CoastWise Tidal Crossing Structure Sizing Criteria for Ecological Resilience – Phase 2: Sizing Criteria Threshold Analysis and Concept Validation Testing

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MEMORANDUM

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This memorandum summarizes work performed as part of Phase 2 of the CoastWise (CW) tidal crossing structure sizing criteria study. The criteria study is being completed on behalf of the CoastWise Steering Committee (CWSC) as a supplement to the development of the CW tidal crossing design guidelines. The engineering team (ET) assisting the CWSC with development of the CW Guidelines[1] is led by Interfluve, with assistance from Woods Hole Group and Vanasse Hangen Brustlin.

1.0 Introduction

Phase 1 of this study involved the collection of data and existing models for tidal crossing sites to be considered for evaluation as well as refinement of the sizing criteria study design. The objectives for Phase 2 of the study were to:

1. assess the applicability of tidal synchrony (peak hydraulic head differential (PHHD) and timing (phase lag)) and instantaneous hydraulic head differential (IHHD)[2] threshold value(s) as performance criteria for tidal crossing structures (local to the structure), and
2. validate the effectiveness and applicability of tidal synchrony and HHD-based threshold criteria for sizing tidal crossing structures that will alleviate tidal restriction to the upstream tidal basin.

The objectives included not only assessing the effectiveness of these criteria but doing so under a variety of conditions and also comparing modeling methods. The following sections summarize the results of this Phase 2 effort and associated tasks. The Phase 2 work included: 1) model development and simulations for each site, 2) performance criteria testing for each site, 3) evaluating trends in performance criteria, sensitivity/correlations, and 4) reporting. The study did not consider any flooding or other adverse impacts which typically would be done in sizing a new or replacement tidal crossing structure.

[1] Moore, S., M. Burke, M. Shultz, R. Hamilton, J. Aman, E. Bartow-Gillies, W. Bennett, R. Blunt, J. Carter, M. Craig, C. Enterline, J. Gabrielson, J. Bell, P. Taylor, and S. Widing. 2023. The CoastWise Approach: Achieving Ecological Resilience and Climate-Ready Road Crossings in Tidal Environments. Maine Coastal Program.

[2] Tidal synchrony, PHHD, and IHHD are further defined in Section 2.0, the Glossary (Appendix H), and Phase 1 document (Appendix I)

The design tides selected for evaluating performance criteria included the highest astronomical tide (HAsT) both for present-day conditions and for a future sea level scenario. The future sea level rise (SLR) scenario selected for this study in consultation with the CWSC is the intermediate (central estimate) for the year 2100 which projects an increase in sea level of 3.6 feet from the year 2000[3].

At the completion of Phase 1, a total of eleven (11) tidal crossing sites were identified for inclusion in the sizing criteria study with the sites all located in Maine, as shown in Figure 1. Table 1 lists the 11 sites evaluated as part of this study along with the different site characteristics.

The site characteristics listed in Table 1 indicate a selection of tidal marsh sites of varying size from 2.8 acres at Site 8 -Old Ferry Road in Wiscasset, ME to 140 acres at Site 2 - Cousins River, upstream of Route 1 in Yarmouth, ME (sizes estimated at HAsT elevation). The approximate marsh elevation for the sites is generally within the range of 4 to 5.5 ft NAVD88 with the exception of Back River in Woolwich, ME where the marsh elevation in the basin upstream of Route 1 is approximately 2.4 ft. The HAsT elevations for the sites were obtained from mapping layers available from the Maine Geological Survey[4]. The HAsT elevations are generally within the range of 6.2 – 6.9 ft NAVD88 with the exception of Schoppee Marsh (8.9 ft) and at the entrance to Back River (4.8 ft).

The upstream watershed size and riverine flows for the sites (mean annual flow as given by USGS Streamstats[5]) are also provided in Table 1. Site 2 – Cousins River has the highest input base flow at 9.1 cfs while the remaining sites all have input flows less than 2.5 cfs. An approximate bankfull width[6] measured via aerial photography is also provided in Table 1.

The marsh area at HAsT without/with SLR is included in the Table 1 site characteristics to give perspective of how the upstream marsh basin will change at each of the sites in correlation with this sea level. There are some rather substantial changes in area (increase by a factor greater than 1.5) for six of the sites with the largest area increases occurring at Site 6 – Small Point Rd (factor of 2.2), Site 10 - Fish Point Road (factor of 2.8), and Site 11 -Drakes Island Road (factor of 4.6).

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[3] Sweet, W. V., B. D. Hamlington, R. E. Kopp, C. P. Weaver, P. L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A. S. Genz, J. P. Krasting, E. Larour, D. Marcy, J. J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K. D. White, and C. Zuzak, 2022: Global and regional sea level rise scenarios for the united states: updated mean projections and extreme water level probabilities along u.s. coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp.

[4] Maine Geological Survey, 2021, Highest Astronomical Tide Line. https://www.maine.gov/dacf/mgs/hazards/highest_tide_line/index.shtml. Accessed July 24, 2023.

[5] https://streamstats.usgs.gov/ss/

[6] Measured using GIS tools by identifying the transition from channel to marsh platform (right and left top of bank) at a representative location downstream of the structure which is not influenced by the structure.

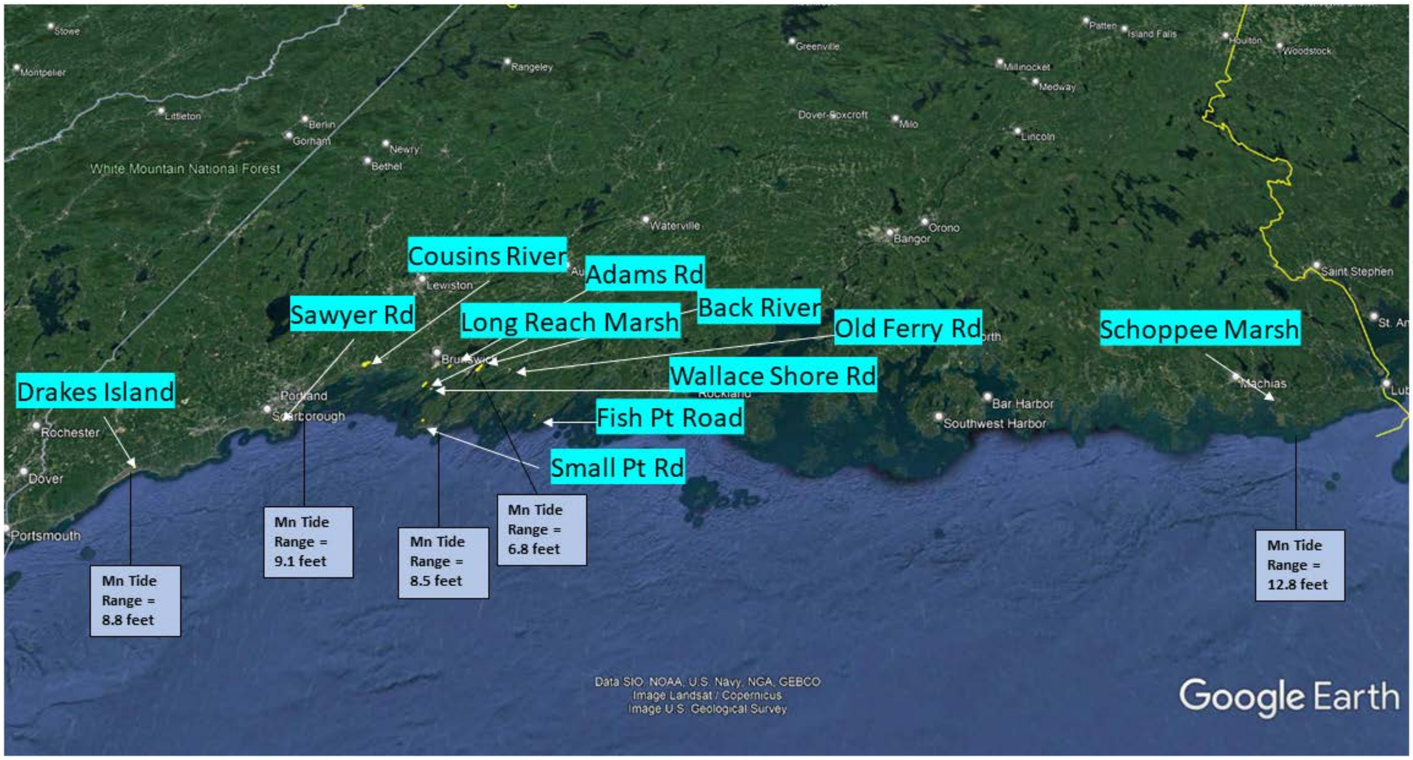


Figure 1. Tidal crossing sites selected for the sizing criteria study and mean (Mn) tidal range based on NOAA tides and currents stations.

Table 1. List of tidal crossing sites selected for the sizing criteria study and different site characteristics.

Site No.	Site Name	Mean Tide Range (ft	HAsT (ft, NAVD)	HAsT w/ SLR (ft, NAVD)	Area @ HAsT (Ac)	Area @ HAsT w/ SLR (Ac)	Approx. Marsh Elev. (ft, NAVD)	Vol. btwn Marsh & HAsT (Ac-f	Vol. btwn Marsh & HAsT w/ SLR (Ac-ft	Modeled riverine input (cfs)	Watershed Drainage Area (ac)*	Approx. Bankfull Width (ft)**	Culvert Length (ft)	Existing US invert elev. (ft)	Existing DS invert elev. (ft)	Existing opening width (ft)	Existing opening height (ft
1	Long Reach Marsh/Long Reach Lane	7.9	6.9	10.5	27	31	4.9	48.2	153	0.8	96	12	25	0	0	12	4.5
2	Cousins River, Yarmouth	6.8	6.7	10.3	140	150	5.5	60.2	421.2	9.1	10707	110	32	-7.87	-8.29	50	15.5
3	Back River Creek/Route One	7.2	4.8	8.4	142.1	159	2.4	333.7	861.2	1	883	85	96	-3.1	-3.1	6' diam	6' diam
4	Schoppee Marsh	13.1	8.9	12.5	64	82	4.1	143.3	376.7	0	115	50	29.4	-0.64	-2.57	3' diam	3' diam
5	Spurwink Marsh/Sawyer Road	5.5	6.5	10.1	100	182	4.5	154.1	650.9	2.5	2356	32.5	42	-2.9	-3	12	11
6	Small Point Road	6.4	6.8	10.4	4.4	14.3	4.5	27.8	125.1	1.25	83	16	30	1.5	1.5	2	2.25
7	Thomas Bay Marsh/Adams Road	5.7	6.7	10.3	29	34	5	33.8	143.6	5	685	13	60	-1.25	-1.25	13.1' arch	8.3' arch
8	Old Ferry Road	6.2	6.5	10.1	2.8	4.3	5.1	3.3	16.1	2.5	173	10	60	1	-1	3' diam	3' diam
9	Wallace Shore Road	3.7	6.6	10.2	11.4	20.6	5.4	11.5	70.5	0.5	109	12	40	4.75	3.71	4	2
10	Fish Point Road/Pemaquid Beach	3.25	6.2	9.8	2.9	8.2	4.6	3.4	22	0.1	18	6	40	1.6	2.4	(2) 3' diam	(2) 3' diam
11	Drakes Island Rd (west)	8	6.6	10.2	13	60	5	16.6	143.9	1	96	18	25	-0.25	-0.7	15	7.5-9

*obtained via USGS streamstats

**measured via aerial photography

2.0 Site Model and Criteria Testing Results

For the evaluation of performance criteria at the 11 sites, tidal hydraulic models (either pre-existing or newly developed for this study) were utilized to simulate the tidal crossings under the specified design tides with a range of hydraulic structure opening sizes. The models utilized included various types and dimensions (0-D, 1-D, and 2-D); the models used for each site and model assumptions are provided in Appendix A.

Model simulations were conducted in an iterative manner with an increase in the hydraulic opening size (span) in order to reduce the peak hydraulic head differential (PHHD), the phase lag (difference in timing of peaks), and the instantaneous hydraulic head differential (IHHD). In computing IHHD, calculations were made during the flood and ebb portion of the tide cycle, however, the low water differences attributed to differences in the upstream and downstream channel elevations (or inflow) were excluded from the calculations. An example time series of water levels and the computed IHHD is shown in Figure 2. The limits of the IHHD calculation for the purposes of defining performance criteria are indicated by the vertical black dashed lines in Figure 2. A graphic depicting the PHHD and phase lag is shown in Figure 3.

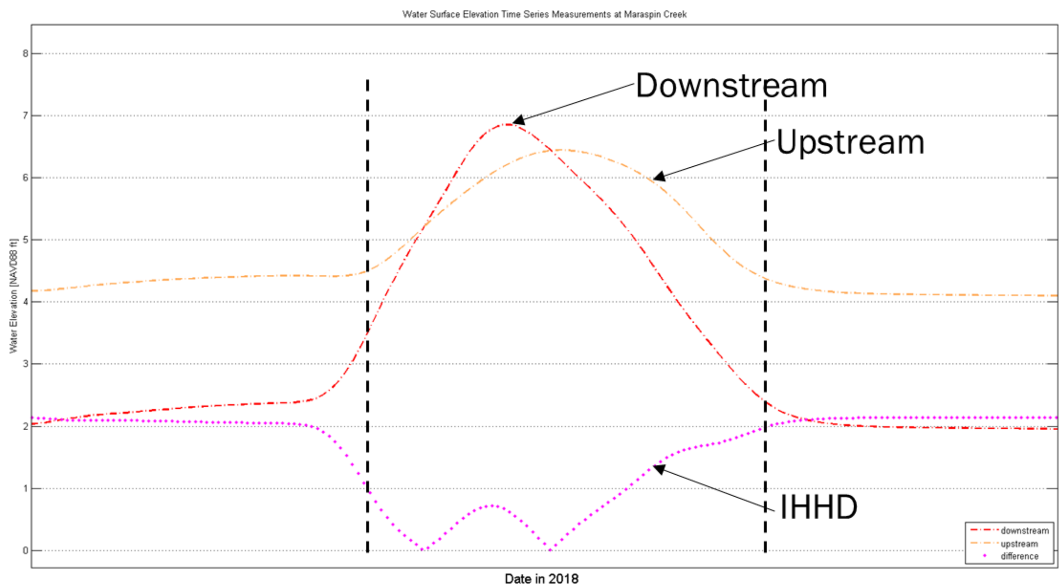


Figure 2. Example time series of water levels downstream and upstream of a tidal crossing along with the calculated IHHD. The black vertical dashed lines indicate the limits of the IHHD calculation for defining performance criteria for the hydraulic structure opening.

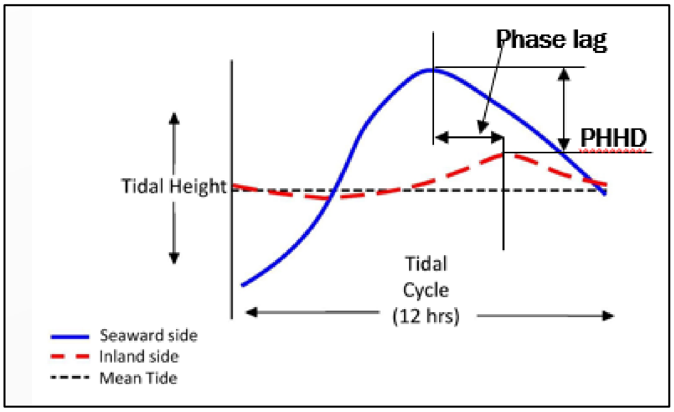


Figure 3. Example time series of water levels downstream and upstream of a tidal crossing with PHHD and phase lag metrics defined.

A total of 18 models were utilized and approximately 450 model simulations were conducted for evaluation of performance criteria. The minimum values of PHHD, IHHD, and phase lag from the set of model simulations at each tidal crossing site for both present-day HAsT and HAsT with SLR are shown in Table 2. As one might expect, the minimum values obtained were with the maximum span evaluated for each of 11 sites. Table 3 provides summary statistics for each metric.

Table 2. Minimum IHHD, PHHD, and phase lag simulated at each tidal crossing site for the selected design tides.

					Present-day HAsT			HAsT w/ SLR		
Site No.	Site Name	Area @ HAsT (Ac)	Area @ HAsT w/ SLR (Ac)	Evaluated Range of spans (ft)	Min IHHD (ft)	Min PHHD (ft)	Min Phase Lag (min)	Min IHHD (ft)	Min PHHD (ft)	Min Phase Lag (min)
1	Long Reach Marsh/Long Reach Lane	27	31	10-80	0.04	0.01	0	0.08	0	6
2	Cousins River, Yarmouth	140	150	50-120	0.11	-0.01	0	0.17	-0.01	0
3	Back River Creek/Route One	142	159	10-100	0.54	0.02	6	0.9	0.03	6
4	Schoppee Marsh	64	82	10-60	0.43	0	0	0.63	0	0
5	Spurwink Marsh/Sawyer Road	100	182	20-200	0.45	0	10	0.57	0	5
6	Small Point Road	4.4	14.3	6-40	0.04	0	0	0.08	0	0
7	Thomas Bay Marsh/Adams Road	29	34	5-60	0.01	-0.03	6	0.08	0	0
8	Old Ferry Road	2.8	4.3	3-12	0.05	0	0	0.07	0	0
9	Wallace Shore Road	11.4	20.6	5-50	0.10	0	0	0.22	0.00	0
10	Fish Point Road/Pemaquid Beach	2.9	8.2	3-30	0.04	0	0	0.06	0	0
11	Drakes Island Rd (west)	13	60	6-40	0.06	0	0	0.14	0	6

Table 3. Summary statistics for the minimum IHHD, PHHD, and phase lag across the 11 evaluation sites.

	Present-day HAsT			HAsT w/ SLR		
Statistic Param.	Min IHHD (ft)	Min PHHD (ft)	Min Phase Lag (min)	Min IHHD (ft)	Min PHHD (ft)	Min Phase Lag (min)
Range	0.01 - 0.54	0 - 0.02	0 - 10	0.06 - 0.9	0 - 0.03	0 - 6
Mean	0.17	0.01	2	0.27	0.00	2
Std	0.20	0.01	4	0.29	0.01	3
Median	0.06	0.00	0	0.14	0.00	0

The results in Tables 2 and 3 indicate that for all evaluation sites, the minimum PHHD was close to zero (less than 0.05 feet). The minimum phase lag between all the sites was less than 10 minutes, except at Site 5 – Spurwink Marsh/Sawyer Road where the minimum phase lag was 10 minutes during present-day HAsT.

