



CLIMATE CHANGE PREPAREDNESS & RESILIENCE

APPENDIX A:

EVALUATION OF UPSTREAM FLUX IN THE MYSTIC RIVER AND ALEWIFE BROOK

City of Cambridge

11.15.2017

DRAFT



Acknowledgments

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<http://www.cambridgema.gov/CDD/Projects/Climate/climatechangeresilienceandadaptation.aspx>



Evaluation of Upstream Flux in the Mystic River and Alewife Brook

Introduction

The potential for flanking and overtopping of the Amelia Earhart (AE) Dam under projected climate change conditions has serious implications for the communities along the Mystic River. Future storm surge events, coupled with sea level rise, that compromise the AE dam result in increased water levels in the Mystic River and probable inundation of surrounding communities. Results from the Boston Harbor Flood Risk Model (BH-FRM) indicate that extreme storm surge events under 2070 climate projections produce overland flooding extending upstream to Alewife Brook and Fresh Pond in Cambridge, MA (Bosma et al., 2015). These storm surge events reverse the flow of water in the Mystic River and deliver additional volumes of water upstream of the AE Dam. In addition, the freshwater flow normally advancing downstream towards the AE Dam is backed up in the upper portions of the system due to the elevated tailwater conditions in Boston Harbor. This additional water driven upstream not only causes flooding, especially in the lower elevation areas surrounding Alewife Brook in Cambridge, but also has the potential to introduce salt laden ocean water to the Fresh Pond Reservoir in Cambridge, MA. The Fresh Pond Reservoir is a vital part of the drinking water supply system for the City of Cambridge and potential introduction of salt water into the Fresh Pond Reservoir represents a significant risk to the entire City of Cambridge. Therefore, the City of Cambridge desired an increased understanding of the volume and concentration of salt water propagating upstream into the Fresh Pond Reservoir.

The BH-FRM, a hydrodynamic model of the Boston Harbor area, was primarily developed to probabilistically evaluate inundation throughout the region. While the model comprehensively simulates the physical processes associated with coastal storm events (e.g., storm surge, waves, winds, sea level rise, etc.), the model does not currently include salinity transport, and the mixing of fresh and saline water is not considered. Ocean water and river water are treated the same. However, as a first order approximation of the transport of salt water upstream in the Mystic River and Alewife Brook, flow reversals in the river system were evaluated in the BH-FRM for a representative 100-year return period storm surge water level condition in 2070. In addition, a 10-year return period storm surge water level condition was also evaluated. These storm surge conditions represent typical nor'easter type storm events, which typically consist of a longer duration than hurricane events. For these particular storm events, approximately a 36-hour nor'easter event was simulated. These results for the upstream intrusion of salt water are

shown for a period of the nor'easter event during the portion of the storm event that overtops and flanks the AE Dam (during a high tide cycle). The storm surge conditions were also combined with a 100-year, 24-hour precipitation condition in 2070 (simulated as a constant discharge). Evaluation of the flow reversal (as a surrogate for salinity) will indicate the progression of ocean based water upstream, including the volume of water transported into the Fresh Pond system and the duration of time water is directed upstream. However, while there is a clear indication that ocean based, salt-laden water will propagate upstream to Fresh Pond; the salinity concentration of this water is unknown. In this analysis it is assumed that if water is directed upstream it would be primarily salt laden.

First Order Assessment of Salinity Penetration

Figure 1 presents the time series of water surface elevation just downstream of the AE Dam used to represent the 100-yr storm surge event. The time series shows the area surrounding the peak of the surge where the AE dam is overtopped/flanked. The zero time on Figure 1 corresponds to the approximate time the AE dam is overtopped/flanked. Figures 2 through 8 present the progression of the storm surge based flood waters propagating up the Mystic River system. Figure 2 shows the area near the AE dam shortly following the flanking and overtopping during a 2070 storm event (approximately a 100-yr return period level). This example also includes a 2070 100-yr, 24-hr discharge in the Mystic River. The AE Dam pumps remain active, as needed, throughout the simulations. The colors in the figure indicate the water surface elevation (in meters NAVD88) and the black arrows indicate direction of flow (also shown by the red arrows).

Figure 2 illustrates the initial stages of upstream transport of water in the Mystic River. While there is a higher water surface elevation downstream of the AE Dam (as illustrated by the blue color) than in the Mystic River, the AE dam is being flanked on both sides and overtopped. All 3 pumps are actively pumping at the dam; however they are unable to handle the overall volume of water entering the area. The flow in the river system begins to transport water upstream, which is assumed to include saline water. It is likely that the salt laden ocean water is transported along the bottom of the river, while fresher water delivered from the precipitation based discharge is on the surface. In order to quantify this process further a three dimensional model would be required. The confluence of precipitation based discharge and upstream directed surge water occurs at the locations shown in the dashed ovals. It is at these locations that a convergence of flux occurs.

