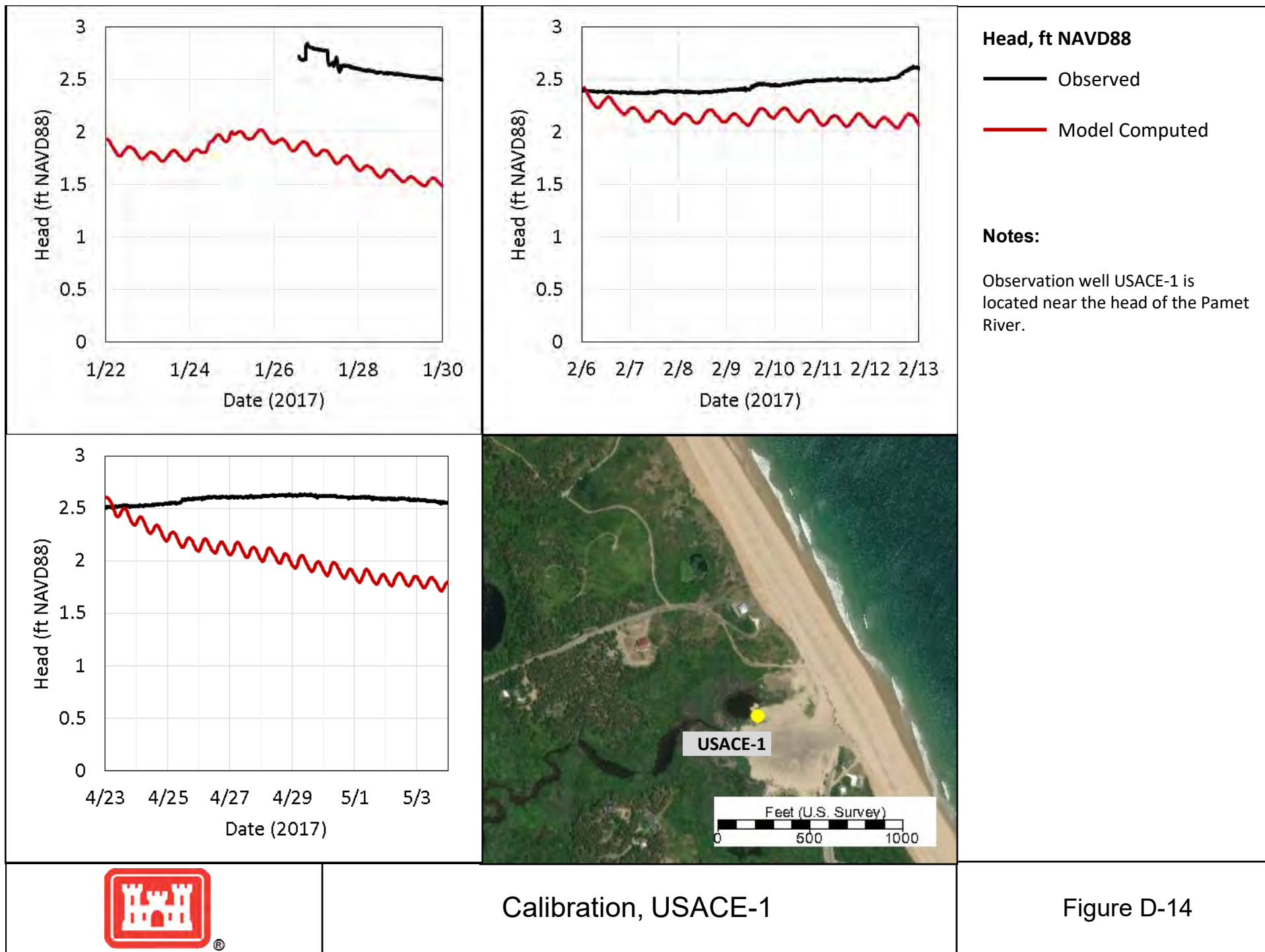
Observation well TSW-203 is located about 7000 ft north of the Pamet River.

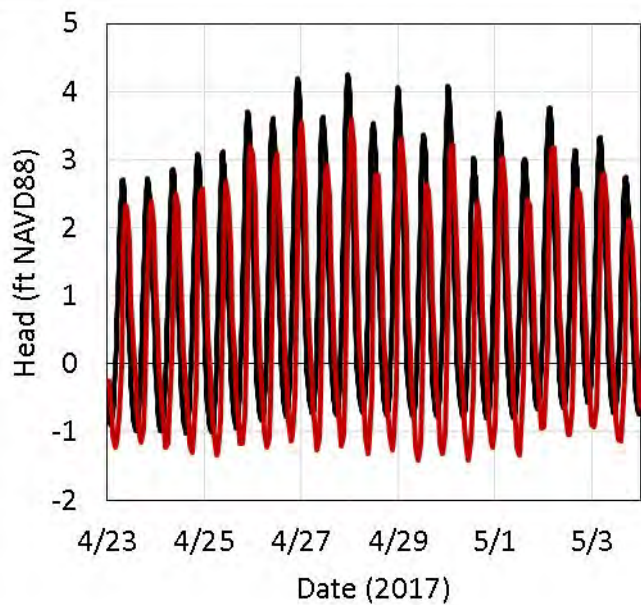
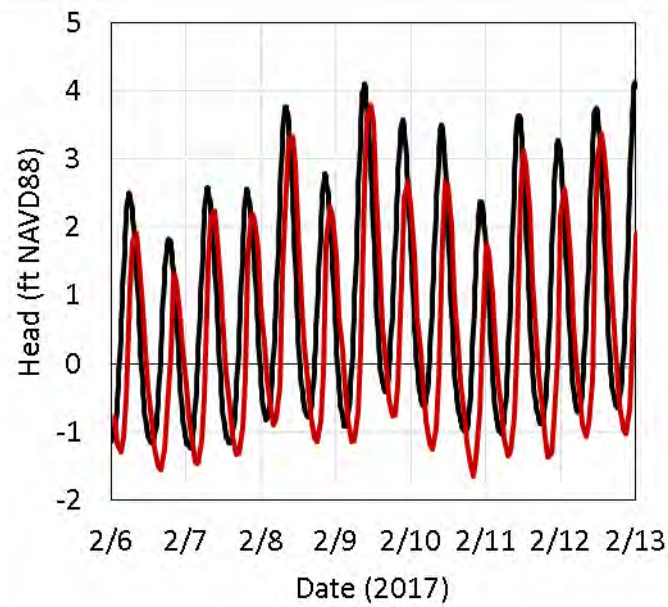
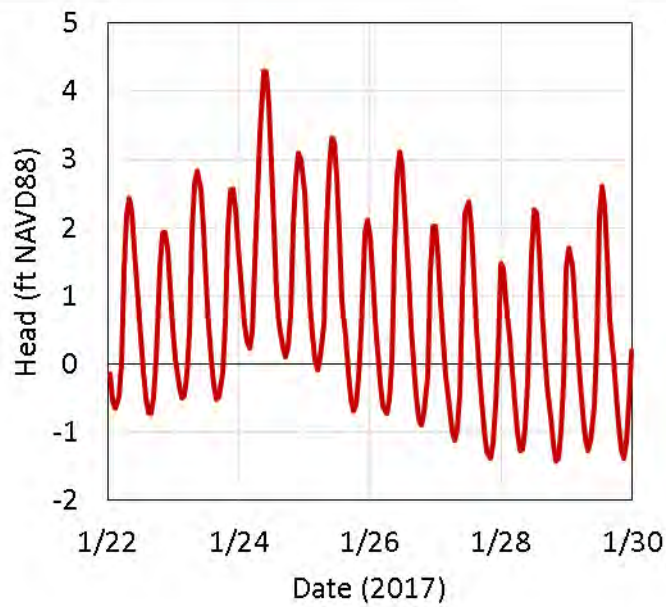
This well is monitored by USGS with a single data point collected each month.



Calibration, TSW-203

Figure D-13





#### Head, ft NAVD88

— Observed

— Model Computed

#### Notes:

Observation well USACE-2 is located near the mouth of the Pamet River.

No data was recorded in January.

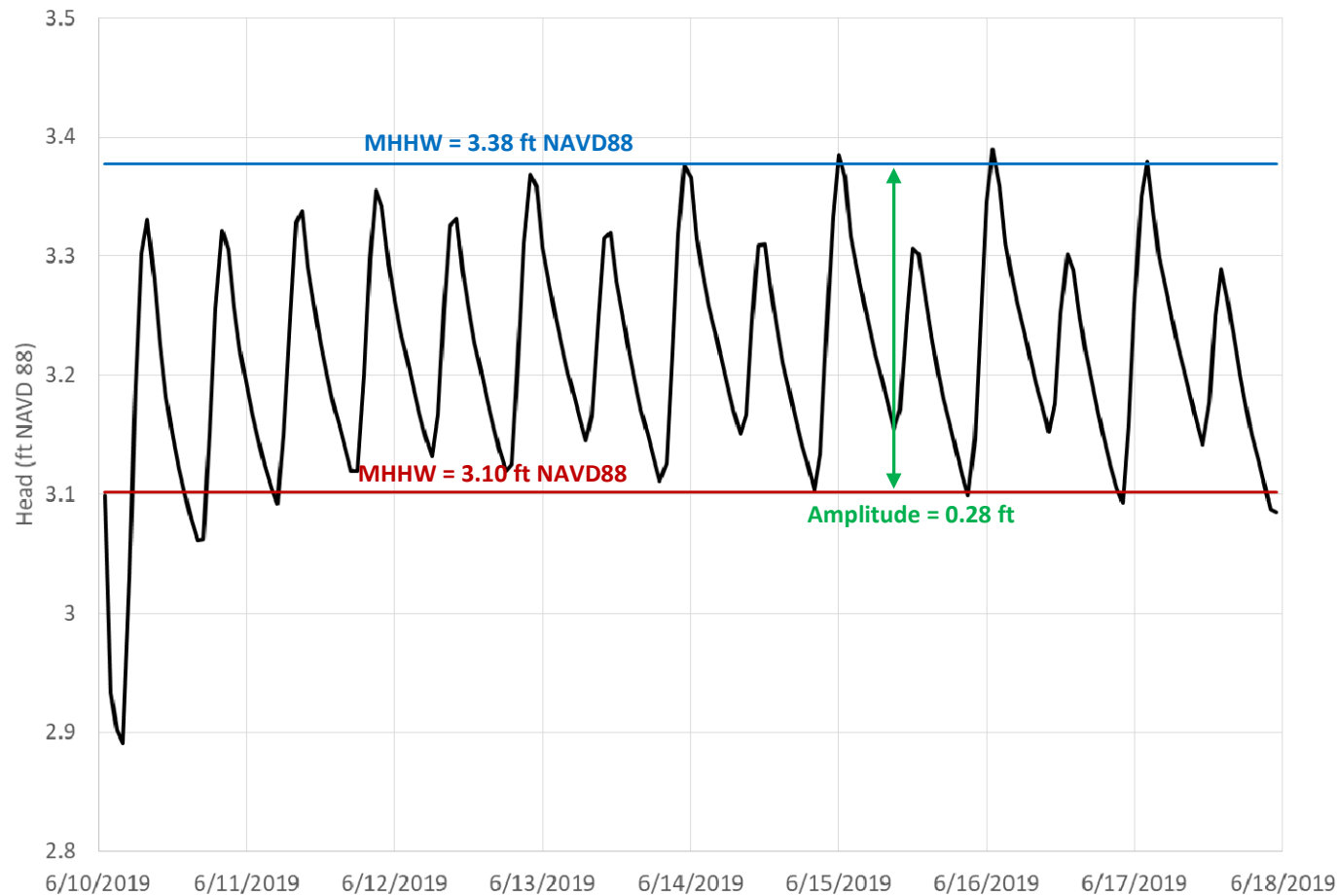


Calibration, USACE-2

Figure D-15

### Legend

- model results
- Mean Lower Low Water (MLLW)
- Mean Higher High Water (MHHW)



### Notes:

This plot is an example showing the computation of comparison parameters for the alternatives with normal tide conditions. This same computation was made for every computational cell in the model and is shown as contour plots in following figures.

The MHHW is the average of the higher of the two high tides for each day of the model run. The first two days were removed from the computation to account for the spin up period.

The MLLW is the average of the lower of the two low tides for each day of the model run. The first two days were removed from the computation to account for the spin up period.

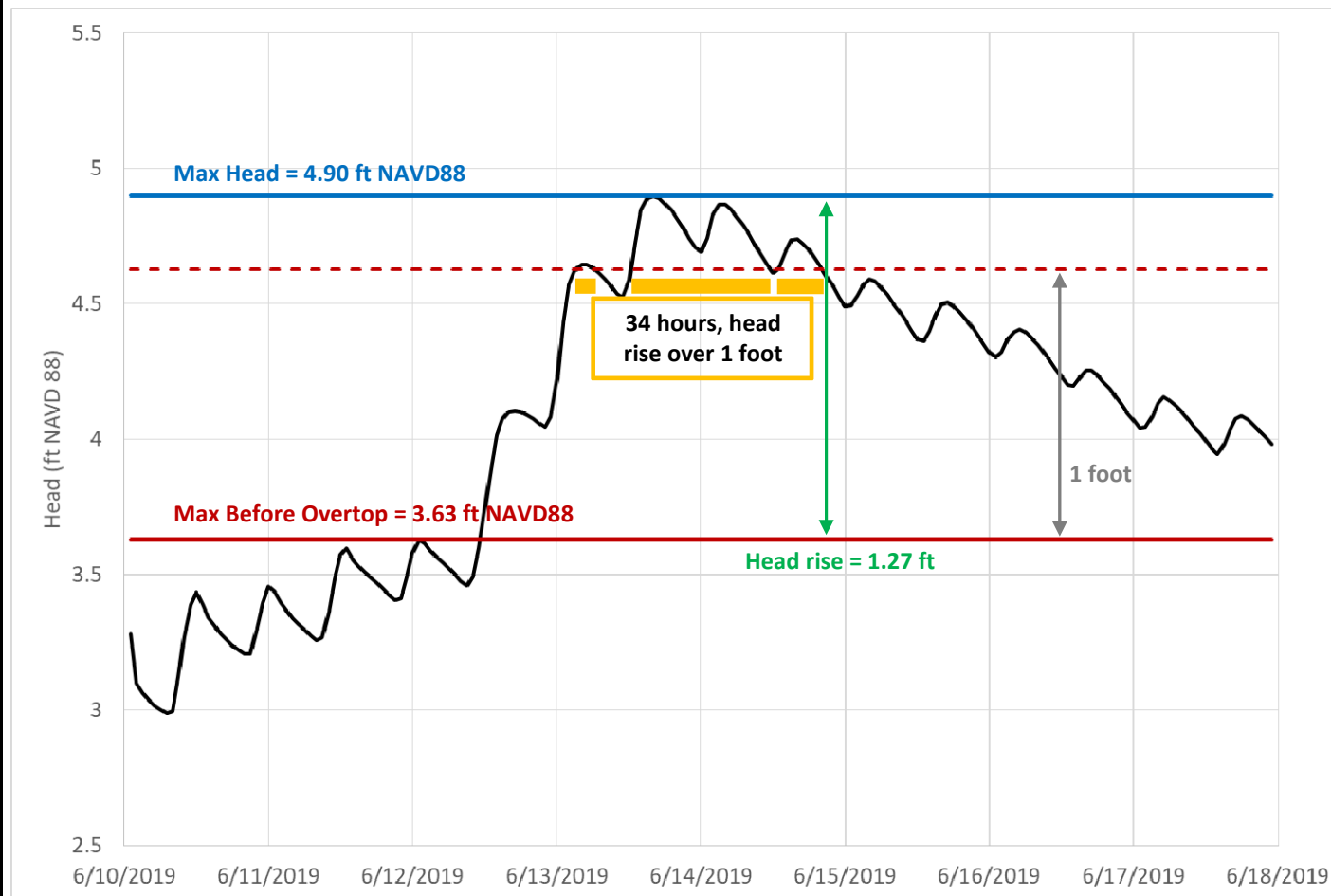
Comparisons between the alternatives are made by computing the difference between MHHW and MLLW (referred to as amplitude in this report).



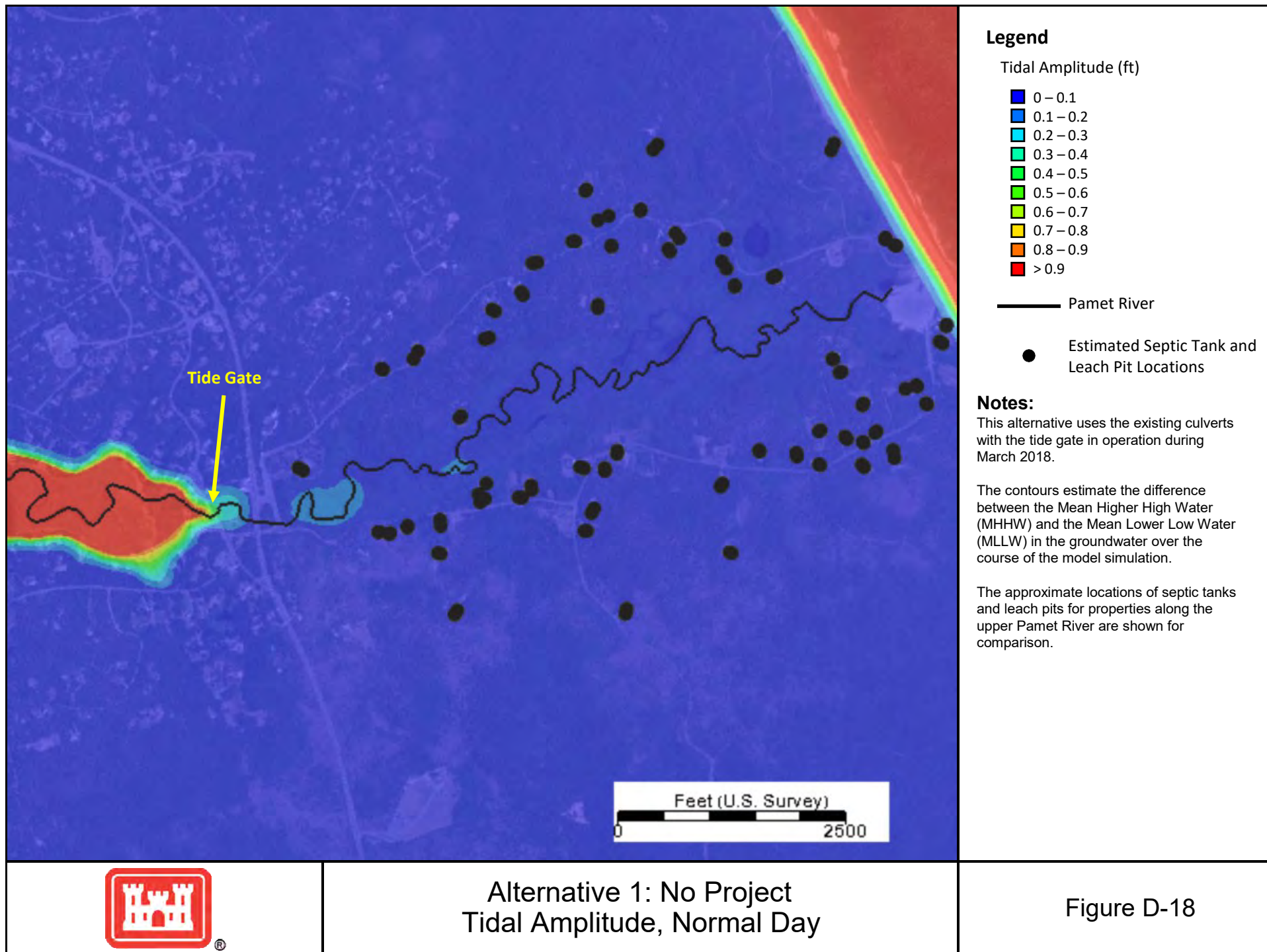
Example Computations for Normal Tide Alternative Runs

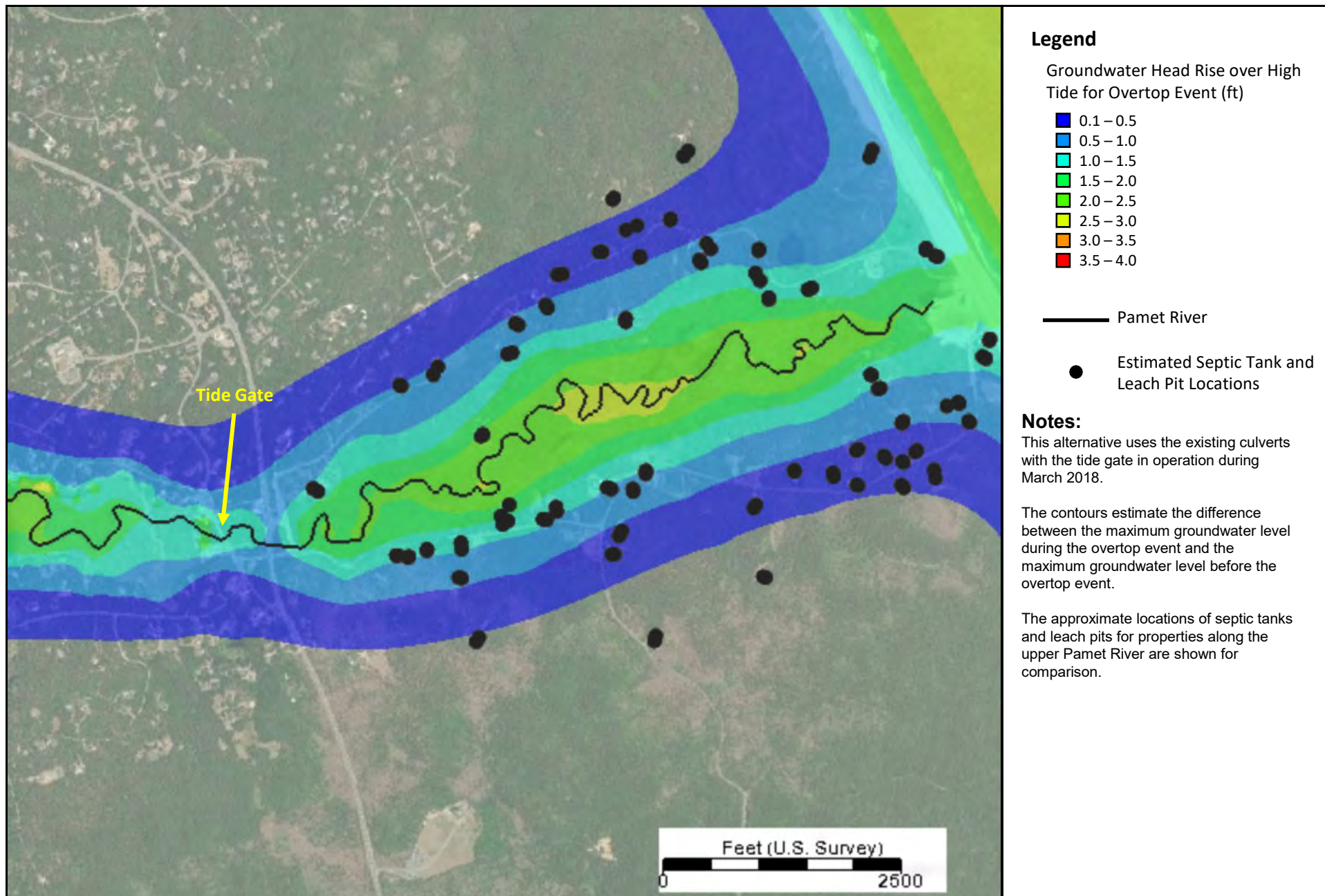
Figure D-16





In order to estimate the amount of time that high heads would be expected to remain, the number of hours where the head is more than 1 foot above the previous maximum head is also reported.

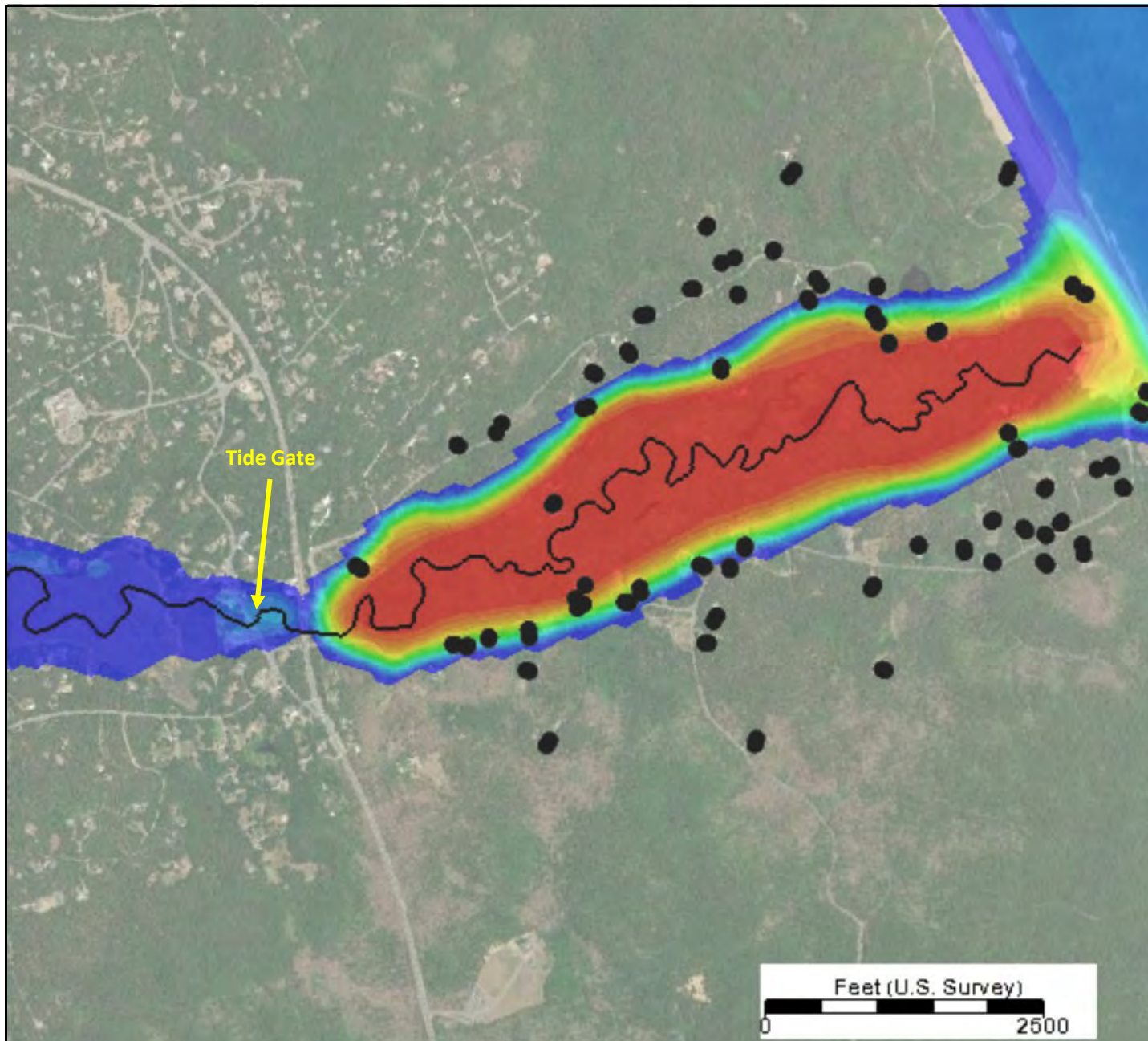




Alternative 1: No Project  
Head Rise over High Tide for Overtop Event

Figure D-19





### Legend

Hours GW At Least 1 Foot Higher

|          |           |
|----------|-----------|
| 0 - 10   | 100 - 110 |
| 10 - 20  | 110 - 120 |
| 20 - 30  | 120 - 130 |
| 30 - 40  | 130 - 140 |
| 40 - 50  | 140 - 150 |
| 50 - 60  | 150 - 160 |
| 60 - 70  | 160 - 170 |
| 70 - 80  | 170 - 180 |
| 80 - 90  | 180 - 190 |
| 90 - 100 | 190 - 200 |

 Pamet River

 Estimated Septic Tank and Leach Pit Locations

### Notes:

This alternative uses the existing culverts with the tide gate in operation during March 2018.

The contours estimate the number of hours that the groundwater elevation will be at least 1 foot higher than the maximum level during the days prior to the flood. Note that the groundwater levels had not all returned to normal when the scenario finished, so some areas may see longer periods of high groundwater.

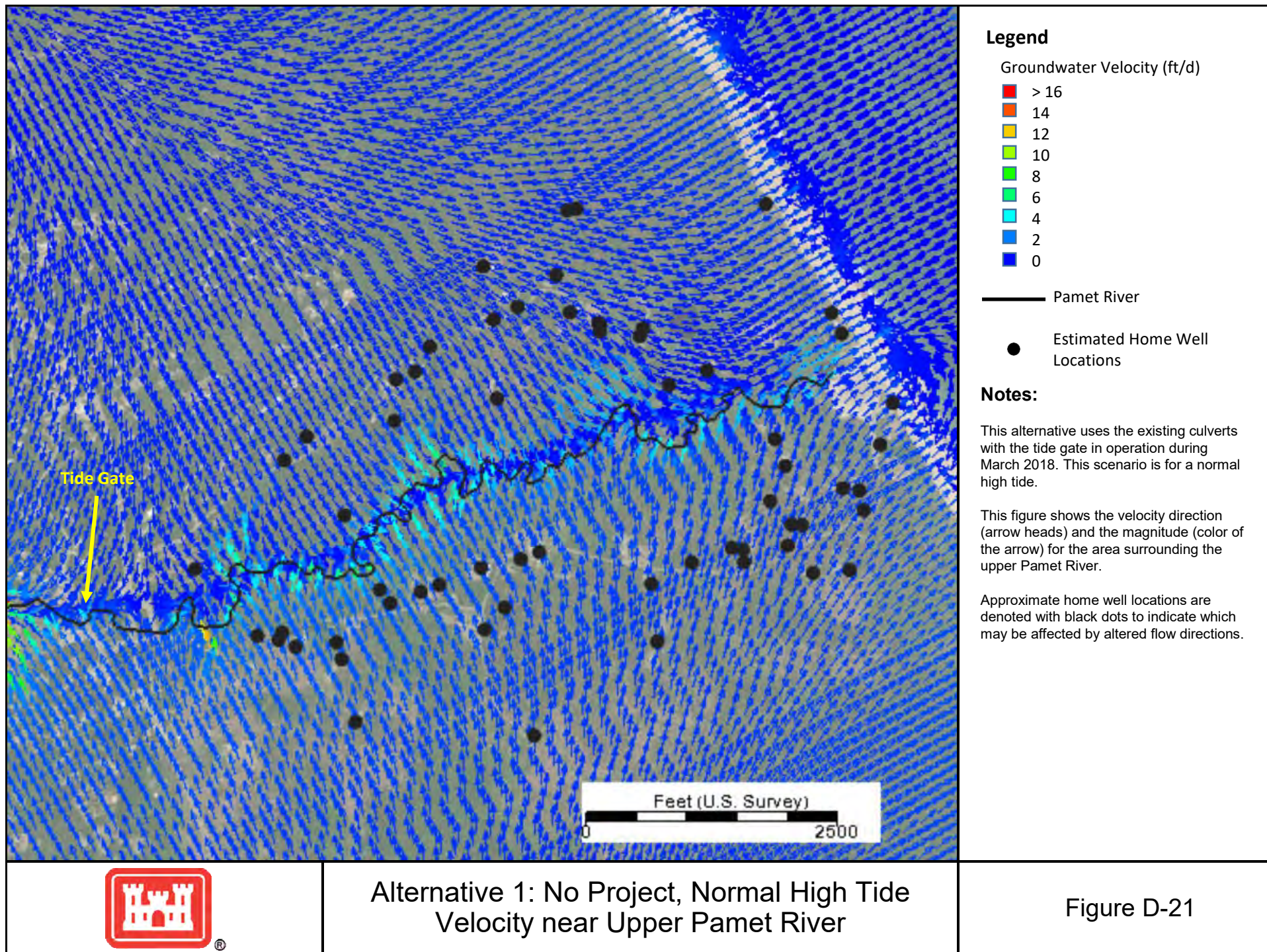
The approximate locations of septic tanks and leach pits for properties along the upper Pamet River are shown for comparison.