The minimum IHHD values had a greater range between all the sites. The mean (minimum IHHD) was approximately 0.2 and 0.25 ft for present-day HAsT and HAsT with SLR, respectively, however three sites had larger minimum IHHD values between 0.4 and 0.9 ft. Those sites include Site 3 – Back River/Route One, Site 4 – Schoppee Marsh, and Site 5 – Spurwink Marsh/Sawyer Road which are three of the larger-sized marsh systems. In contrast, Cousins River (Site 2) is the largest sized system and had a minimum IHHD of less than 0.2 ft. An explanation for this could be the higher marsh elevation in the Cousins River (smaller volume between the marsh and design tide) in comparison with the other large systems, combined with the higher riverine discharge into the Cousins River.

For each evaluation site, performance curves were developed for the three metrics (PHHD, IHHD, and phase lag) to show the values achieved with an increase in the span of the hydraulic opening. Separate performance curves were developed for the present-day HAsT and HAsT with 3.6 ft of SLR. An example of the performance curves is shown in Figure 4 for Site 5 – Sawyer Rd/Spurwink Marsh. The plots on the left in Figure 4 (top and bottom) are for present-day HAsT while the plots on the right in Figure 4 are for HAsT with SLR. Based on the results presented in Tables 2 and 3, a preliminary set of criteria was selected for the 3 metrics accordingly as below (subject to further discussion and adjustment by the CWSC upon reviewing the results of this study):

Preliminary Selected Criteria:

1. IHHD < 0.5 feet
2. PHHD < 0.1 feet
3. Phase lag < 15 min

The site summary statistics (Table 3) and prior study experience led to the preliminary selected criteria. For IHHD, the criteria was set using the mean plus the standard deviation (and rounding down to 0.5 ft). For PHHD, the criteria was set knowing hydraulic model precision is typically not less than 0.1 ft, and a difference of 1.2 inches is rather insignificant. For phase lag, less than 15 min was met at all of the sites for both design tides.

This set of criteria is also indicated by vertical dashed lines on the performance curves shown in Figure 4. IHHD < 0.5 ft was not met in the HAsT with SLR scenario, however, so the dashed dark blue line on the top-left panel in Figure 4 indicates where IHHD < 0.6 ft.

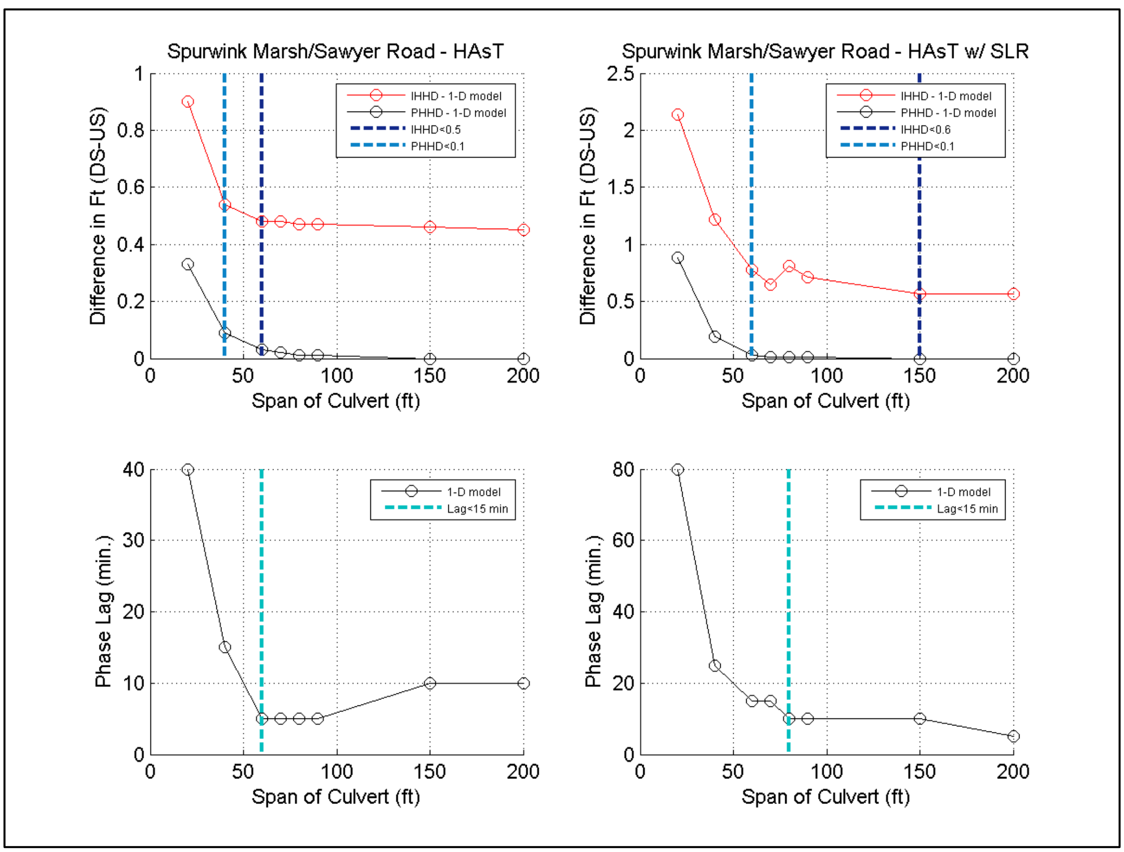


Figure 4. Hydraulic structure sizing performance curves with HHD curves presented in the top panels and the phase lag curve presented in the lower panel. Left plots for present-day HAsT and right plots for HAsT with SLR.

In reviewing the performance curves shown in Figure 4, one can see how the PHHD, IHHD, and phase lag decrease with an increase in structure span. The PHHD < 0.1 ft criteria is met with a 40-ft span in present-day HAsT however with SLR, this criteria is met with a 60-ft span. The IHHD < 0.5 ft criteria is met with a 60-ft span in present-day HAsT, however, with SLR this criteria is not met even with spans of 150-200 ft[7] (for this site, the IHHD criterion was increased to be < 0.6 ft). The phase lag < 15 min. criteria is met with a 60-ft span in present-day HAsT and then with an 80-ft span with SLR. The SLR scenario requires larger spans in order to meet the criteria, as one would expect. The CoastWise guidelines recommend structure sizing for future, not current, sea levels, which will be the focus when integrating results from this study into the guidelines document.

These curves also reveal there is an inflection point where there are minimal changes in the metrics with an increase in span. For example, an 80-ft span produces a phase lag of 10 min. in HAsT with SLR (lower right plot in Figure 4) and the phase lag remains at 10 min for a 90-ft and 150-ft spanned structure. It is not until a 200-ft span is utilized when the phase lag is reduced to 5 min. So, the minimum span would be selected at or near this inflection point as there is an insignificant benefit with a larger, more costly structure. One could also calculate the rate of change in the slope of this curve and identify the span size when there is little to zero change in the slope.

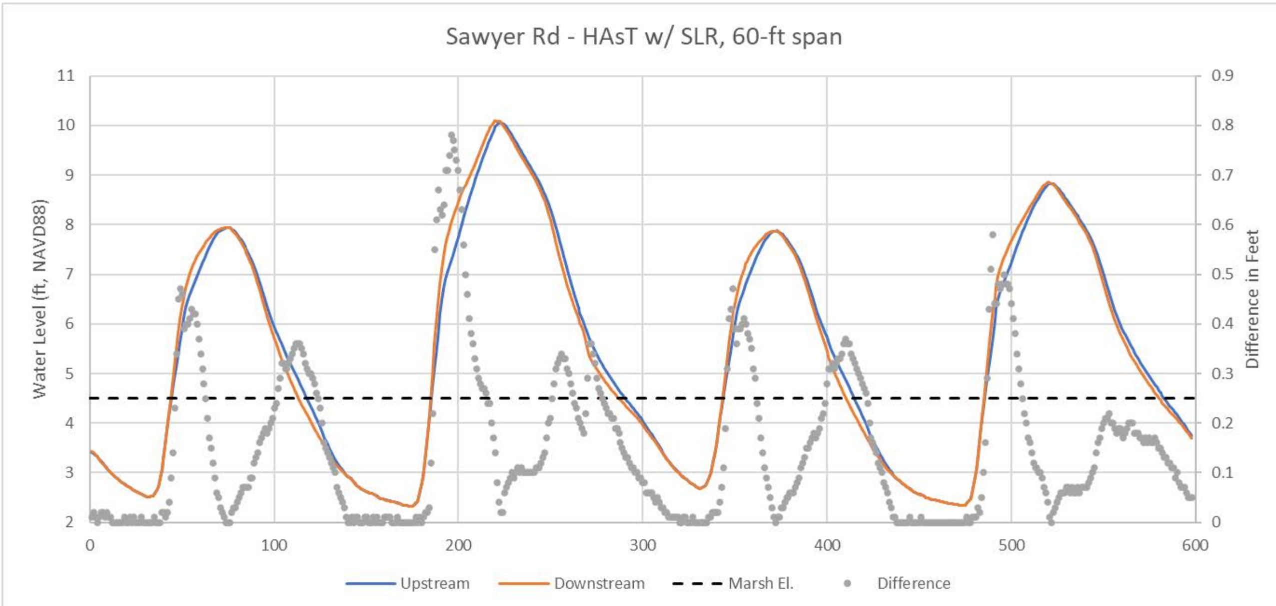
Example modeled time series of water levels for the Spurwink Marsh (upstream and downstream of Sawyer Road) are shown in Figure 5 for the HAsT with SLR scenario and a 60-ft span (panel a) and an 80-ft span (panel b). The plots in Figure 5 also show the calculated IHHD (circular grey markers) with the difference values shown on the right y-axis. Panel (a) of Figure 5 indicates there are minor differences in the peak tide elevations on either side of the structure (the 60-foot span meets the PHHD < 0.1 ft criteria), however the IHHD values are up to 0.8 ft during the highest incoming tide. The time series for an 80-ft span (panel (b) of Figure 5) shows even better alignment between the downstream and upstream water levels. Both the PHHD < 0.1 ft criteria and phase lag < 15 min. criteria are met, however, the IHHD remains greater than 0.5 ft on the incoming tide. This might be considered an acceptable difference of IHHD in this case, as it does not appear it will significantly limit the hydroperiod for future evolution and resilience of the marsh. It should be noted that in many cases, aquatic organism passage is also an essential design objective. In cases where PHHD criteria would be met, but IHHD may not be met, it will be recommended to check simulated hydraulic conditions to assess aquatic organism passage potential. In this context, IHHD becomes an important criteria since IHHD >0 indicates an increase in velocity over what naturally would occur. An assessment of velocities could also be made comparing with allowable velocities for target species.

Additional performance curves and sample water level time series figures are included in Appendix B for all (11) evaluation sites. Results are not presented with SLR for Site 7 - Thomas Bay Marsh/Adams Road because of difficulties with running the 1-D model. Table 4 lists the resultant structure spans at each site that meet the preliminary selected criteria.

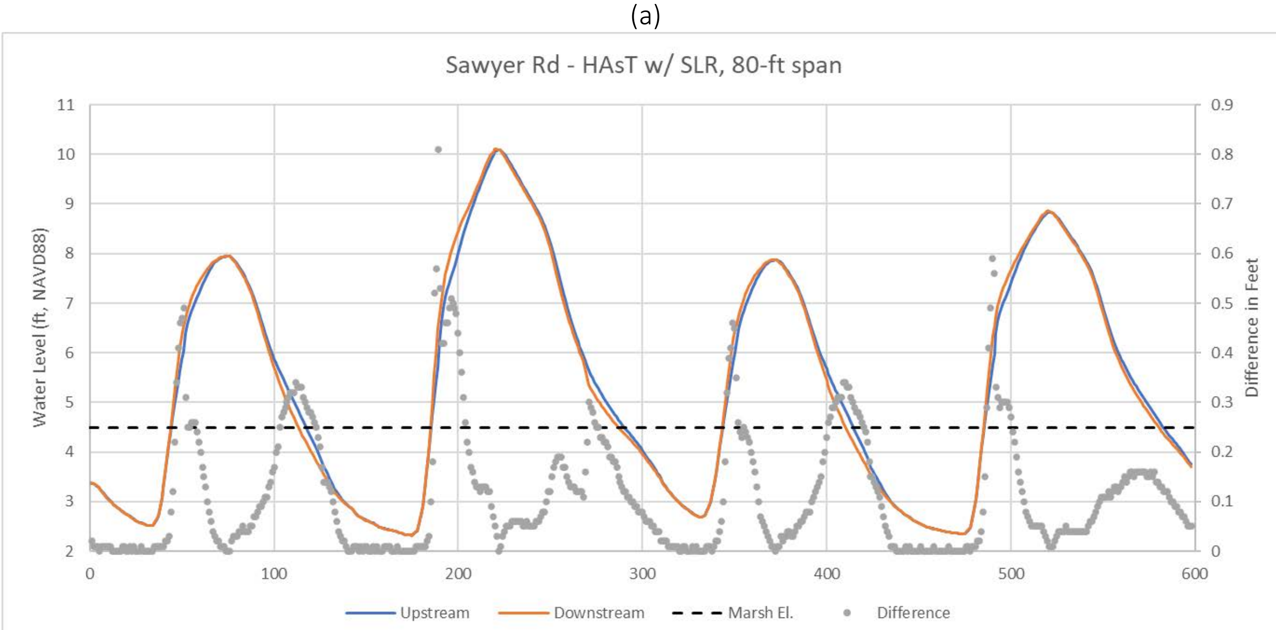
[7] At Spurwink Marsh/Sawyer Rd the 150-ft span produces <0.6 ft of IHHD but this head difference was not reduced further even with a 200-ft span. Based on additional model testing without a crossing, the long length of the roadway at this site plays a role in requiring an even more expansive opening to meet the IHHD < 0.5 ft criterion.

Table 4. Span sizes required to meet the preliminary sizing performance criteria.

Site No.	Site Name	Area @ HAsT (Ac)	Area @ HAsT w/ SLR (Ac)	Present-day HAsT			HAsT w/ SLR		
				Span IHHD < 0.5 (ft)	Span PHHD < 0.1 (ft)	Span LAG < 15 min (ft)	Span IHHD < 0.5 (ft)	Span PHHD < 0.1 (ft)	Span LAG < 15 min (ft)
1	Long Reach Marsh/Long Reach Lane	27	31	15	15	20	25	15	15
2	Cousins River, Yarmouth	140	150	70	70	70	80	60	50
3	Back River Creek/Route One	142	159	100	60	70	100	60	70
4	Schoppee Marsh	64	82	50	20	20	50	20	20
5	Spurwink Marsh/Sawyer Road	100	182	60	40	60	150	60	80
6	Small Point Road	4.4	14.3	10	6	10	20	10	10
7	Thomas Bay Marsh/Adams Road	29	34	35	18	18			
8	Old Ferry Road	2.8	4.3	6	3	3	6	3	3
9	Wallace Shore Road	11.4	20.6	15	10	5	25	10	10
10	Fish Point Road/Pemaquid Beach	2.9	8.2	5	3	3	11	5	5
11	Drakes Island Rd (west)	13	60	8	6	8	30	15	20



(a)



(b)

Figure 5. Time series of water levels upstream (blue) and downstream (orange) of the Sawyer Road tidal crossing in Spurwink Marsh with absolute differences (grey markers, values on right y-axis) for HAsT with SLR with a 60-ft span opening (panel a) and an 80-ft span (panel b).

After reviewing the results for all sites, the following summary remarks can be made:

1) The SLR scenario requires larger spans to meet a specific set of criteria. The CoastWise Guidelines recommend sizing structures for future sea levels.
2) All three metrics are important to consider for marsh resilience with performance criteria defined for each. This is exemplified in the results for Site 6 -Small Point Road (see performance curve and time series figures in Appendix B) where a 10-ft span meets the PHHD and phase lag criteria, however the water level time series indicate a structure restriction is evident during the running tides leading to a higher IHHD. This restriction is minimized when increasing the span to 20 ft which in turn meets the IHHD critieria.
3) The preliminary PHHD and phase lag criteria require similar structure spans with the exception of a few cases.
4) The preliminary IHHD <0.5 ft criteria is more stringent than the other 2 criteria and requires a larger span.
5) The preliminary IHHD <0.5 ft criteria was not met for 3 of the larger marsh systems even with substantially larger spans.
6) The elevation and size of the marsh contributes to the attenuation of tides and non-linear response upstream of a crossing which, in combination with the structure opening, affects IHHD.
7) Similar IHHD levels can occur on the flood and ebb tides. The timing of max IHHD is generally shown at a mid-tide level, or higher.
8) Differences in channel elevations upstream and downstream of the crossing can affect the drainage and computed IHHD. Care should be taken to exclude the low portion of the tide cycle from the IHHD calculation.
9) The ability to meet a set of performance criteria does not appear affected by the input watershed, using an annual base flow.

3.0 Sensitivity to Model Approach, Parameters, and Assumptions

3.1 Sensitivity to Model Simulation Approach

As various modeling approaches may be used to evaluate tidal marsh systems and tidal crossing hydraulics, in addition to 1-D and 2-D models, a set of 0-D models were developed for seven (7) of the evaluation sites. The 0-D models were developed using the same data that were used in the more detailed (either 1-D or 2-D) model approach. The same set of model simulations and range of hydraulic structure openings were evaluated with the 0-D model.

Figure 6 shows an example of the structure sizing performance curves generated using the 0-D model compared with those produced using the 1-D model at Site 5 – – Sawyer Rd/Spurwink Marsh. Comparisons for the remaining 6 sites are included in Appendix C.