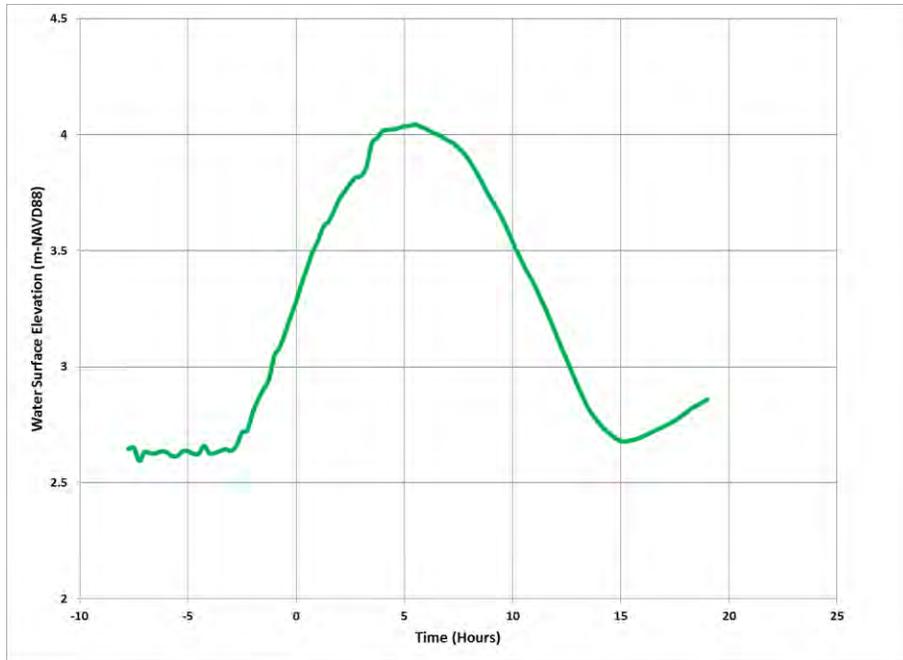


Figure 1: Storm surge hydrograph of water surface elevation downstream of the AE Dam during the simulated 100-year return period water level event.