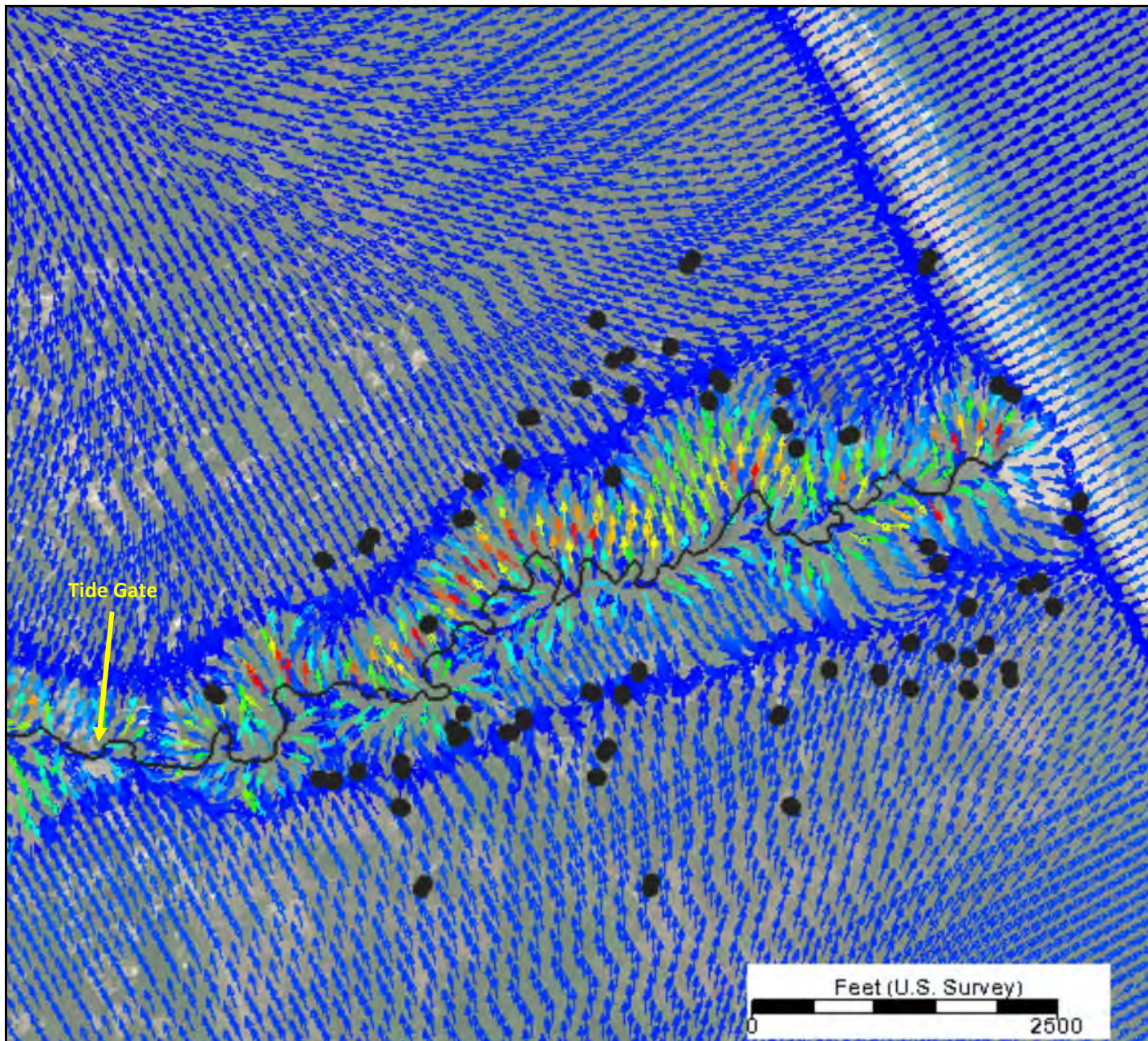
Alternative 1: No Project  
Time GW At Least 1 Foot Higher (hours)

Figure D-20



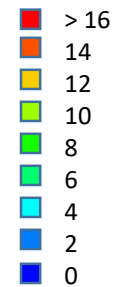






### Legend

Groundwater Velocity (ft/d)



— Pamet River

● Estimated Home Well Locations

### Notes:

This alternative uses the existing culverts with the tide gate in operation during March 2018. This scenario is for the peak of an overtop event.

This figure shows the velocity direction (arrow heads) and the magnitude (color of the arrow) for the area surrounding the upper Pamet River.

Approximate home well locations are denoted with black dots to indicate which may be affected by altered flow directions.



Alternative 1: No Project, Overtop Event  
Velocity near Upper Pamet River

Figure D-22



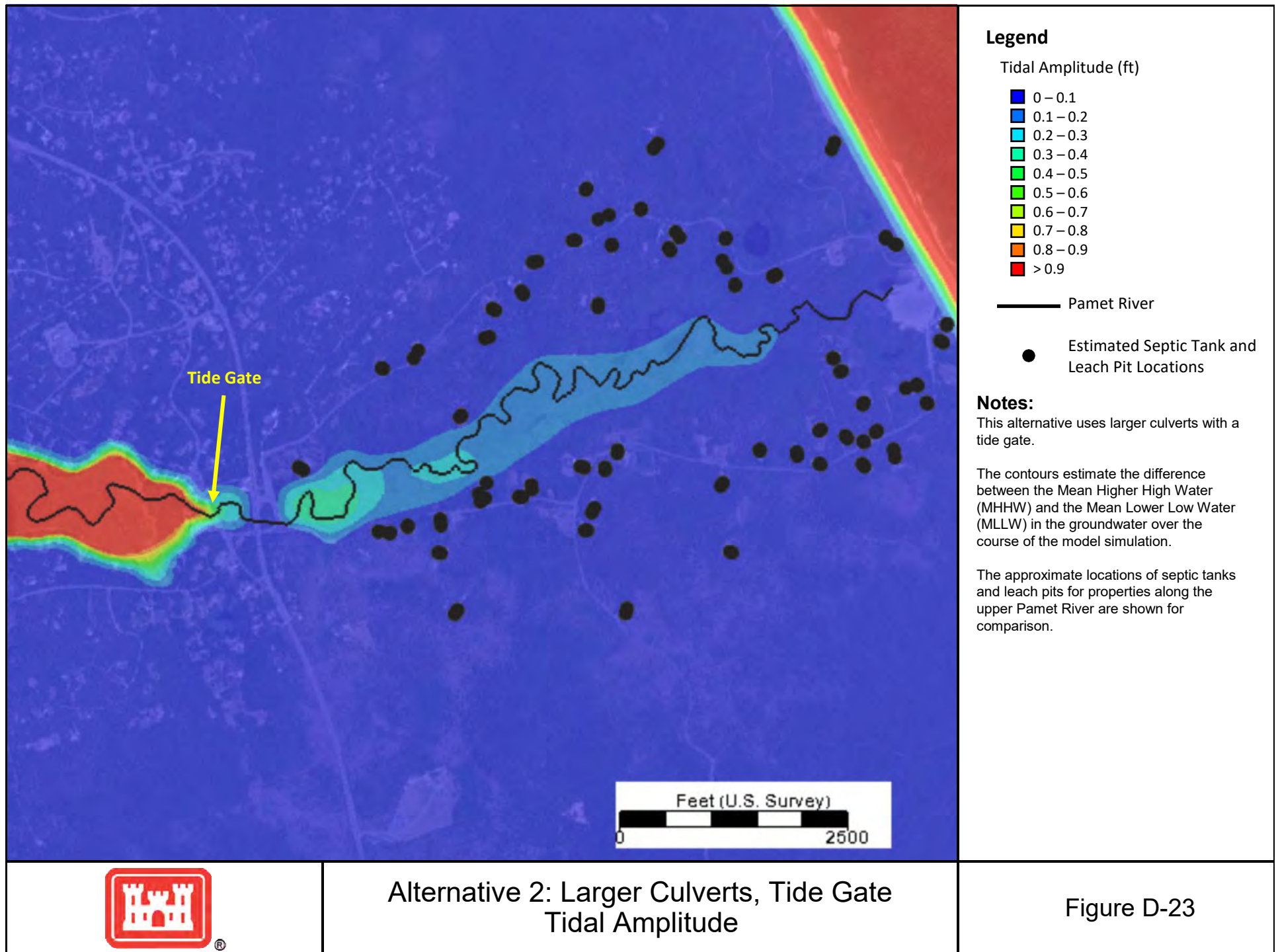
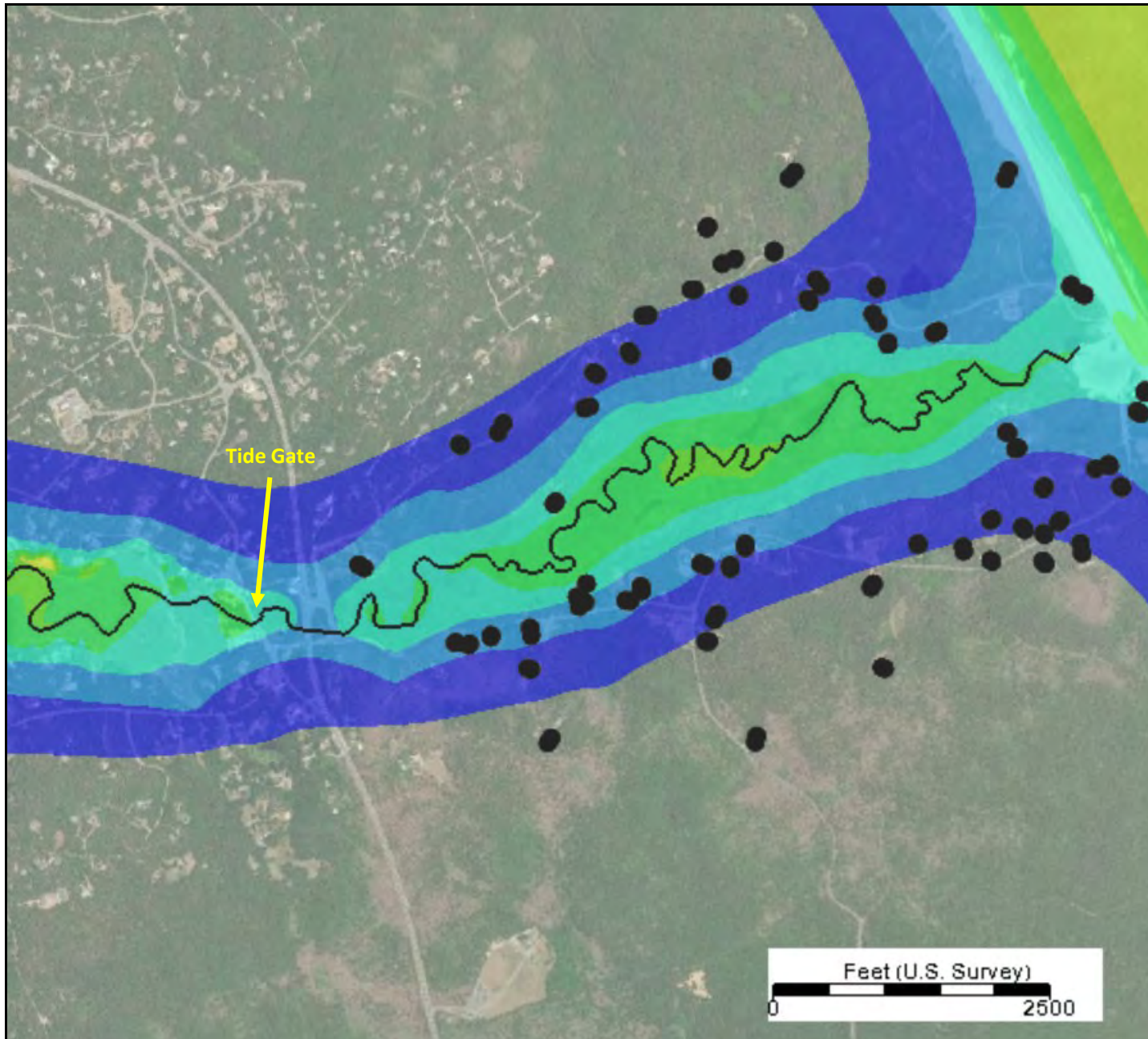


Figure D-23



### Legend

Groundwater Head Rise over High Tide for Overtop Event (ft)

- 0.1 – 0.5
- 0.5 – 1.0
- 1.0 – 1.5
- 1.5 – 2.0
- 2.0 – 2.5
- 2.5 – 3.0
- 3.0 – 3.5
- 3.5 – 4.0

— Pamet River

● Estimated Septic Tank and Leach Pit Locations

### Notes:

This alternative uses larger culverts with a tide gate.

The contours estimate the difference between the maximum groundwater level during the overtop event and the maximum groundwater level before the overtop event.

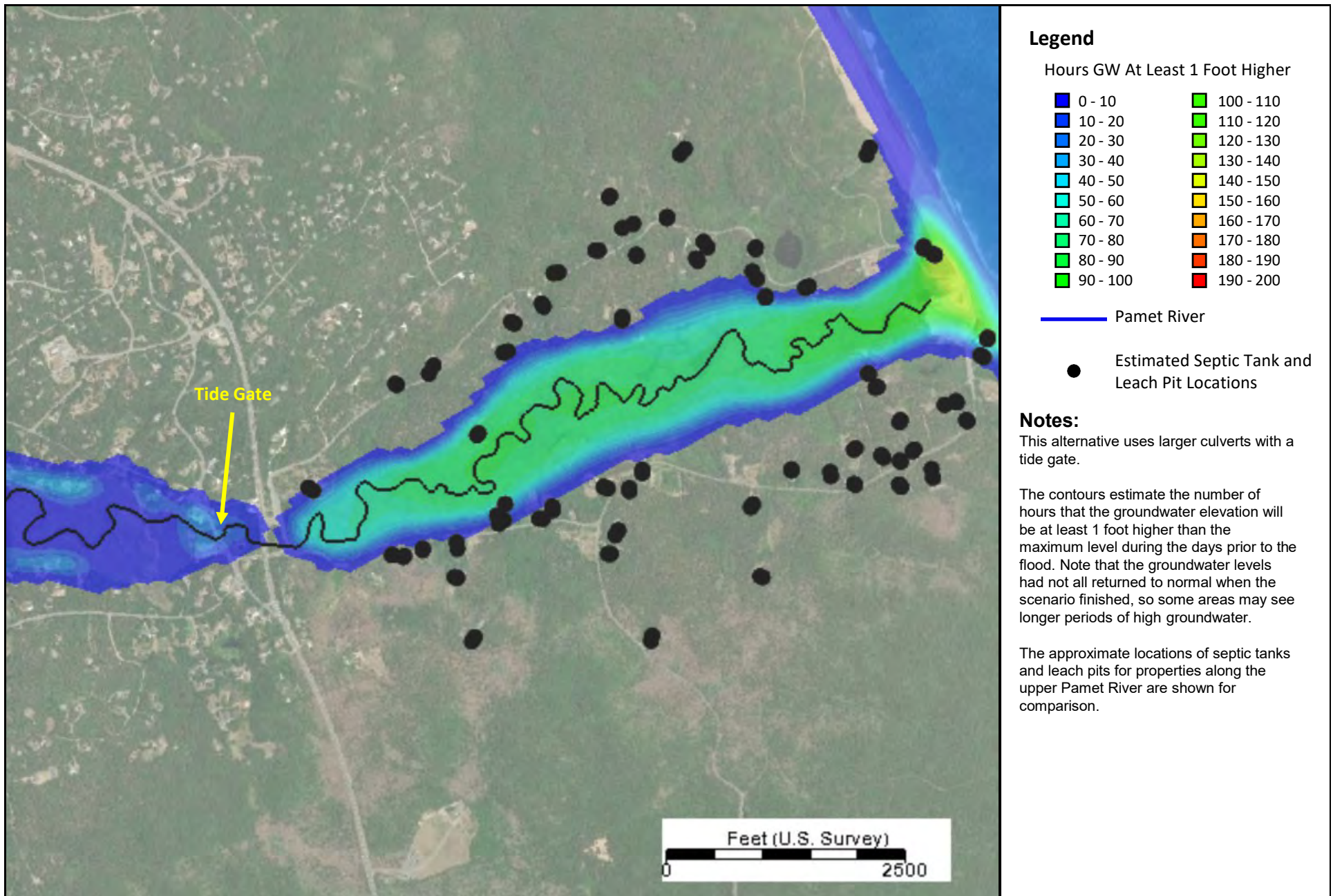
The approximate locations of septic tanks and leach pits for properties along the upper Pamet River are shown for comparison.



Alternative 2: Larger Culverts, Tide Gate  
Head Rise over High Tide for Overtop Event

Figure D-24

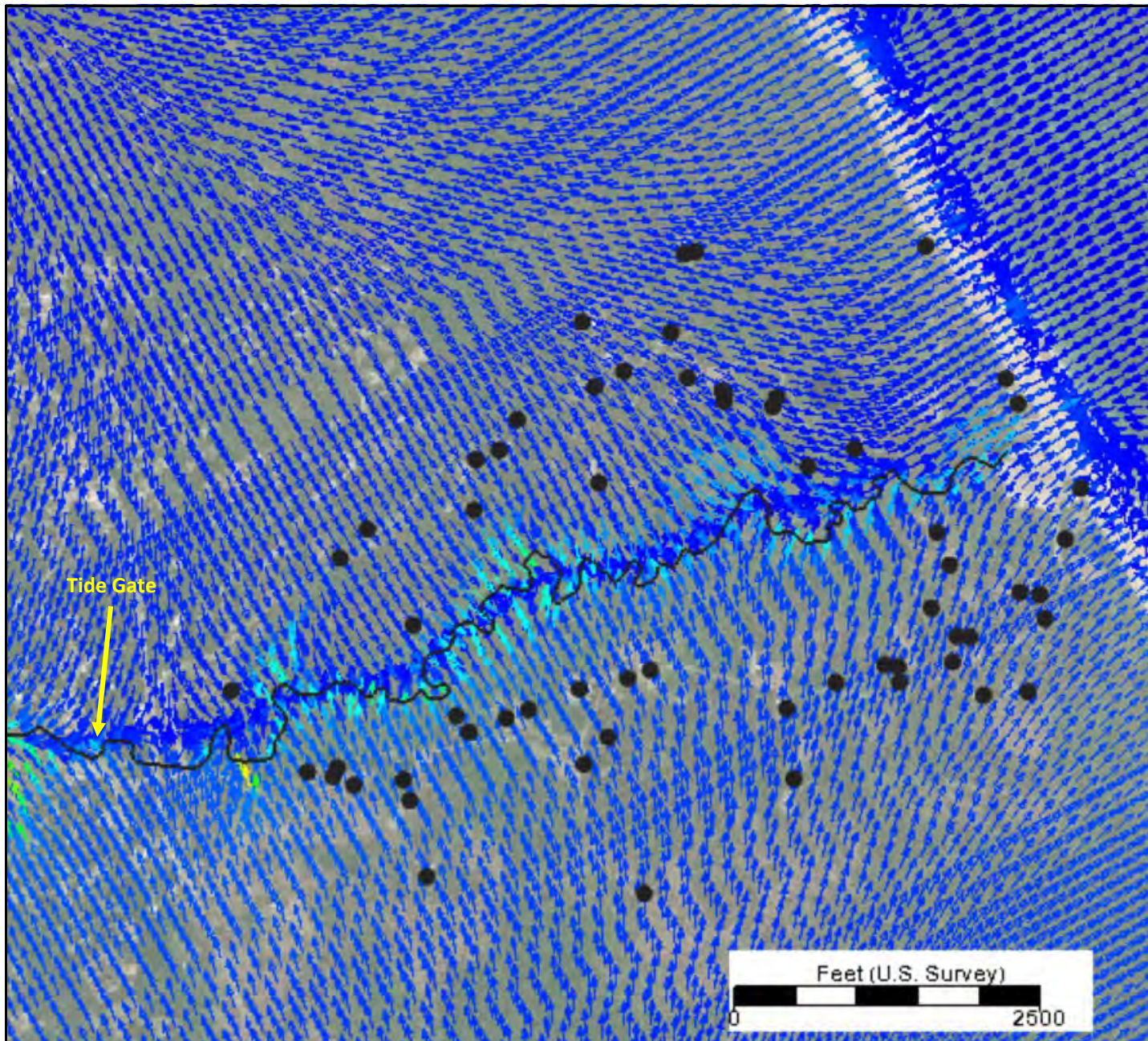




Alternative 2: Larger Culverts, Tide Gate  
Time GW At Least 1 Foot Higher (hours)

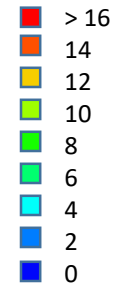
Figure D-25





### Legend

Groundwater Velocity (ft/d)



— Pamet River

● Estimated Home Well Locations

### Notes:

This alternative uses larger culverts with a tide gate. This scenario is for a normal high tide.

This figure shows the velocity direction (arrow heads) and the magnitude (color of the arrow) for the area surrounding the upper Pamet River.

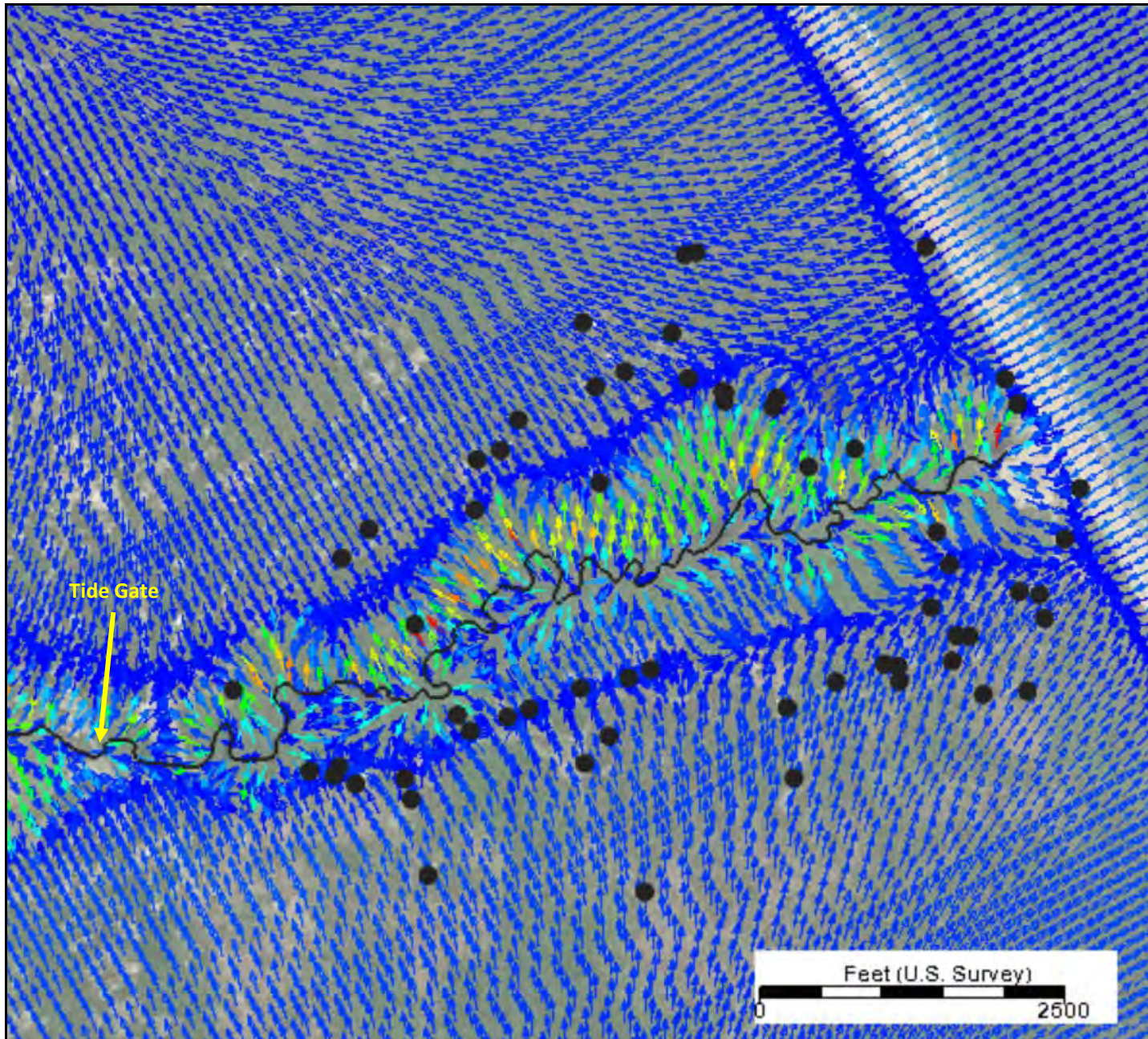
Approximate home well locations are denoted with black dots to indicate which may be affected by altered flow directions.



Alternative 2: Larger Culverts, Tide Gate, Normal High Tide  
Velocity near Upper Pamet River

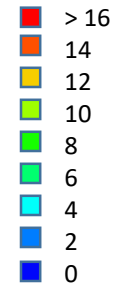
Figure D-26





### Legend

Groundwater Velocity (ft/d)



— Pamet River

● Estimated Home Well Locations

### Notes:

This alternative uses larger culverts with a tide gate. This scenario is for the peak of an overtop event.

This figure shows the velocity direction (arrow heads) and the magnitude (color of the arrow) for the area surrounding the upper Pamet River.

Approximate home well locations are denoted with black dots to indicate which may be affected by altered flow directions.



Alternative 2: Larger Culverts, Tide Gate, Overtop Event  
Velocity near Upper Pamet River

Figure D-27



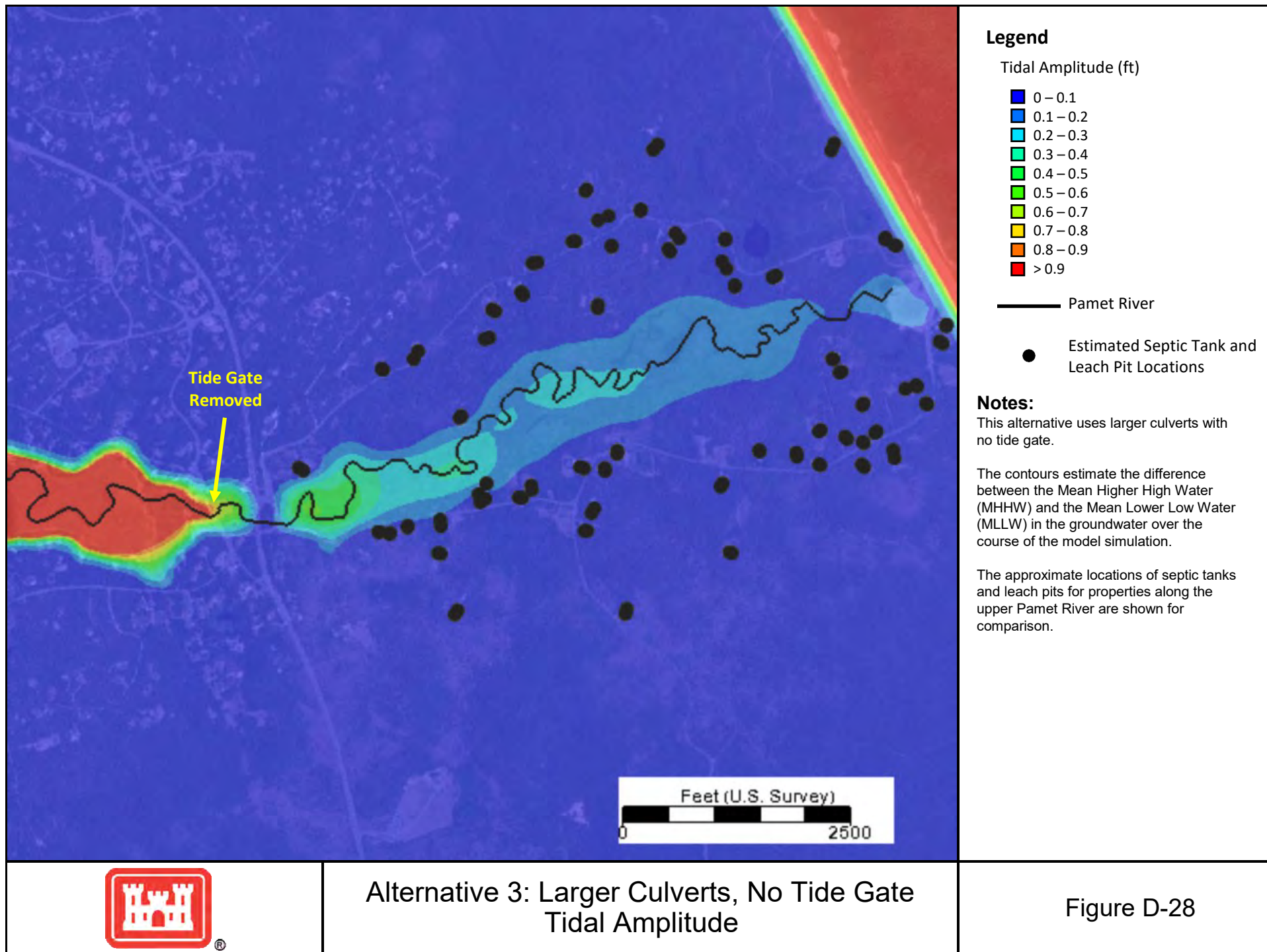
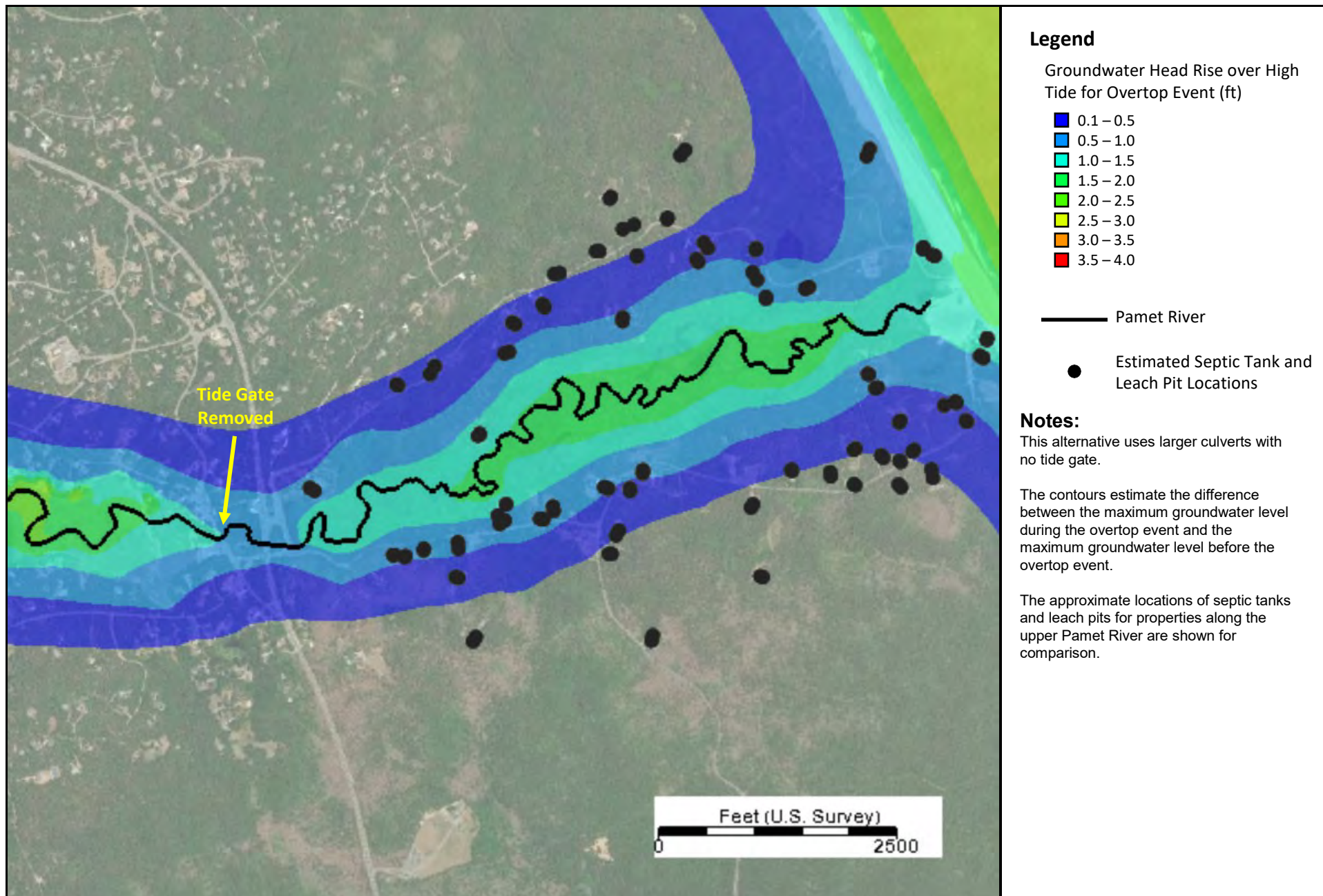