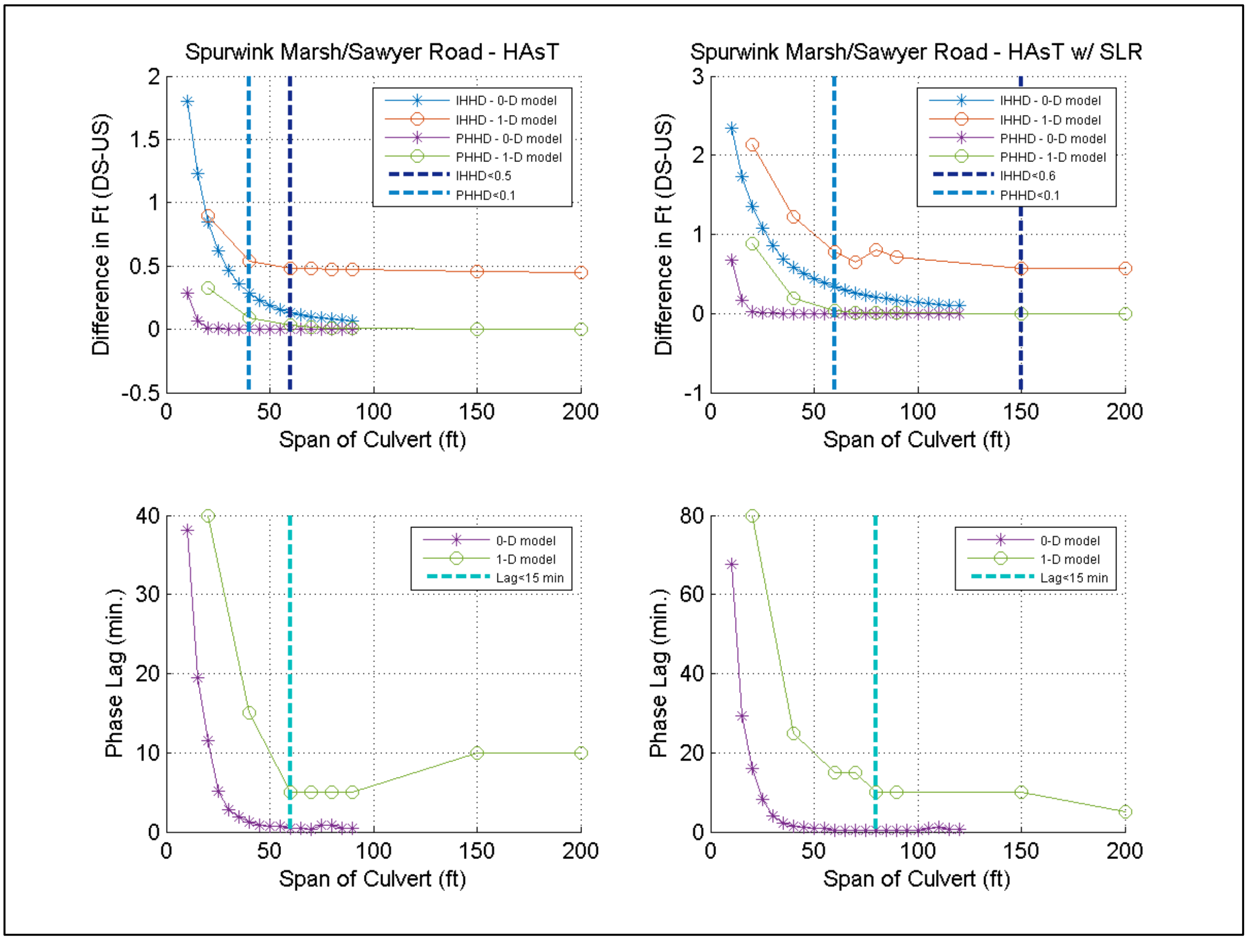


Figure 6. Hydraulic structure sizing performance curves for 0-D and 1-D model simulations (HHD curves presented in the top panels and the phase lag curve presented in the lower panels). Left plots for present-day HAsT and right plots for HAsT with SLR.

The performance curves shown in Figure 6 show the 0-D model produces lower HHD and phase lag values in comparison to the 1-D model. The 0-D IHHD values are on average approximately 40% of the 1-D IHHD values. This is expected since the 0-D model does not consider bed roughness, channel sinuosity, connectivity, drainage patterns, etc.

The curves in Figure 6 indicate an IHHD performance criteria may be best suited for an initial evaluation of structure sizing using a 0-D model. IHHD in a 0-D model appears to more truly reflect any tidal restriction posed by the crossing structure since other potential restrictive factors are not included in the model. The results also indicate a more stringent IHHD criteria may be appropriate when using a 0-D model. For example, using a criteria of IHHD < 0.25 feet would result in an 80-ft span being selected at Spurwink Marsh for HAsT with SLR. This is the same span size that would be selected using the phase lag criteria with a 1-D model.

Similar results are seen at the other evaluation sites to varying degrees when comparing the 1-D results with a 0-D model. In the case of Back River where the 0-D results are compared with the same from a 2-D model, there is better agreement in IHHD between the two model approaches. This can be attributed to the fact that the 0-D model does in this case consider some complexities of the system (i.e., multiple basins upstream with an upstream tidal crossing) that contribute to the tidal restriction identified by IHHD.

3.2 Sensitivity to Model Parameters

Another consideration in modeling tidal crossing hydraulics, are the parameters specified in the model setup including frictional effects for the channel and marsh platform as well as the crossing structure itself. The frictional effects of the of the channel, marsh platform, and hydraulic structure are typically specified in the model using roughness coefficients (such as the Manning's n roughness coefficient). The most appropriate roughness coefficient to apply in the model is typically within the range of acceptable values based on laboratory and field data, which is then refined in the model calibration and validation process. This can be done to determine a roughness coefficient for the channel and marsh platform in a model of existing conditions with available field measurement data. For a newly proposed hydraulic structure, however, it is up to the modeler to select a roughness coefficient for the structure walls and bottom within a range of acceptable values.

To assess the sensitivity of a selected Manning' n roughness coefficient for the hydraulic structure, three sites were modeled with 3 different roughness values for the structure. The Manning' n roughness coefficient was varied to include a low roughness value of 0.01, a mid-range of 0.014, and what can be considered the upper range for a concrete culvert structure at 0.02.

The same set of model simulations and range of hydraulic structure openings were evaluated for 3 sites, with each site using a different model simulation approach from 0-D, 1-D, and 2-D to assess the sensitivity of varying roughness / model type on the ability to meet performance criteria.

Figures showing the performance curves with a varied structure roughness are included in Appendix D. The general observations made from the sensitivity runs are that the roughness coefficient specified for the structure in the 1-D and 2-D models (Sawyer Rd/Spurwink Marsh and Back River, respectively) had minimal effects on the HHD metrics (< 0.05 ft) and phase lag (5-6 min.). The specified structure roughness has a greater effect in the 0-D model (see Figure for Long Reach Marsh) and the resultant HHD values. This is because it is the primary parameter within the 0-D model for controlling the tidal attenuation of the structure (aside from the opening size), and other system parameters affecting tidal attenuation are not explicitly included in a 0-D model. The differences are relatively small using the Long Reach Marsh 0-D model, however, with IHHD differences being < 0.1 feet for the selected structure span using the preliminary performance criteria (span of 15-20 ft).

3.3 Sensitivity to Including Potential Future Accretion

There is the potential for future accretion of a marsh surface with an increase in sea level. The degree of assumed future accretion influences the volume of an upstream basin, as well as the frequency, duration, and depth of inundation of the marsh surface. To examine the effects of including/not including accretion on the structure sizing performance criteria, additional simulations with SLR were conducted to evaluate sensitivity to potential future upstream sediment accretion. These simulations were conducted for 4 evaluation sites including a 0-D model site, a 1-D model site, and two 2-D simulated sites.

Given the uncertainty of predicted accretion[8], two accretion levels were evaluated as part of the analysis: 0.6 ft and 1.8 ft, or 17% and 50% of the projected increase in sea level. The 0.6-ft accretion level equates to approximately 1.8 mm/yr (based on historical accretion observed at a marsh site in ME[9]) whereas 1.8 ft is a hypothetical scenario given in the CW guidelines

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[8] As further detailed in the Coastwise Manual, future accretion will be a function of sediment delivery during large tidal exchange events (primarily during storms).

[9] Weston, N. B., Rodriguez, E., Donnelly, B., Solohin, E., Jezycki, K., Demberger, S., et al. (2023). Recent acceleration of wetland accretion and carbon accumulation along the U.S. East Coast. Earth's Future, 11, e2022EF003037. https://doi.org/10.1029/2022EF003037

which assumes accretion will occur at half the rate of sea level rise. Another potential scenario is negative accretion (i.e., where there is conversion of tidal marsh to tidal flat) but this was not evaluated as part of this study.

The performance curves for different accretion levels are shown in Appendix E for the 4 sites, and the Spurwink Marsh/Sawyer Rd 0-D model results are shown in Figure 7. It is evident that including accretion lowers both HHD and phase lag values, leading to the selection of a reduced span size using a defined set of performance criteria. The 1.8-ft accretion level compared with no accretion resulted in a lower IHHD on the order of 0.5 ft for a range of structure spans, while the 0.6-ft accretion level results in lower IHHD by about 0.25 ft in both the 1-D (Long Reach Marsh) and 2-D models (Back River and Wallace Shore Rd). The effects are less (about half the difference) using the 0-D model for Sawyer Rd/Spurwink Marsh. Also, the PHHD and time lag differences are less and more quickly converge for the different accretion levels in comparison to IHHD.

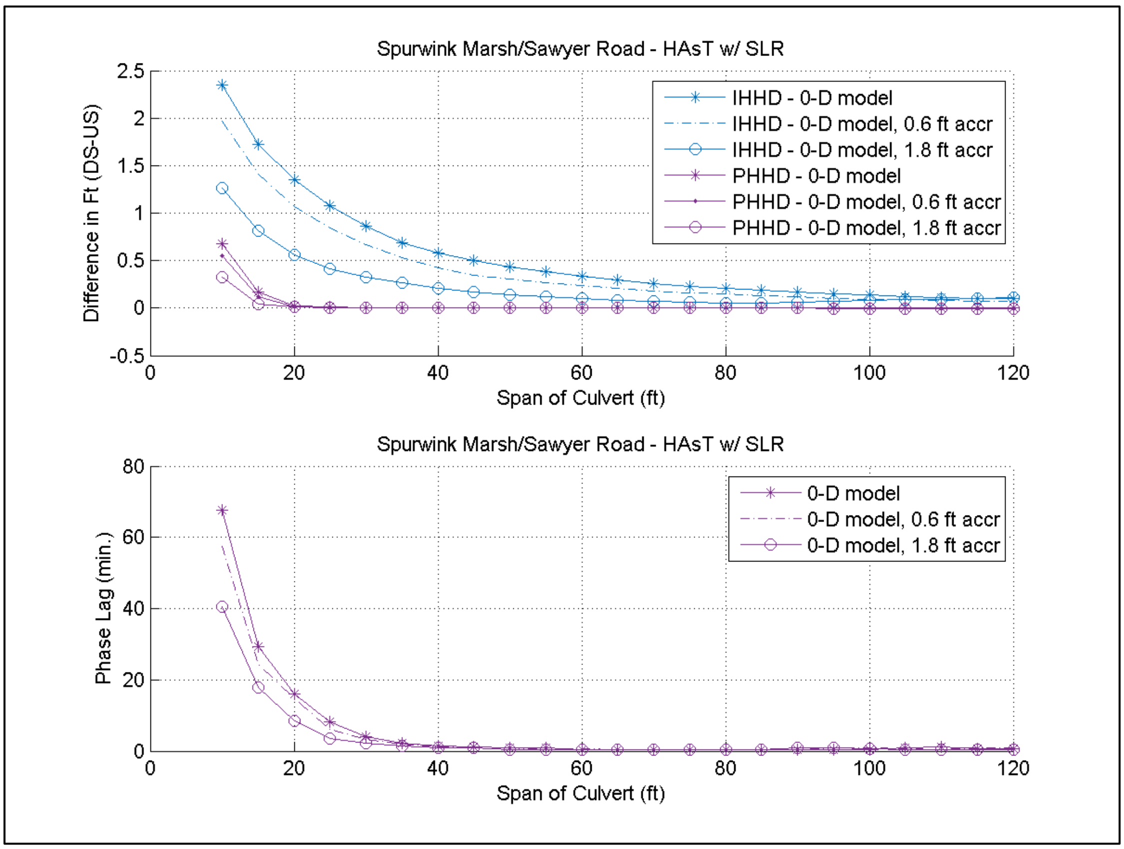


Figure 7. Hydraulic structure sizing performance curves for with varying levels of accretion (HHD curves presented in the top panel and the phase lag curve presented in the lower panel).

3.4 Assessment of Upstream Tidal Patterns

Additional model simulations were conducted for a subset of the sites having more detailed 1-D and 2-D model representations (Sawyer Rd 1-D model, Back River 2-D model, and Wallace Shore Rd 2-D model). These model simulations included a naturalized, unrestrictive tidal flow condition with the roadway crossing removed in order to assess whether similar inundation patterns exist throughout the marsh system (with and without the crossing). Table 5 lists the calculated performance metrics at each site with a crossing/selected structure span (based on a review of the performance criteria) and the naturalized condition. Figure 8 shows the locations within each marsh system where the metrics were calculated.

The results listed in Table 5 show that with a naturalized (no crossing) condition, the IHHD is reduced in comparison to the with crossing/selected span scenario. In the HAsT with SLR scenario, IHHD is reduced to less than 0.2 ft for Spurwink Marsh/Sawyer Rd and less than 0.1 ft for Back River/Rte. 1. This indicates that even with an appropriately sized hydraulic opening, the crossing itself still poses as a restriction in these larger-sized marsh systems and smaller IHHD can be achieved with a more expansive opening in the crossing. At the Wallace Shore Rd site, a smaller reduction in IHHD is shown to occur with the crossing removed, since the crossing/selected span already provides close to an unrestricted condition (with IHHD < 0.25 ft). Important to note is that even with a naturalized condition, IHHD > 0.0 due to other system factors, so zero IHHD should not be considered as a possible performance criterion.

Table 5 also lists the same metrics calculated at a point located further upstream in the marsh system and shows the differences in metrics between the naturalized condition and the selected crossing span for each site (at both the crossing and a point located further upstream). For example, in a present-day HAsT at a location in the marsh further upstream of Sawyer Rd, the IHHD is 1.55 and 1.46 ft with the 90-ft span and no crossing, respectively. As one might expect, there is additional instantaneous head difference (over 1 ft) further upstream of the crossing due to other system factors (i.e., sheetflow over the marsh, friction, etc.) that affects the tidal signal at the upstream location. An increase in IHHD at the upstream location is shown to occur (over the IHHD at the crossing) for the three sites evaluated. There are some increases in PHHD and phase lag at the upstream location as well, particularly in the present-day HAsT at Back River.

The difference in IHHD (between the w/ span and no crossing scenarios) is shown to be generally higher at the crossing than at the upstream location. For example, in HAsT with SLR at Sawyer Rd the difference in IHHD at the crossing is 0.53 ft, while the difference at the upstream location is 0.21 ft. This indicates tidal attenuation due to the crossing is more local to (or in close proximity to) the crossing itself and less a factor at an upstream location where the other system factors play a larger role in the tidal dampening that occurs. This is shown to be the case at all of the sites evaluated, for both design tides.

Time series figures are provided in Appendix F which show the crossing upstream and downstream water levels for the naturalized condition, and then a comparison of water levels at the upstream location between the naturalized condition and the selected crossing span(s). Figure 9 shows an example of a zoomed (14-hour) view of the comparisons (naturalized vs. selected span) over a single tidal cycle at the Back River upstream location during a HAsT with SLR. This comparison indicates that while the peak tides are close to equivalent, there are some larger differences during the flood and ebb of the tides. These differences result in a slightly reduced hydroperiod with the selected (100-ft) span for marsh elevations greater than 5 ft (as annotated on Figure 9), however the differences are relatively small on the order of 24 minutes.

Figure 8. Stations used for assessing upstream tidal patterns (top: Wallace Shore Rd, bottom left: Back River, bottom right: Sawyer Rd)

Table 5. Comparison of metrics between a naturalized condition and selected structure span(s) upstream/downstream of a crossing and a location further upstream of crossing. The up-arrows indicate an increase in the metric at the upstream location.