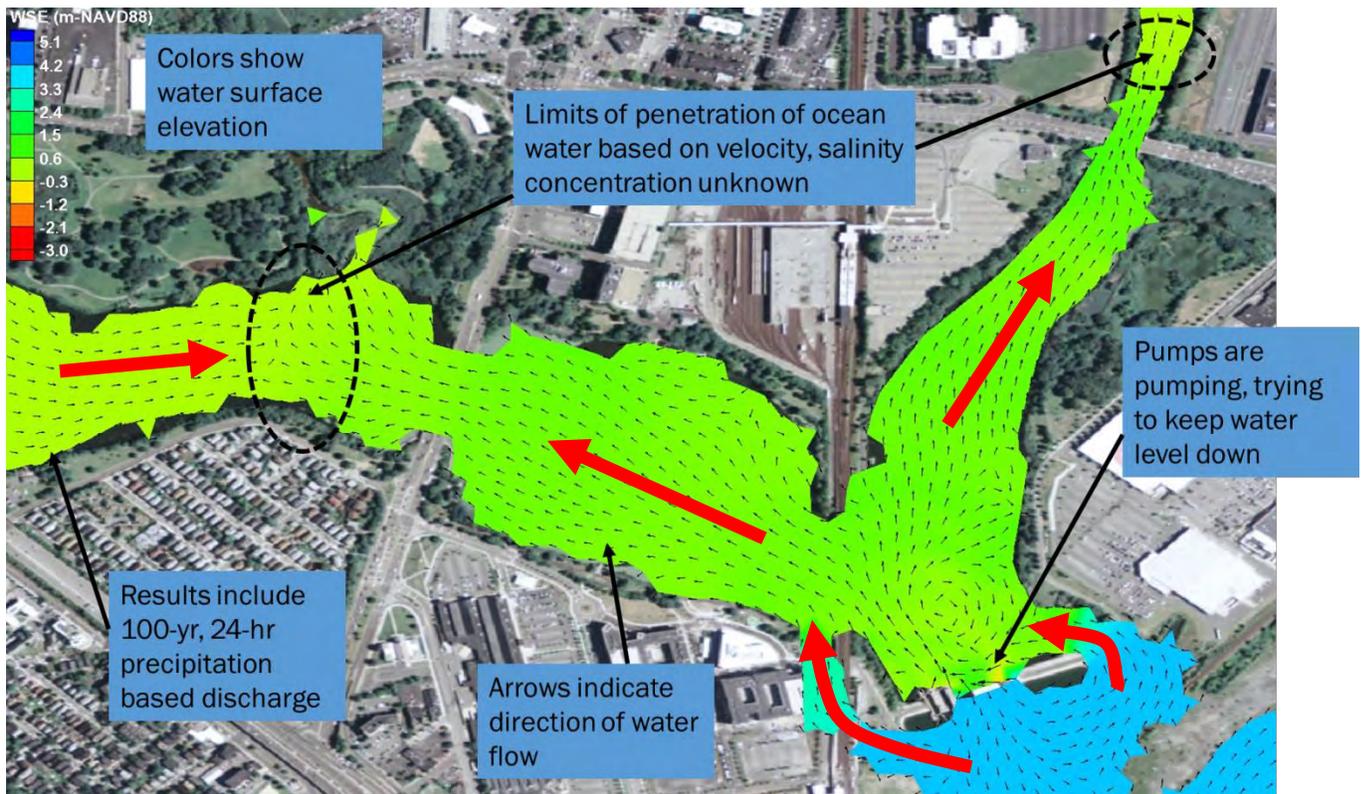


Figure 2: Full breaching of the AE Dam in 2070 during a 100-year return period water level event. While this model time step does not represent the initial dam flanking and/or overtopping, at this time ocean based water significantly begins to propagate upstream.

Approximately 30 minutes later in the storm progression, the upstream based flow advances farther up the Mystic River and a flow convergence occurs at the I-93 crossing of the Mystic River (Figure 3). Pumps at the AE dam are still working at full capacity, but have become completely overwhelmed by the ocean based volumetric flux into the system. Minor overbank flooding also starts to occur on the north bank of the Mystic River as the water surface elevations in the river increase. The inset on Figure 3 shows the storm surge hydrograph downstream of the AE dam with the red bar indicating the approximate time during the event.

Approximately 2 hours after the development of upstream directed flow, the net flow is upstream throughout the entire Mystic River and Alewife Brook system (Figure 4). The increase head of water at the AE dam caused by the storm surge results in water being backed up and/or transported upstream even in the upper portions of the system. At this point in the storm progression, there is also the start of significant overbank flooding as areas begin to be inundated with storm surge.