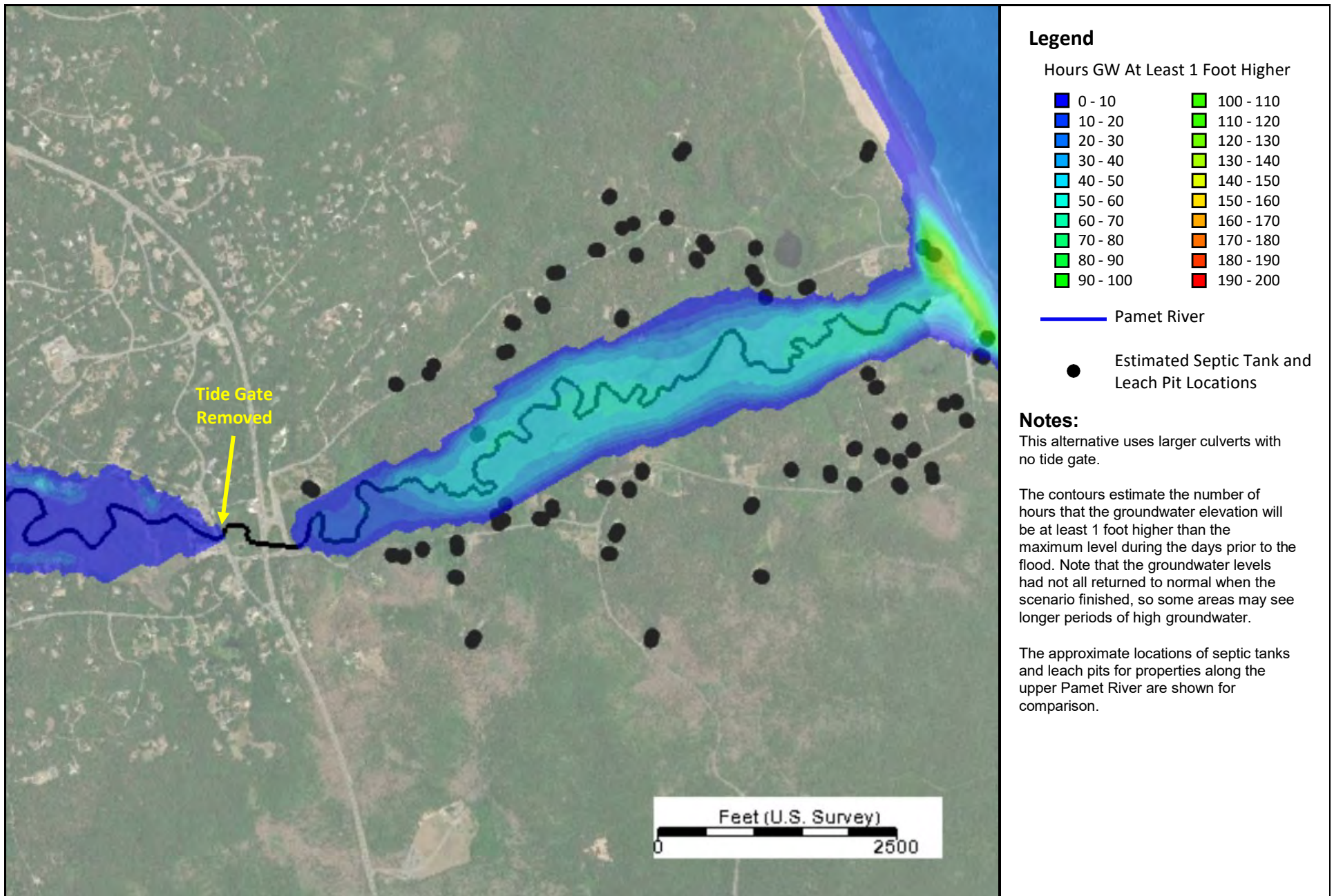
Figure D-28





Alternative 3: Larger Culverts, No Tide Gate  
Head Rise over High Tide for Overtop Event

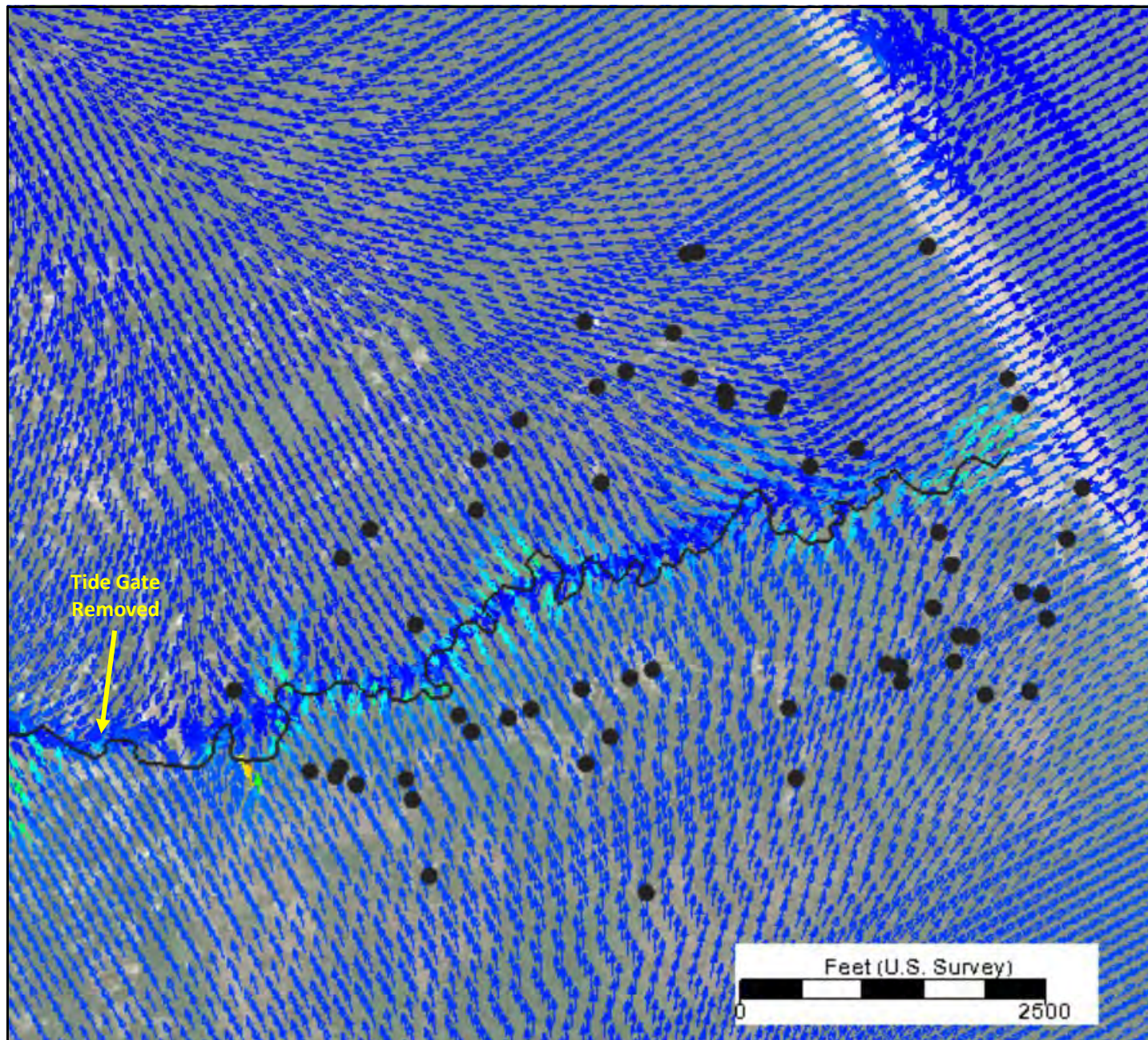
Figure D-29



Alternative 3: Larger Culverts, No Tide Gate  
Time GW At Least 1 Foot Higher (hours)

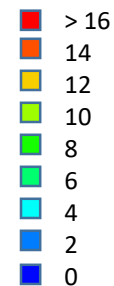
Figure D-30





### Legend

Groundwater Velocity (ft/d)



— Pamet River

● Estimated Home Well Locations

### Notes:

This alternative uses larger culverts with no tide gate. This scenario is for a normal high tide.

This figure shows the velocity direction (arrow heads) and the magnitude (color of the arrow) for the area surrounding the upper Pamet River.

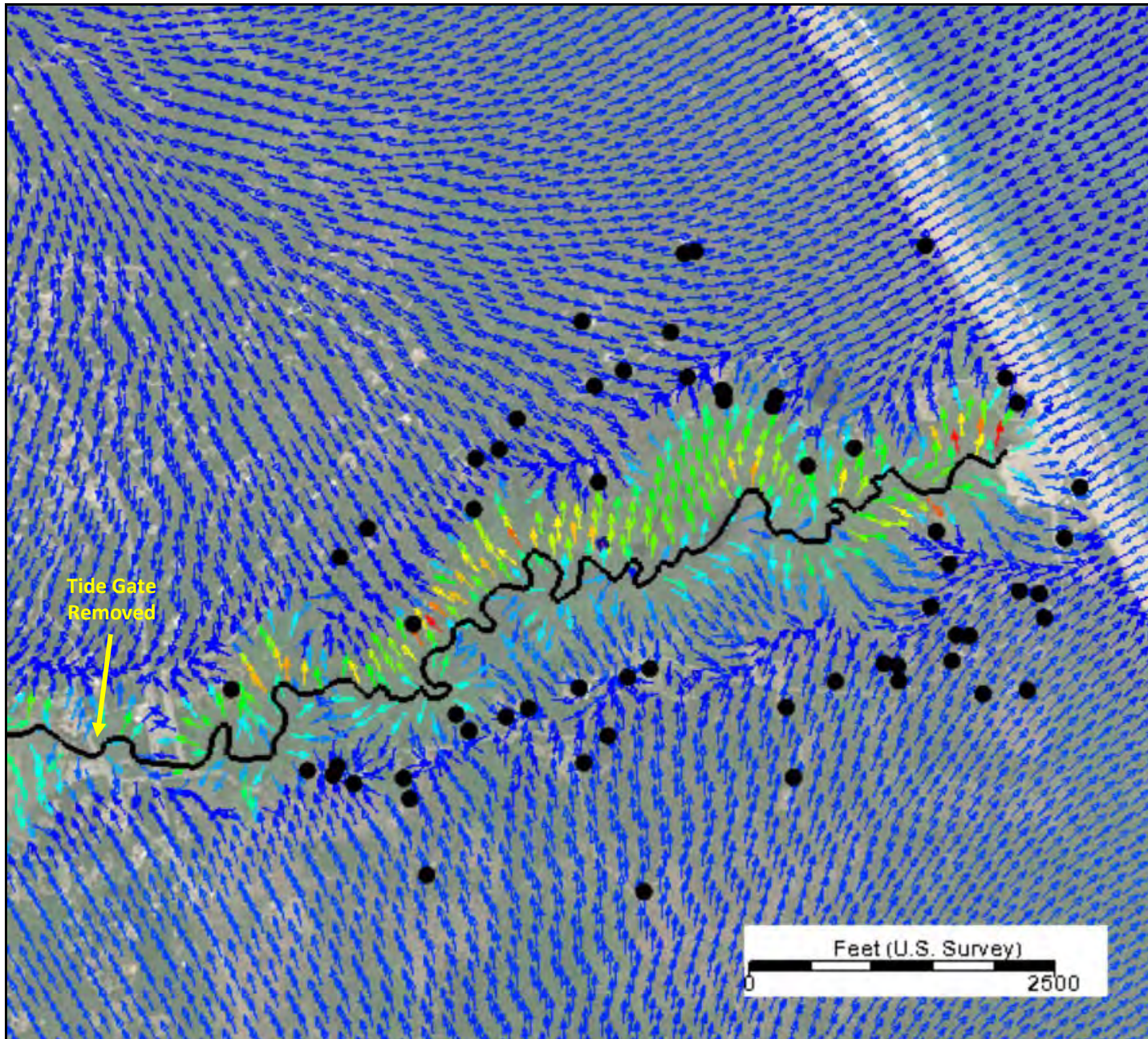
Approximate home well locations are denoted with black dots to indicate which may be affected by altered flow directions.



Alternative 3: Larger Culverts, No Tide Gate, Normal High Tide  
Velocity near Upper Pamet River

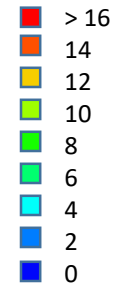
Figure D-31





### Legend

Groundwater Velocity (ft/d)



— Pamet River

● Estimated Home Well Locations

### Notes:

This alternative uses larger culverts with no tide gate. This scenario is for the peak of an overtop event.

This figure shows the velocity direction (arrow heads) and the magnitude (color of the arrow) for the area surrounding the upper Pamet River.

Approximate home well locations are denoted with black dots to indicate which may be affected by altered flow directions.



Alternative 3: Larger Culverts, No Tide Gate, Overtop Event  
Velocity near Upper Pamet River

Figure D-32



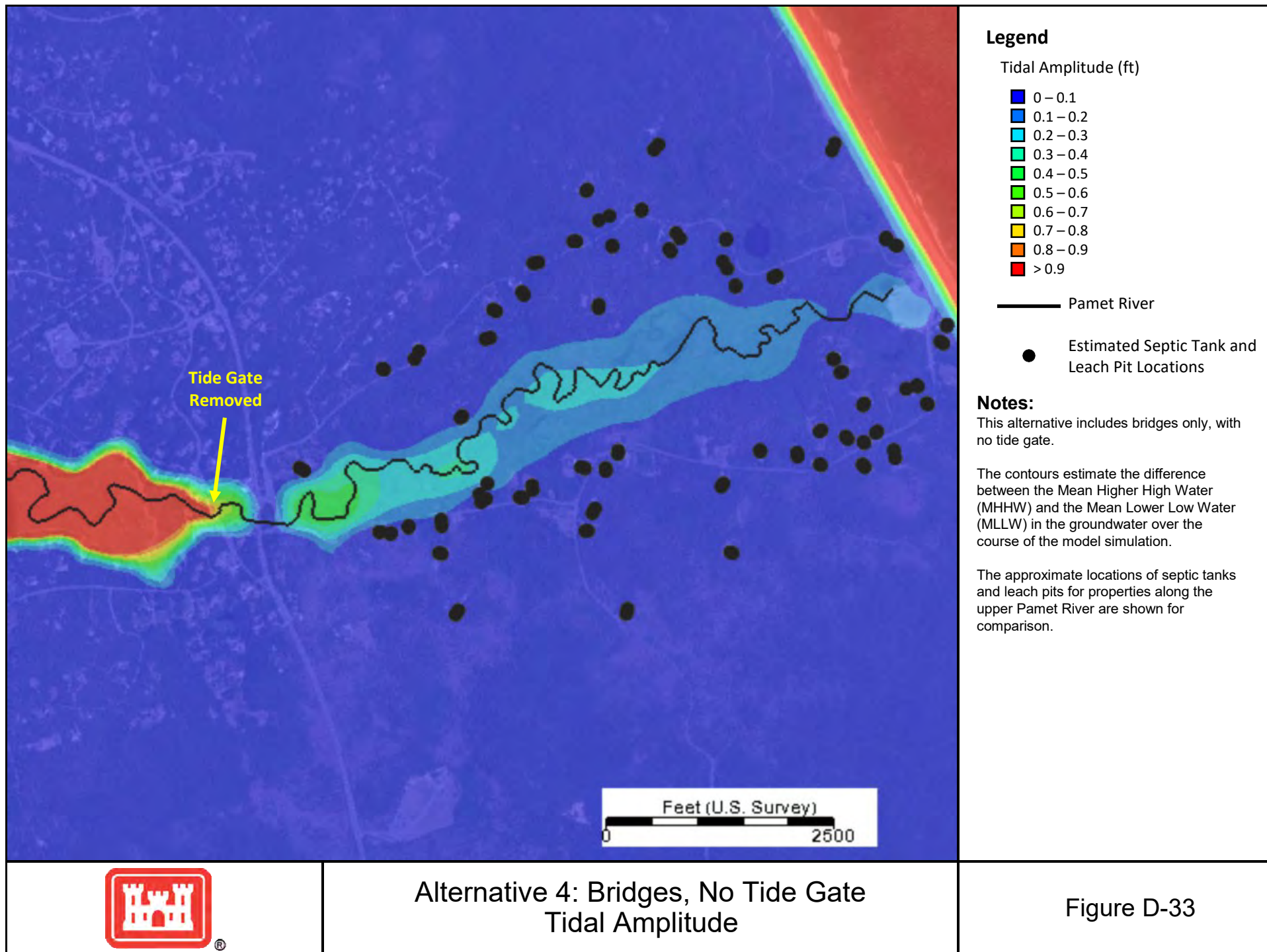
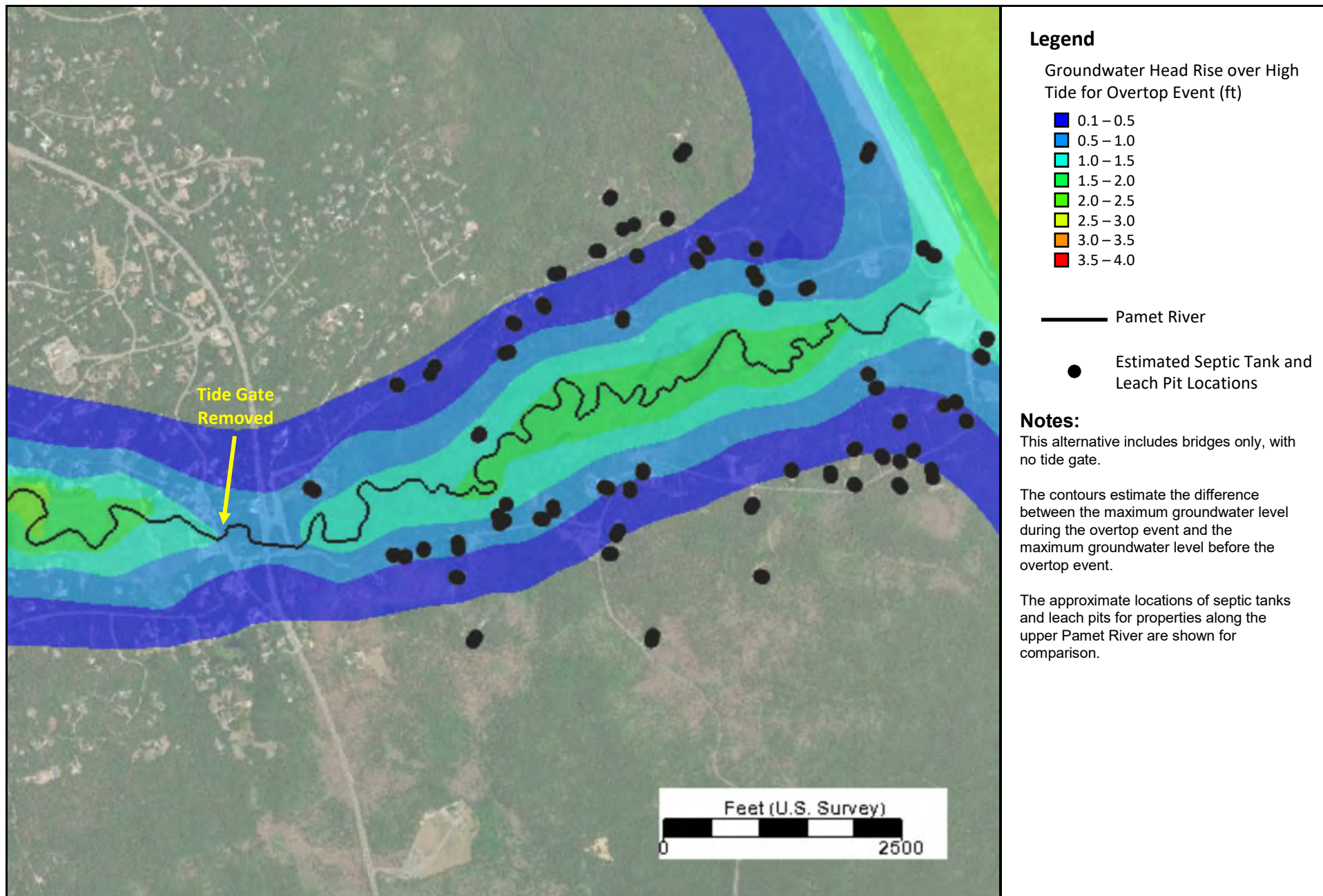


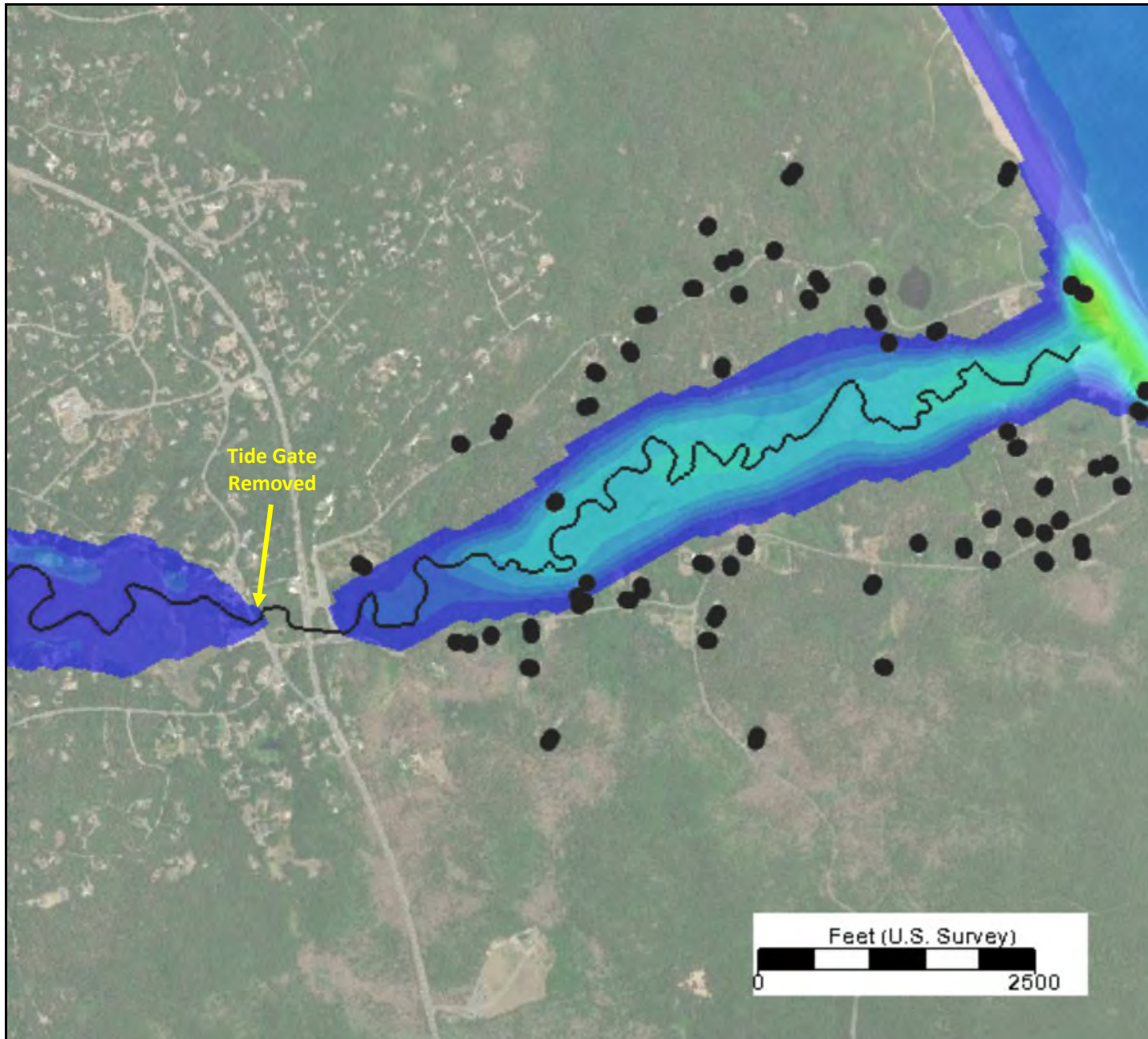
Figure D-33



Alternative 4: Bridges, No Tide Gate  
Head Rise over High Tide for Overtop Event

Figure D-34





### Legend

Hours GW At Least 1 Foot Higher

|          |           |
|----------|-----------|
| 0 - 10   | 100 - 110 |
| 10 - 20  | 110 - 120 |
| 20 - 30  | 120 - 130 |
| 30 - 40  | 130 - 140 |
| 40 - 50  | 140 - 150 |
| 50 - 60  | 150 - 160 |
| 60 - 70  | 160 - 170 |
| 70 - 80  | 170 - 180 |
| 80 - 90  | 180 - 190 |
| 90 - 100 | 190 - 200 |

 Pamet River

 Estimated Septic Tank and Leach Pit Locations

### Notes:

This alternative includes bridges only, with no tide gate.

The contours estimate the number of hours that the groundwater elevation will be at least 1 foot higher than the maximum level during the days prior to the flood. Note that the groundwater levels had not all returned to normal when the scenario finished, so some areas may see longer periods of high groundwater.

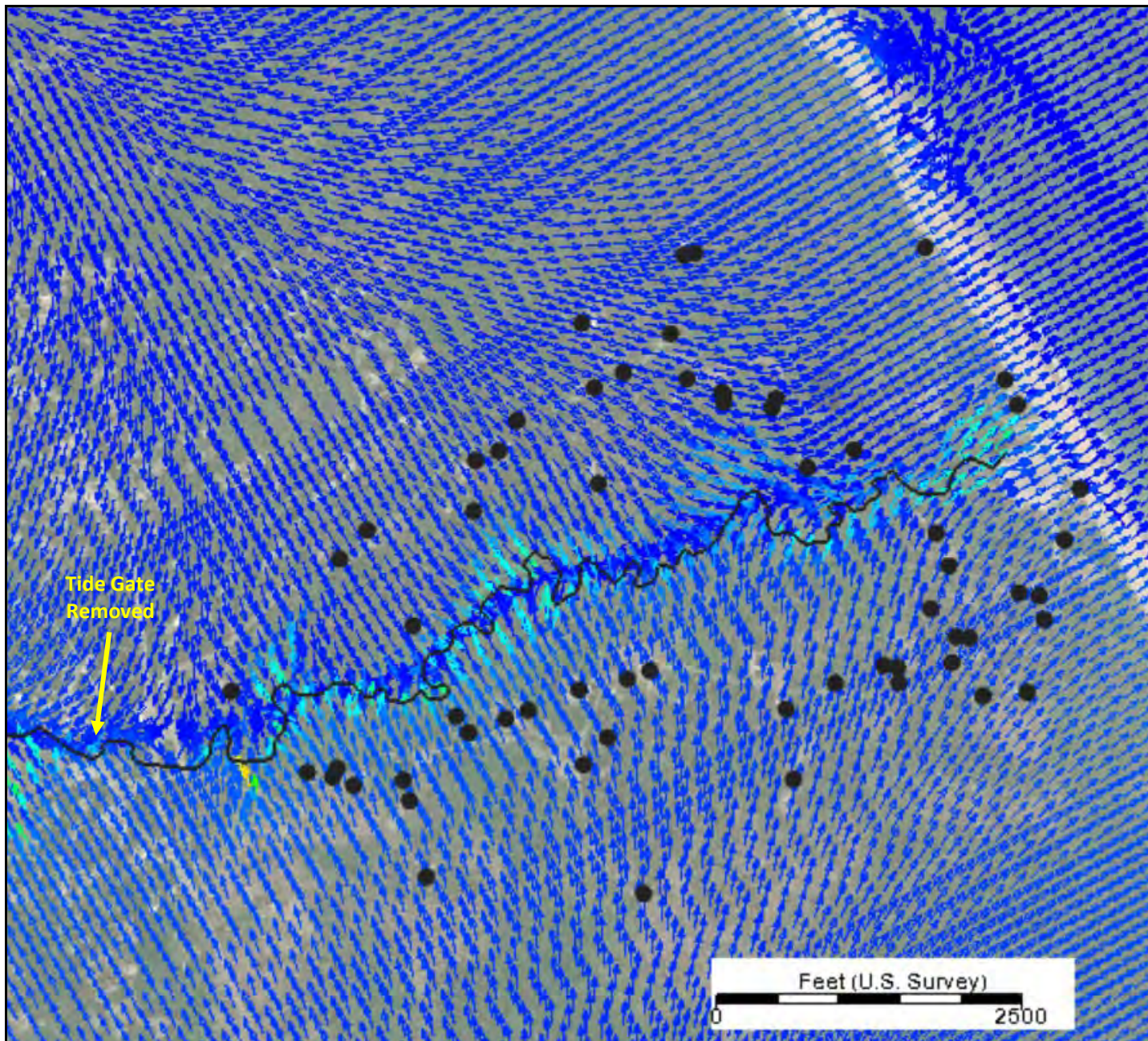
The approximate locations of septic tanks and leach pits for properties along the upper Pamet River are shown for comparison.



Alternative 4: Bridges, No Tide Gates  
Time GW At Least 1 Foot Higher (hours)

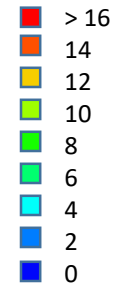
Figure D-35





### Legend

Groundwater Velocity (ft/d)



— Pamet River

● Estimated Home Well Locations

### Notes:

This alternative uses bridges with no tide gate. This scenario is for a normal high tide.

This figure shows the velocity direction (arrow heads) and the magnitude (color of the arrow) for the area surrounding the upper Pamet River.