Spurwink Marsh/Sawyer Road	Present-day HAsT			HAsT w/ SLR		
	IHHD (ft)	PHHD (ft)	Phase Lag (min)	IHHD (ft)	PHHD (ft)	Phase Lag (min)
US-DS w/ 90-ft span	0.47	0.01	5	0.71	0.01	10
US-DS w/ No Crossing	0.24	0.00	5	0.18	0.00	0
Upstream Site w/ 90-ft span	1.55↑	0.01	15 ↑	2.21↑	0.01	10
Upstream Site w/ No Crossing	1.46↑	0.00	5	2.00↑	0.00	5
Difference at crossing	0.23	0.01	0	0.53	0.01	10
Difference at Upstream Site	0.09	0.01	10	0.21	0.01	5

Back River Creek/Route One	Present-day HAsT			HAsT w/ SLR		
	IHHD (ft)	PHHD (ft)	Phase Lag (min)	IHHD (ft)	PHHD (ft)	Phase Lag (min)
US-DS w/ 100-ft span	0.54	0.02	6	0.90	0.03	6
US-DS w/ No Crossing	0.06	0.00	0	0.06	0.00	0
Upstream w/ 100-ft span	2.32↑	0.07↑	6	0.90	0.03	6
Upstream Site w/ No Crossing	2.38↑	0.04↑	6 ↑	0.80↑	0.00	0
Difference at crossing	0.48	0.02	6	0.84	0.03	6
Difference at Upstream Site	-0.06	0.03	0	0.10	0.03	6

Wallace Shore Road	Present-day HAsT			HAsT w/ SLR		
	IHHD (ft)	PHHD (ft)	Phase Lag (min)	IHHD (ft)	PHHD (ft)	Phase Lag (min)
US-DS w/ 25/40-ft spans	0.10	0.00	0	0.22	0.00	0
US-DS w/ No Crossing	0.05	0.00	0	0.14	0.00	0
Upstream w/ 25/40-ft spans	0.14↑	0.00	0	0.26↑	0.00	0
Upstream Site w/ No Crossing	0.13↑	0.00	0	0.23↑	0.00	0
Difference at crossing	0.05	0.00	0	0.08	0.00	0
Difference at Upstream Site	0.01	0.00	0	0.03	0.00	0

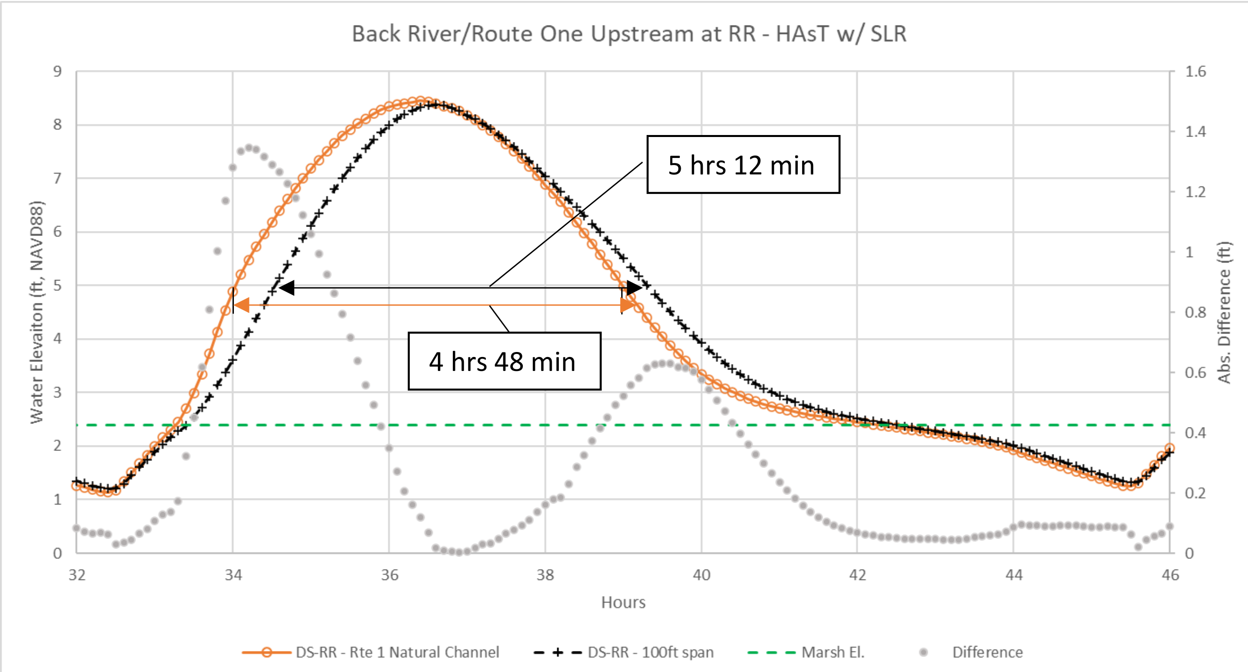


Figure 9. Time series of water levels and differences between a naturalized condition and selected structure span(s) at a point located upstream in Back River (difference values on right y-axis).

4.0 Discussion of Trends and Correlations

The sizing study included an analysis of any trends that could be identified from the model results at the eleven (11) evaluation sites for the design tides (highest astronomical tide (HAsT) both for present-day conditions and a future sea level). In reviewing the model results and metrics together with the site characteristics, a correlating trend was found between the minimum IHHD and the marsh wetted area. This can be seen in Figure 10 where both of these are shown (on different y axes) and an increase in wetted area at the design tide (bar chart, right y-axis) is generally followed by the minimum IHHD achieved (line with markers, left y-axis). An exception to this trend is the Cousins River site which has the second largest area and a rather low minimum IHHD (0.1 to 0.2 ft). As noted earlier, the lower IHHD at this site may be attributed to the relatively high riverine inflow or higher marsh platform elevation (in comparison to other sites).

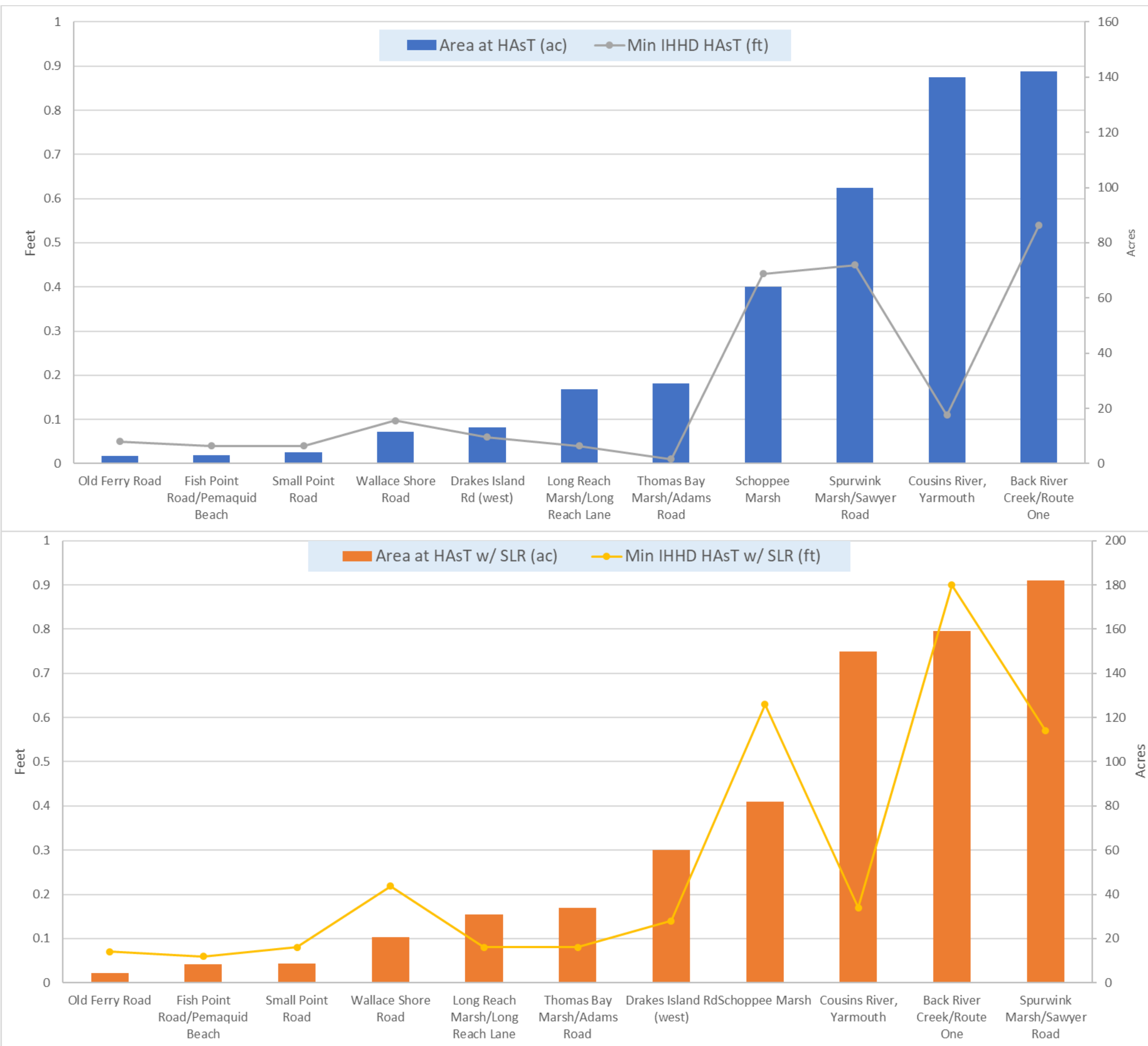


Figure 10. Trends of wetted area and minimum IHHD in sizing study for HAsT with SLR (values of min IHHD on left y-axis and area on right y-axis).

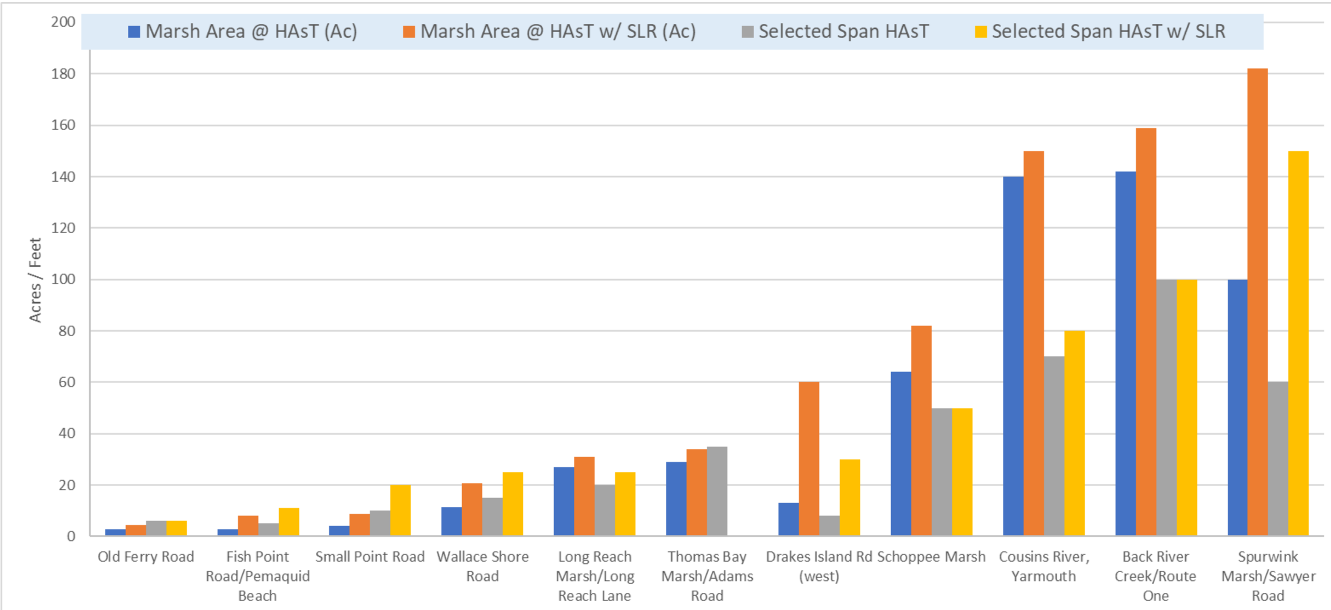


Figure 11. Bar charts of area at HAsT and then HAsT with SLR and the selected structure spans using the initial performance criteria.

Similar trends were also found between marsh area at the design tides and the required structure span using the initial set of sizing performance criteria. These can be seen in the bar chart shown in Figure 11. As one might expect, a larger marsh area (and associated upstream basin volume) requires a larger span to adequately convey unrestricted tidal flow for sites having a similar tidal range. Figure 9 also indicates an increase in marsh size with SLR translates to a similar increase in the required span (e.g., a 50% in marsh size w/ SLR resulted in similar percent increase in span).

The correlation of selected spans using the different metrics/performance criteria was also investigated with the following site characteristics:

1) marsh area at the design tides, and
2) the upstream basin volume between the marsh elevation and the design tide.

The results based on use of all criteria (max span resulting from the combined IHHD, PHHD, and Phase lag criteria) are presented for HAsT and HAsT with SLR in Figures 12 and 13. Figure 12 presents the results for marsh area while Figure 13 presents the results for upstream basin volume above the marsh platform. Two variations of the criteria were investigated where V1 is the preliminary set of criteria introduced earlier and V2 lessens the IHHD criteria to where the minimum IHHD is < 1.0 ft. The V2 variation was selected based on it being met by all the sites evaluated in this study. These two variations are shown in Figures 12 and 13. The results presented in Figure 13 for present-day HAsT (top panels) exclude the Cousins River site which was shown to be in outlier.

The results in Figure 12 show the marsh area is fairly well correlated with the selected span size where the preliminary set of criteria (V1 in left panel) produces a lesser correlation in comparison with the revised criteria (V2 in right panel). The R^2 correlation coefficient is shown on the plots in Figure 12 where a value closer to 1.0 indicates a better correlation. The slope of the linear fit is also shown in Figure 12 which indicates the relation between structure span required to have minimally restricted tides and marsh area upstream of a crossing. The required span size (in feet) is 0.56 to 0.65 times the marsh area (in acres) using the V1 criteria and 0.48 times the marsh area using the V2 criteria.

No.	Site Name
1	Long Reach Marsh/Long Reach Lane
2	Cousins River, Yarmouth
3	Back River Creek/Route One
4	Schoppee Marsh
5	Spurwink Marsh/Sawyer Road
6	Small Point Road
7	Thomas Bay Marsh/Adams Road
8	Old Ferry Road
9	Wallace Shore Road
10	Fish Point Road/Pemaquid Beach
11	Drakes Island Rd (west)

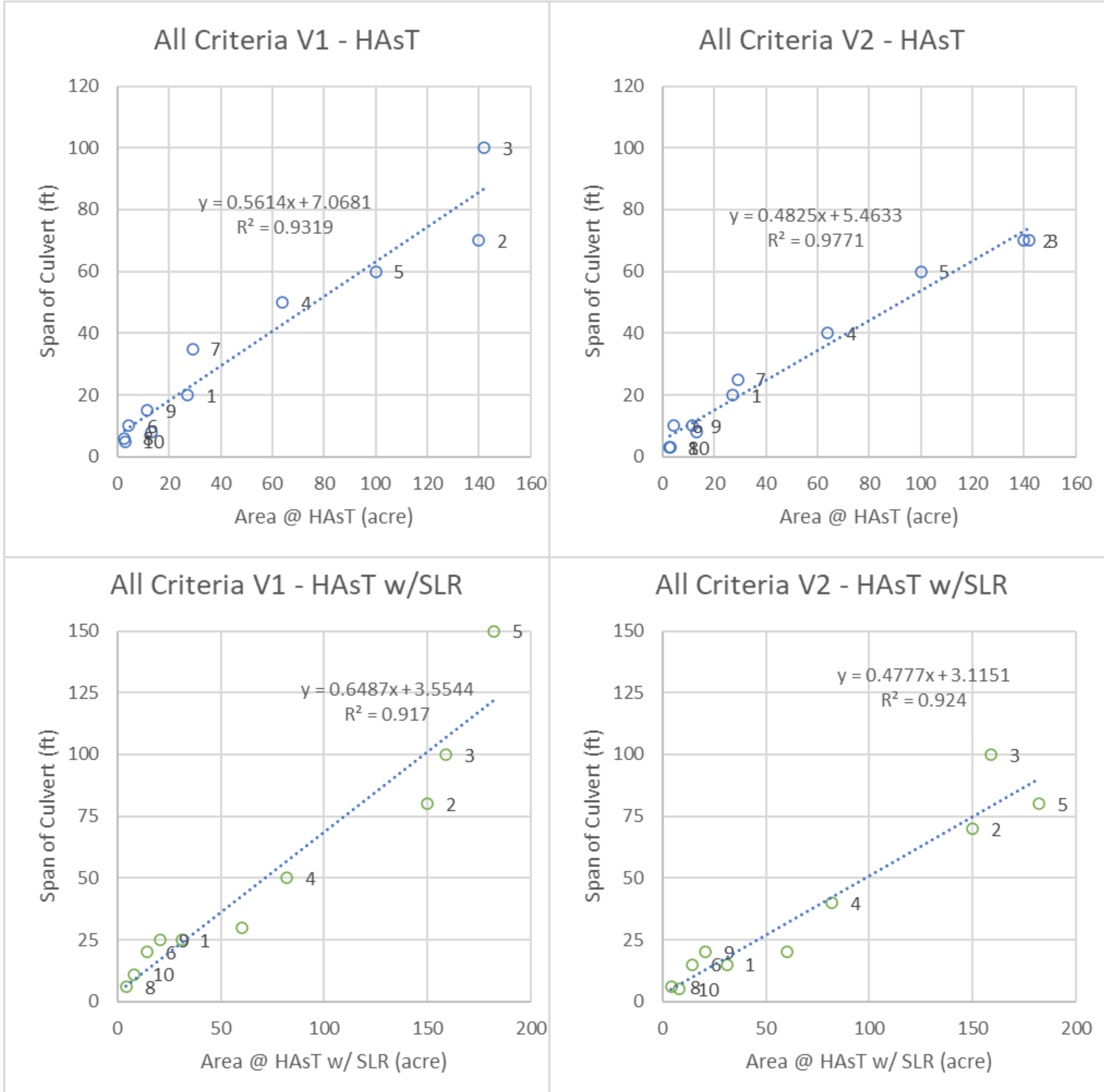


Figure 12. Plots showing area at design tide and the selected structure span based on initial performance criteria (V1,left) and revised set of criteria using IHHD < 1.0 ft (V2,right) at HAsT (top) and HAsT with SLR (bottom)

No.	Site Name
1	Long Reach Marsh/Long Reach Lane
2	Cousins River, Yarmouth
3	Back River Creek/Route One
4	Schoppee Marsh
5	Spurwink Marsh/Sawyer Road
6	Small Point Road
7	Thomas Bay Marsh/Adams Road
8	Old Ferry Road
9	Wallace Shore Road
10	Fish Point Road/Pemaquid Beach
11	Drakes Island Rd (west)