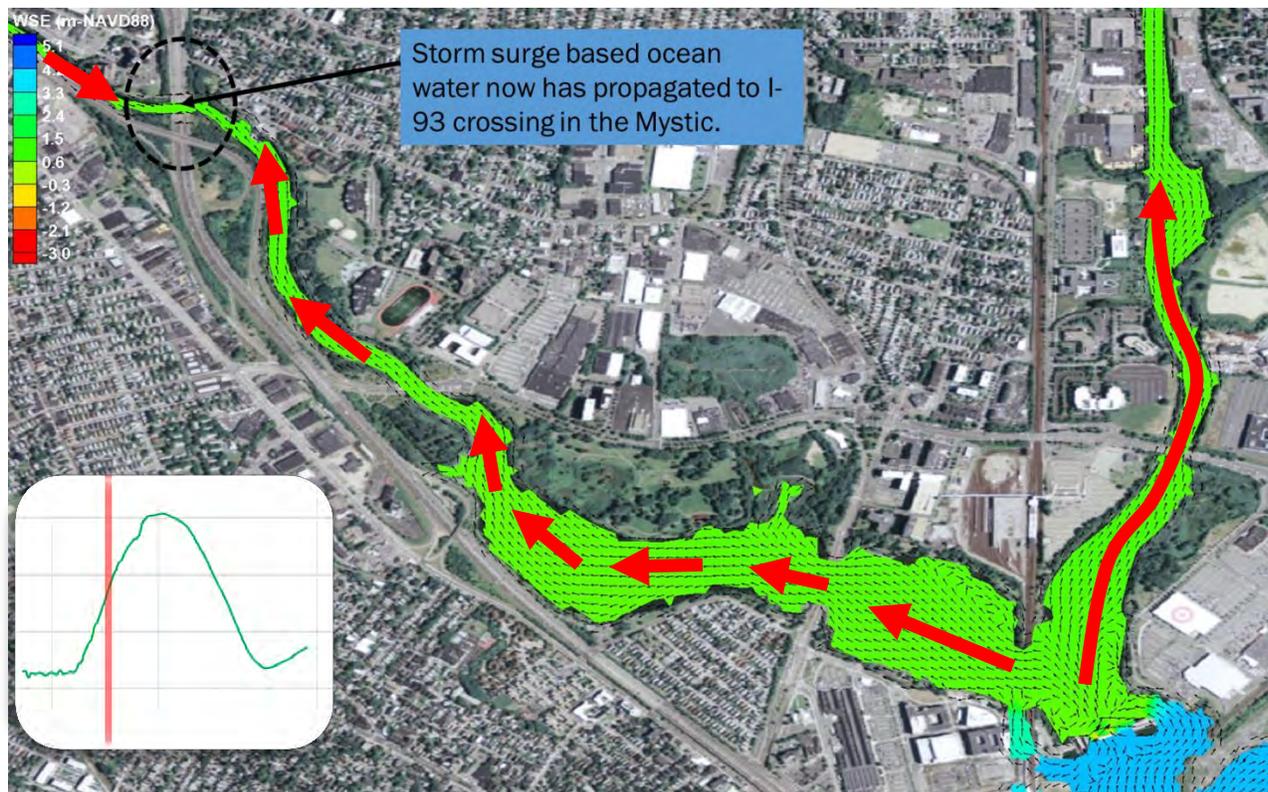


Figure 3: Approximately 15-30 minutes after Figure 2. The flow reversal point continues to move upstream as the storm continues to strengthen. At this point, the flow has reversed (is flowing upstream) at the I-93 crossing of the Mystic River.

Approximately 4 hours after the development of upstream directed flow (Figure 5), the overbank flooding has expanded significantly, including in the areas at the head of Alewife Brook. During this time of the storm passage, the volumetric upstream flux is near the peak level and water is strongly flowing upstream and flood waters are migrating towards Fresh Pond. Overland storm surge flooding reaches the Fresh Pond Reservoir approximately 8 hours after the development of upstream directed flow (Figure 6). At this time, the volumetric flux has begun to reduce in magnitude; however, there remains a strong upstream directed flow of water that expands the inundated areas in the Fresh Pond region. While flood water is now flowing into Fresh Pond, the salt concentration level is unknown.

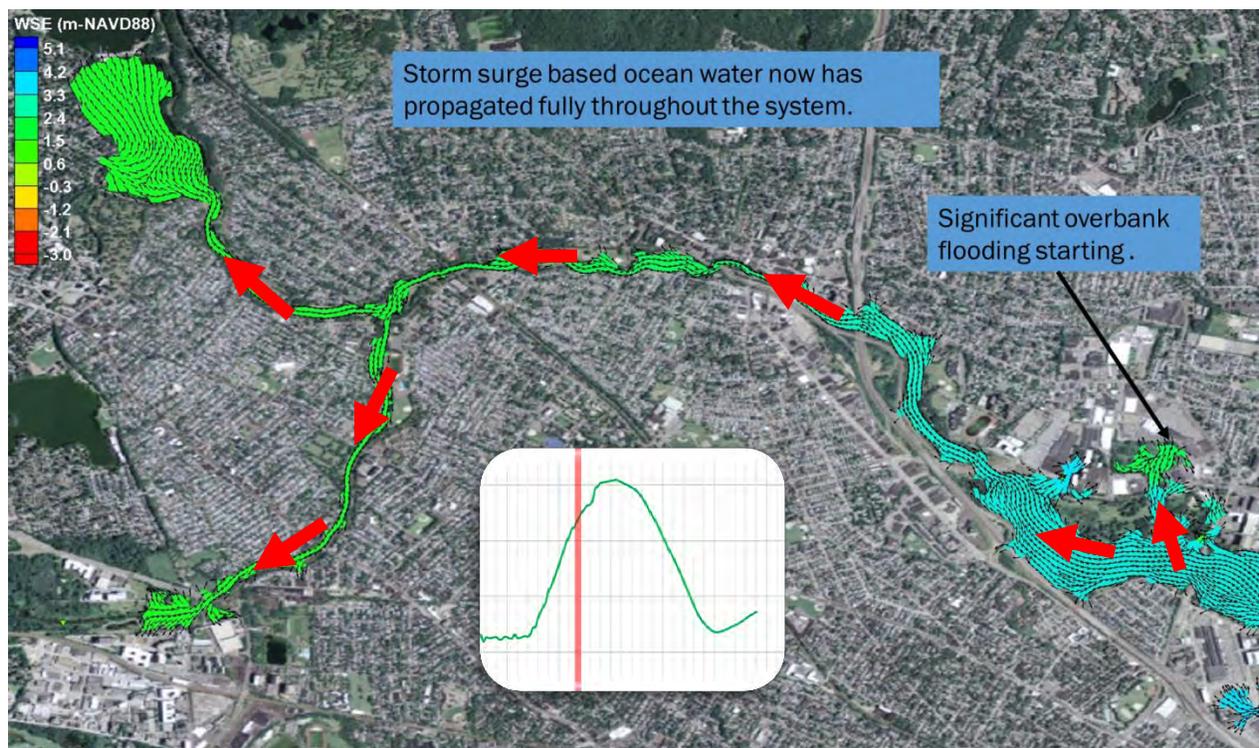


Figure 4: Approximately 2 hours after Figure 2. Flow has now reversed (flowing upstream) throughout the Mystic River and Alewife Brook. Significant overbank flooding has also started in Everett.