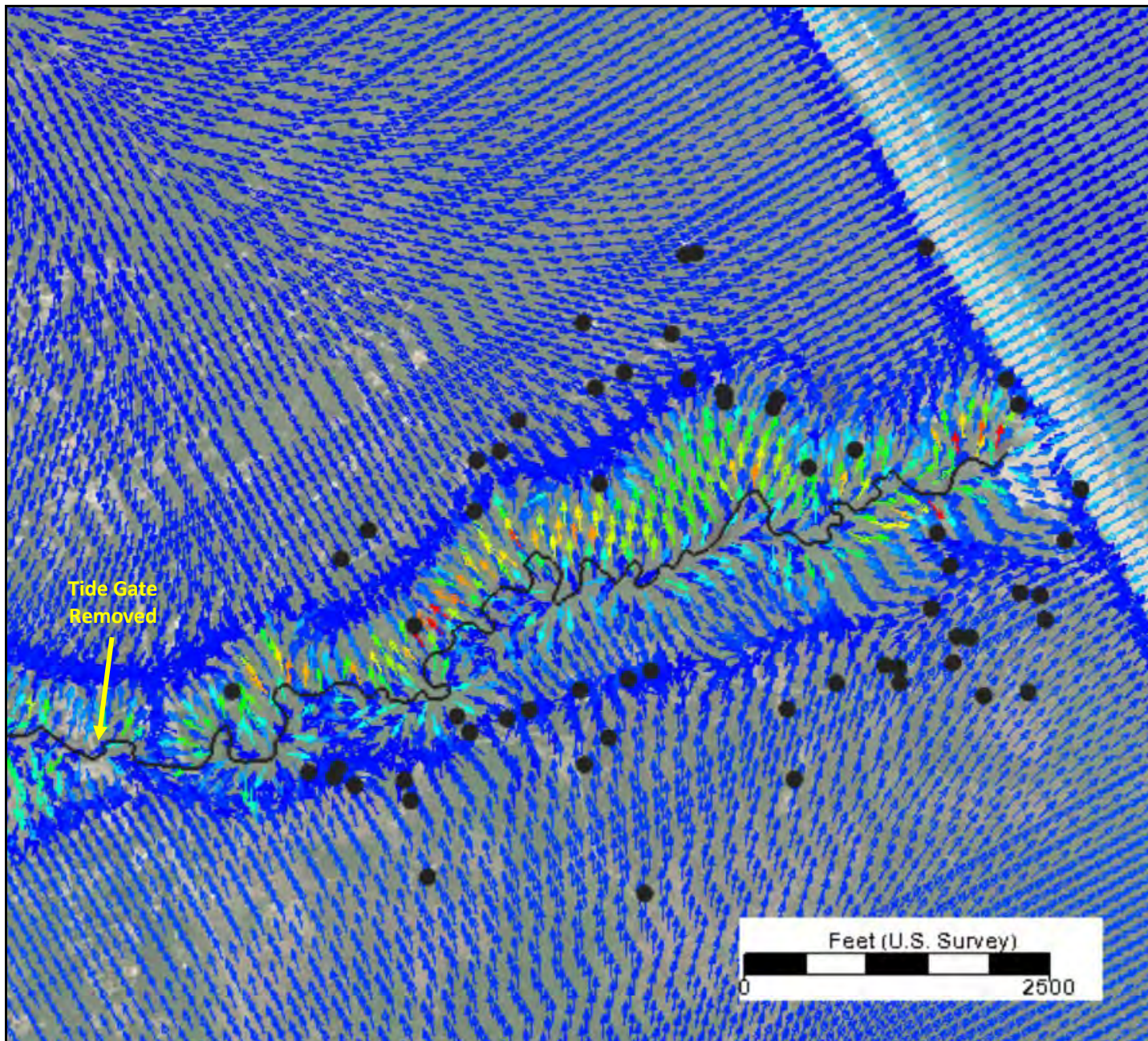
Approximate home well locations are denoted with black dots to indicate which may be affected by altered flow directions.



Alternative 4: Bridges, No Tide Gate, Normal High Tide  
Velocity near Upper Pamet River

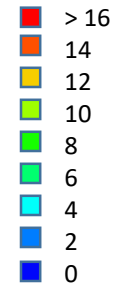
Figure D-36





### Legend

Groundwater Velocity (ft/d)



— Pamet River

● Estimated Home Well Locations

### Notes:

This alternative uses bridges with no tide gate. This scenario is for the peak of an overtop event.

This figure shows the velocity direction (arrow heads) and the magnitude (color of the arrow) for the area surrounding the upper Pamet River.

Approximate home well locations are denoted with black dots to indicate which may be affected by altered flow directions.



Alternative 4: Bridges, No Tide Gate, Overtop Event  
Velocity near Upper Pamet River

Figure D-37



**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT E**  
**RIVERINE (HEC-RAS) MODEL ANALYSIS**  
**FIGURES E-1 to E-43**