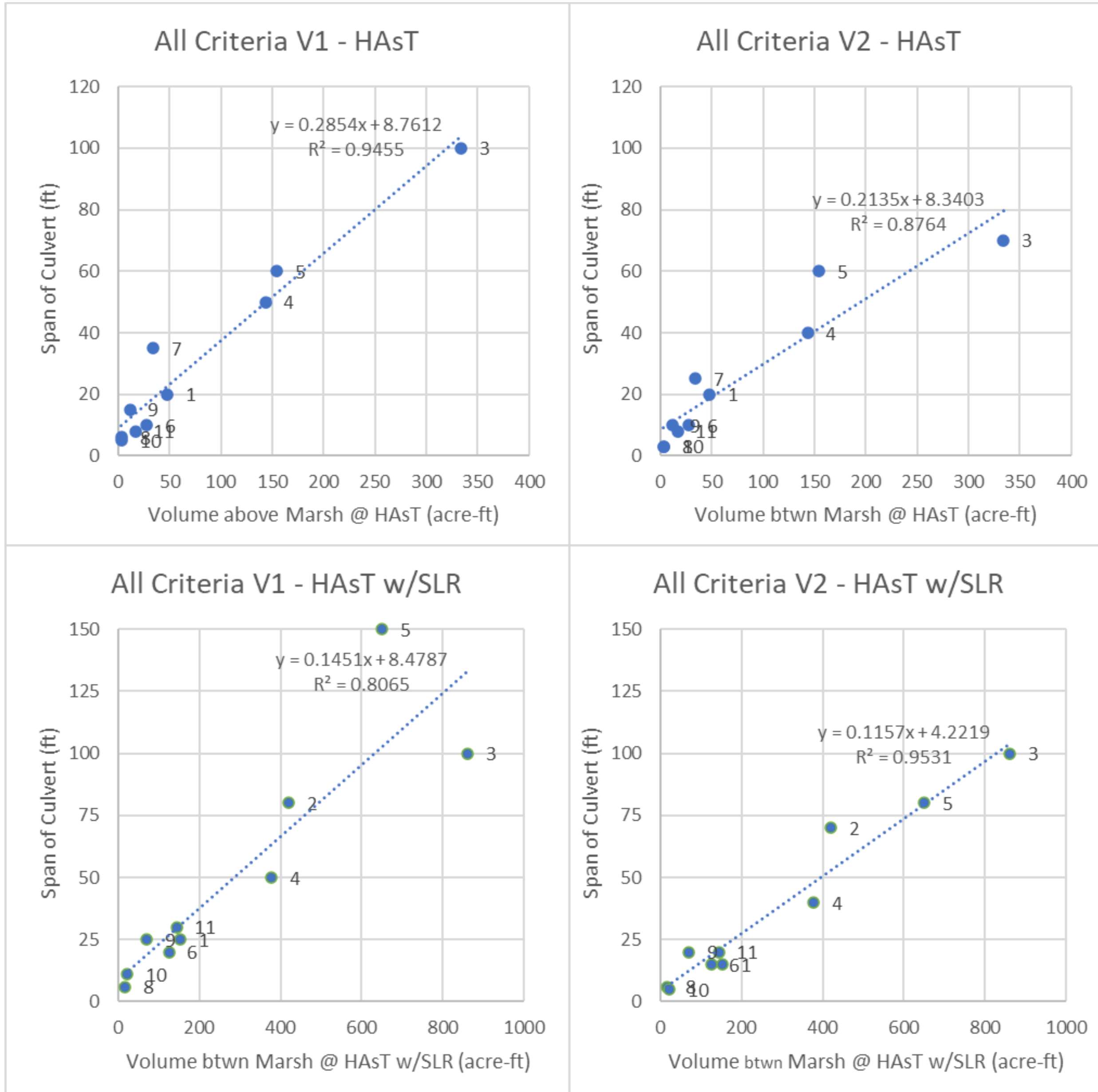


Figure 13. Plots showing basin volume above the marsh elevation at design tide and the selected structure span based on initial performance criteria (V1,left) and revised set of criteria using IHHD < 1.0 ft (V2,right) at HAsT (top) and HAsT with SLR (bottom)

Table 6. Correlation coefficients for the selected spans using variations in the combined performance criteria and different site characteristics.

	Marsh Area at Design Tide		Vol. btwn. Marsh and Design Tide	
Design Tide	All criteria v1	All criteria v2	All criteria v1	All criteria v2
Present-day HAsT	0.9319	0.9771	0.9455	0.8764
HAsT w/ SLR	0.9170	0.9240	0.8065	0.9531

The results in Figure 13 show the basin volume above the marsh platform up to the design tide is also well correlated with the selected span size where the preliminary set of criteria (V1 in left panel) produces a better correlation for present-day HAsT and the revised criteria (V2 in right panel) produces a better correlation for HAsT with SLR.

The correlation coefficients for the 2 sets of combined criteria, 2 site characteristics, and 2 design tides are shown in Table 6 with the highest coefficients highlighted in green. Overall, the marsh area at the design tide is well correlated with the selected span for both design tides using the different variations in criteria. The basin volume between the marsh platform and design tide was more correlated with the selected span for HAsT with SLR vs. present-day HAsT. The V2 criteria generally produces a better correlation coefficient among the evaluated variations.

The correlation coefficients for the individual criteria, 2 site characteristics, and 2 design tides are shown in Table 7 with coefficients above 0.9 highlighted in green. Figures 14 and 15 show the plots for the individual criteria .

Table 7. Correlation coefficients for the selected spans using the individual performance criteria and different site characteristics.

	Marsh Area at Design Tide				Vol. btwn. Marsh and Design Tide			
Design Tide	Span IHHD < 0.5 (ft)	Span PHHD < 0.1 (ft)	Span LAG < 15 min (ft)	Span IHHD < 1.0 (ft)	Span IHHD < 0.5 (ft)	Span PHHD < 0.1 (ft)	Span LAG < 15 min (ft)	Span IHHD < 1.0 (ft)
Present-day HAsT	0.9286	0.9609	0.9547	0.8432	0.9409	0.9142	0.8354	0.8791
HAsT w/ SLR	0.9170	0.9527	0.9426	0.9415	0.8065	0.8307	0.8785	0.9164

The results indicate for present-day HAsT, the PHHD and Phase lag criteria produce span sizes that are most correlated with the marsh area, although the IHHD < 0.5 ft criteria also shows good correlation. For present-day HAsT, the basin volume above the marsh platform shows a lesser correlation using the Phase Lag criteria while the IHHD < 0.5 ft criteria shows the best correlation. This appears to be attributed to three of the larger-sized basins (Cousins River, Schoppee Marsh, and Back River) where other system factors contribute to tidal attenuation in the upstream basin and in these cases, the more stringent IHHD criteria may be considered better to use.

For the design tide with SLR, the marsh area is also well correlated with selected spans with the PHHD, Phase lag, and IHHD < 1.0 ft criteria producing the best results. There is less correlation with basin volume in this scenario, although the lessened IHHD < 1.0 ft criteria produces a good correlation and Phase lag also has a correlation close to 0.9. In this scenario with a higher depth of flow within the structure the IHHD values will be larger due to increased energy losses, so a lessened IHHD criteria may be more appropriate as indicated with the higher correlation.

No.	Site Name
1	Long Reach Marsh/Long Reach Lane
2	Cousins River, Yarmouth
3	Back River Creek/Route One
4	Schoppee Marsh
5	Spurwink Marsh/Sawyer Road
6	Small Point Road
7	Thomas Bay Marsh/Adams Road
8	Old Ferry Road
9	Wallace Shore Road
10	Fish Point Road/Pemaquid Beach
11	Drakes Island Rd (west)

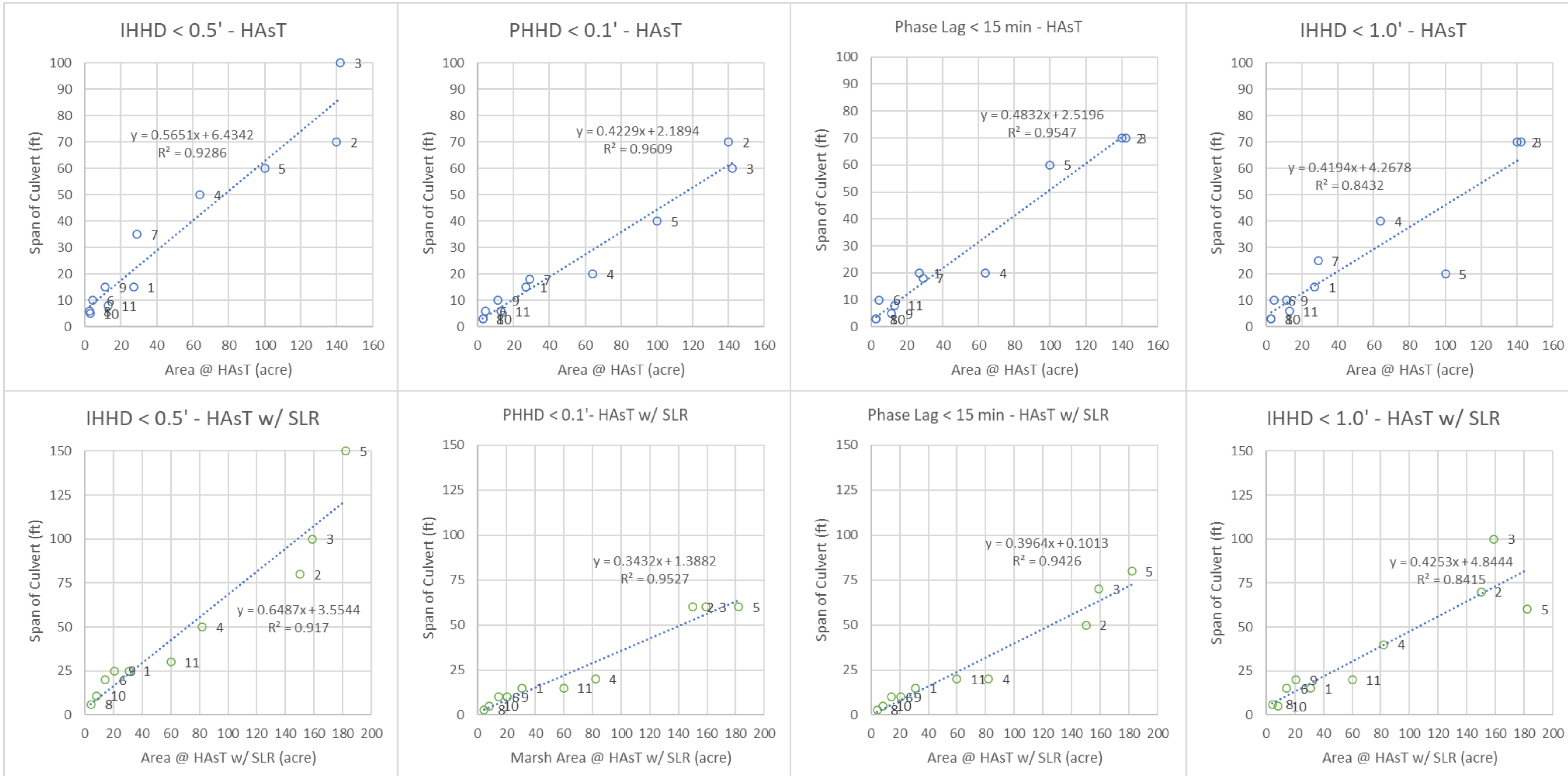


Figure 14. Plots showing area at design tide and the selected structure span based on individual performance criteria for HAsT (top) and HAsT with SLR (bottom).

No.	Site Name
1	Long Reach Marsh/Long Reach Lane
2	Cousins River, Yarmouth
3	Back River Creek/Route One
4	Schoppee Marsh
5	Spurwink Marsh/Sawyer Road
6	Small Point Road
7	Thomas Bay Marsh/Adams Road
8	Old Ferry Road
9	Wallace Shore Road
10	Fish Point Road/Pemaquid Beach
11	Drakes Island Rd (west)

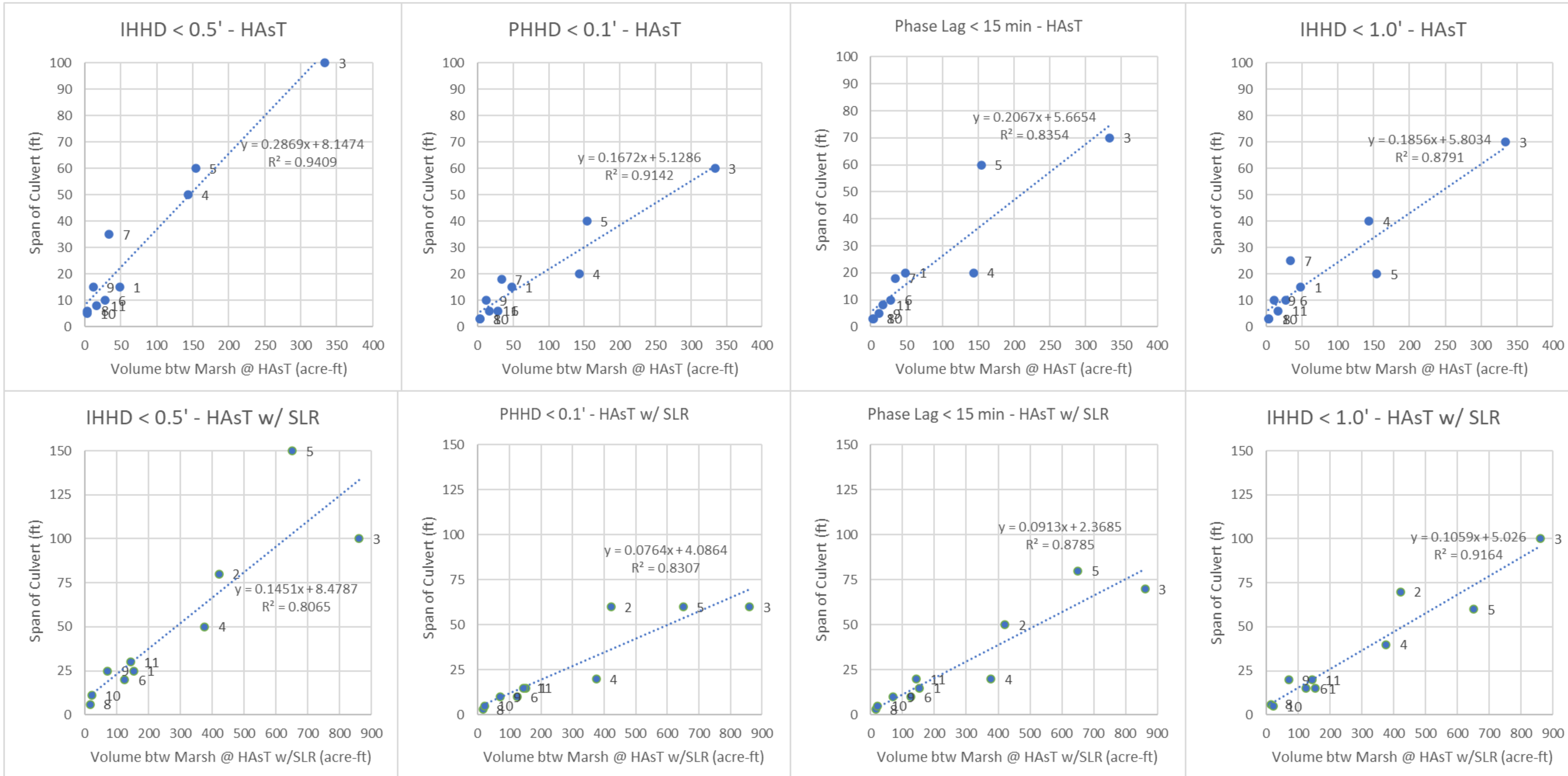


Figure 15. Plots showing basin volume between the marsh elevation and design tide vs. the selected structure span based on individual performance criteria for HAsT (top) and HAsT with SLR (bottom)

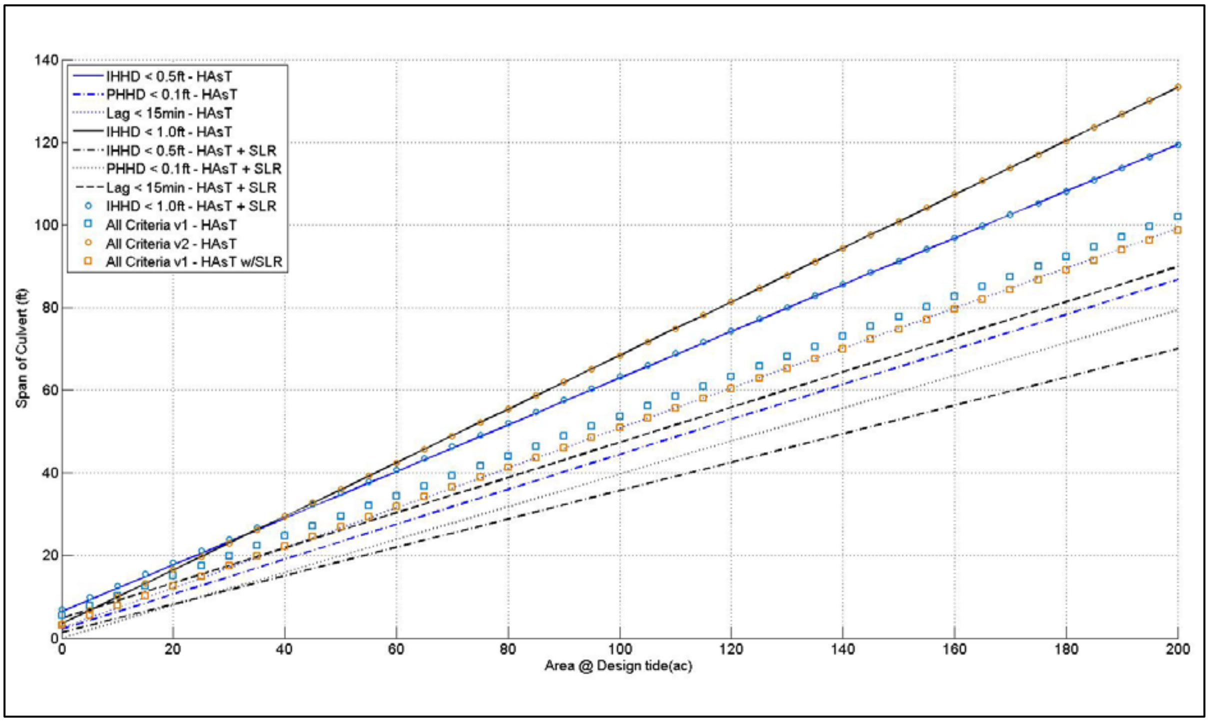


Figure 16. Comparison of linear trends for area at design tide vs. the selected structure span based on individual and combined performance criteria (both HAsT and HAsT with SLR)