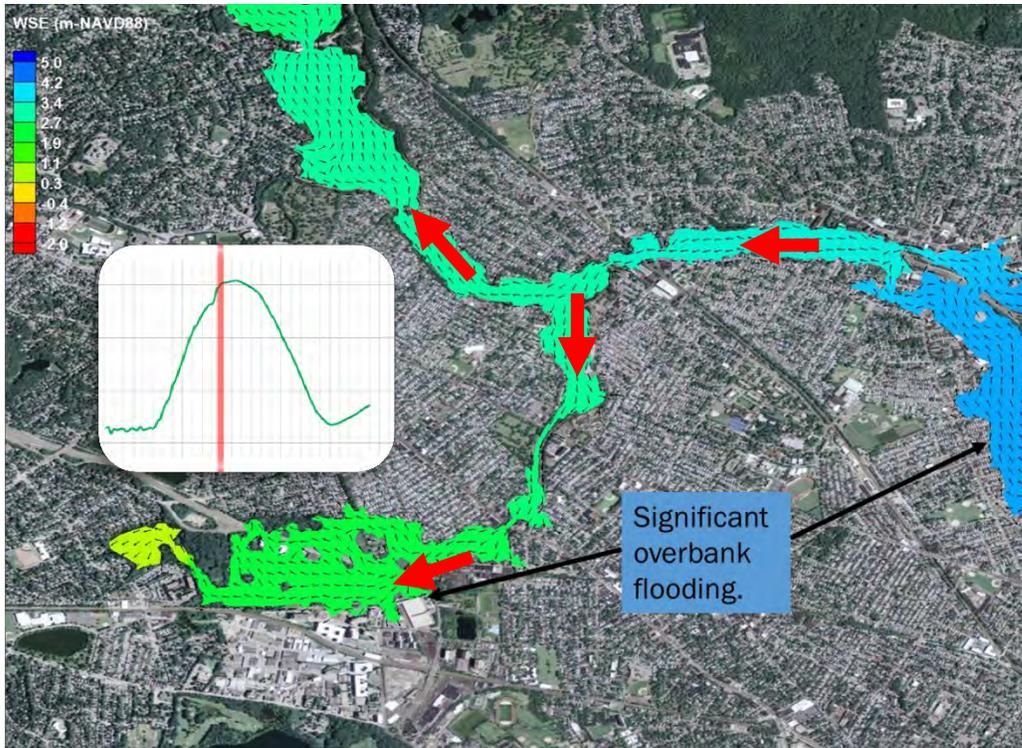


Figure 5: Approximately 4 hours after Figure 2. Significant and widespread overbank flooding has developed along both the Mystic River and along Alewife Brook. Net upstream flows are now pushing water towards Fresh Pond.

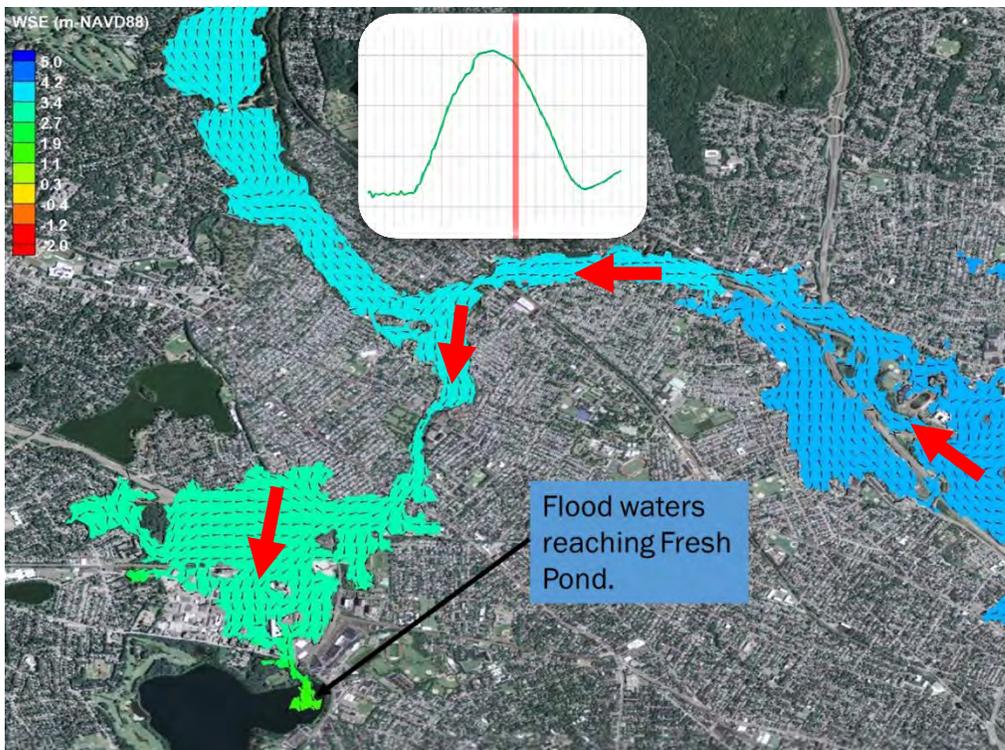


Figure 6: Approximately 8 hours after Figure 2. Flood waters have now propagated to Fresh Pond.