**REFERENCED FROM: CHAPTER 7**

**Pamet River Hydrologic & Hydraulic Assessment**

*Quantitative Data Analysis*

**(HEC-RAS Model)**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

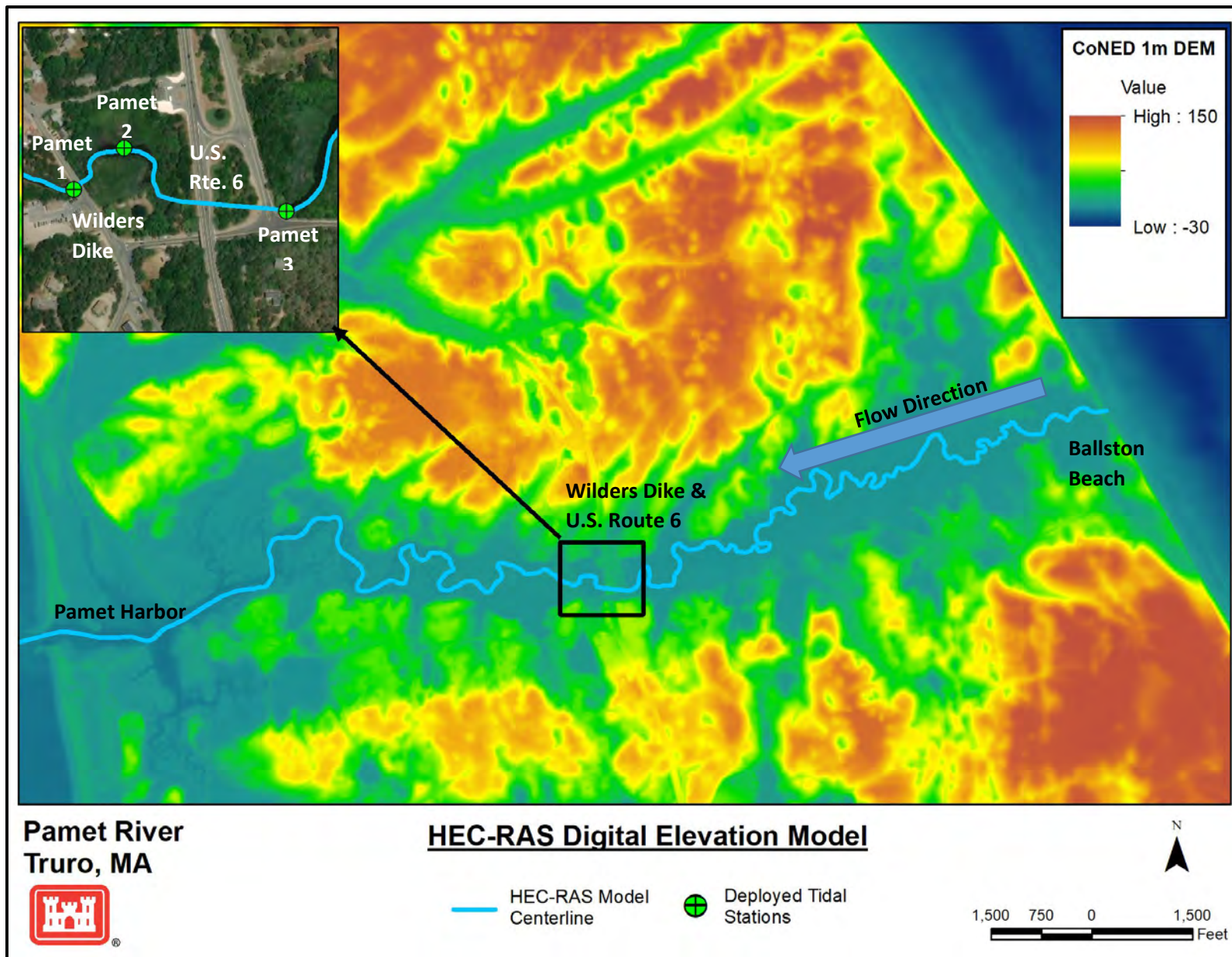


Figure E-1. HEC-RAS LOCATION MAP



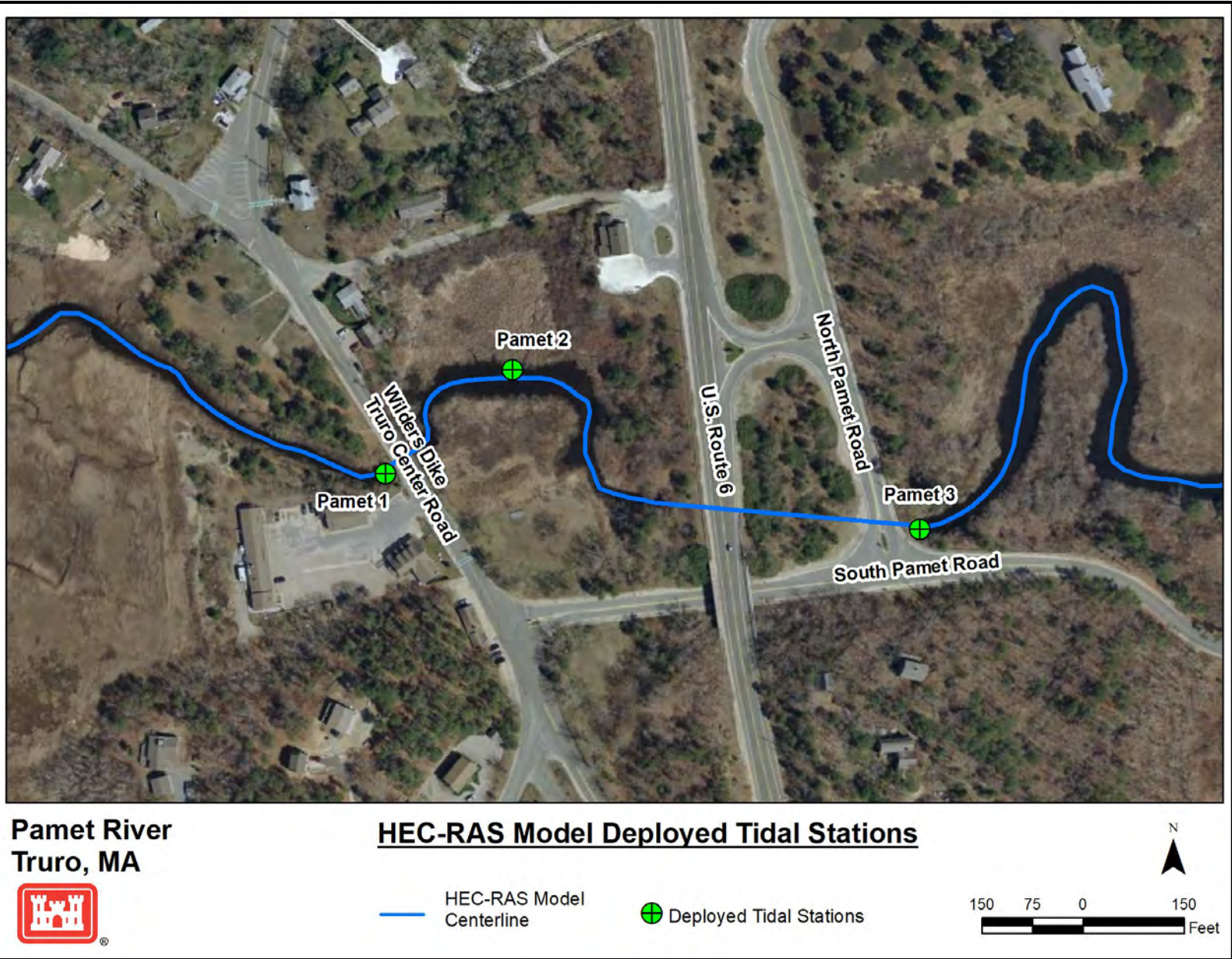


Figure E-2. HEC-RAS Model Deployed Tidal Stations



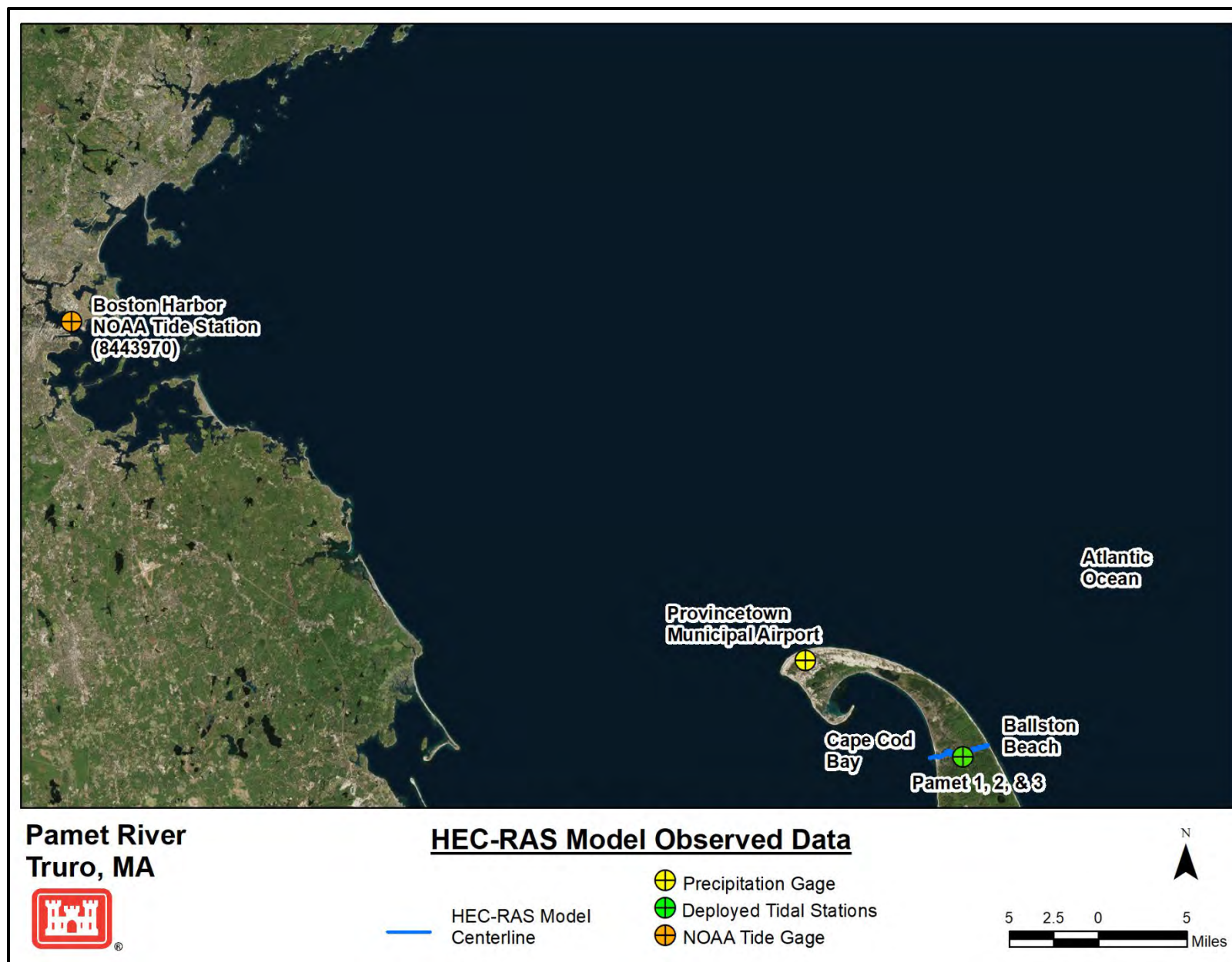


Figure E-3. HEC-RAS Model Observed Data

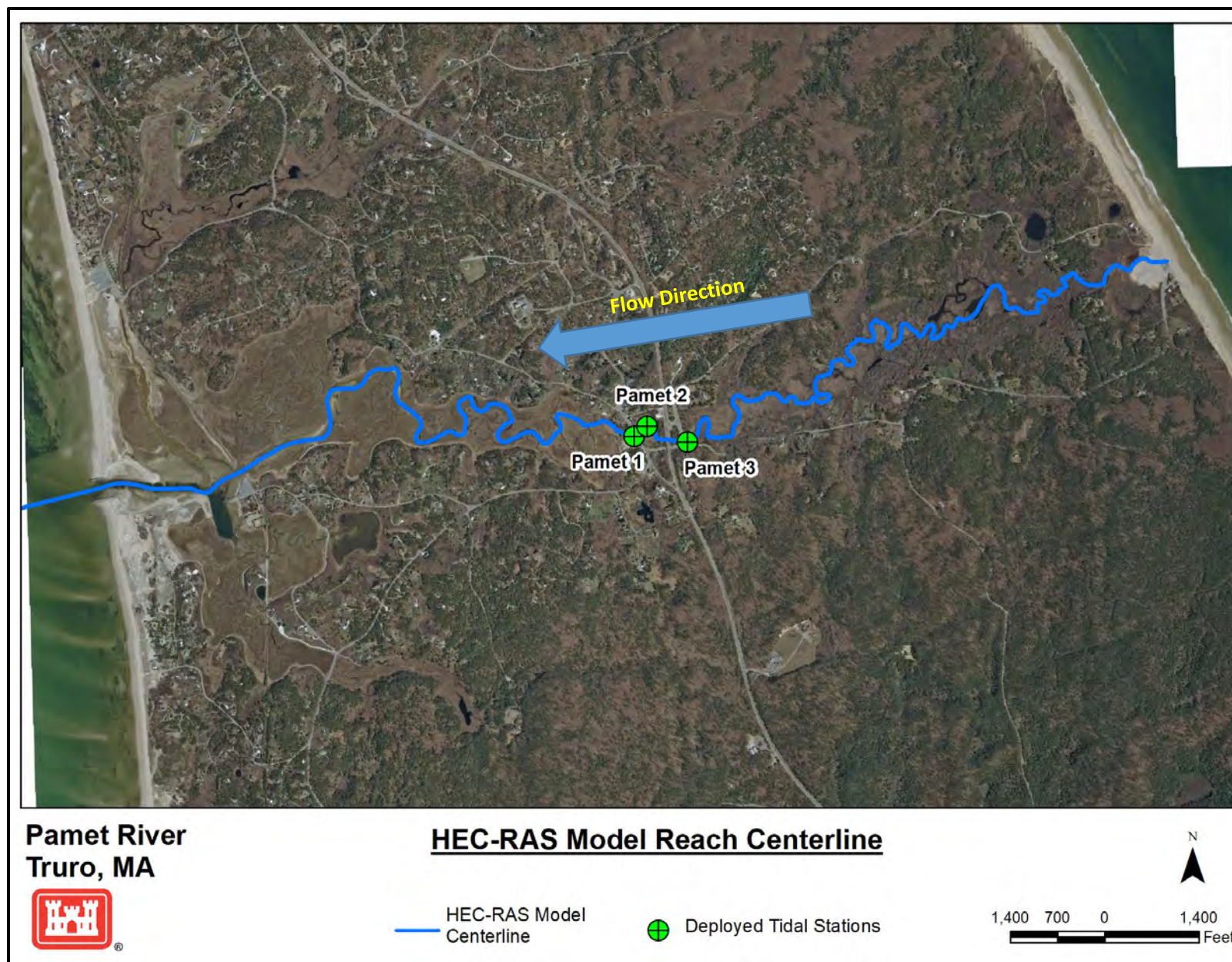


Figure E-4. HEC-RAS Model Reach Centerline



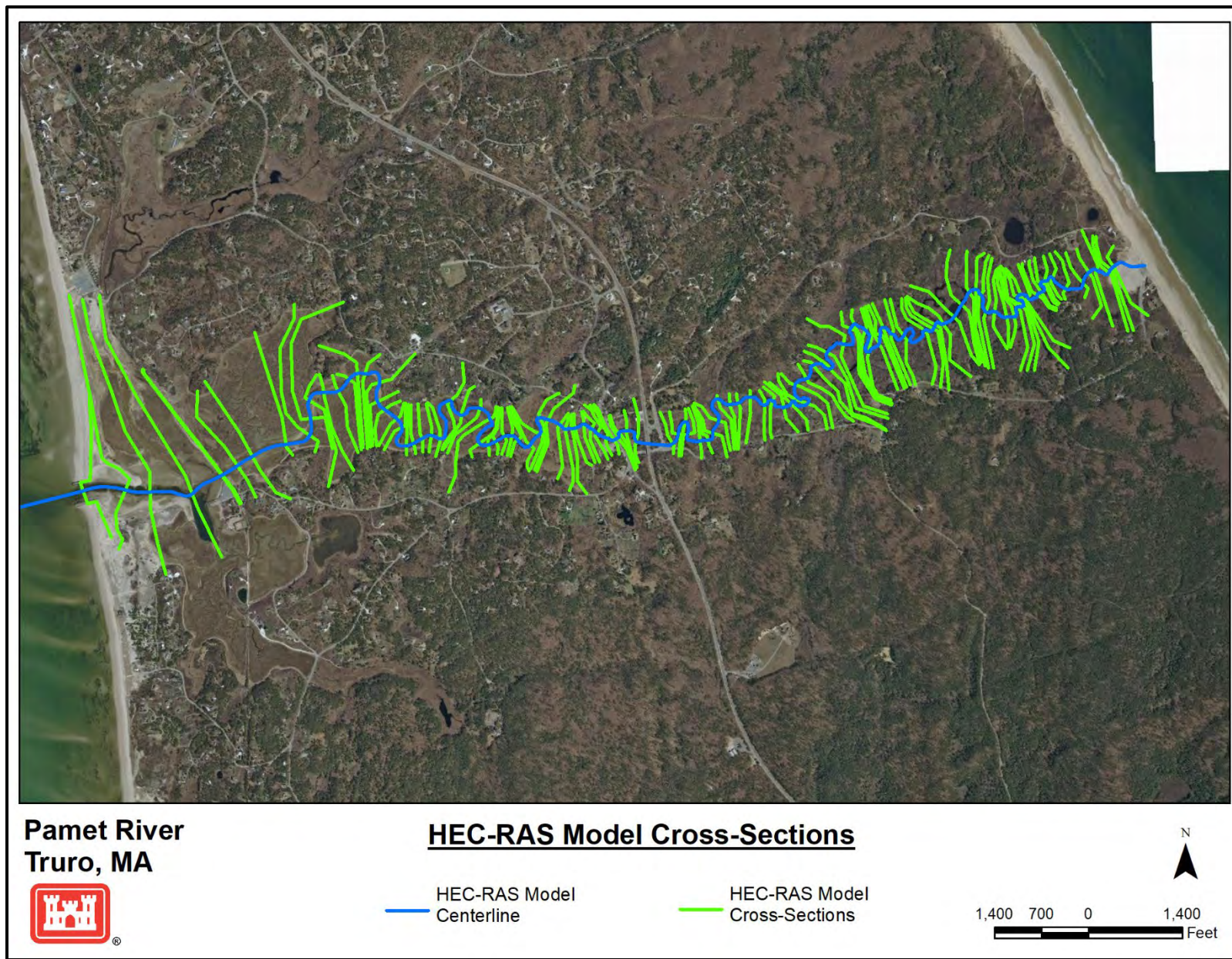


Figure E-5. HEC-RAS Model Cross-Sections



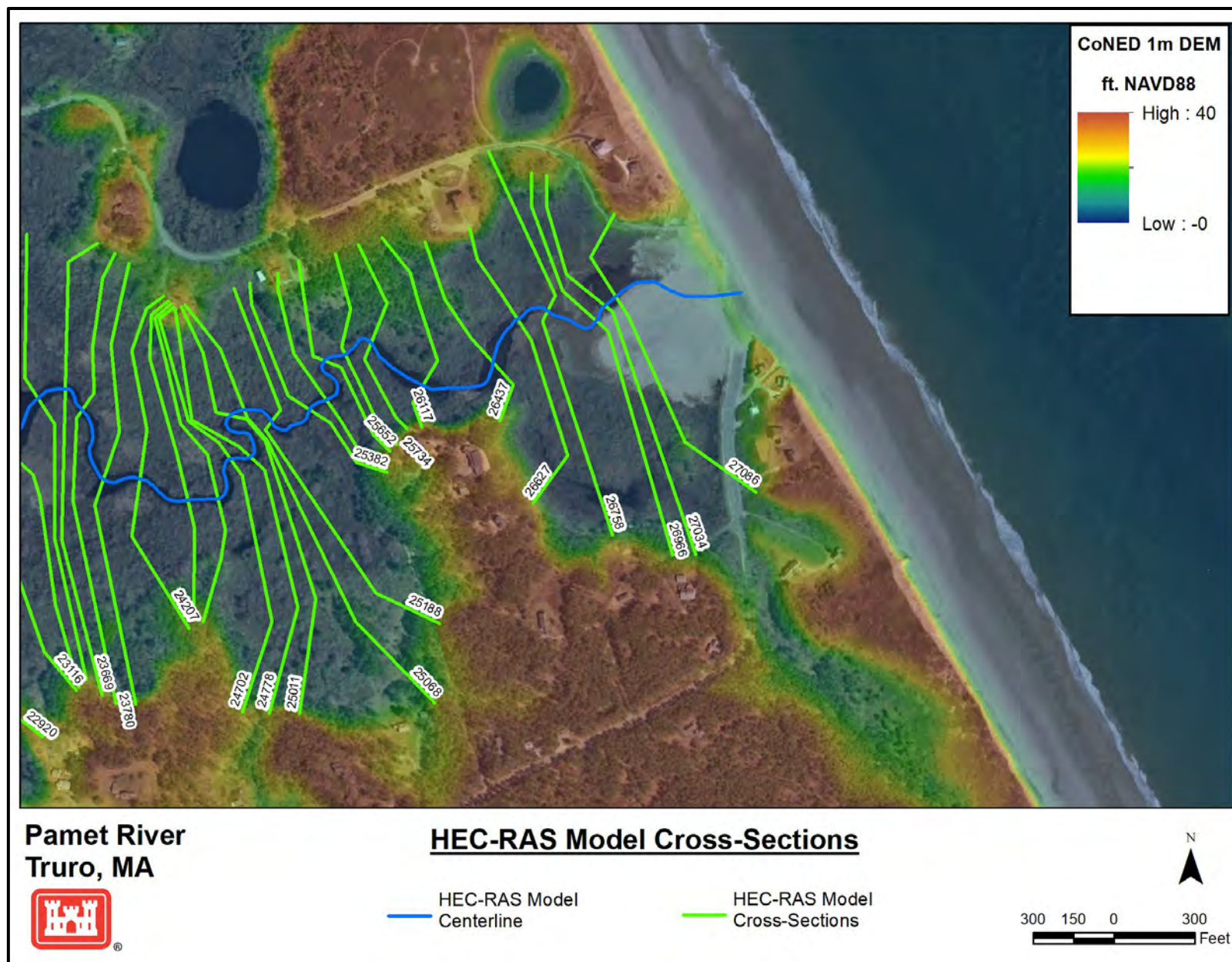


Figure E-6. HEC-RAS Model Sections at Ballston Beach



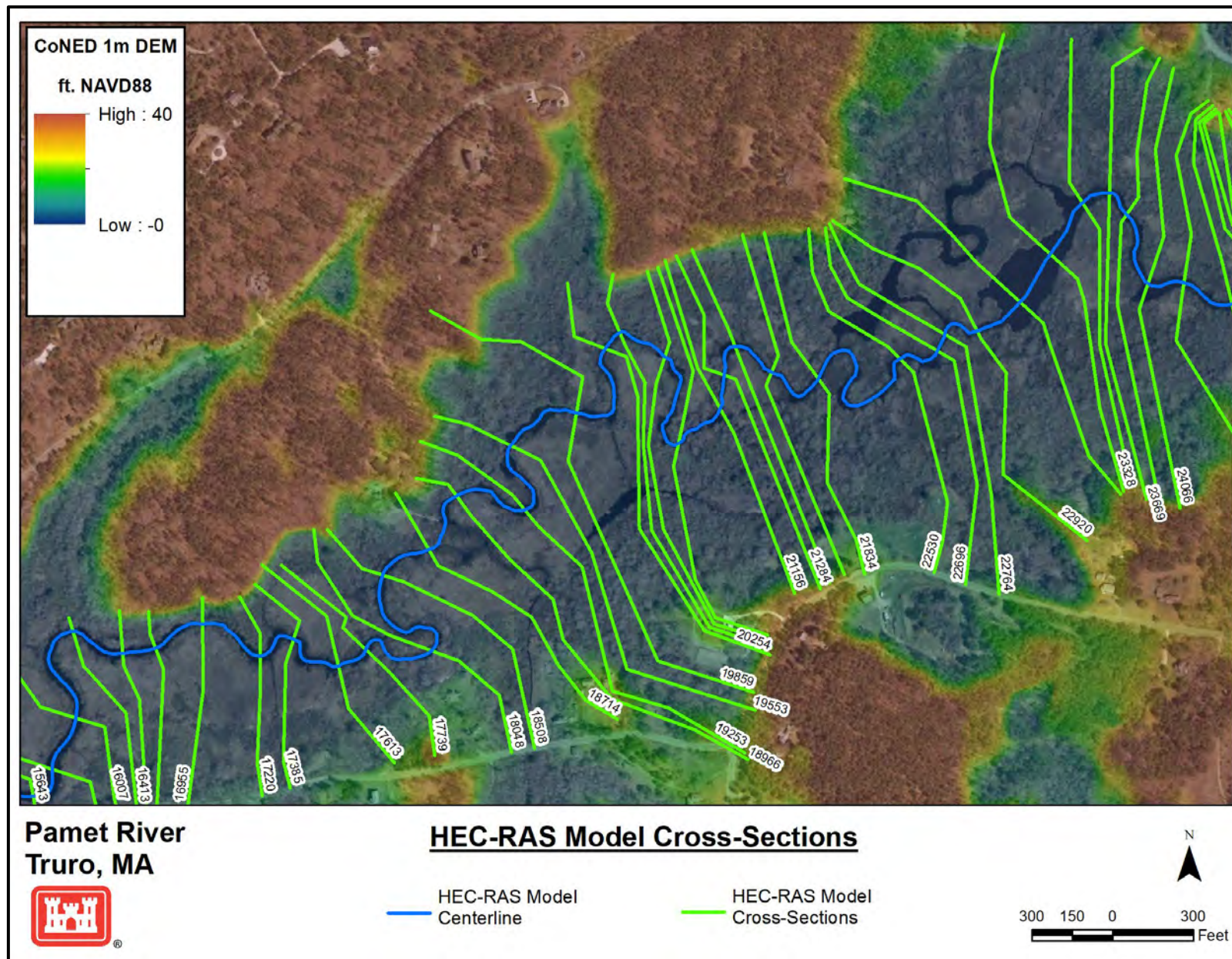


Figure E-7. HEC-RAS Model Cross-Sections at Upper Pamet River



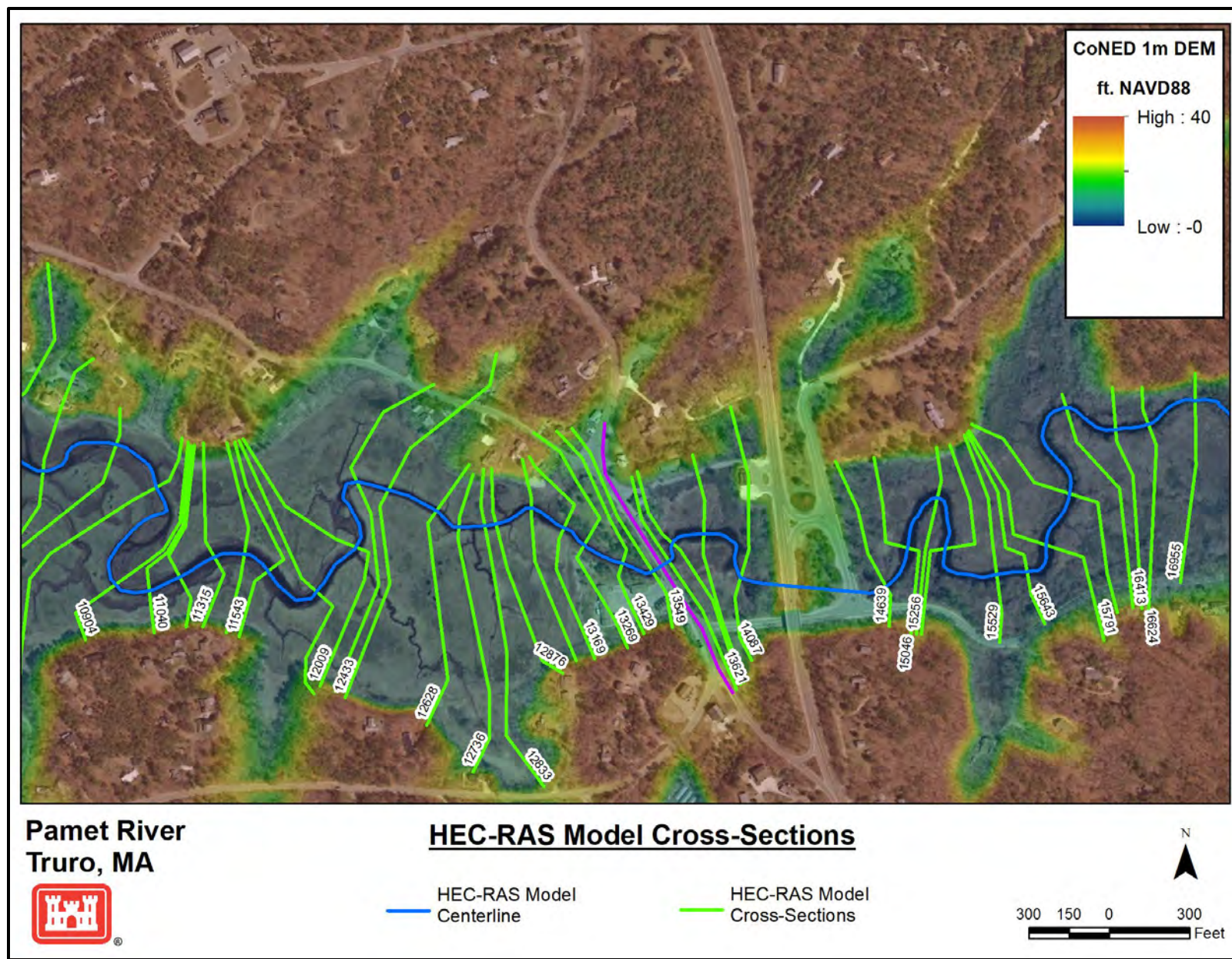


Figure E-8. HEC-RAS Model Cross-Sections at Wilders Dike & U.S. Route 6



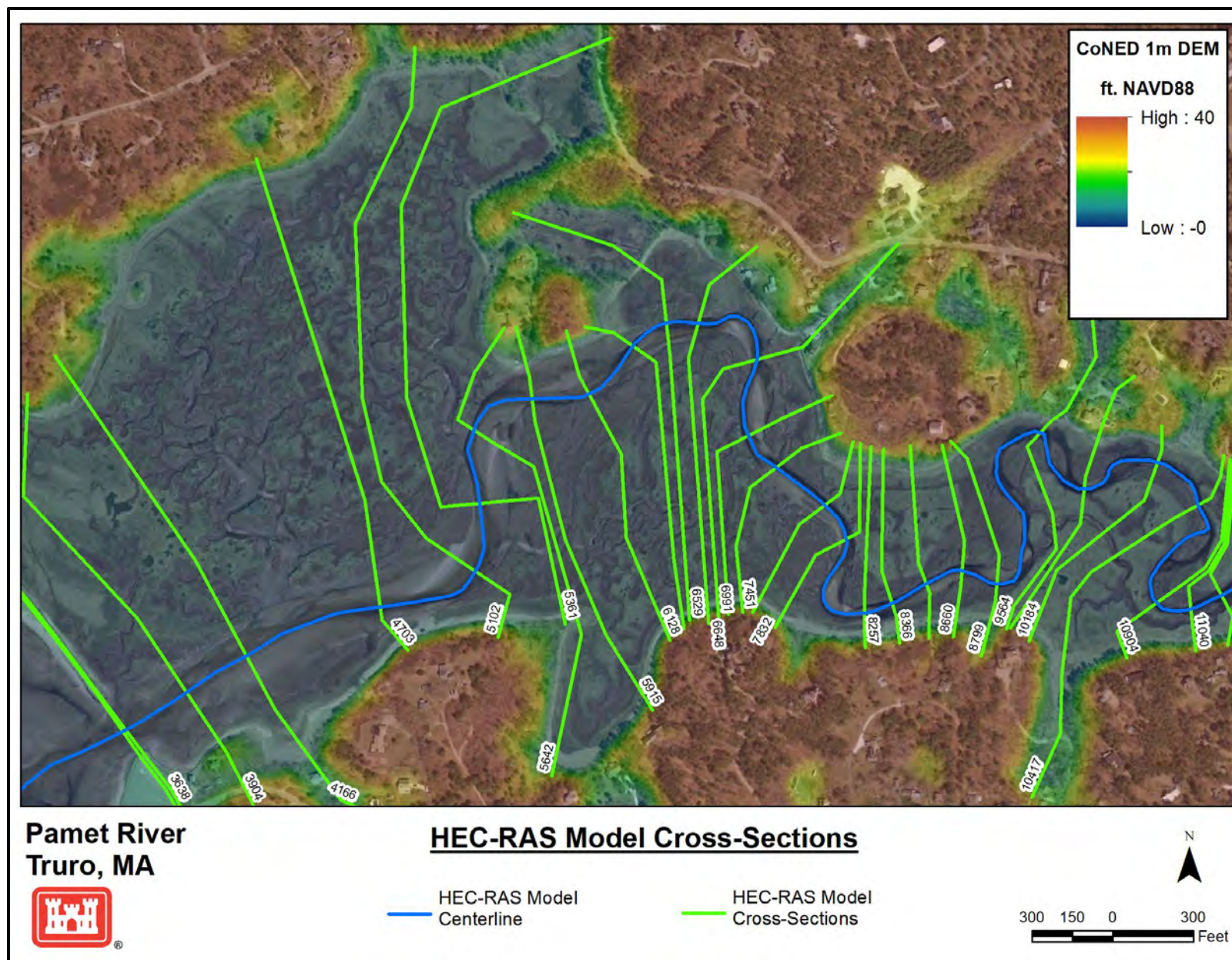


Figure E-9. HEC-RAS Model Cross-Sections at Lower Pamet River



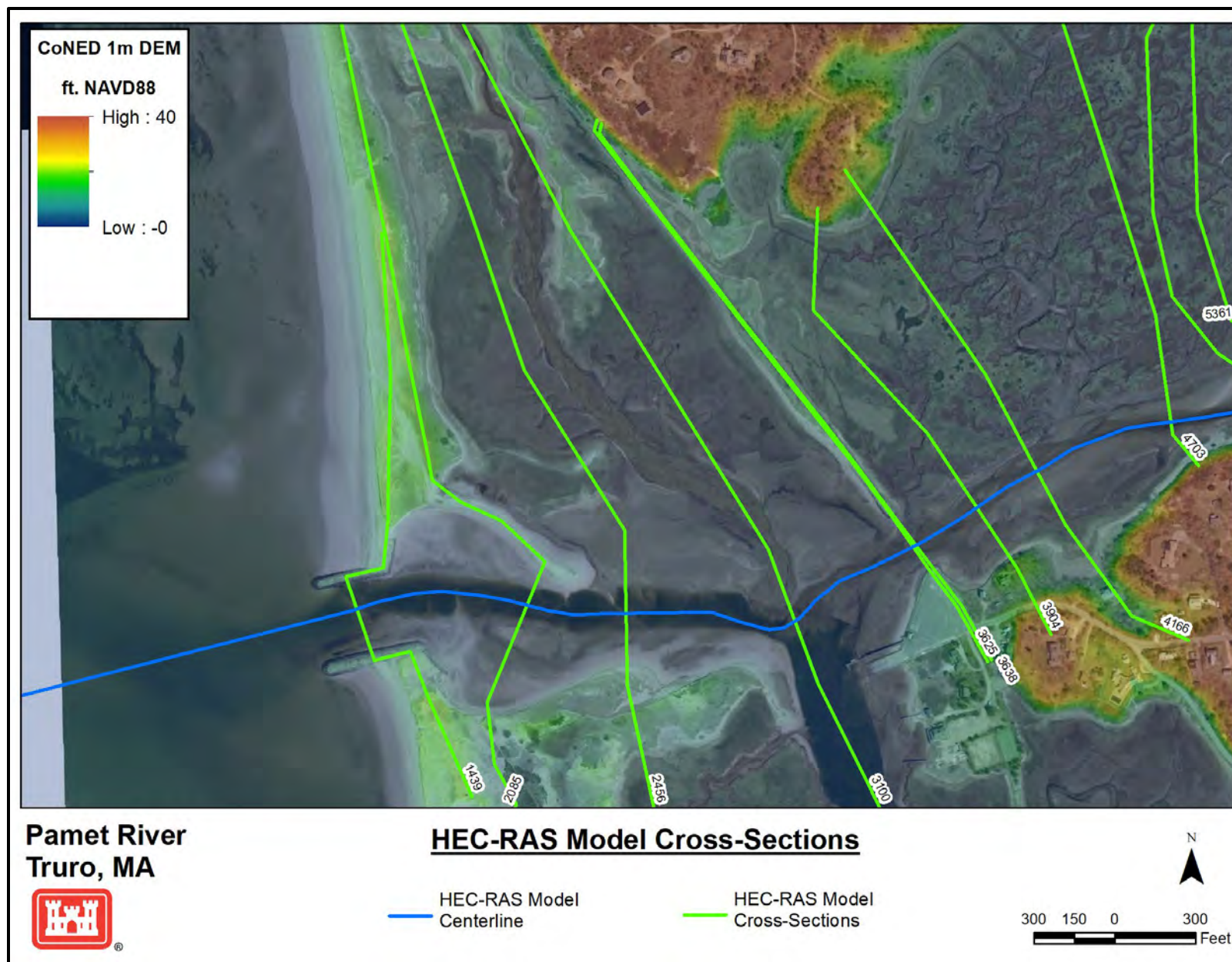


Figure E-10. HEC-RAS Model Cross-Sections at Pamet Harbor

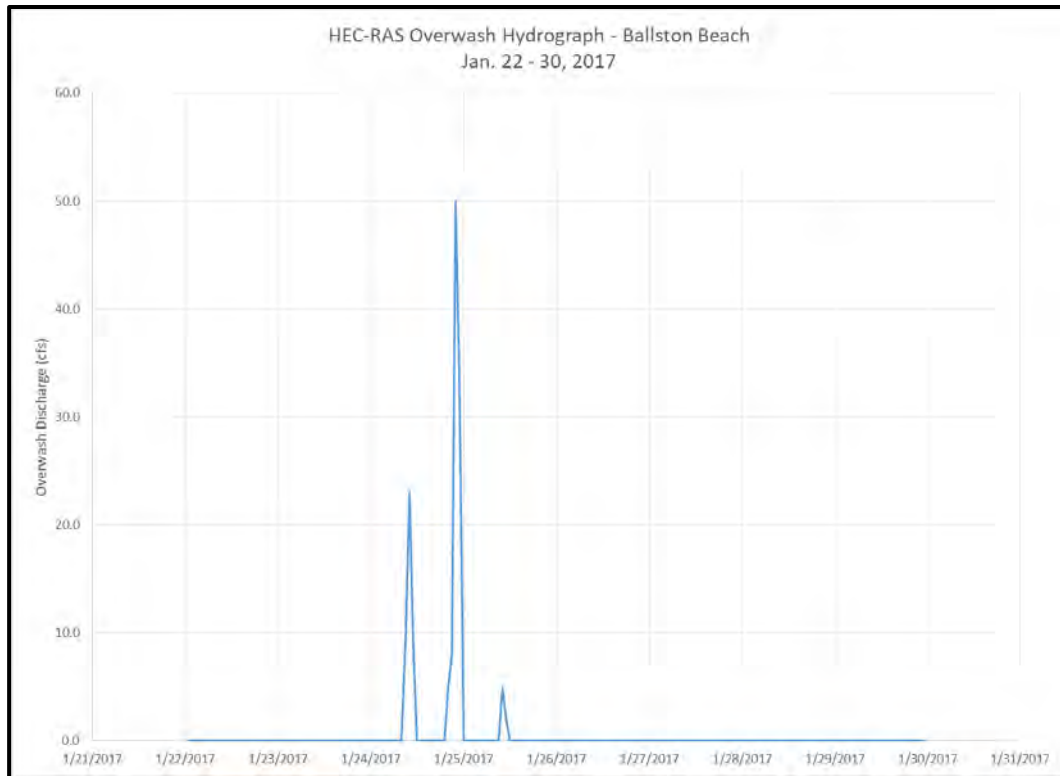


Figure E-11. HEC-RAS Overwash Hydrograph at Ballston Beach for Jan. 22 – 30, 2017 Event

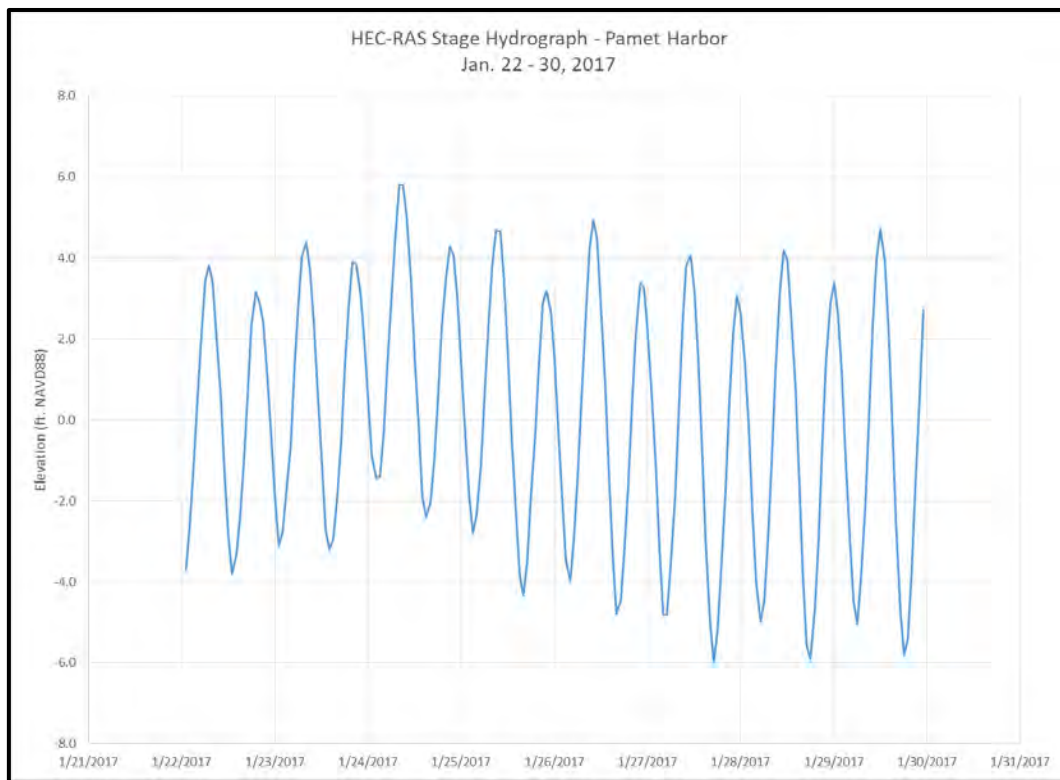


Figure E-12. HEC-RAS Stage Hydrograph at Pamet Harbor for Jan. 22 – 30, 2017 Event



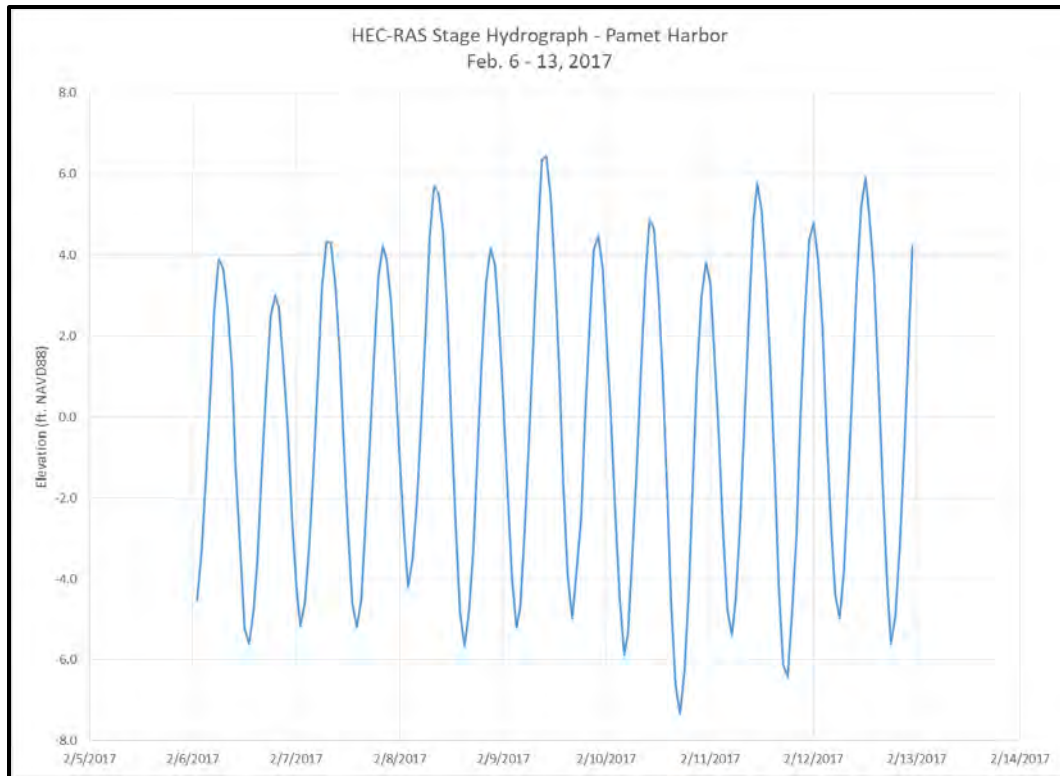


Figure E-13. HEC-RAS Stage Hydrograph at Pamet Harbor for Feb. 6 – 13, 2017 Event

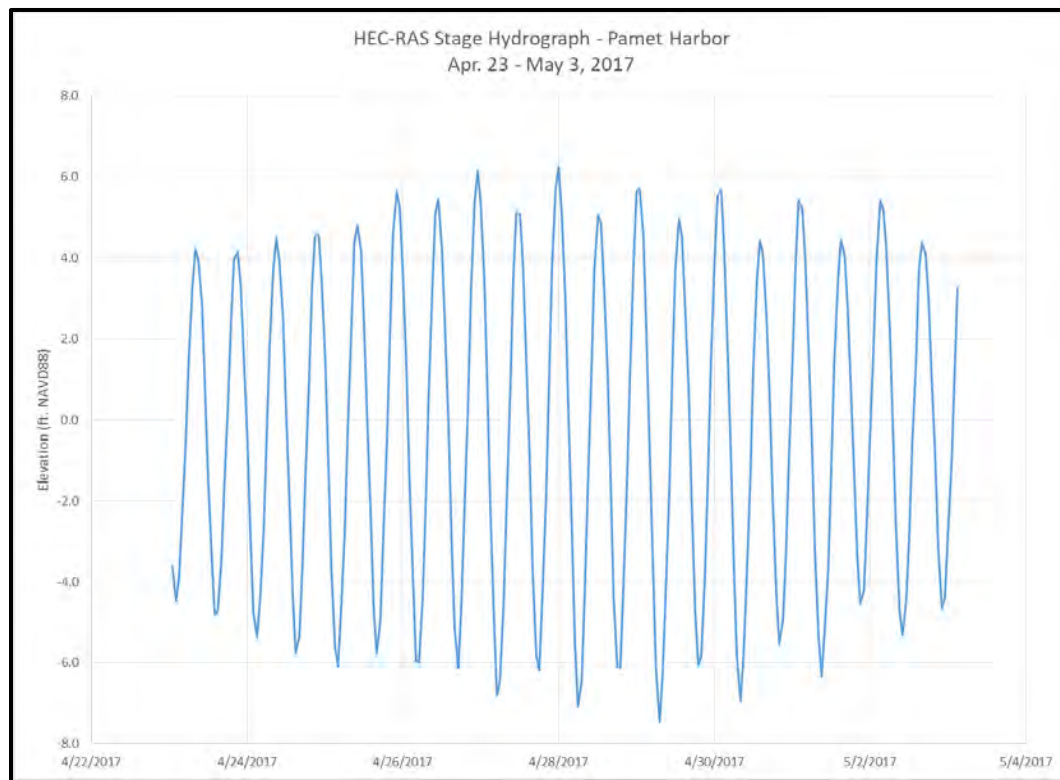


Figure E-14. HEC-RAS Stage Hydrograph at Pamet Harbor for Apr. 23 – May 3, 2017 Event

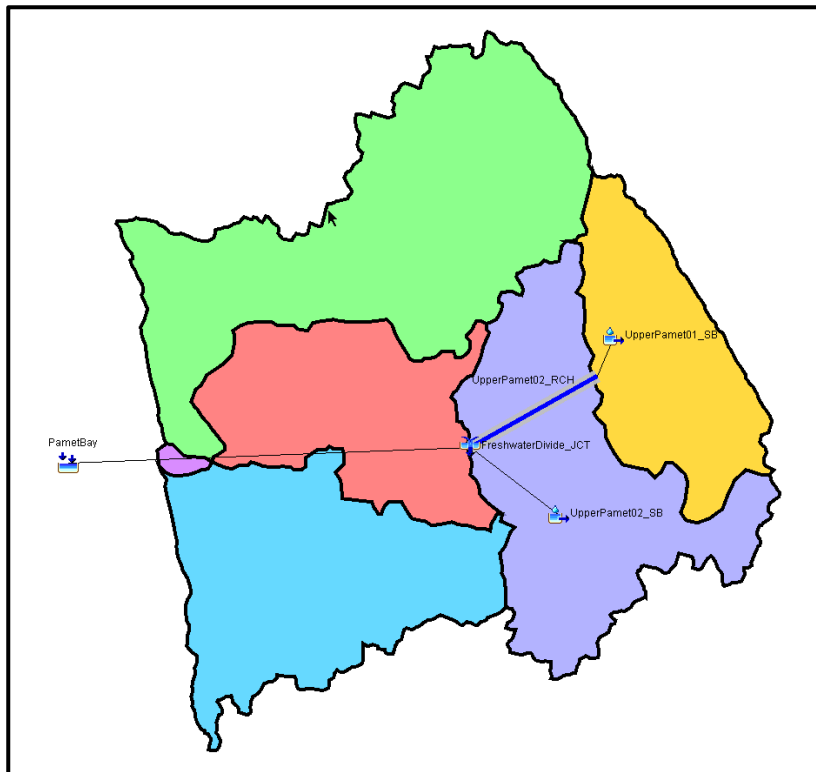


Figure E-15. HEC-HMS Model Subbasins and Schematic for Pamet River Watershed

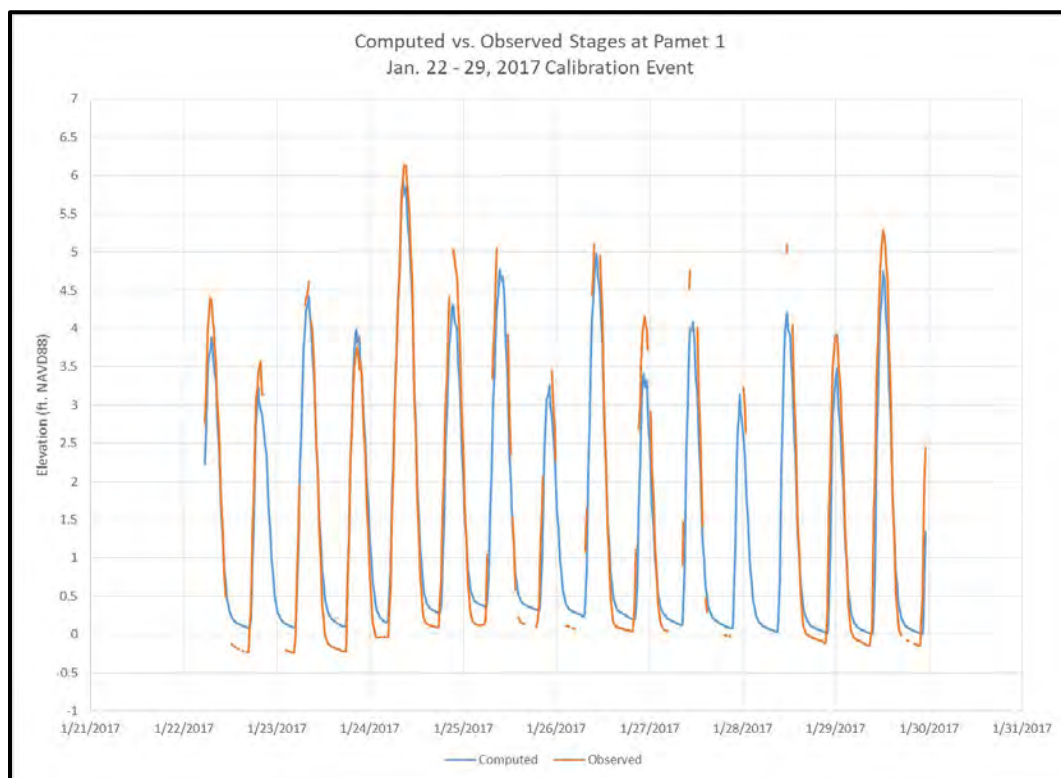


Figure E-16. Computed vs. Observed Stages at Pamet 1 for Jan. 22 – 29, 2017 Event

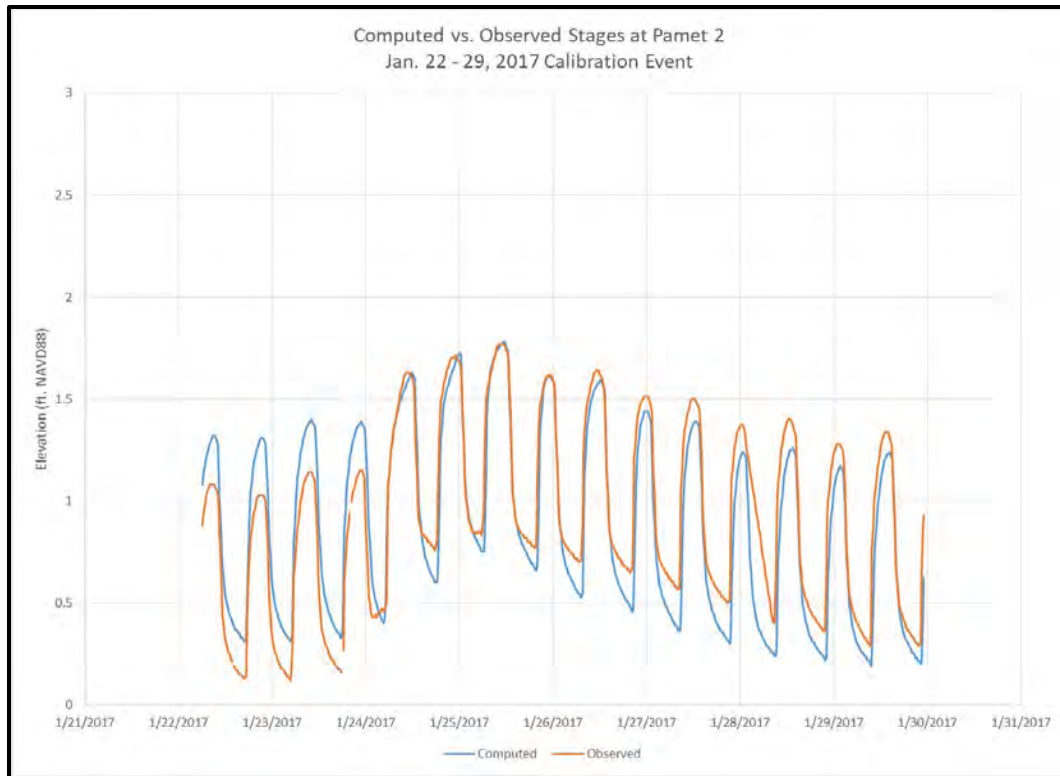


Figure E-17. Computed vs. Observed Stages at Pamet 2 for Jan. 22 – 29, 2017 Event

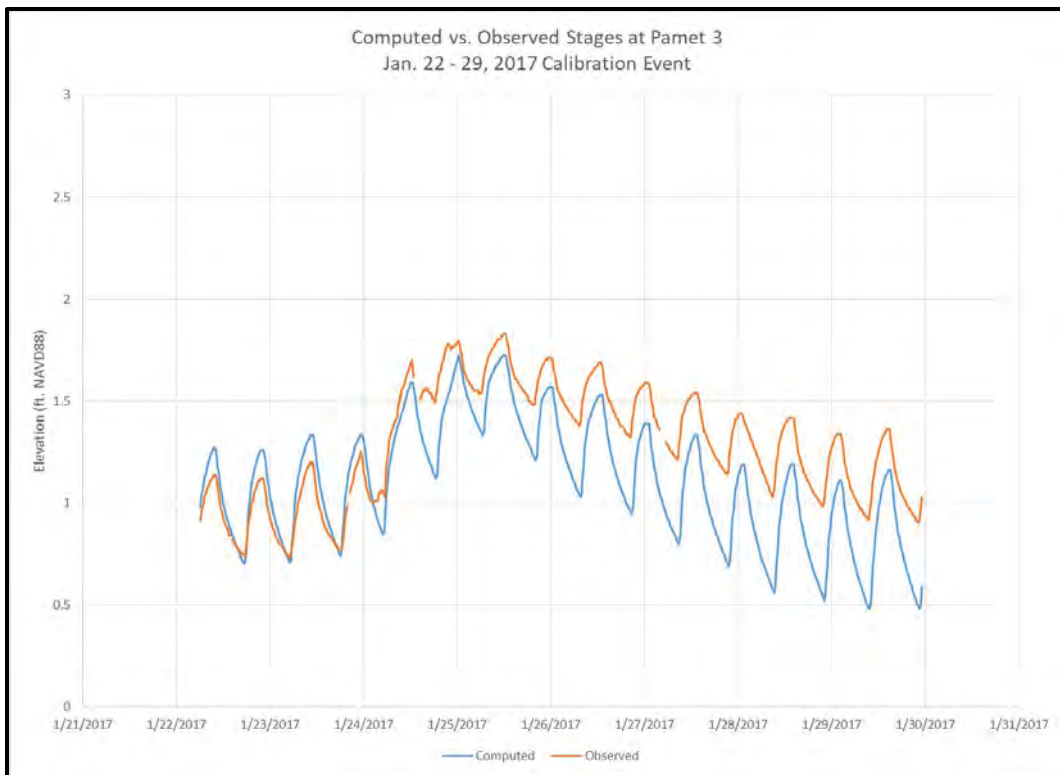


Figure E-18. Computed vs. Observed Stages at Pamet 3 for Jan. 22 – 29, 2017 Event