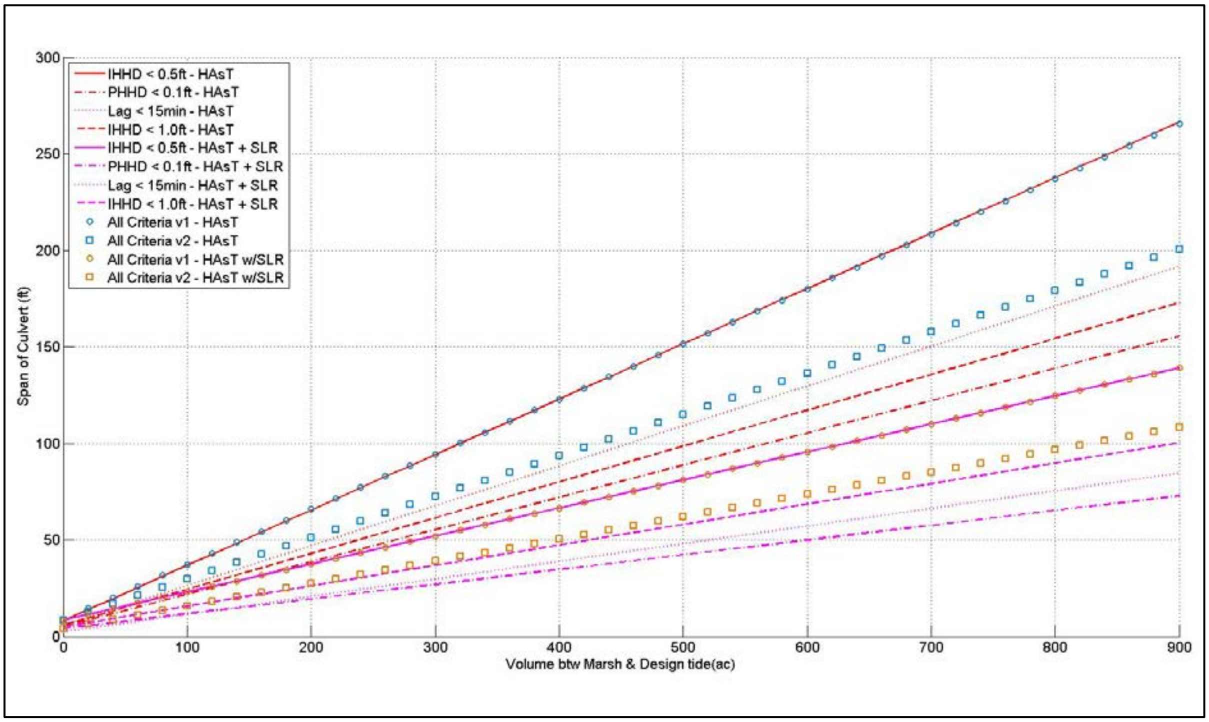


Figure 17. Comparison of linear trends for volume between marsh elevation and design tide vs. the selected structure span based on individual and combined performance criteria (both HAsT and HAsT with SLR)

A comparison of all the linear trends for the area at design tide and the selected structure span based on combined and individual performance criteria is provided in Figure 16 for both HAsT and HAsT with SLR. The main observations made in reviewing these comparisons are:

1) There is some consistency between both HAsT and HAsT w/ SLR design scenarios as shown by All Criteria V2 (both having a correlation above 0.9), although the range in the structure spans between all the trends is rather significant (~20-foot range in spans for an area of 60 acres).
2) The IHHD < 0.5' criteria is generally more stringent and produces larger span sizes.
3) It is evident for the HAsT scenario, the Phase Lag < 15 min criteria produces a trend most consistent with All Criteria v2.
4) For the SLR case, IHHD < 1.0' criteria produces a trend most similar to All Criteria v2. The PHHD and Phae lag criteria produce trends resulting in smaller spans.
5) If these relationships are to be used, the trends for All Criteria v2 are recommended.

The same comparison of linear trends is provided in Figure 17 for volume between the marsh and design tide versus the selected structure span for both HAsT and HAsT with SLR. The main observations made in reviewing these comparisons are:

6) There is less consistency and a large range in the structure spans between all the trends (i.e., ~50-foot range in spans at a volume of 200 ac-ft). This gives an indication that the volume above the marsh platform is not well correlated with the selected spans.
7) It is evident the trends for HAsT and HAsT with SLR are not consistent, so there is not a linear relationship between an increase in volume with depth and the span size needed. It should be noted that 3 of the larger sites evaluated had large increases in volume with the added SLR and less of a change in area.
8) If these relationships are to be used, the HAsT trends are more conservative.

5.0 Conclusions & Recommendations

Based on the results of the sizing criteria study, the following conclusions and recommendations can be made. Input from the CWSC is needed before incorporating any tidal crossing performance criteria recommendations in the CW tidal crossing design guidelines document.

- It is suggested that a combination of criteria be used for sizing a crossing structure including PHHD, phase lag, and IHHD.
- The preliminary criteria defined in this study appear to be reasonable although IHHD < 0.5 ft was not met for all of the evaluation sites. Small values of IHHD (< 0.5 ft) may be hard to achieve for large marsh systems, especially for the design tide with added SLR. The IHHD criteria may need to be adjusted based on the project objectives, limitations, or feasibility.
- Sensitivity to culvert roughness is more apparent in 0-D models and less important in 1-D and 2-D models where other system factors are represented and play a more significant role in a crossing's tidal hydraulics.
- Incorporation of future accretion does affect the results in that it reduces IHHD and the required span based on a set of criteria.[10] Not accounting for accretion will provide some level of assurance (or safety factor) that a crossing structure is appropriately sized for a future condition with an increased sea level, especially since the prediction of sea level rise and associated accretion have substantial uncertainty. If

[10] This also highlights the importance of proper verification and ground-truthing of marsh surface elevation data (i.e., LiDAR) used in any modeling study. As detailed in the Coastwise Manual, the use of LiDAR can be problematic if there is a positive elevation bias due to dense marsh vegetation which, if not corrected, can result in smaller design span.

including accretion, it should be based on measured accretion rates in the region. However, the potential for negative accretion or conversion of salt marsh to tidal flat should also be considered for each site.

- Design tides w/ SLR requires larger spans to meet the specific criteria vs. the present-day HAsT. The selection of a SLR scenario will therefore drive the resultant span selected for a tidal crossing site using CW guidance. Given the uncertainty associated with SLR and potential accretion, consideration should be given to the amount of conservatism that is appropriate for a specific crossing. For example, selecting the highest SLR scenario and not accounting for potential marsh accretion would be a conservative approach resulting in a structure size that accommodates a level of uncertainty.
- The size of the upstream basin, elevation of the marsh platform, and connectivity to other basins affect the ability to meet performance criteria, particularly IHHD. It is thus important to include all upstream areas subject to future flooding in a modeling study/sizing evaluation.
- Based on the sites evaluated, the size of watershed and the use of an average freshwater inflow does not affect the ability to meet performance criteria.
- Other aspects of the tidal system may influence the ability to meet performance criteria due to their complexity (i.e., multiple inlets, gates, upstream/downstream crossings, etc.). To solely assess the tidal crossing structure being replaced, any upstream/downstream crossings and/or tidal gate structures should be removed or opened to no longer pose a restriction in a modeling study/sizing evaluation. The closure of other inlets should be considered for the sizing evaluation if there is the potential for that in the future.
- The amount of uncertainty that exists within the model including model skill, input data, and other undefined errors should be considered when determining whether performance criteria are met. For example, if the model or survey error is shown to be 0.2 feet, than agreement with performance criteria within 0.1 feet may be considered acceptable. If the model is biased in any way, that should also be considered when trying to meet a set of specified performance criteria.
- Additional tidal attenuation can occur upstream of a tidal crossing due to other natural system factors (i.e., frictional effects of marsh sheet flow). This can be quantified using a detailed 1-D or 2-D model approach and should be considered when evaluating a structure size for meeting performance criteria[11]. If the upstream basin is rather confined with steep slopes, this natural tidal attenuation may be reduced with an increase in sea level. Other system factors may come into play, however, and contribute to the upstream tidal attenuation such as an increased inundation extent, flow through other types of vegetation/land use, etc.
- In evaluating the correlation between site characteristics and selected spans based on a combined set of performance criteria, the marsh area at the design tide was found to be well correlated for both present-day and future SLR conditions.
- The basin volume between the marsh elevation and the design tide was found to have good correlation with selected spans for the future SLR condition, especially with the lessened IHHD < 1.0 criteria, but was not well correlated for the present-day design tide using the Phase lag criteria. This indicates the value of utilizing a combined set of criteria, as IHHD in some cases may be a better indicator of tidal transparency (unrestricted tides).

[11] Further guidance on considerations for selecting an appropriate model type can be found in the Coastwise Manual.

Appendix A – List of model types used for tidal crossing sites and model assumptions

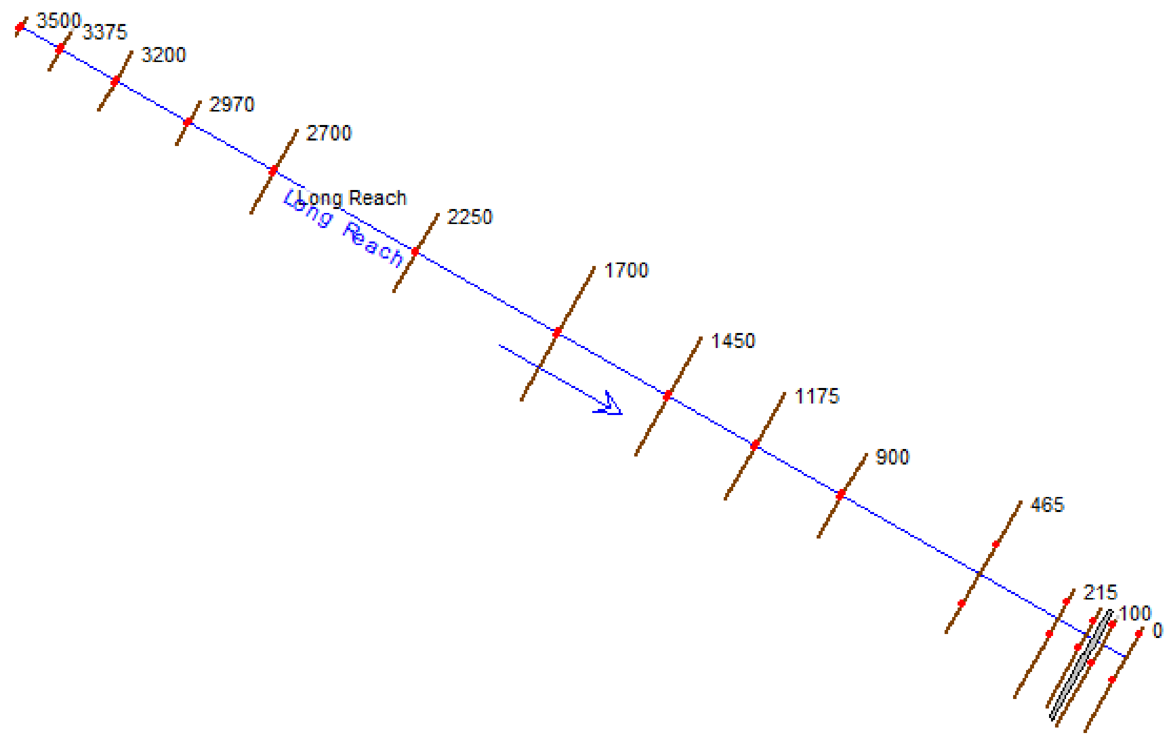
No.	Site Name	Town	0-D mode	1-D model	2-D model	Measured Tide Data	System Type
1	Long Reach Marsh/Long Reach Lane	Harpswell	Y -new	Y - existing HECRAS		Y	Salt marsh, no riverine input
2	Cousins River, Yarmouth	Yarmouth			Y - existing SRH	Y	Salt marsh
3	Back River Creek/Route One	Woolwich	Y -new		Y - existing SRH	Y	Brackish/fresh marsh, minor riverine input
4	Schoppee Marsh	Machias			Y - existing HECRAS	Y	Salt marsh, little to no riverine input
5	Spurwink Marsh/Sawyer Road	Cape Elizabeth	Y -new	Y - existing HECRAS		Y	Salt marsh, long low elevation causeway
6	Small Point Road	Phippsburg		Y - existing HECRAS		Y	Salt marsh
7	Thomas Bay Marsh/Adams Road	Brunswick	Y -new	Y - existing SWMM		Y	Salt marsh
8	Old Ferry Road	Wiscasset	Y -new	Y - new		Y	Salt marsh
9	Wallace Shore Road	Harpswell			Y - new	Y	Salt marsh
10	Fish Point Road/Pemaquid Beach	Bristol	Y -new	Y - new		Y	Salt marsh
11	Drakes Island Rd (west)	Wells	Y -new	Y - new		Y	Salt marsh, minor riverine input

Modeling Assumptions:

1. Design tide –HAsT, Highest Astronomical Tide (Source: MGS)
2. Design SLR – 3.6 feet (Intermediate, central estimate for 2100)
3. For all scenarios, the low chord/culvert obvert elevation is set above highest design tide. The roadway is also elevated to prevent any overtopping.
4. Removed any vertical restrictions within the channels (where appropriate) and lowered the culvert inverts to match the upstream and downstream channel elevation.
5. Hydraulic opening sizing analyses assumes concrete box culverts with Manning's n = 0.014
6. 0-D model has single parameter to account for frictional effects (Manning's n)
7. Mean annual riverine discharge is applied in the models (where applicable)
8. If possible, use same terrain/LiDAR datasets between 0-D / 1-D / 2-D models for consistency
9. Model input and output water levels at an interval of 6 minutes or less

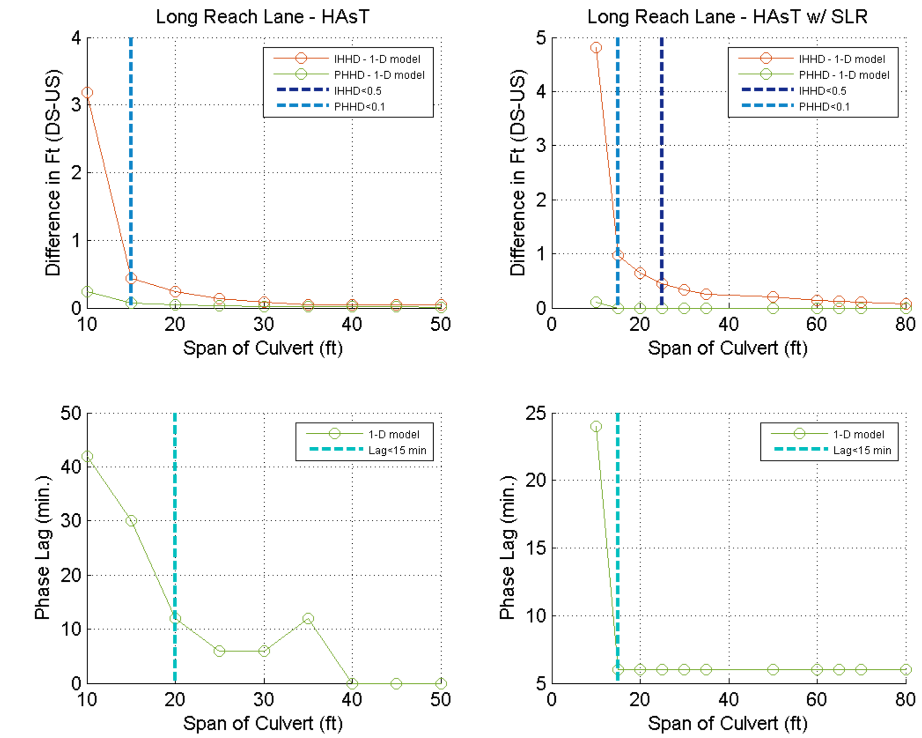
Appendix B – Performance Curves and Time Series Figures – All sites