Figure 7 shows the approximate time of peak inundation (highest water surface elevation) for the Alewife Brook and Fresh Pond region under this particular storm event. The results indicate that the full extent of the Fresh Pond Reservoir has been inundated with flood water. At this time flood waters are receding (flowing back down the Mystic River) as the storm surge levels in Boston Harbor have lowered. There is some small residual upstream flow in Alewife Brook coming from the drainage of flood waters from the Mystic Lakes region. Some of the flood water stored in the Mystic Lakes now drains into Alewife Brook, slightly extending the flooding duration in Alewife Brook compared to the Mystic River. Approximately 17 hours after the development of upstream directed flow (Figure 8), flood waters are now fully draining throughout the entire Alewife Brook and Mystic River system. This includes drainage from all the inundated overland areas that were flooded during the event.

In addition to evaluating the overall temporal and spatial process of flooding of the Mystic River and Alewife Brook region, a time series of volumetric flux (hydrograph) extracted at the transect location shown in Figure 9 was developed for the 100-year surge with 24-hour, 100-year precipitation scenario simulated under 2070 climate conditions.

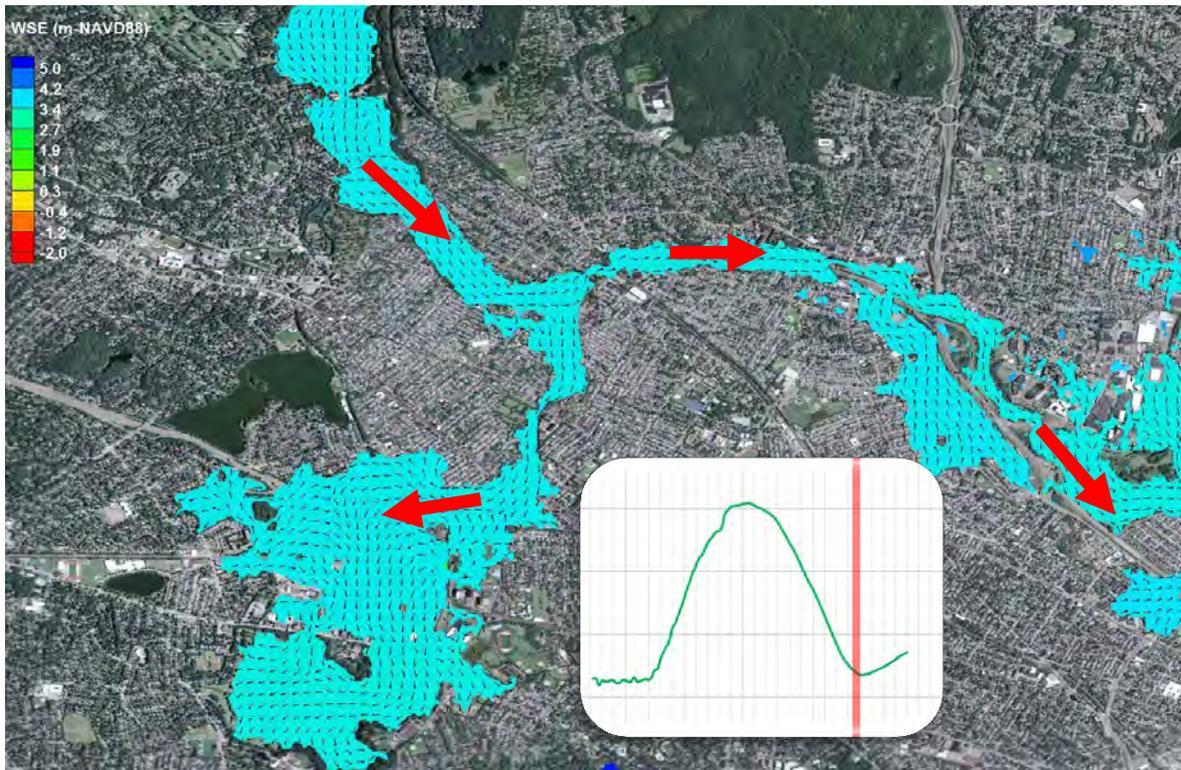


Figure 7: Approximately 15 hours after Figure 2. This is near the peak inundation (peak water surface elevation) in this Fresh Pond area. Storm surge water has started to recede in the Mystic River.