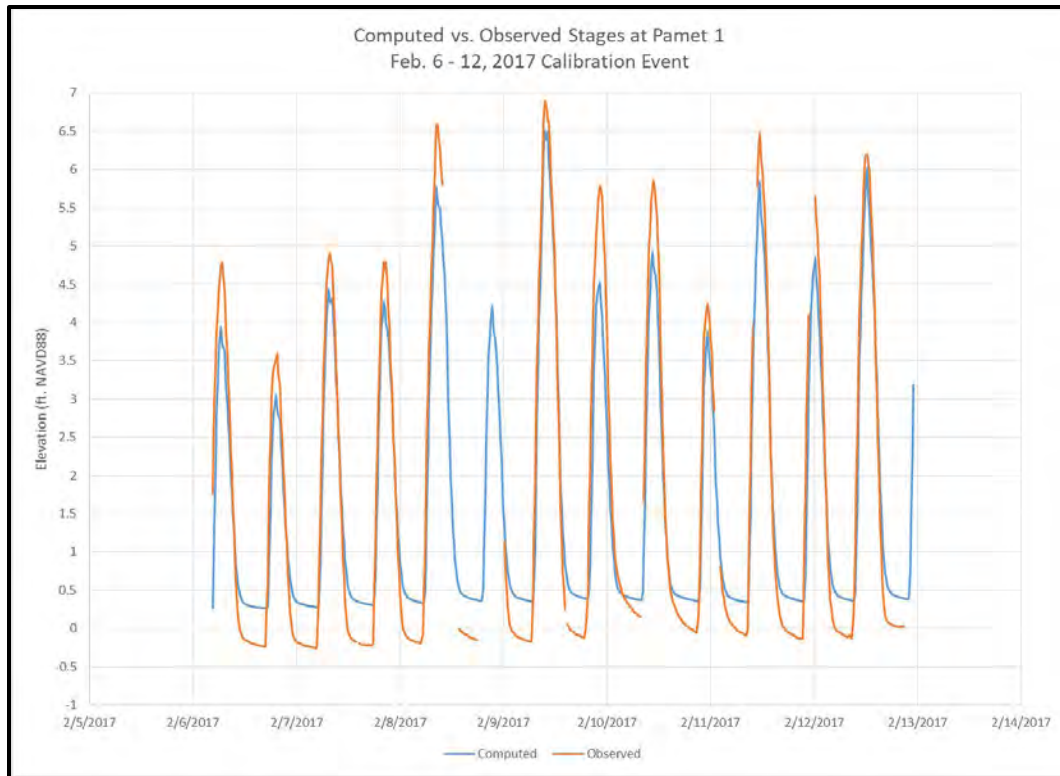


Figure E-19. Computed vs. Observed Stages at Pamet 1 for Feb. 6 – 12, 2017 Event

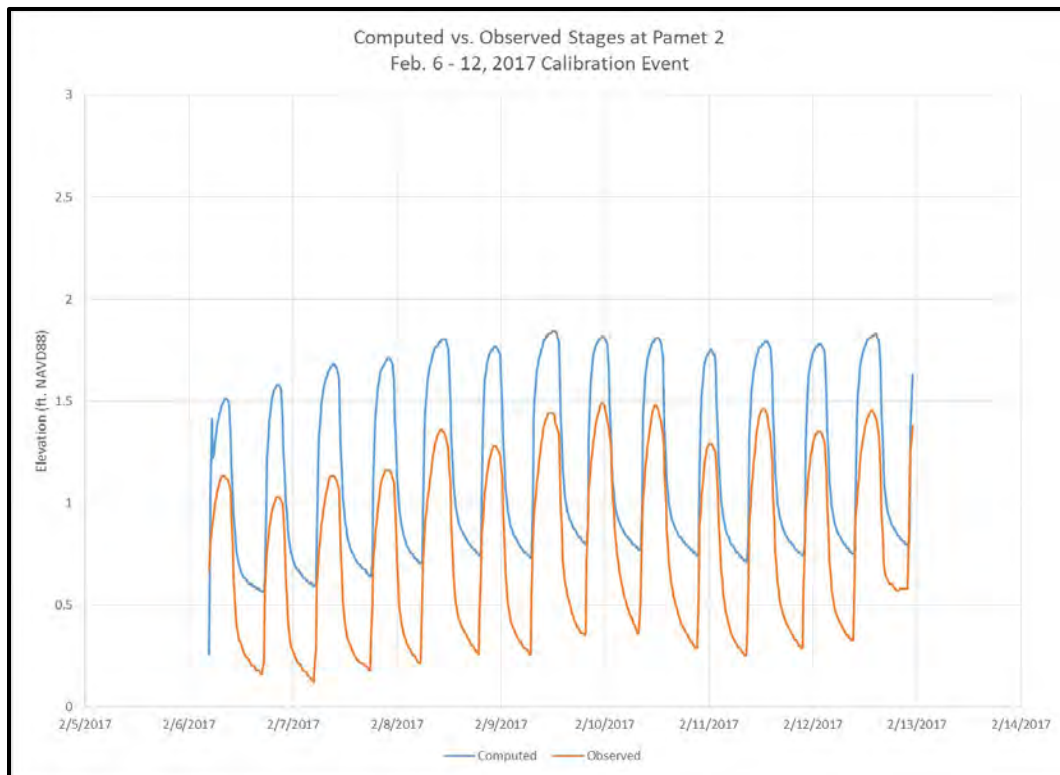


Figure E-20. Computed vs. Observed Stages at Pamet 2 for Feb. 6 – 12, 2017 Event

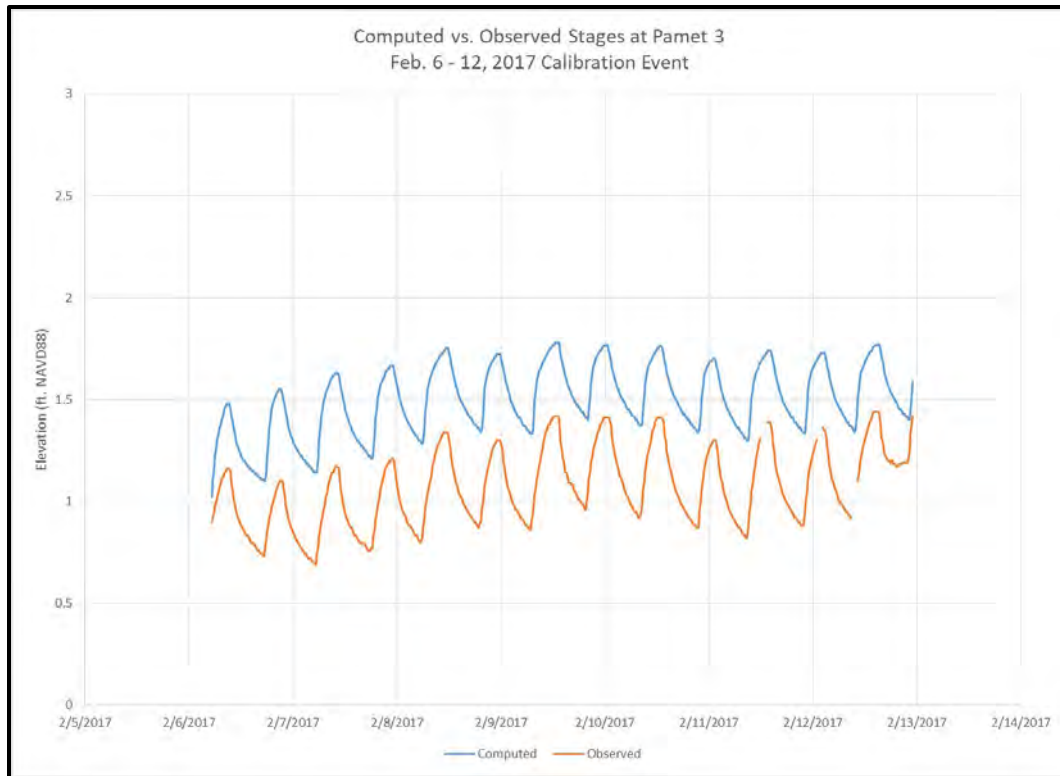


Figure E-21. Computed vs. Observed Stages at Pamet 3 for Feb. 6 – 12, 2017 Event

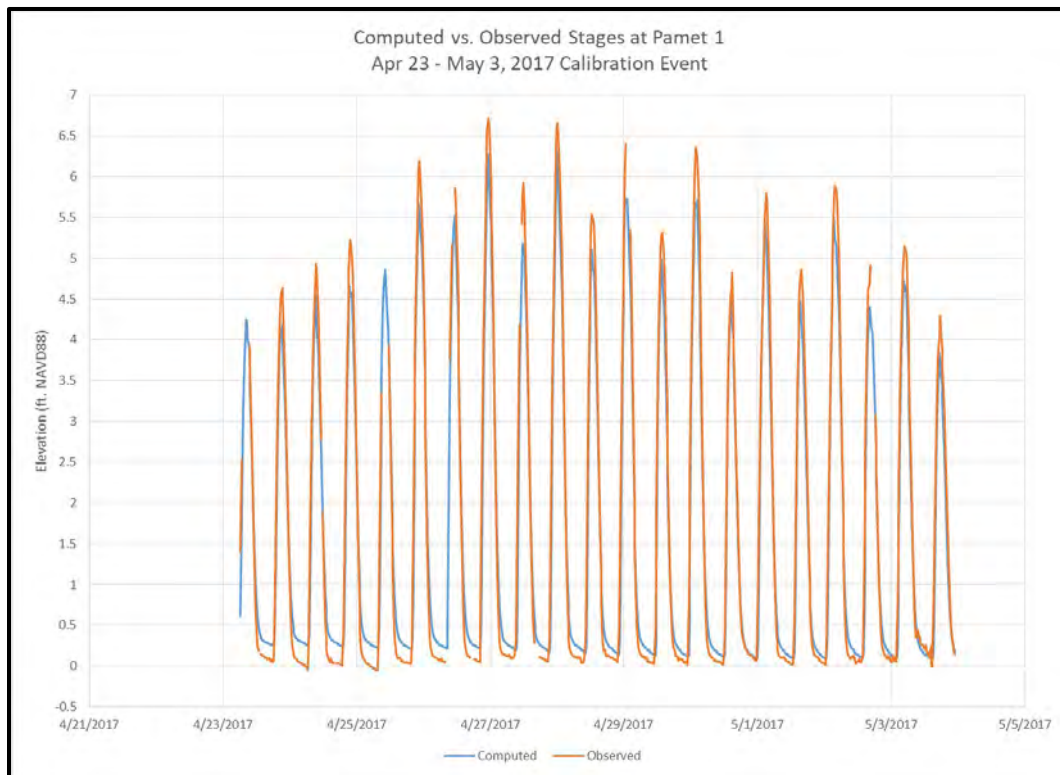


Figure E-22. Computed vs. Observed Stages at Pamet 1 for Apr. 23 – May 3, 2017 Event

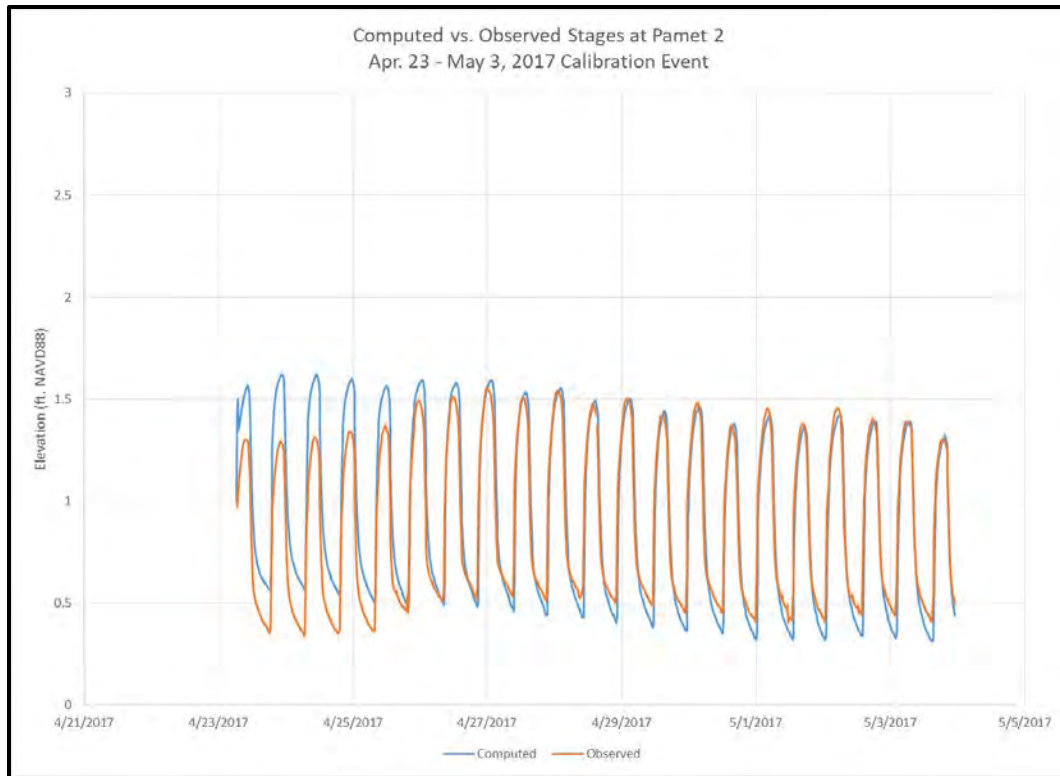


Figure E-23. Computed vs. Observed Stages at Pamet 2 for Apr. 23 – May 3, 2017 Event

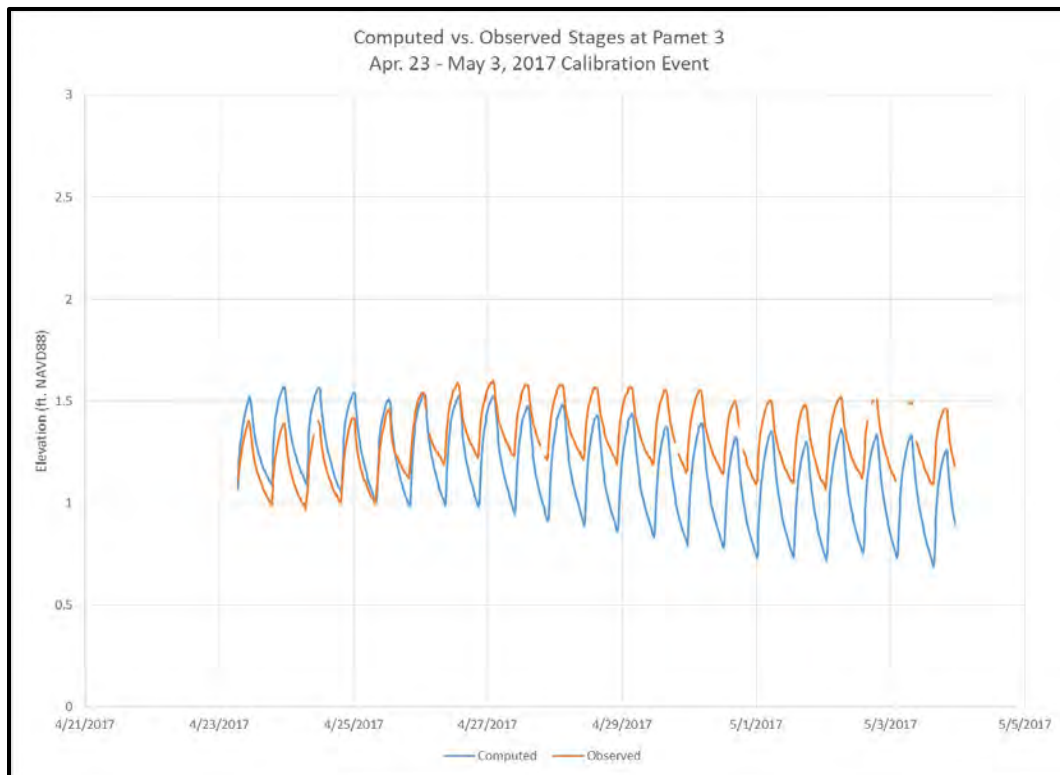


Figure E-24. Computed vs. Observed Stages at Pamet 3 for Apr. 23 – May 3, 2017 Event



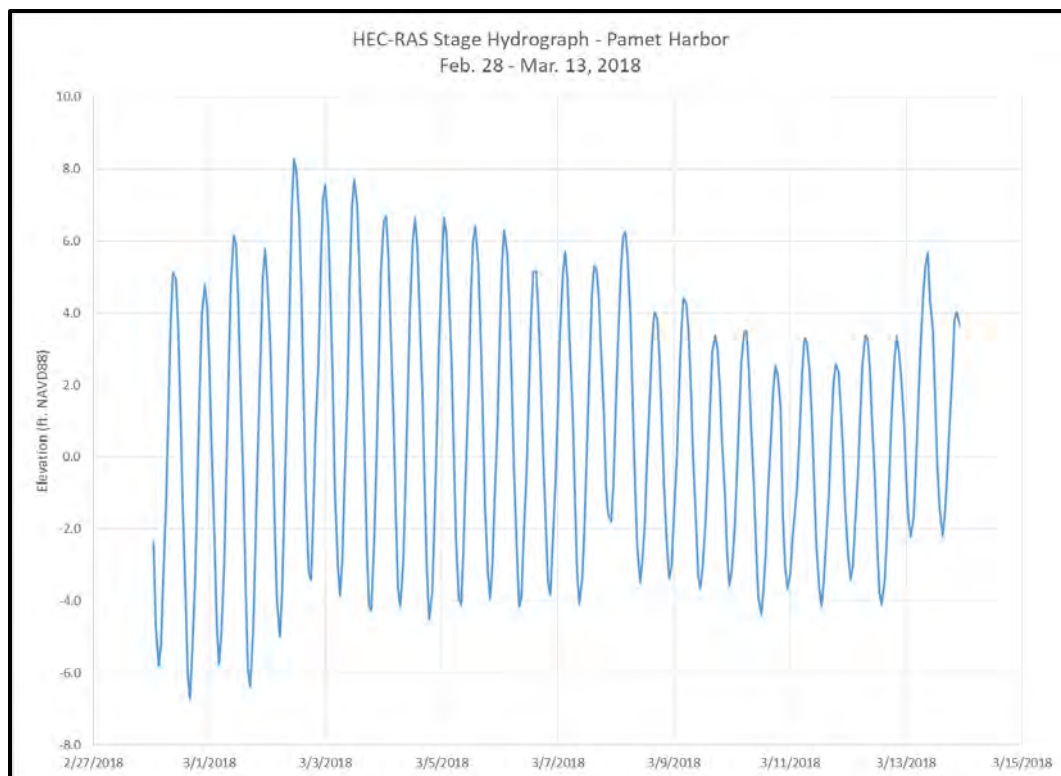


Figure E-25. HEC-RAS Stage Hydrograph at Pamet Harbor for Feb. 28 – Mar. 13, 2018 Event

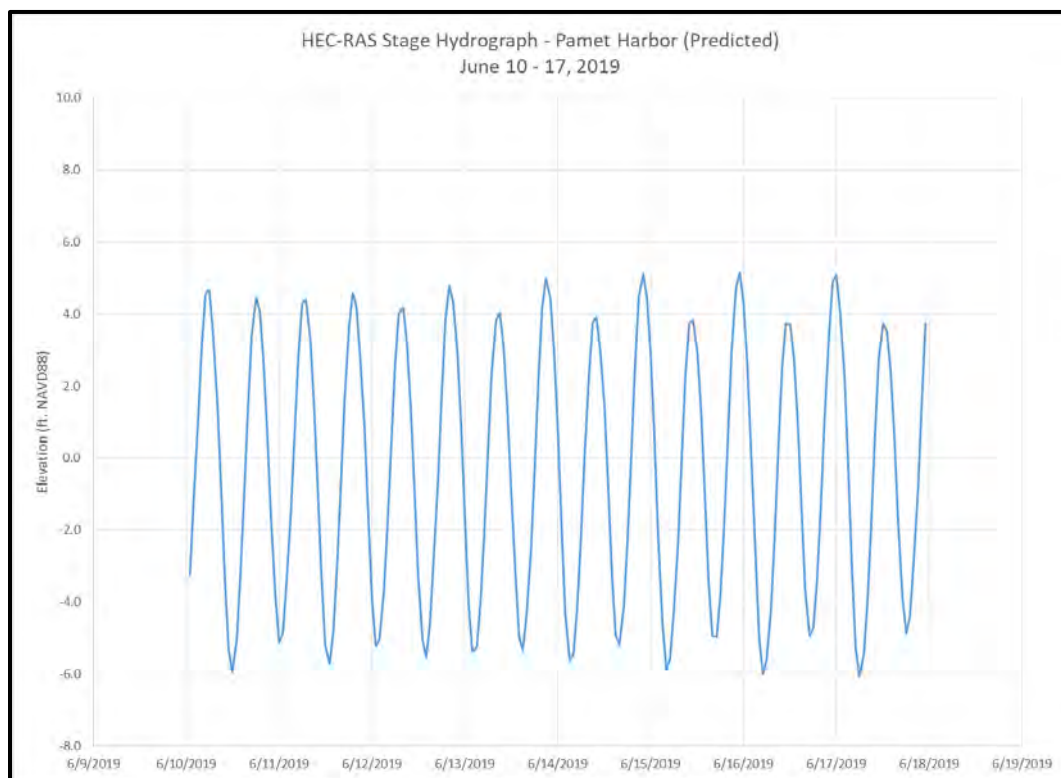


Figure E-26. HEC-RAS Stage Hydrograph at Pamet Harbor for June. 10 – 17, 2019

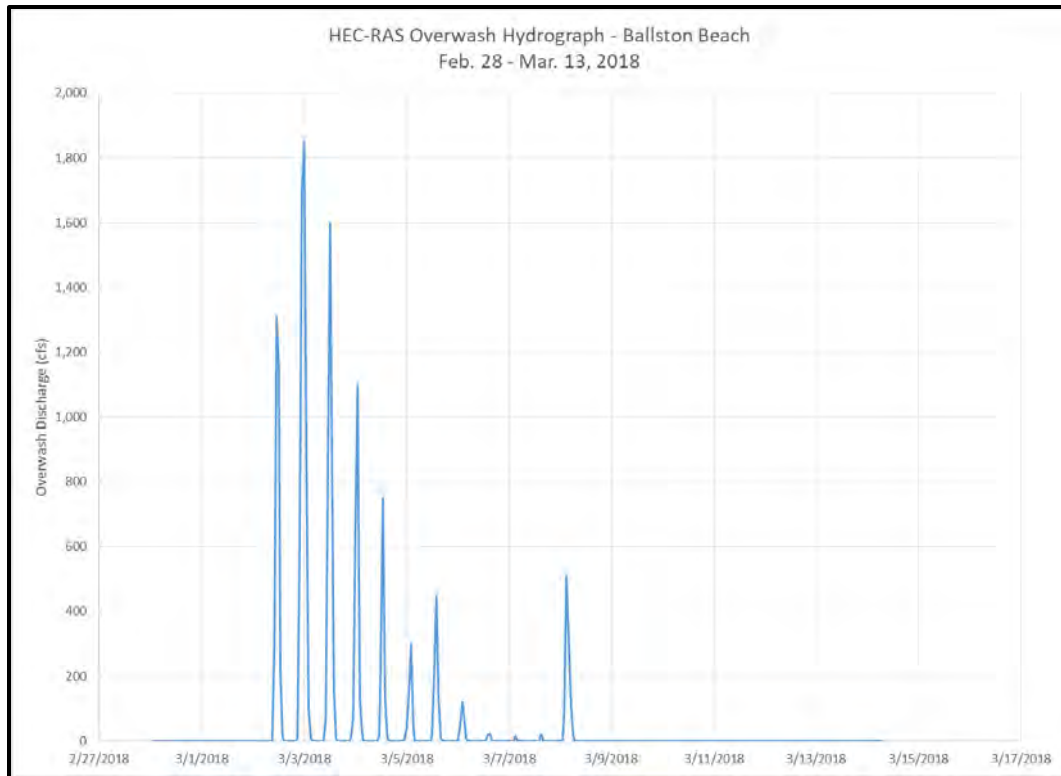


Figure E-27. HEC-RAS Overwash Hydrograph at Ballston Beach for Feb. 28 – Mar. 13, 2018 Event

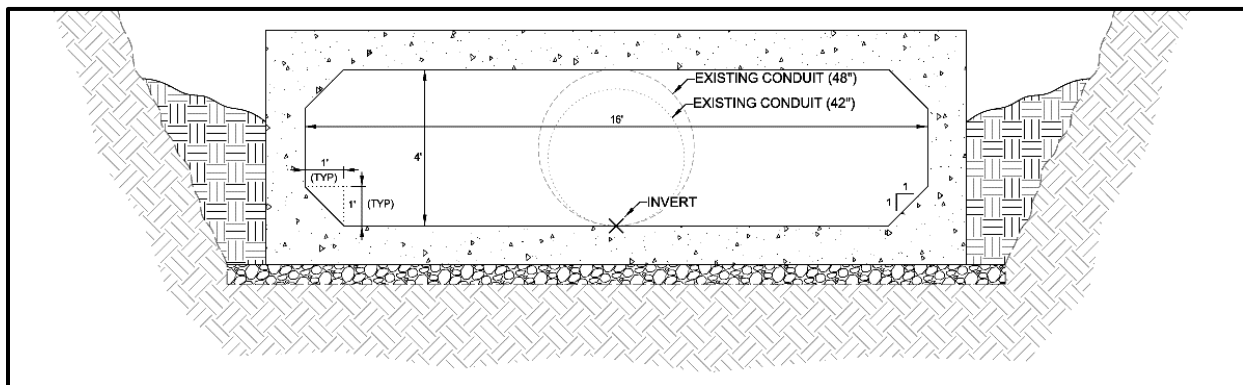


Figure E-28. Typical Box Culvert Cross-Section for Alt. #2 & Alt. #3

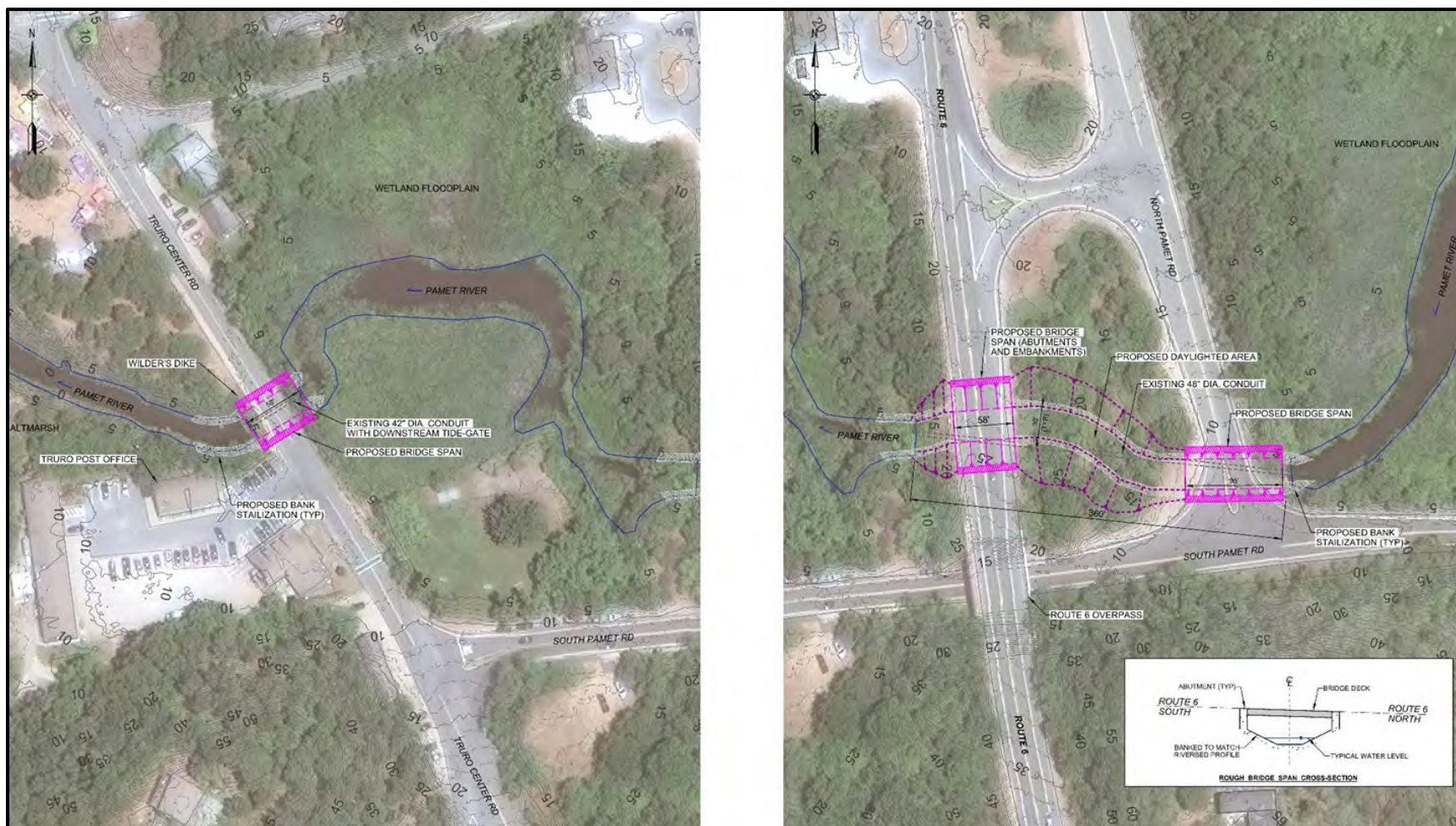


Figure E-29. Bridge Conceptual Plan for Alt. #4



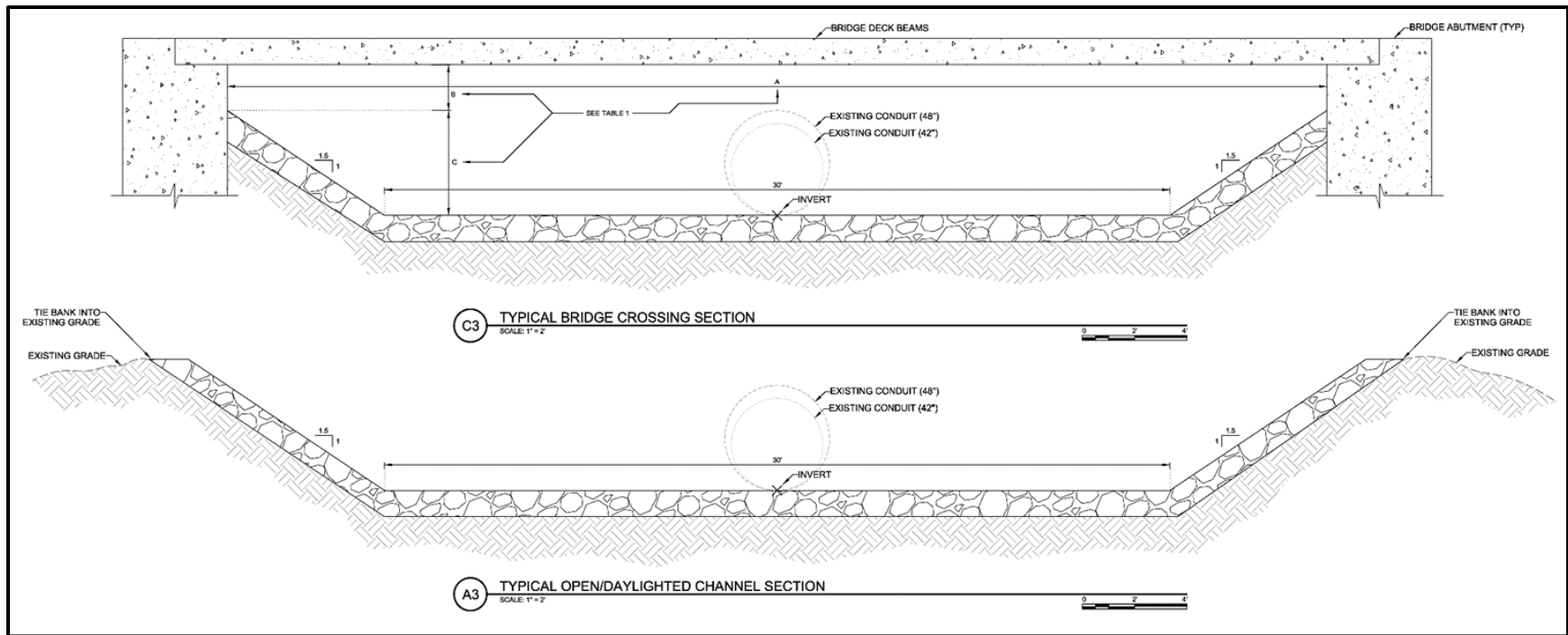


Figure E-30. Typical Cross-Sections for Bridge & Open Channel Sections for Alt. #4