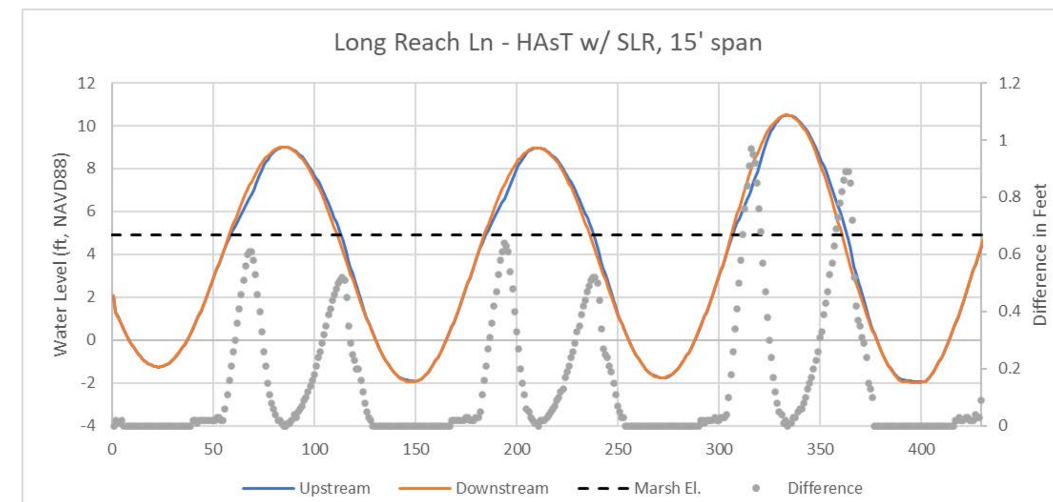
Site 1 – Long Reach Lane

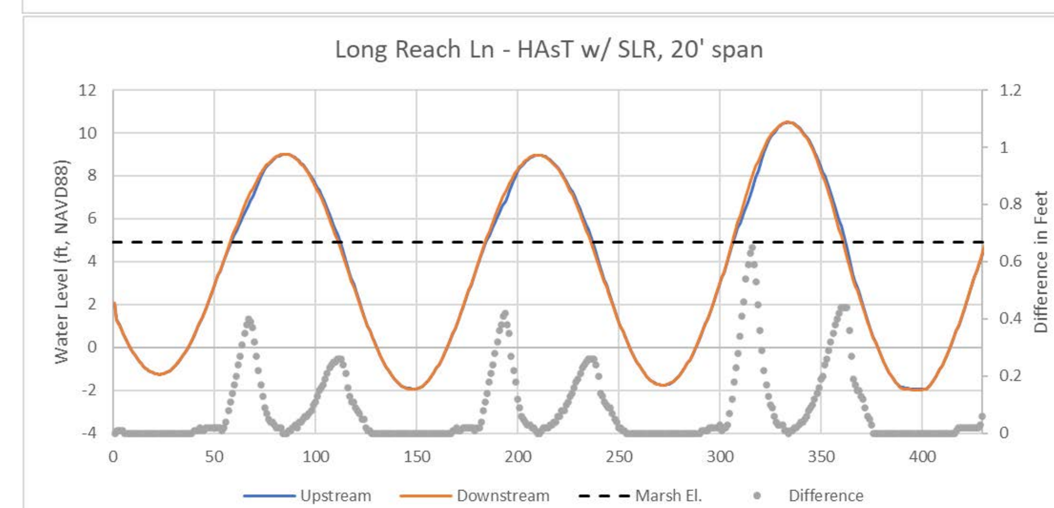


1-D HEC-RAS Model

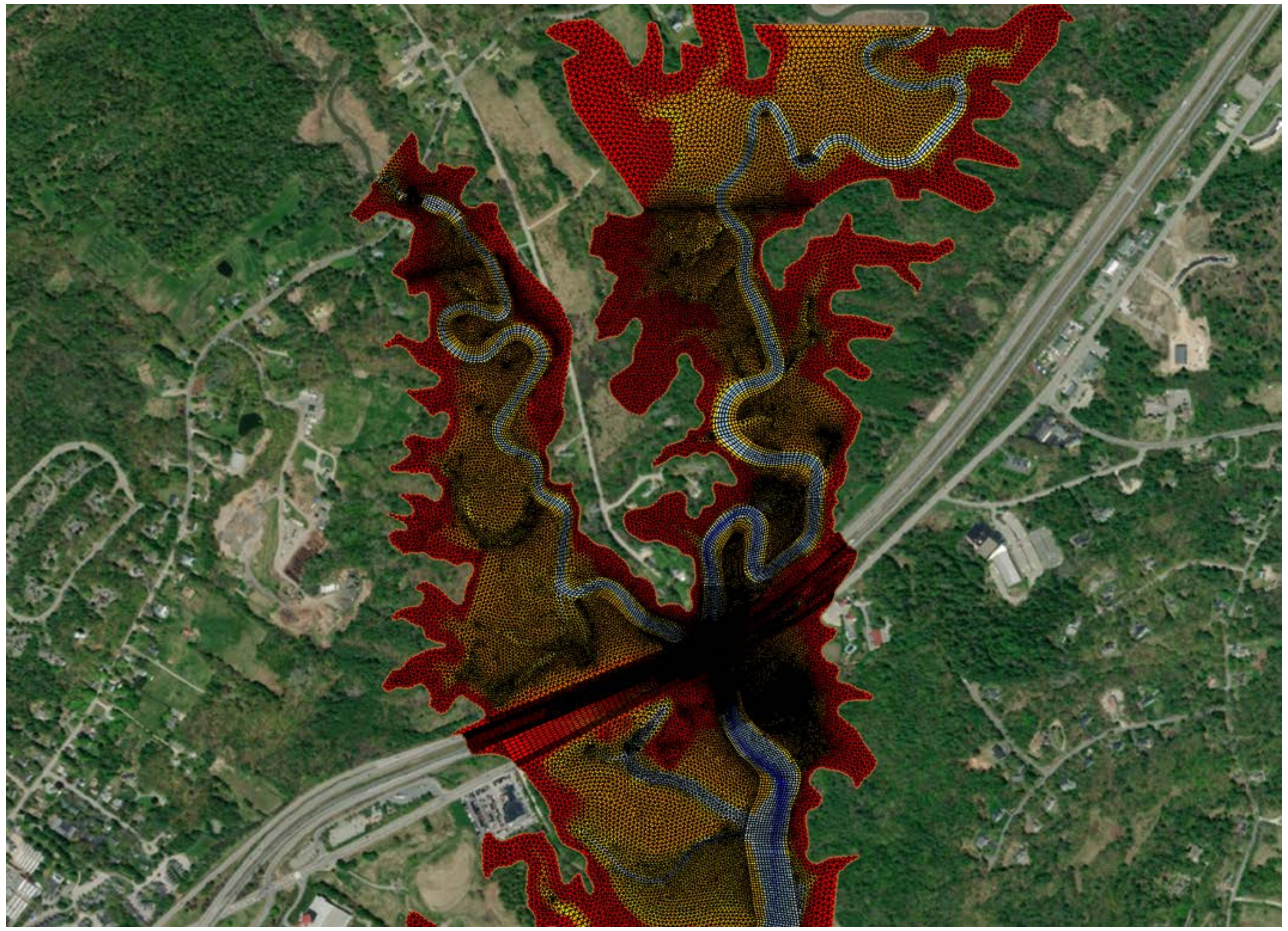
Existing 12-ft span opening





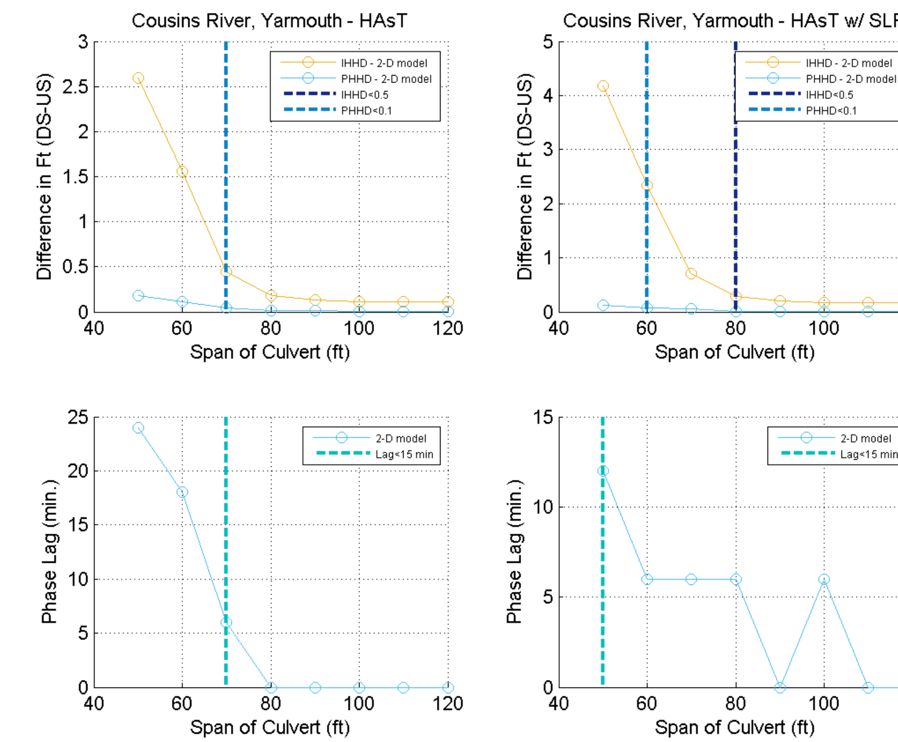


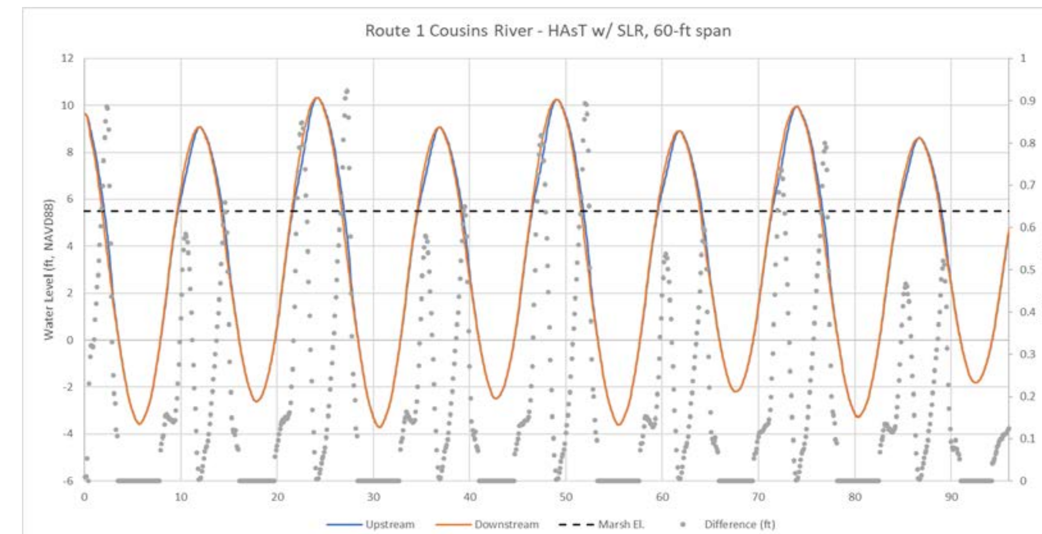
Site 2 – Route 1 Cousins River, Yarmouth