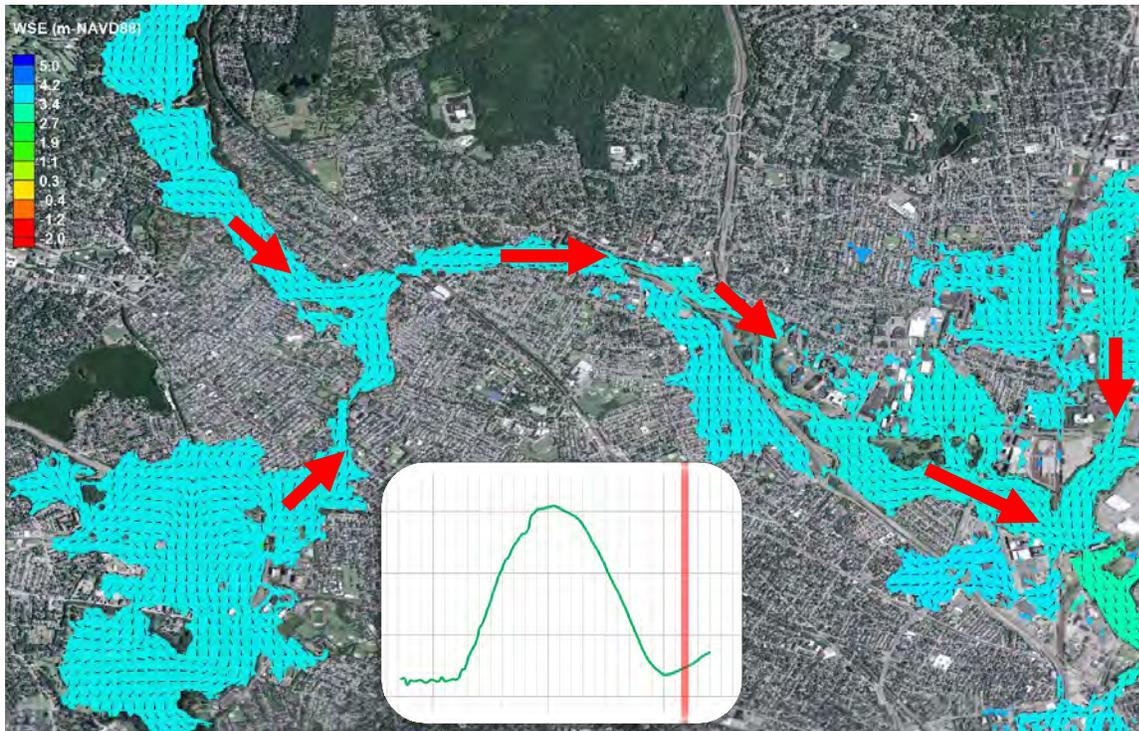


Figure 8: Approximately 17 hours after Figure 2. Water is receding throughout the region.



Figure 9: Location of transect (red line) for volumetric flux extraction.

Figure 10 shows the hydrograph of the 100-year surge combined with a 24-hour, 100-year precipitation based discharge (constant value). Results are shown for the time period when storm waters are propagating upstream. Negative values represent flux upstream (toward Fresh Pond), while positive values represent flux downstream (towards the Mystic River and the

AE Dam). The hydrograph shows that the duration of upstream flux is approximately 15-16 hours long for this typical nor'easter event in the Alewife Brook region. The maximum upstream flux during the event is approximately 2,000 cfs upstream.

The net upstream volume of water crossing the transect presented in Figure 9 is shown in Table 1. While there is little variation in the spatial and temporal propagation of storm surge water in the Mystic River and Alewife Brook when comparing the 10-year surge with the 100-year surge results, there is approximately an additional 10 million cubic feet of water that can be expected to enter the upstream Alewife Brook region under a 100-year surge scenario.

Table 1: Net upstream volume of water at the Alewife Brook transect shown in Figure 8.