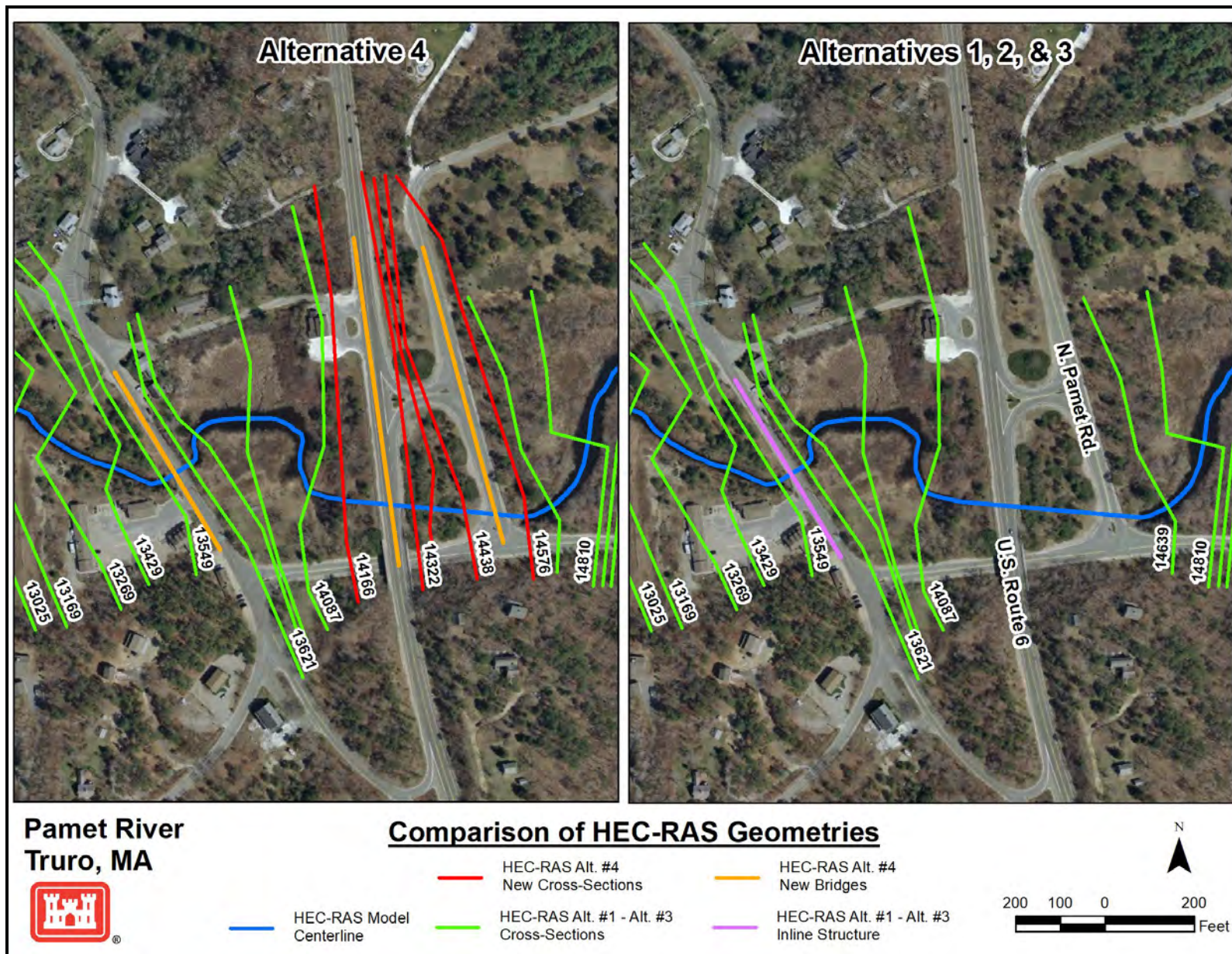


Figure E-31. Comparison of HEC-RAS Geometries for Alt. #4 vs. Alts. #1 - #3



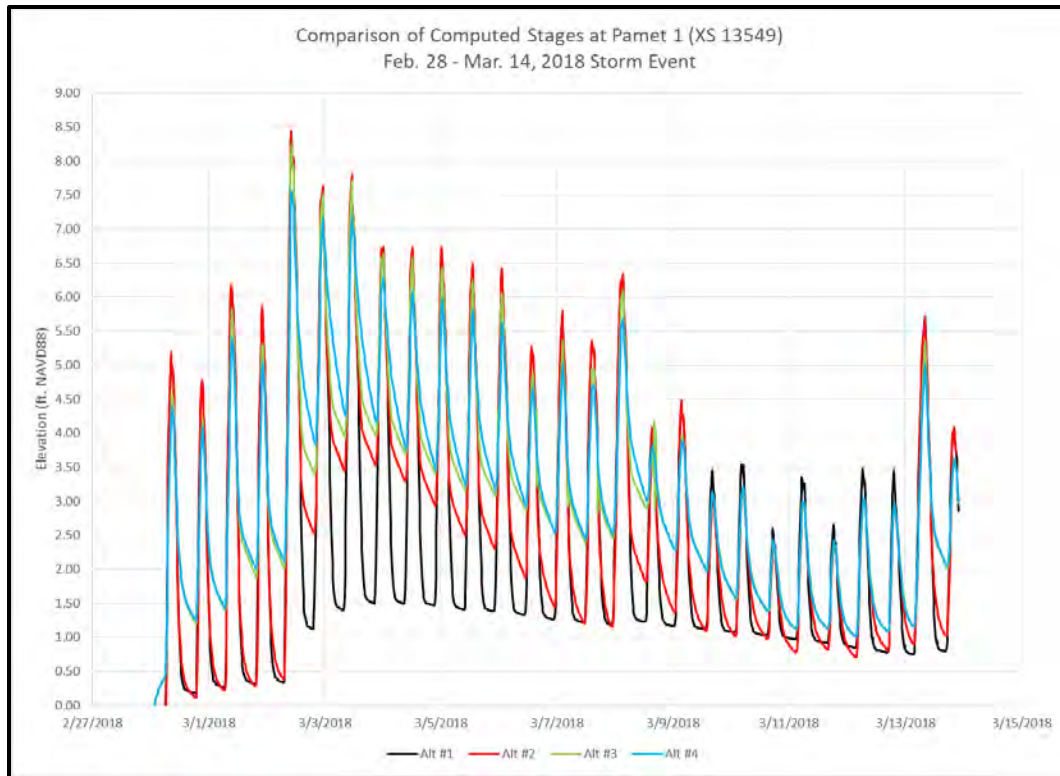


Figure E-32. Computed Hydrographs from March 2018 Event at Pamet 1 for All Alternatives

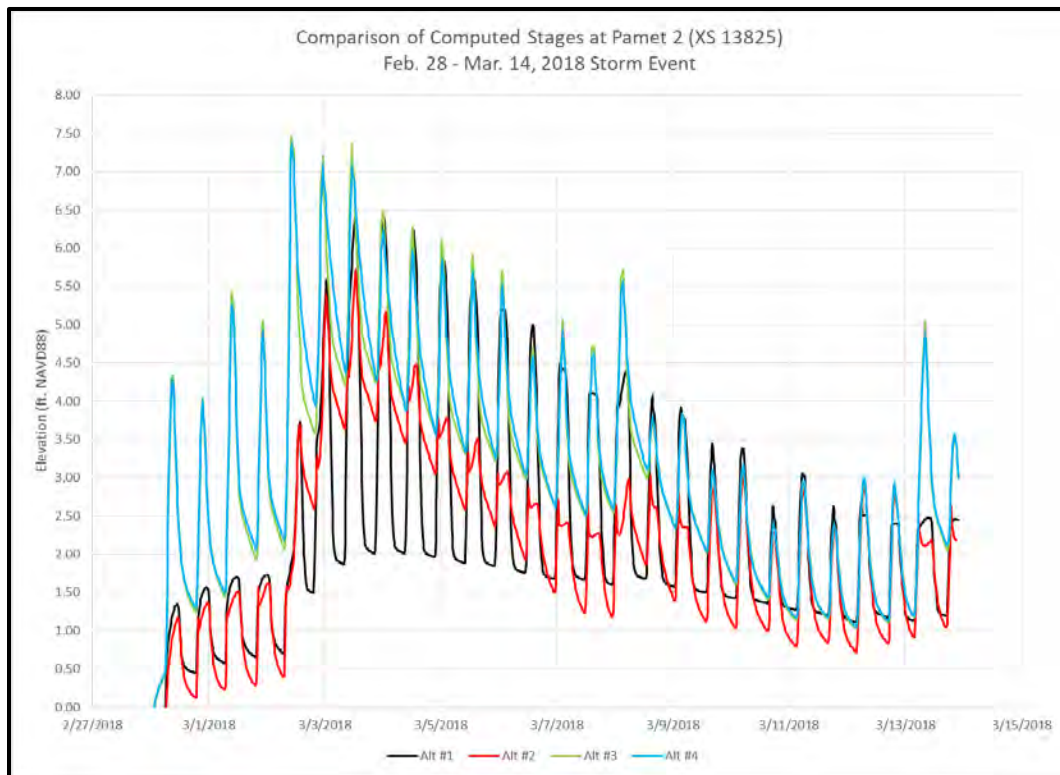


Figure E-33. Computed Hydrographs from March 2018 Event at Pamet 2 for All Alternatives



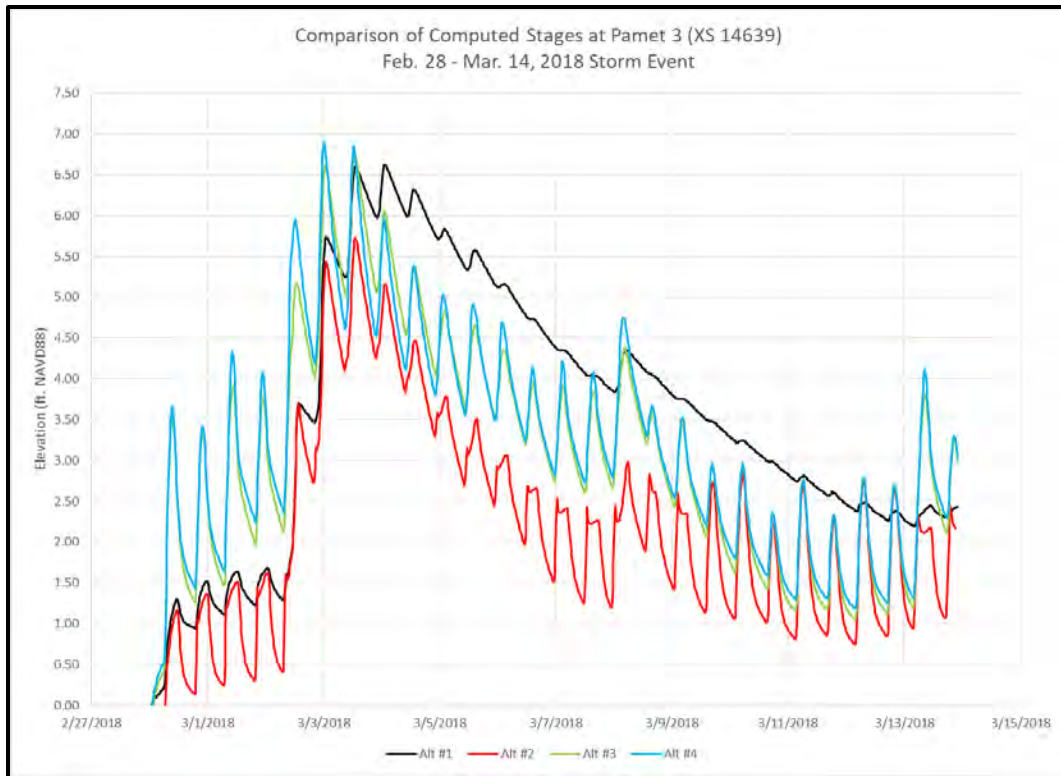


Figure E-34. Computed Hydrographs from March 2018 Event at Pamet 3 for All Alternatives

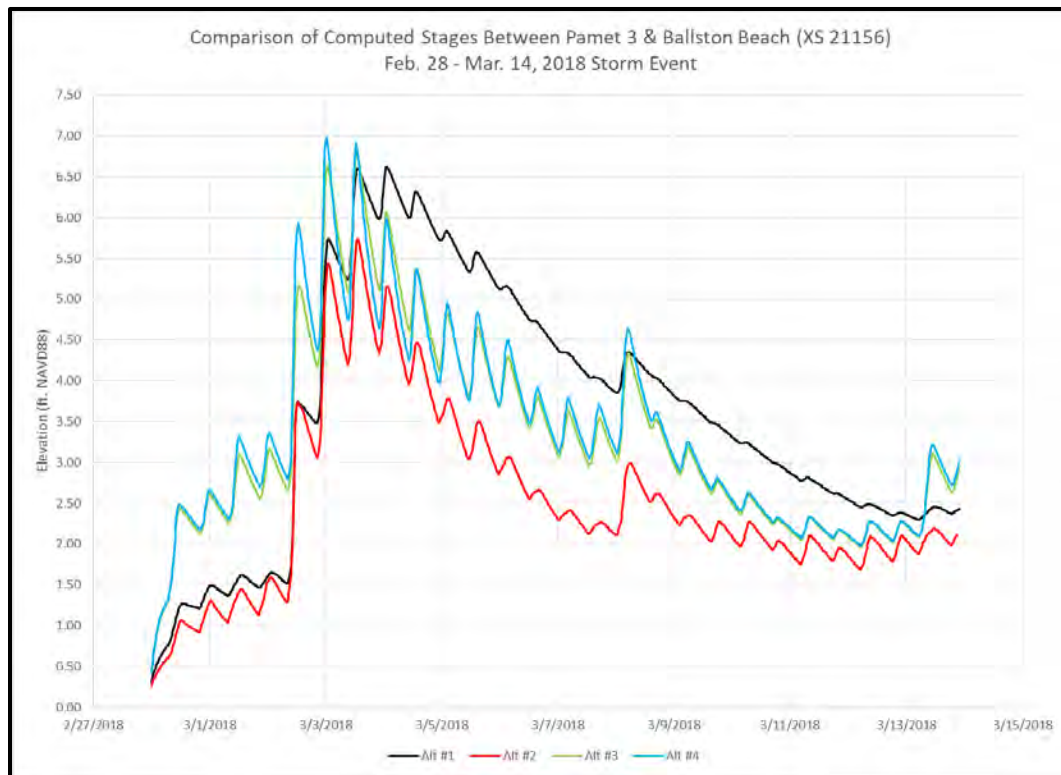


Figure E-35. Computed Hydrographs from March 2018 Event at XS 21156 for All Alternatives

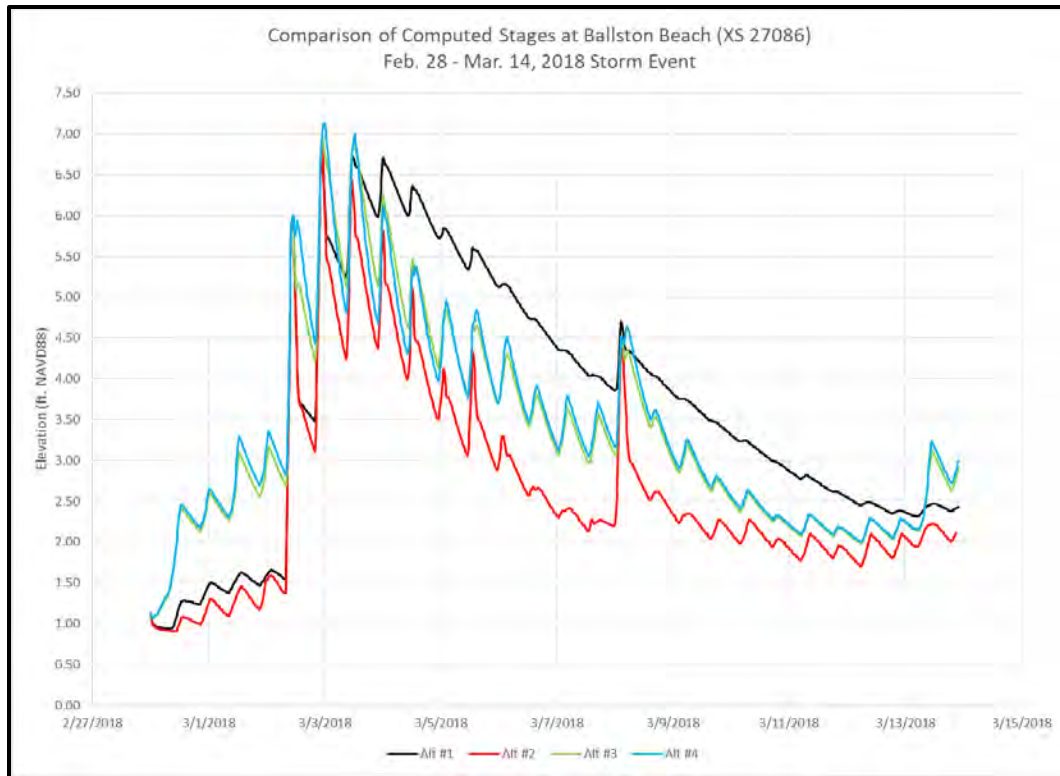


Figure E-36. Computed Hydrographs from March 2018 Event at Ballston Beach for All Alternatives

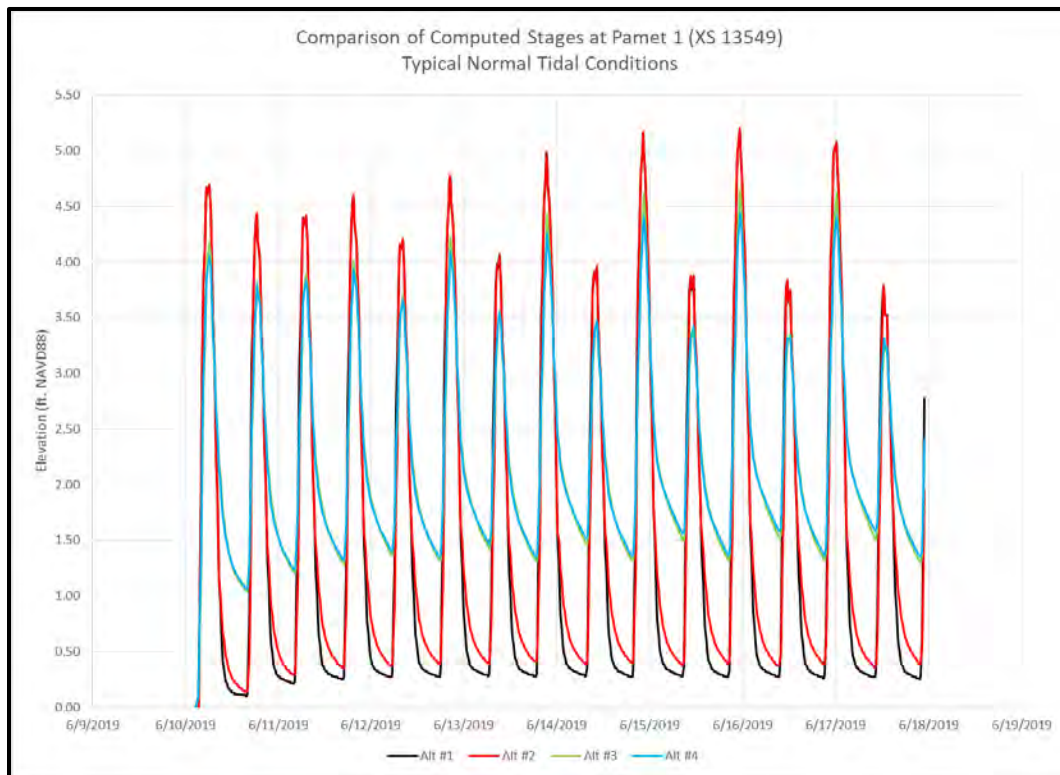


Figure E-37. Computed Hydrographs for Normal Tidal Conditions at Pamet 1 for All Alternatives

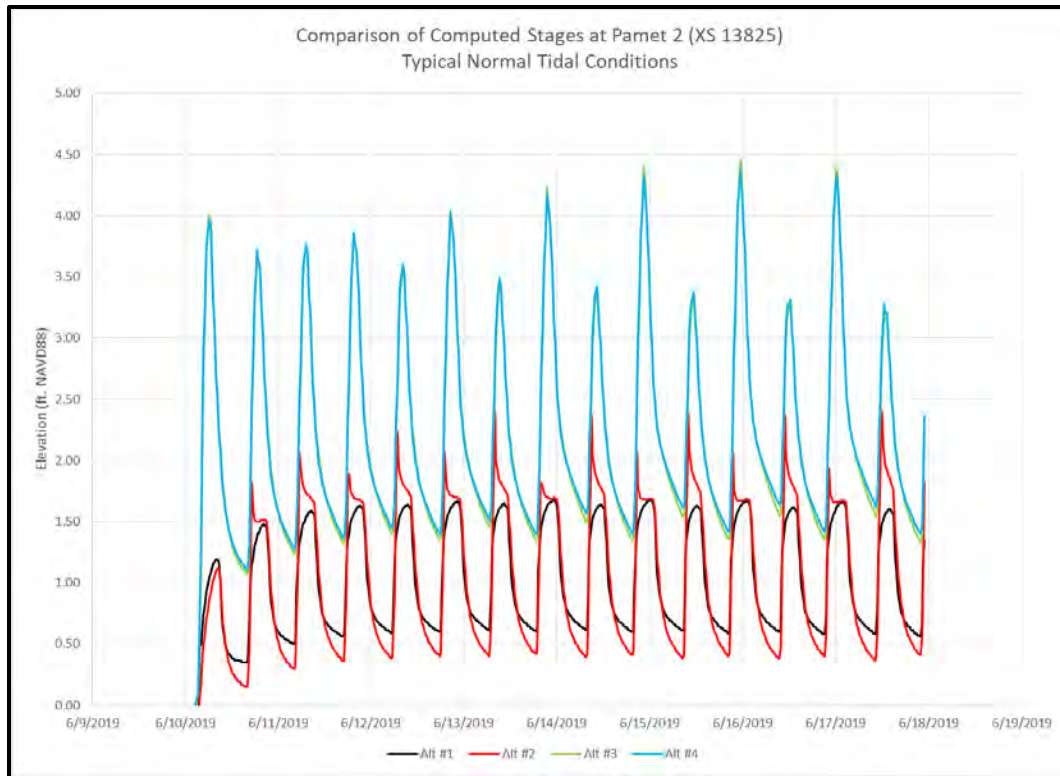


Figure E-38. Computed Hydrographs for Normal Tidal Conditions at Pamet 2 for All Alternatives

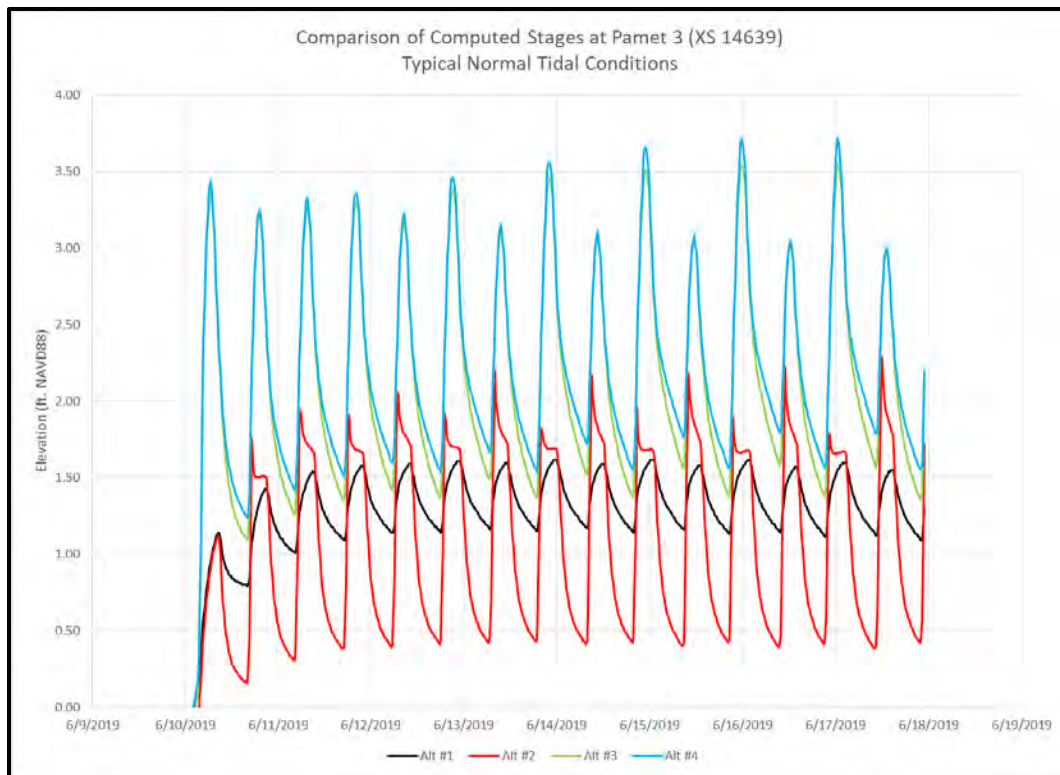


Figure E-39. Computed Hydrographs for Normal Tidal Conditions at Pamet 3 for All Alternatives



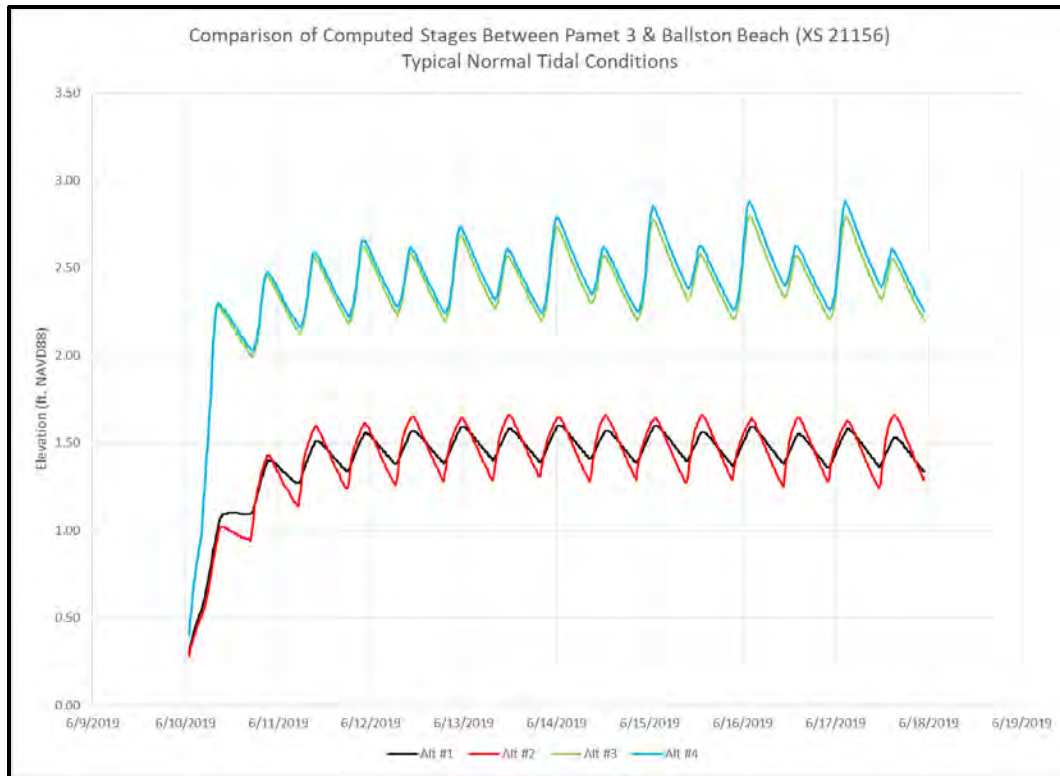


Figure E-40. Computed Hydrographs for Normal Tidal Conditions at XS 21156 for All Alternatives

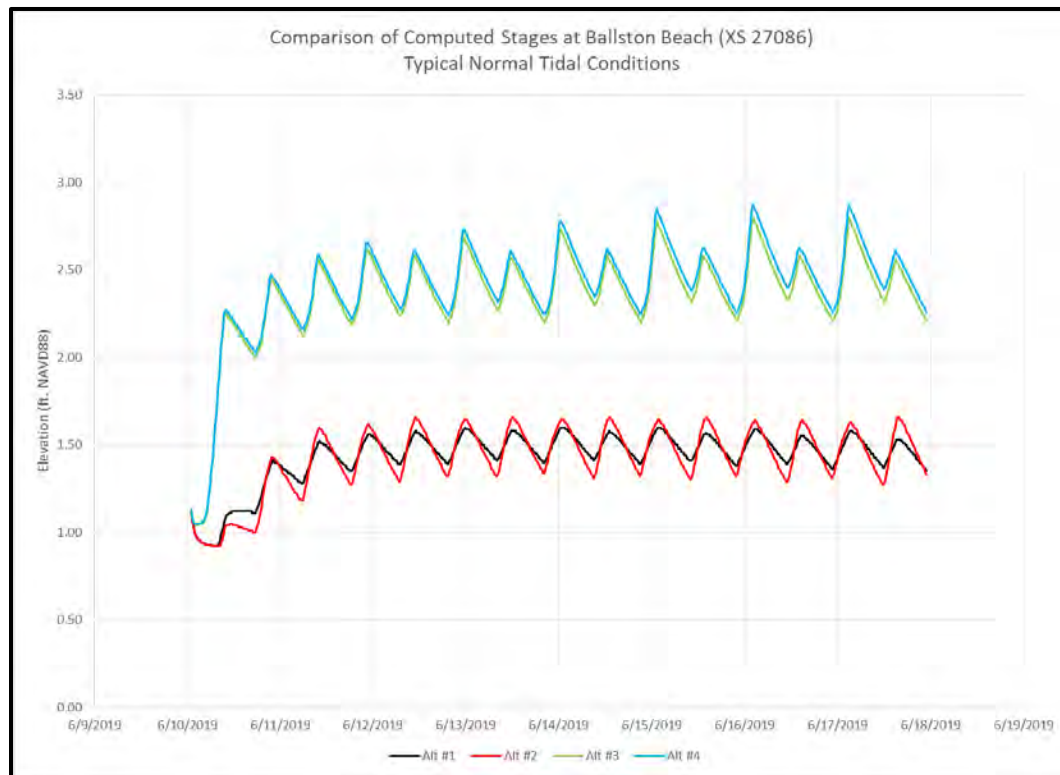


Figure E-41. Computed Hydrographs for Normal Tidal Conditions at Ballston Beach for All Alternatives

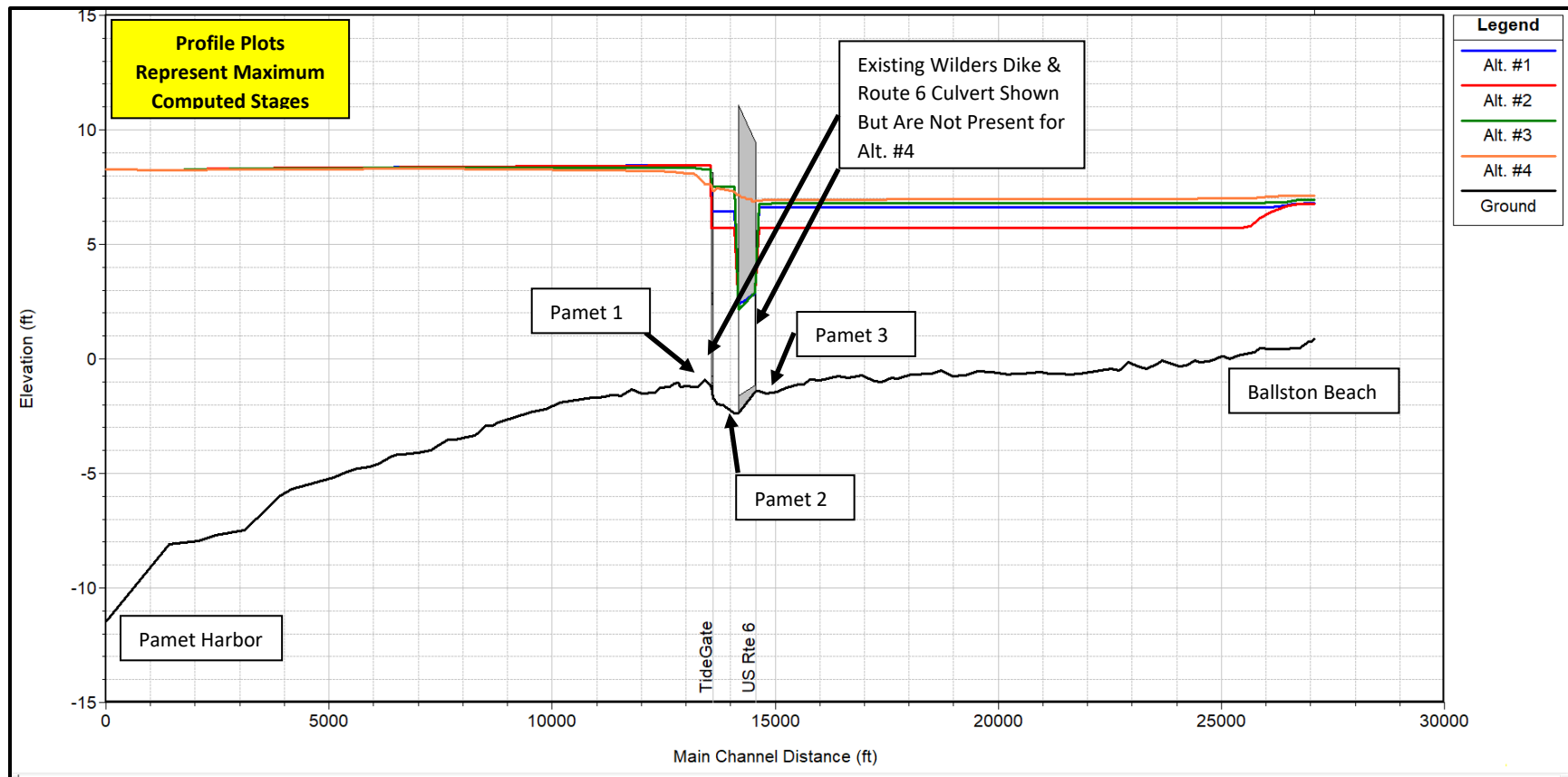


Figure E-42. Computed Pamet River Profile Plot for March 2018 Event for All Alternatives