Scenario	Net Volume (ft ³)
10 year surge with 100-year, 24-hour precipitation	53,528,000
100 year surge with 100-year, 24-hour precipitation	62,709,000

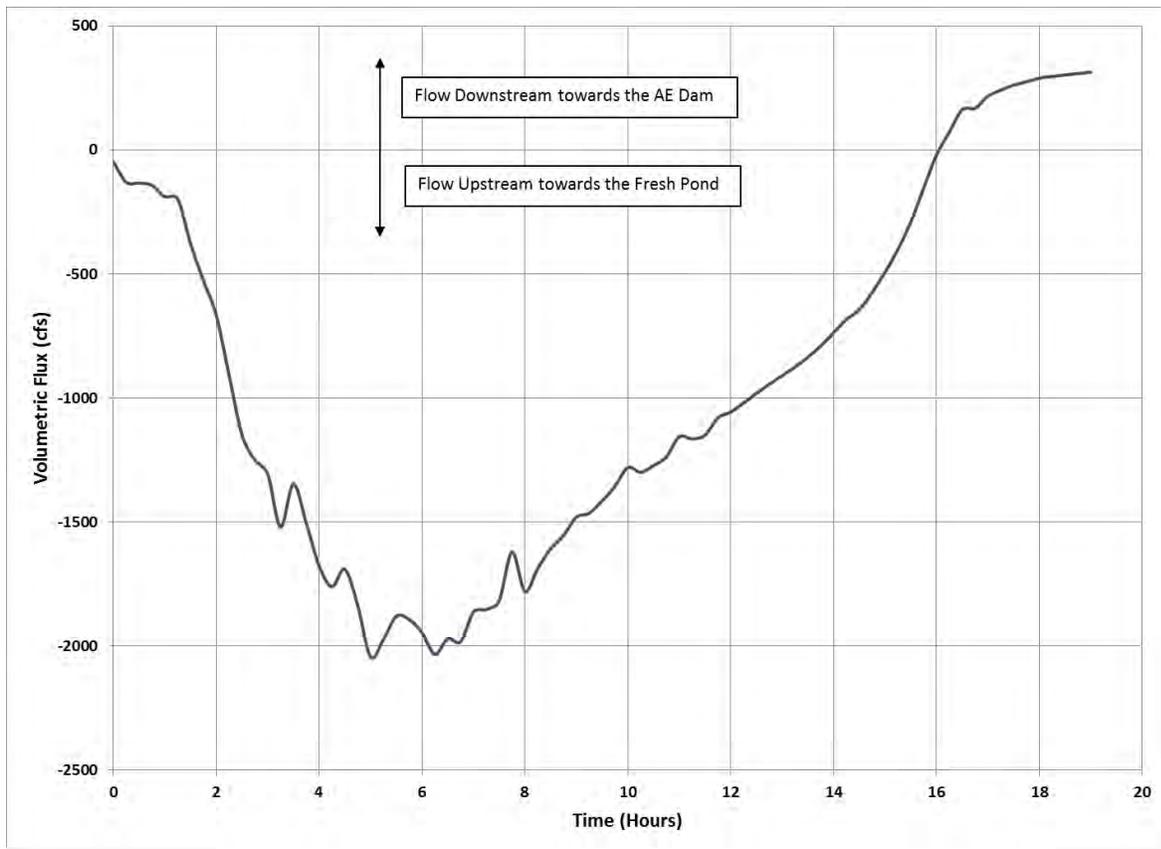


Figure 10: Hydrograph from a 2070 100-year storm surge event at transect shown in Figure 9.

Potential Next Steps

The first order assessment of salinity penetration presented above indicates that salt-laden water is likely transported into the Fresh Pond Reservoir. However, the salt concentrations are not calculated and would require a more comprehensive simulation of the salinity based transport within the Mystic River. The focus of the current application of the BH-FRM was on inundation water surface elevations, winds, velocities, etc., and not on salinity levels and mixing processes. In order to accurately simulate salt transport, a refined model of the Mystic River system, including salinity advection and diffusion would be required to estimate concentration levels. The mixing of saline water with freshwater is a dynamic process that necessitates a three-dimensional (3-D) model to capture:

- The stratification of the river system as the denser salt water penetrates below the freshwater at the surface
- Density driven circulation effects that will develop due to the mixing of the denser salt water and lighter freshwater
- The horizontal and vertical mixing processes that develop in the river system as the salt water propagates upstream

Therefore, if the City of Cambridge is interested in more accurately quantifying the salinity levels transported in the Alewife Brook and Fresh Pond region, a 3-D model of the Mystic River system could be developed as an extension of the BH-FRM model. This would include simulations of storm surge conditions that flank/overtop the AE Dam with more detailed freshwater time varying precipitation based hydrographs to more accurately define the mixing processes. The salinity model would provide salt concentrations that would be expected to infiltrate the Fresh Pond Reservoir, as well as throughout the region. The vertical distribution of saline and fresh water could also be determined throughout the system. Development of this model would cost approximately \$60,000 to \$70,000 and would take approximately 4-5 months to complete.

References

Bosma, K, E.Douglas, P Kirshen, K.McArthur, S.Miller, and C.Watson, 2015. MassDOT-FHWA Pilot Project Report: Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Options for the Central Artery. Falmouth, MA, Woods Hole Group, Inc.