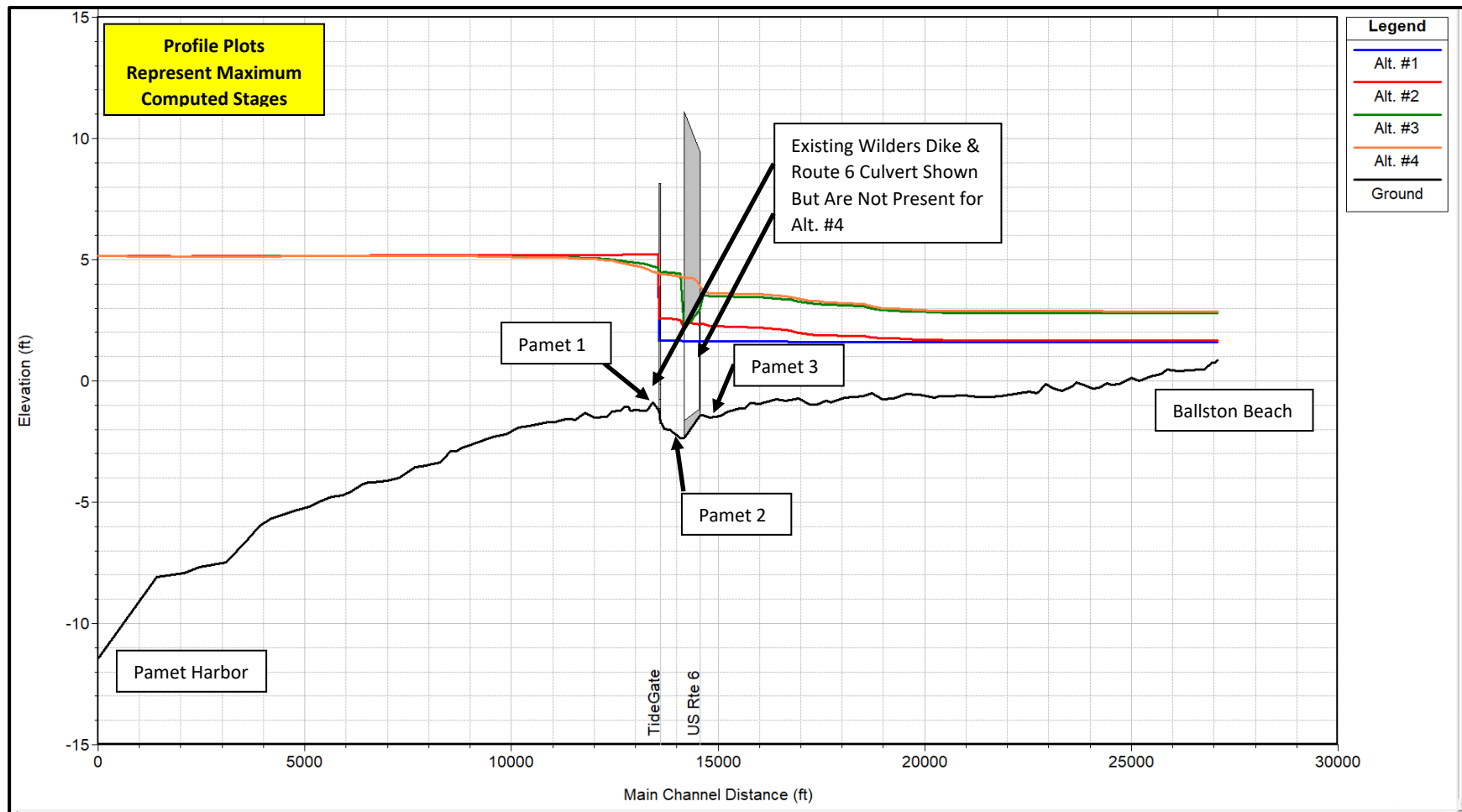


Figure E-43. Computed Pamet River Profile Plot Under Normal Tidal Conditions for All Alternatives



**PAMET RIVER INVESTIGATION**

**Truro, Massachusetts**

**ATTACHMENT F**  
**2018 USGS TIME-DOMAIN**  
**ELECTROMAGNETIC METHOD (TDEM)**  
**FIELD DATA REPORT**

**C.A.P. SECTION 22**

**PLANNING ASSISTANCE TO STATES**

**NOVEMBER, 2019**

## Technical Memorandum

**Date:** 02 July 2019      **By:** C. Kilbridge, USACE-NAE

**Subject:** USGS Time-Domain Electromagnetic Method (TDEM)  
Summary of Field Activities 09 May 2018  
Pamet River Basin, Truro, MA

### GENERAL:

1. Scientists from the Hydrogeophysics Branch, USGS, Storrs, Connecticut, performed a surface geophysical survey at the Pamet River salt marsh restoration project site on Wednesday 09 May 2018. In attendance and/or providing coordination were the following personnel:
  - John Lane, Chief, Hydrogeophysics Branch, USGS
  - Eric White, Geophysicist, USGS
  - Courtney Scruggs, USGS
  - Chris Kilbridge, USACE-NAE
  - Jarrod Cabral, DPW
  - Mark Adams, Cape Cod National Seashore

The geophysical survey mobilization location was south of the Pamet River on Collins Road near existing monitoring well C5 shown on Figure 1. The USGS performed the geophysical survey over two routes, A and J, shown on Figure 2.

### METHODS:

1. The surface-geophysical method performed is called the time-domain electromagnetic method (TDEM). USGS proposed to perform a TDEM geophysical survey as a pilot or prove-out field data collection effort at the Pamet site based on previous discussions with USACE regarding the feasibility for USGS to perform geophysical surveys that can measure the depth to the fresh-saltwater interface. USGS was testing new TDEM equipment that can be towed behind an ATV that was developed by the Department of Geoscience, Aarhus University, Denmark. This technique of applying the TDEM method contrasts to the traditional method of performing stationary vertical soundings.

The TDEM survey is an Electromagnetic Method (EM). EM methods measure variations in electrical resistivity of the bulk subsurface material, whether it is dry unsaturated overburden or saturated glacial deposits. The TDEM method makes use of a direct current (DC) transmitted into the transmitter loop lying on the ground. The current creates a primary, stationary magnetic field. The DC is switched off, which induces an eddy current system in the ground. Because of the ohmic resistance of the subsurface, the current system will decay and further induce a secondary magnetic field that is measured in an induction coil (the receiver coil). The decay rate of the electromagnetic field depends on the resistivity distribution of the subsurface, and is an indication of the electrical resistivity of the subsurface geologic and hydrogeologic properties.

The variations in the electrical resistivity of the subsurface can be related to variations in the physical and chemical properties of soil, rock, and pore fluids (USGS, 2007). In general, once

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background geology and hydrogeology are taken into account, data interpretation of the resistivity data must be interpreted to discern low resistivity salt water zones from high resistivity fresh water zones, and identify the fresh-salt water interface. The pore fluid in the glacial outwash sediment that comprises the overburden underlying Truro, can be a mixture of freshwater and saltwater with varying proportion in closer proximity to the fresh-saltwater interface, and will be embedded in the pores of the host geologic sediment, which will have its own different resistivity corresponding to the mineral composition.

The variation of electrical resistivity of the subsurface can be interpreted to determine the type of geologic material (ie: sand & gravel vs clay), and fresh vs salt water. At shallow depths where typically high resistivity freshwater is found, distinctions can be seen between resistive freshwater and less resistive lithology such as clay layers in the sediment. Below the fresh-salt water interface, highly saline aquifers are difficult to distinguish from intervening clays. In general, the salinity of groundwater is usually the predominant influence on TDEM resistivity measurements (Trabelsi et al, 2013).

2. This new towed method of TDEM survey contrasts with a traditional method in use for over 20 years, of performing TDEM as stationary point soundings, where TDEM Equipment would be set over one x,y location at a time, making acquisition of data to develop a profile cross-section over a transect very time consuming. The towed TDEM equipment tested and used for the Pamet project results in rapid acquisition of data that expands the amount of area that can be surveyed. In the spring 2018, USGS selected several sites on the Cape with different locations relative to the coastline and depth to the water table in order to evaluate the effectiveness of the towed TDEM equipment to rapidly collect data over a long transect to develop a profile of the fresh-salt water interface.

The equipment used by the USGS for the Pamet TDEM geophysical survey is shown on Figures 3 to 5.

3. The feature of greatest interest to USACE was the determination of the depth of the fresh-saltwater interface within the groundwater model area. Since no existing monitoring wells that have been found are deep enough to penetrate the fresh-saltwater interface, having actual data for the depth (or elevation) of this interface can be used to check model calibration and improve predictions made by the model regarding the potential for impacts to existing drinking wells and septic systems due to restoring tidal flow in the upper Pamet River. The USGS performed almost 3 miles of survey along existing fire road paths on routes designated as A and J/K (Figure 2) that had been discussed and field checked for accessibility by the National Park Service.
4. The procedure involves using an ATV to tow a transmitter loop (white plastic square in pictures) and smaller receiver (small yellow box at end of towed line). An electrical current is passed through the transmitter loop which creates a magnetic field around the loop. The magnetic field in turns creates an electrical current in the ground that penetrates at depth and causes a secondary magnetic field that produces a voltage that is detected by the receiver. The strength of the voltage is related to how easily geological material conducts electrical current (ie: freshwater filled overburden is less electrically conductive than salt water that has a higher dissolved ion concentration).



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5. The TDEM method takes vertical soundings of electrical conductivity to a depth of about 300 feet, approximately every 10 feet along a horizontal profile as the equipment is being towed. These vertical soundings can be thought of as virtual 1D wells of data representing the electrical conductivity at depth. The geophysical software can interpret the results to create a profile or cross-section that represents lateral and vertical variations of electrical conductivity. The TDEM equipment that the USGS tested at Pamet had a maximum depth limit of about 230 feet (70 meters) to see the fresh-salt water interface.

### **RESULTS:**

1. USGS performed two transects along the following paths depicted on Figure 2:
  - a. Route A – Beginning on Collins Road near observation well C5 (well log attached), proceeding on a woodland unpaved road in an easterly direction to the sand bluff overlooking the beach south of Ballston Beach. The transect was about 1 mile long.
  - b. Route J and K – Beginning on Collings road and proceeding west toward the town landfill, then proceeding north along Route K toward South Pamet Road and existing Route K near House #41 South Pamet Road, proceeding on South Pamet Road then south on Collins Road to the start location. The transect loop was about 2 miles long.

The completed transects are depicted on Figures 6 through 8.

2. The TDEM survey was unsuccessful in being able to detect the fresh-saltwater interface in groundwater due to several factors. These factors were anticipated in the selection by USGS of the various sites on the Cape where this equipment was pilot tested, but it was hoped that the transect routes selected may afford seeing the fresh-salt water interface in certain portions of the routes:
  - a. Coupling to infrastructure: The primary interference by infrastructure is with conductive utilities such as powerlines and buried pipes. USGS has found that a minimum setback of at least 150 feet is required to avoid electrical interference between the TDEM equipment and utilities. Along Route J/K there was indication of coupling or interference to infrastructure that prevented getting a clear signal on the depth to the fresh-salt water interface.
  - b. Resistive Lithology: A thick high resistivity layer of unsaturated and saturated fresh-water sediments above the fresh-saltwater interface can exceed the depth of penetration of the TDEM equipment. Along Route A to the dune bluff, the data did not show any indication of salt water- it was too deep to see.
3. The degree of impact of infrastructure and thick high resistivity unsaturated/fresh-water saturated zones was greater than the USGS anticipated but was why the USGS wanted to test the towed TDEM technique under a variety of settings where obtaining this type of information would be beneficial to end users.



## Technical Memorandum

### REFERENCES:

Barlow, Paul M., 2003. *Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast*. US Department of the Interior, USGS Circular 1262.

Izuka, Scot K. and Gingerich, Stephen B., 1998. Estimation of the Depth to the Fresh-Water/Salt-Water Interface from Vertical Head Gradients in Wells in Coastal and Island Aquifers. *Hydrogeology Journal* (1998) 6:365-373.

Masterson, John P. and Walter, Donald A., 2009. *Hydrogeology and Groundwater Resources of the Coastal Aquifers of Southeastern Massachusetts*. US Department of the Interior, USGS Circular 1338.

Todd, David K., 1959. *Ground Water Hydrology*. John Wiley & Sons, Inc.

Todd, David K., 1980. *Ground Water Hydrology*. John Wiley & Sons, Inc.

Trabelsi, Fatma, Mammou, Ben Mammou, Abdalla, Tarhouni, Jamila, Piga, Carlo and Ranieri, Gaetano. 2012. Delineation of Saltwater Intrusion Zones Using The Time Domain Electromagnetic Method: the Nabeul-Hammamet Coastal Aquifer Case Study (NE Tunisia). *Hydrogeological Processes*. Published Online 23 May 2012.

## FIGURES





Pamet Observation Wells 12.1.2016

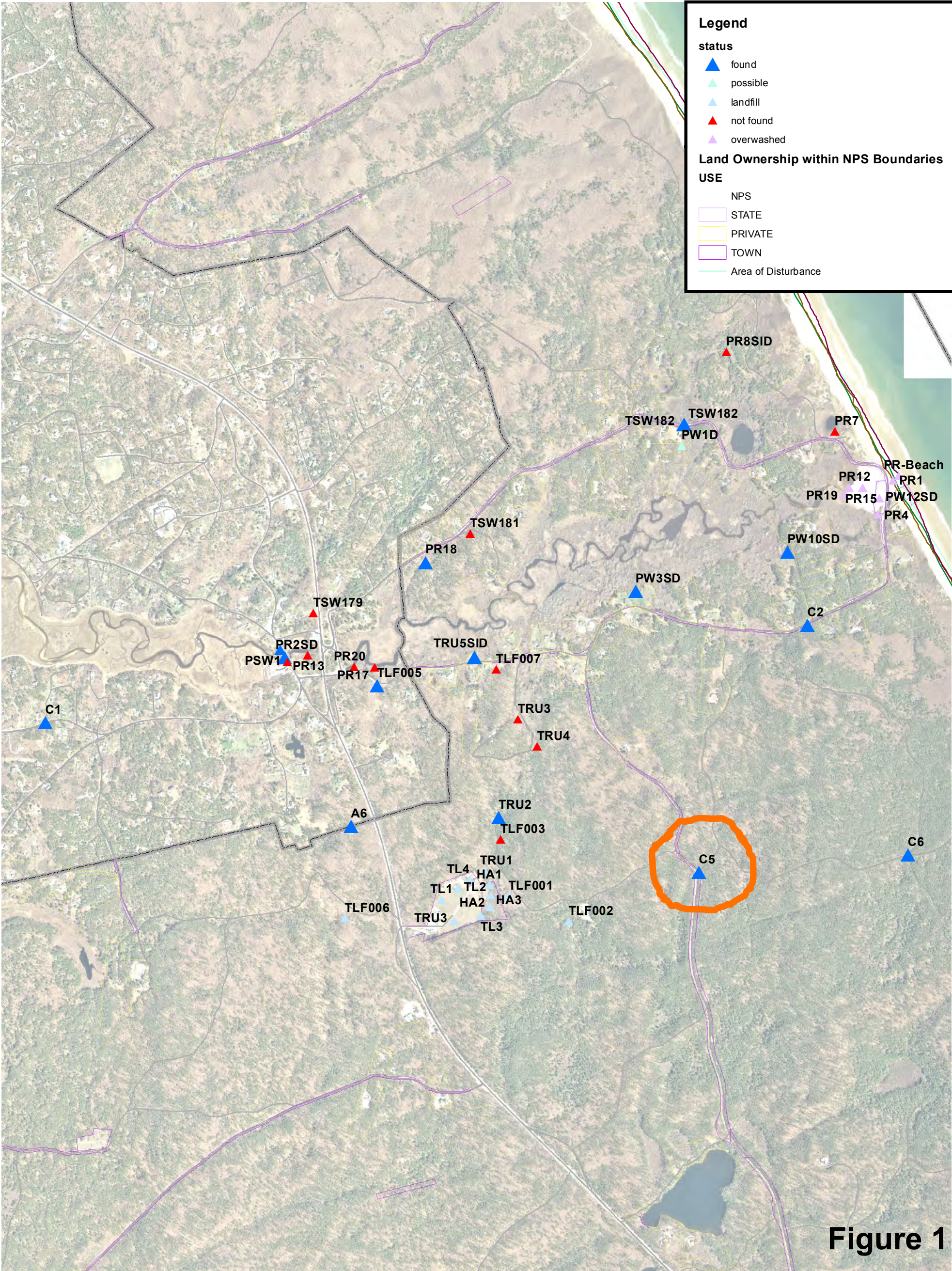
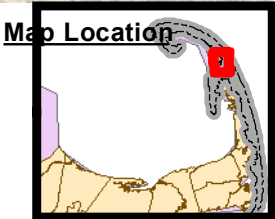


Figure 1



Coordinate System: NAD 1983 UTM Zone 19N  
Projection: Transverse Mercator  
Datum: North American 1983  
False Easting: 500,000.0000  
False Northing: 0.0000  
Central Meridian: -69.0000  
Scale Factor: 0.9996  
Latitude Of Origin: 0.0000  
Units: Meter

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0 0.125 0.25 0.5 0.75 1 Miles



FIGURE 2

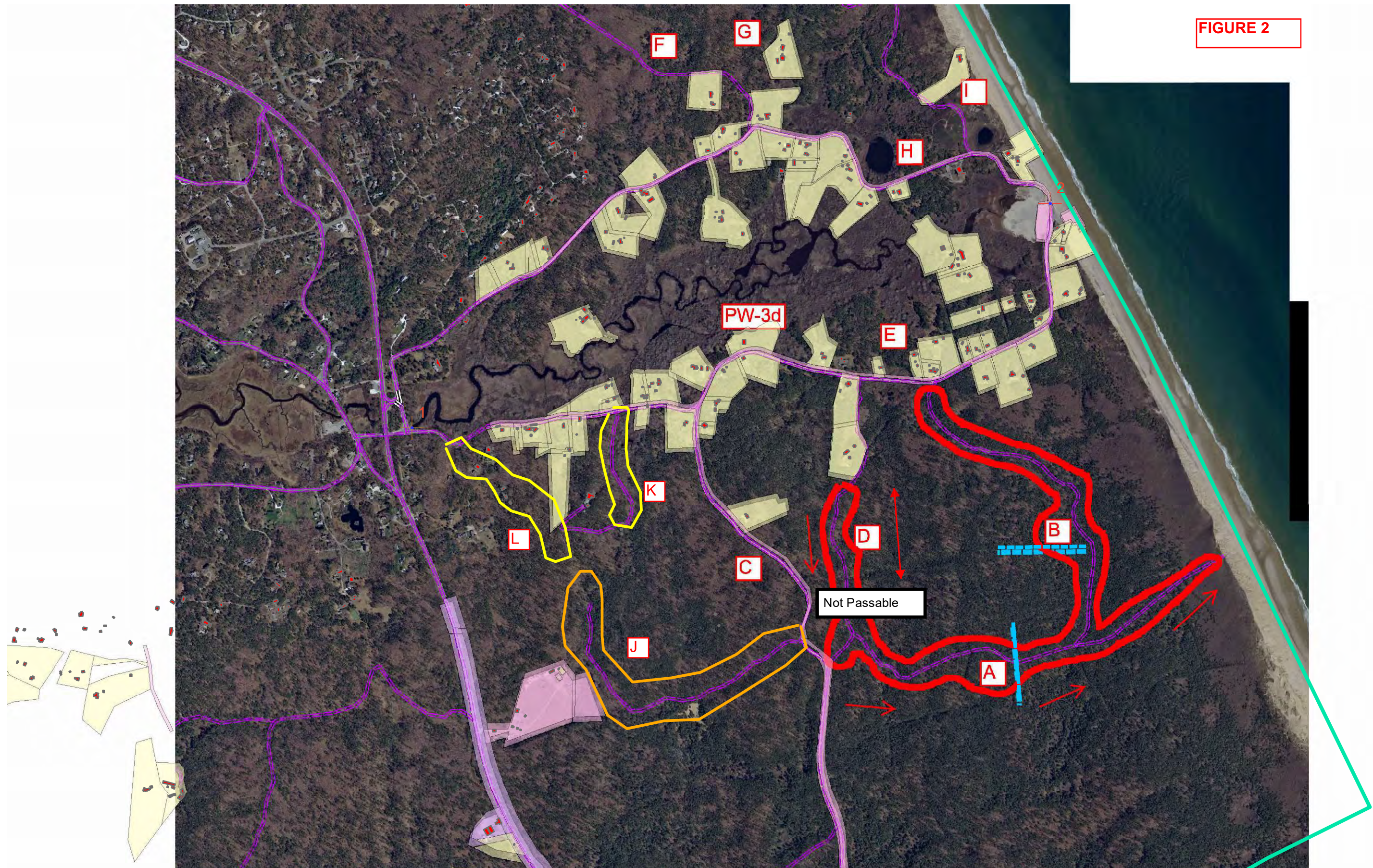




Figure 3 - Pamet River, Truro: Start of Route A at Collins Road Near Well C5

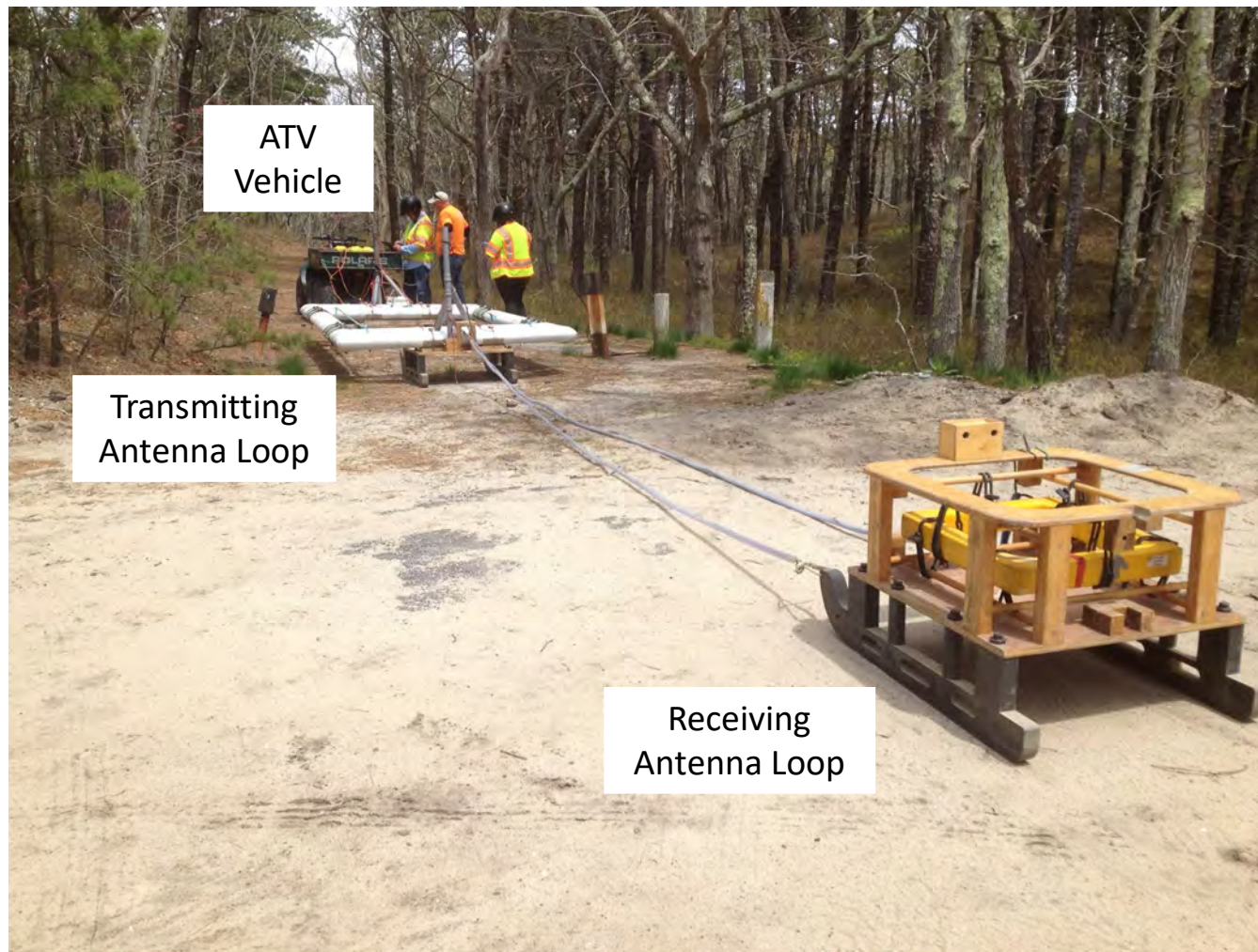




Figure 4 - Pamet River, Truro: TDEM Equipment East End of Route A

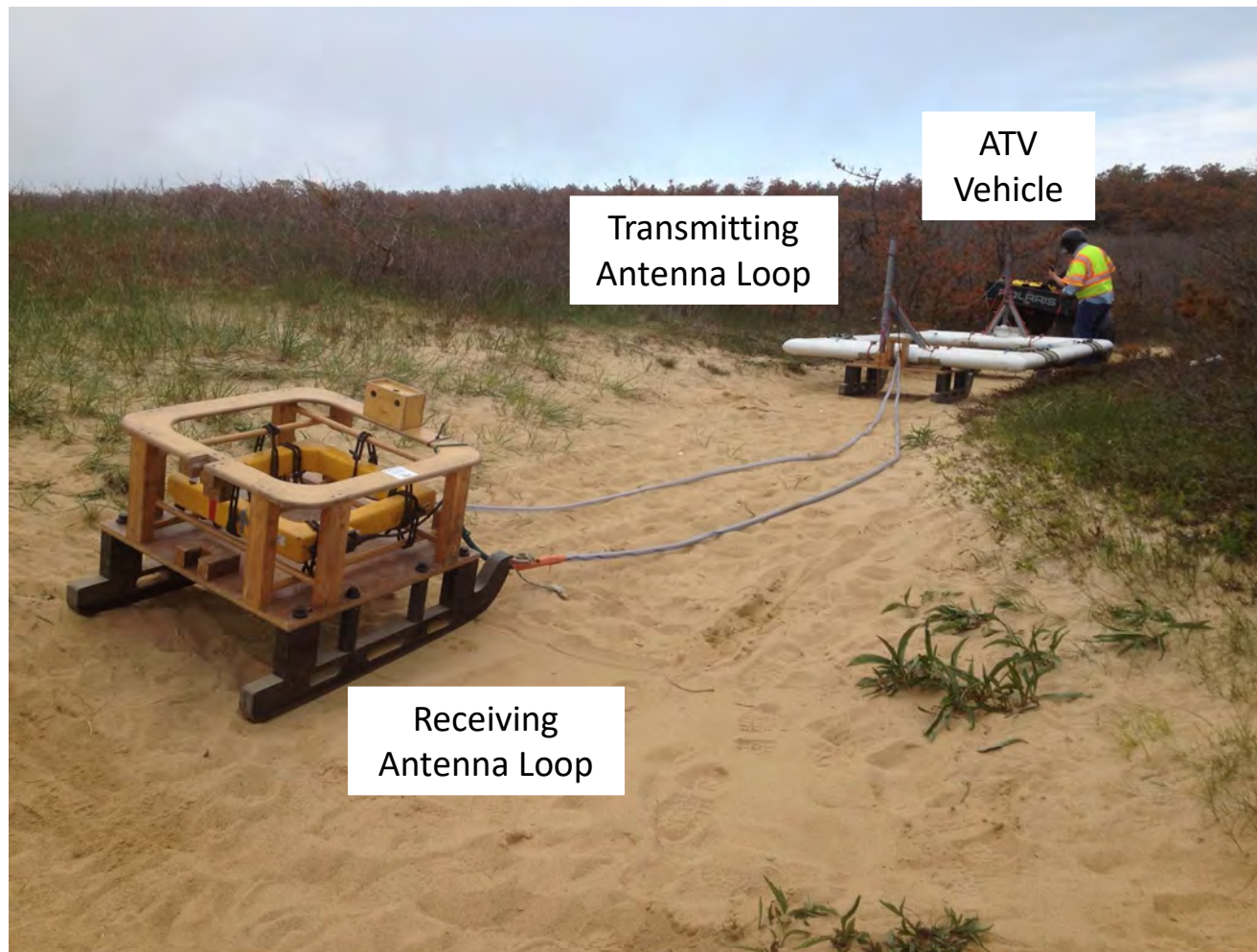


Figure 5 – TDEM Receiver Antenna, East End of Route A





Figure 6 - Pamet River, Truro: Completed TDEM Routes





Figure 7 - Collins Road and Dune Profile (USGS Area 3)

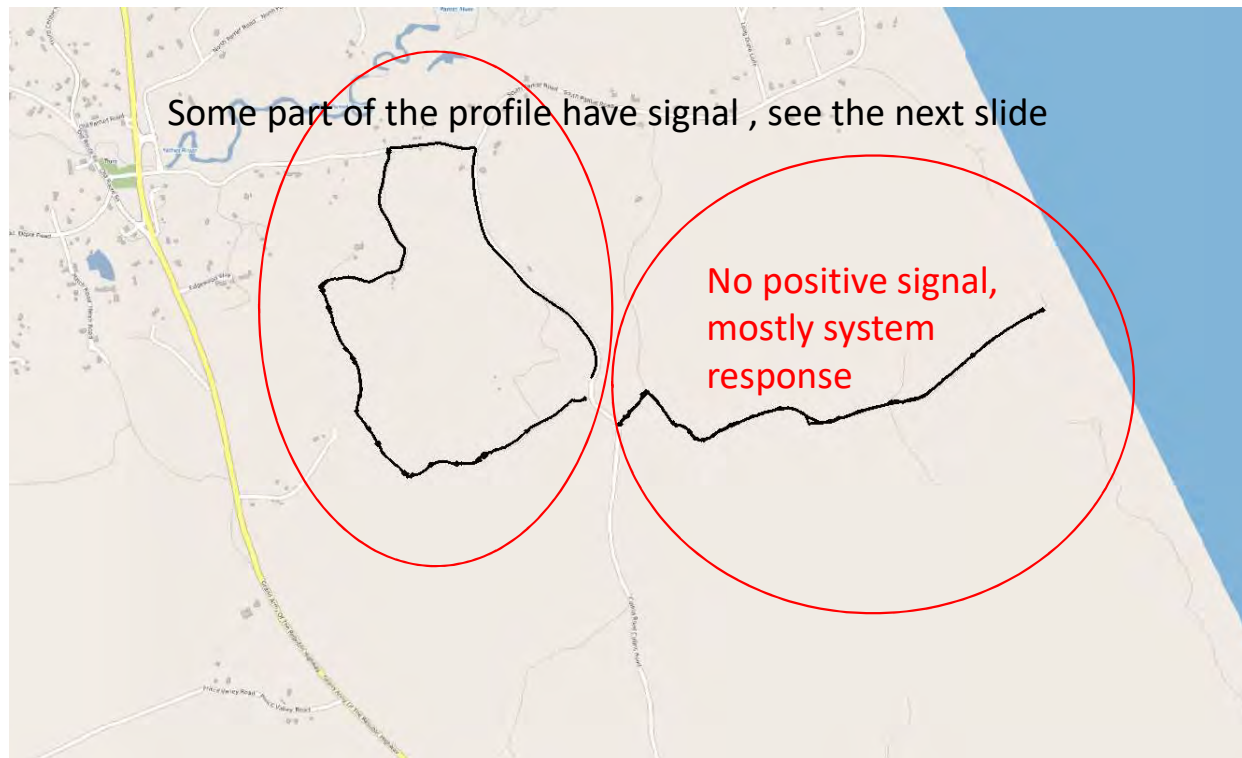


Figure 8 – Collins Road and Dune Profile (USGS Area 3)

This section has some interesting results , Not sure if we can trust it, could be galvanic coupling