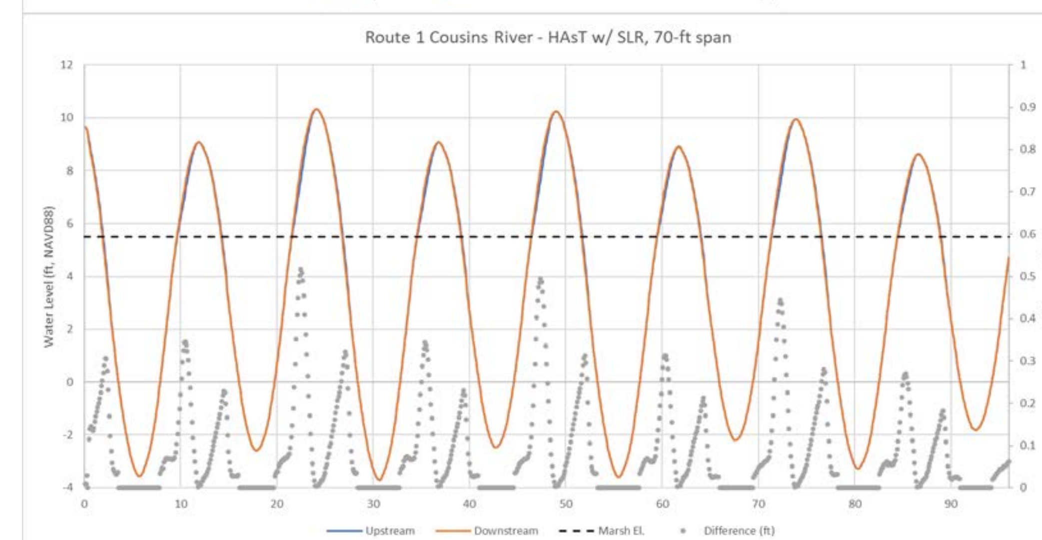


2-D SRH Model

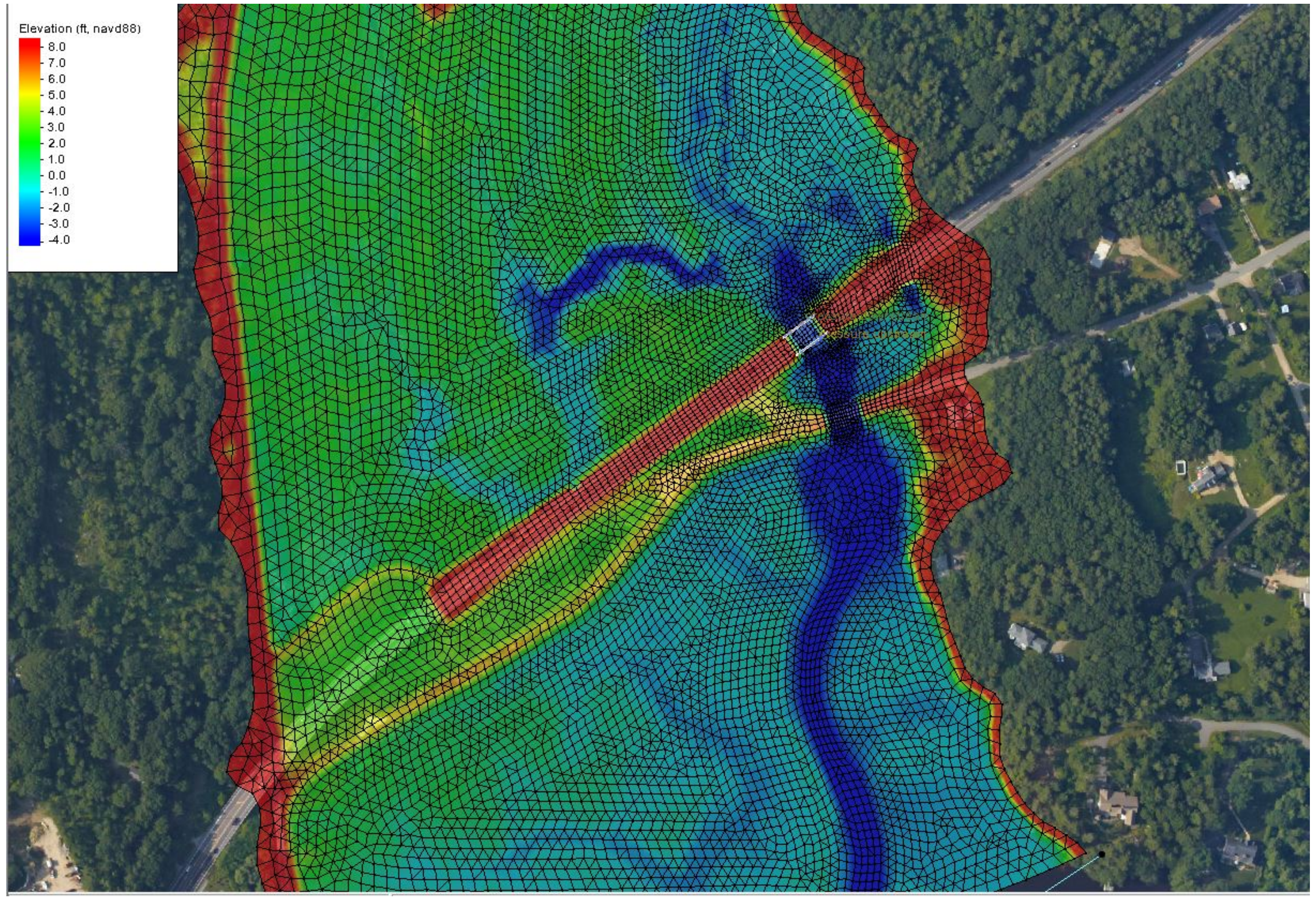
Existing 50-ft span opening





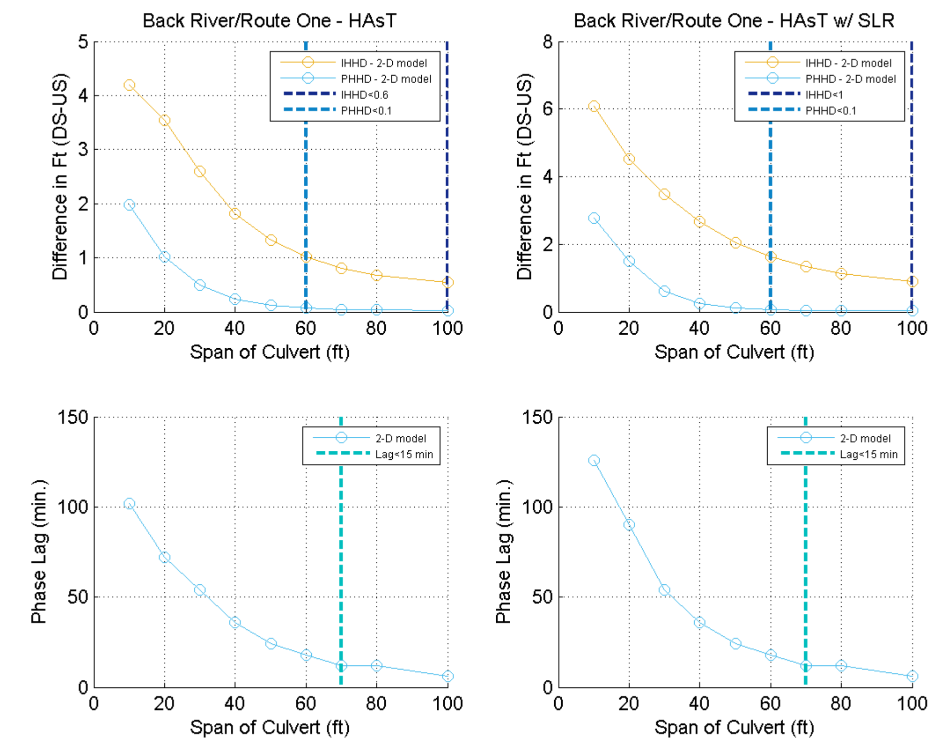


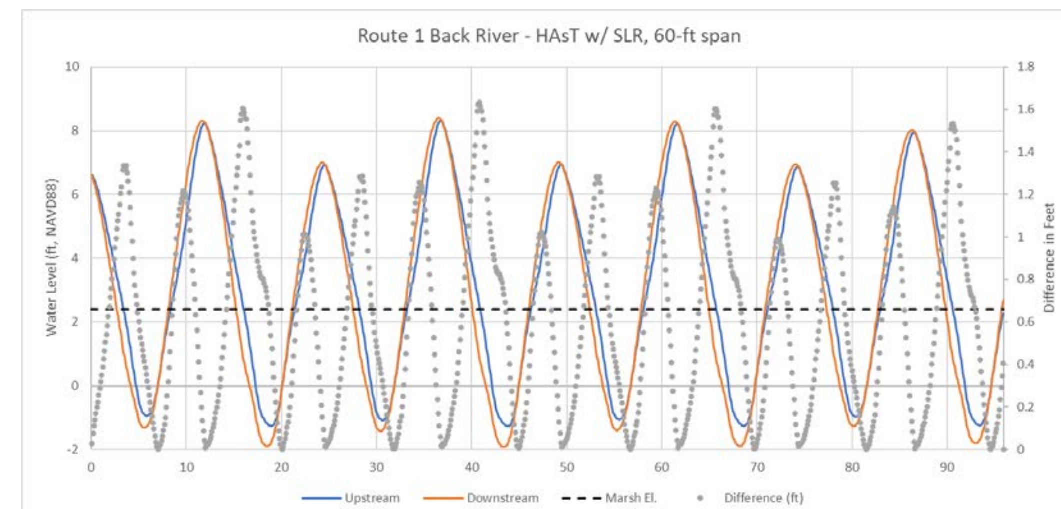
Site 3 – Route 1 / Back River

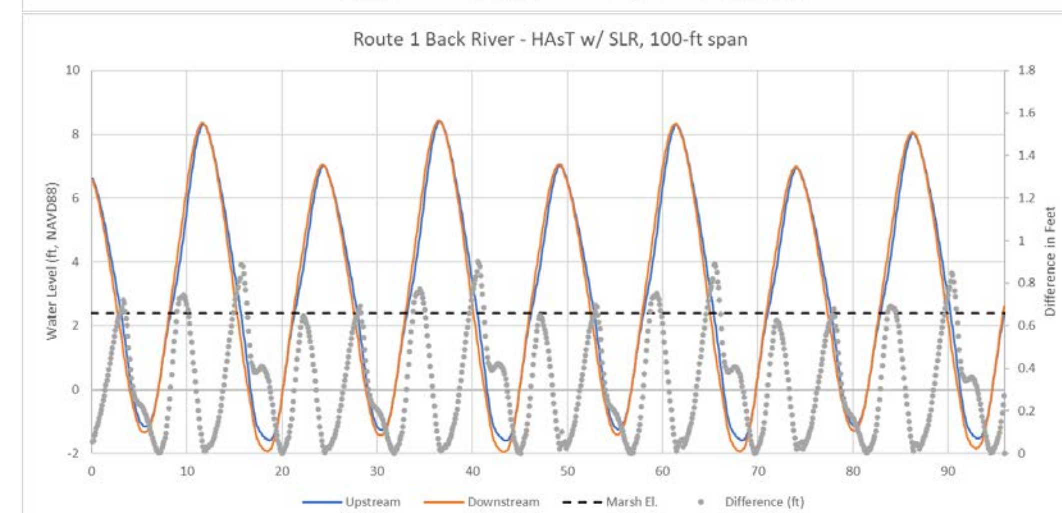


2-D SRH Model

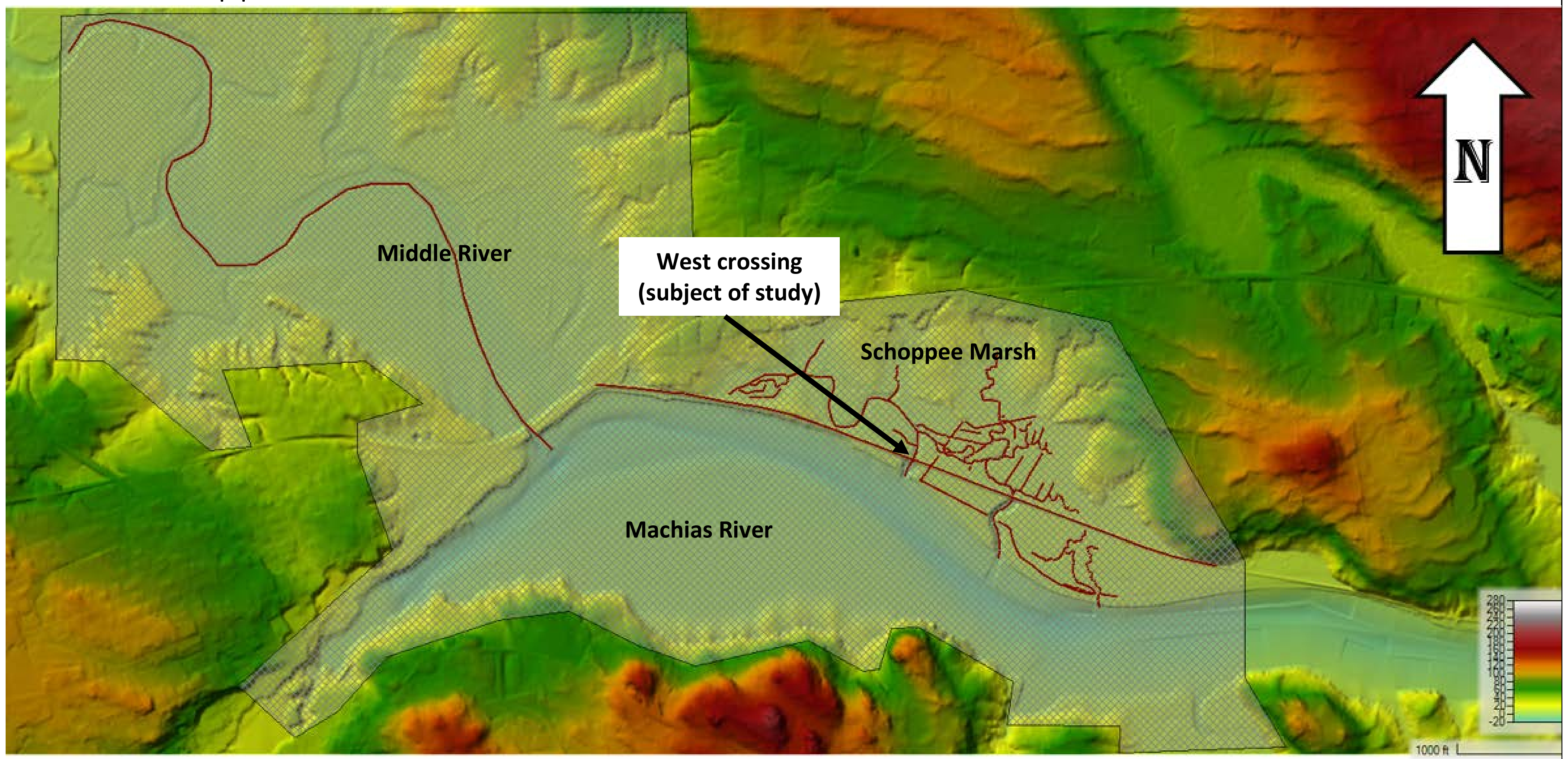
Existing 6-ft diameter culvert





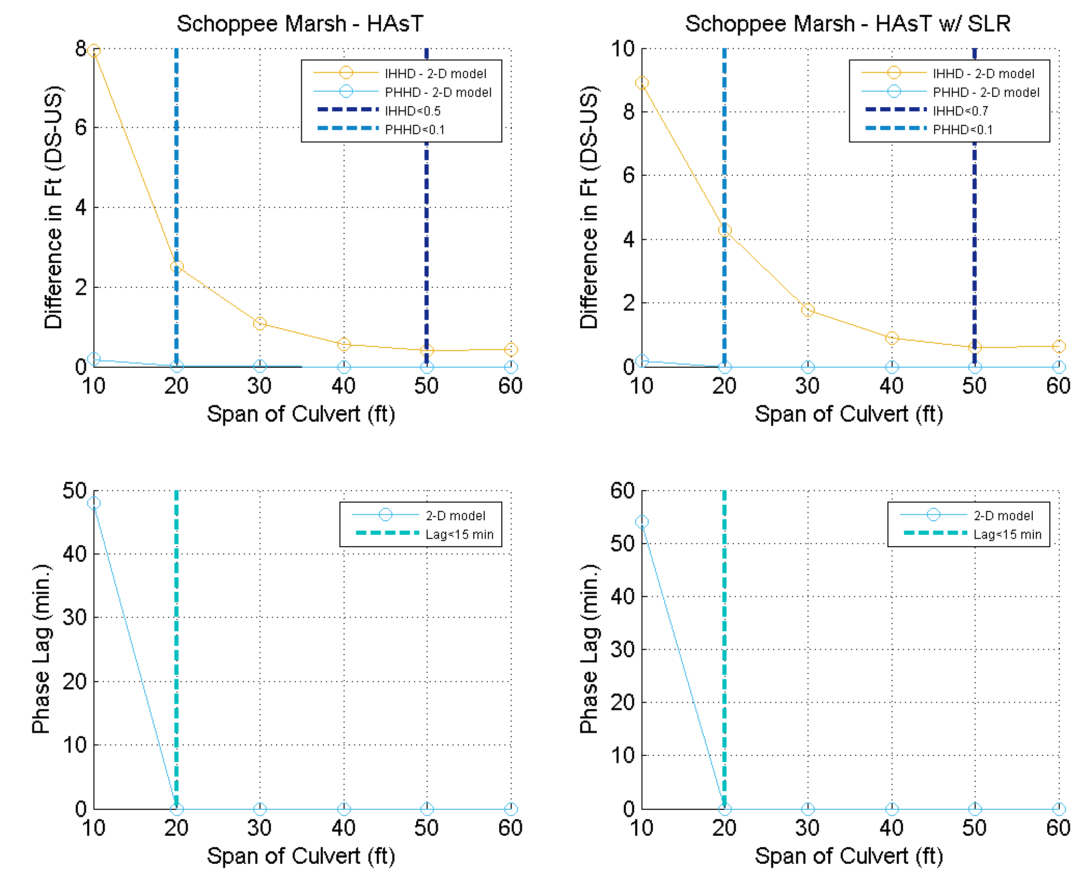


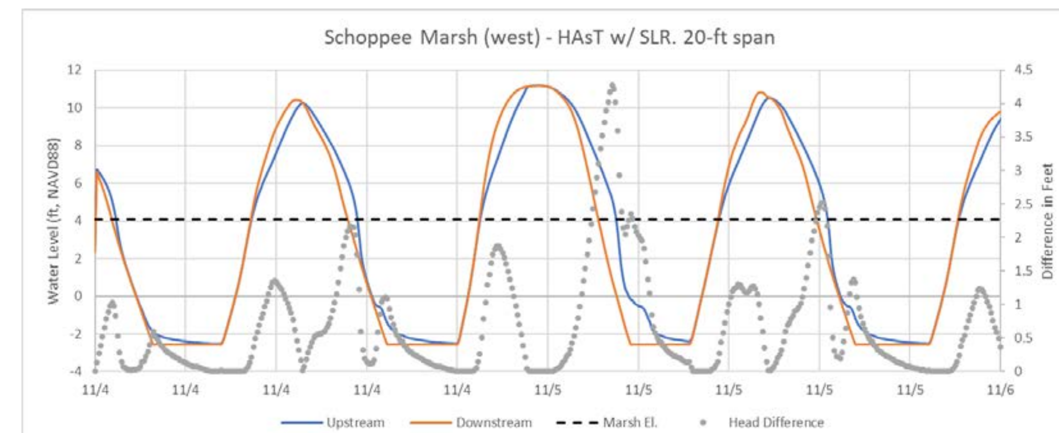
Site 4 – Schoppee Marsh

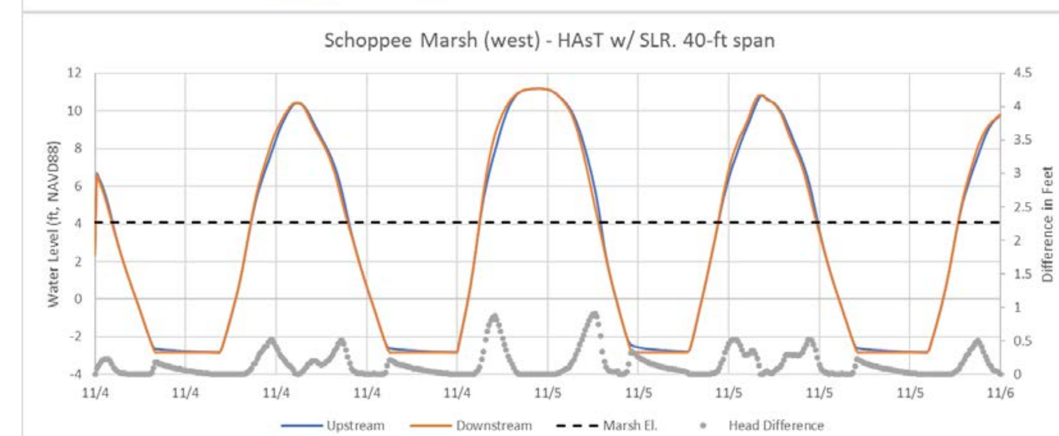


2-D HEC-RAS Model

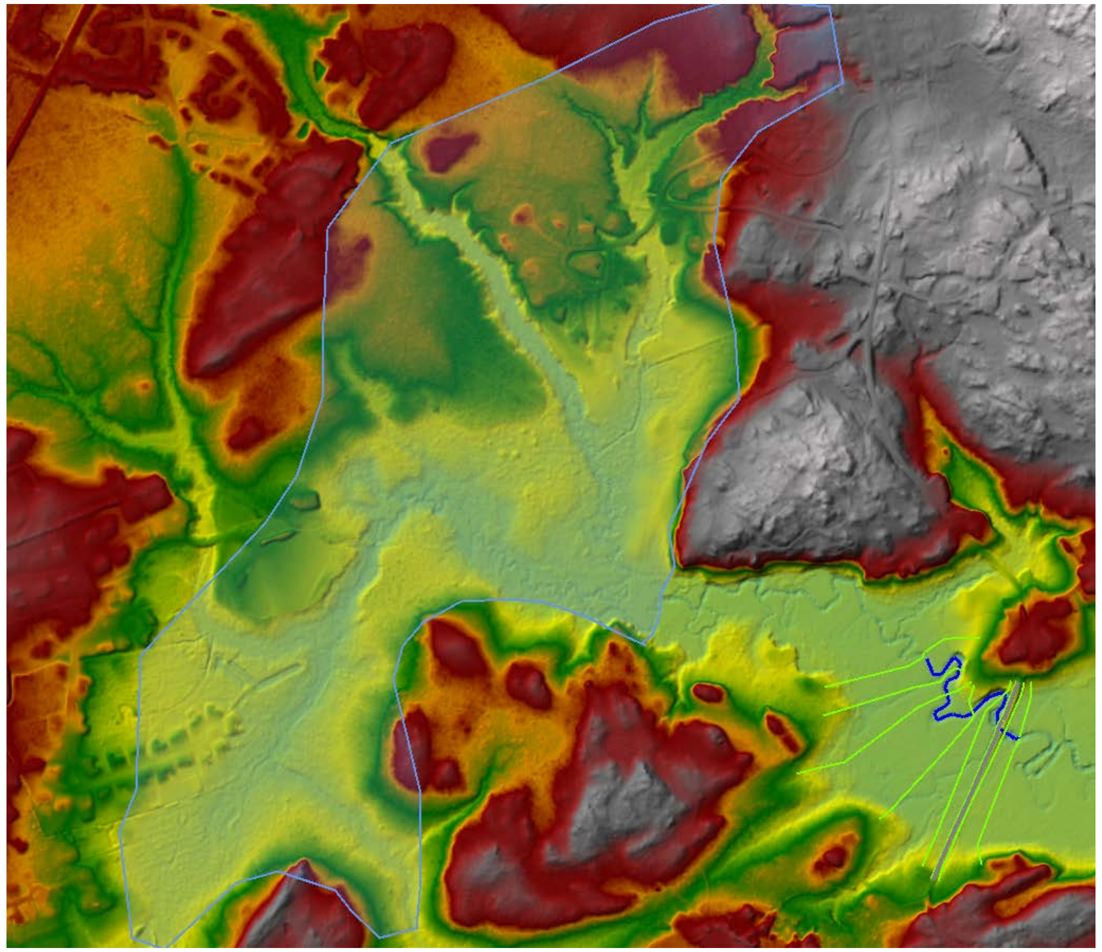
Existing 3-ft diameter culvert





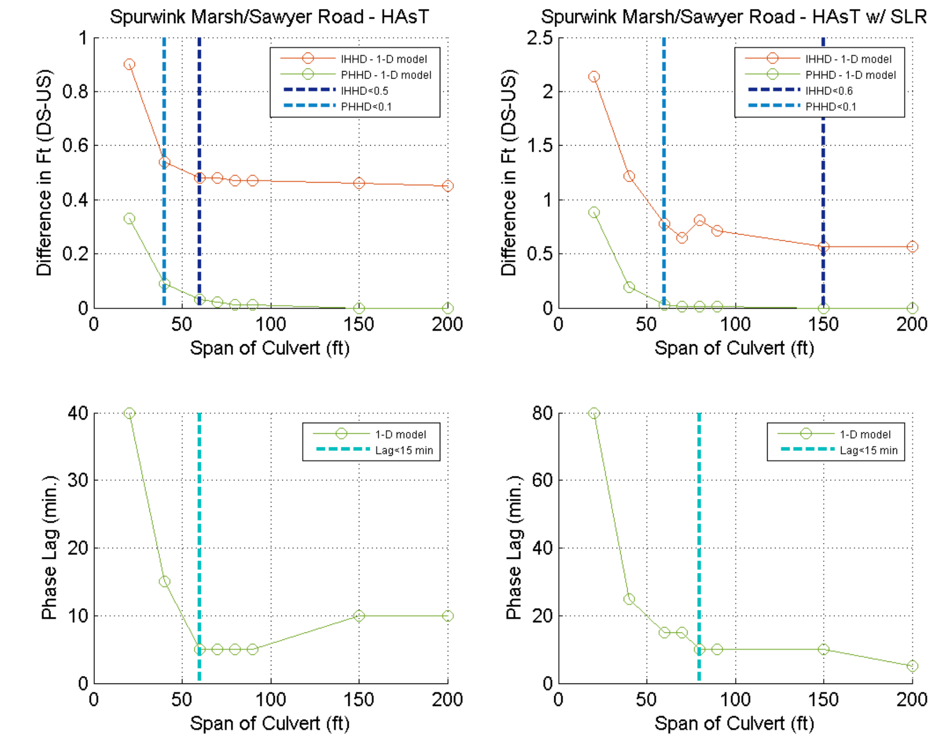


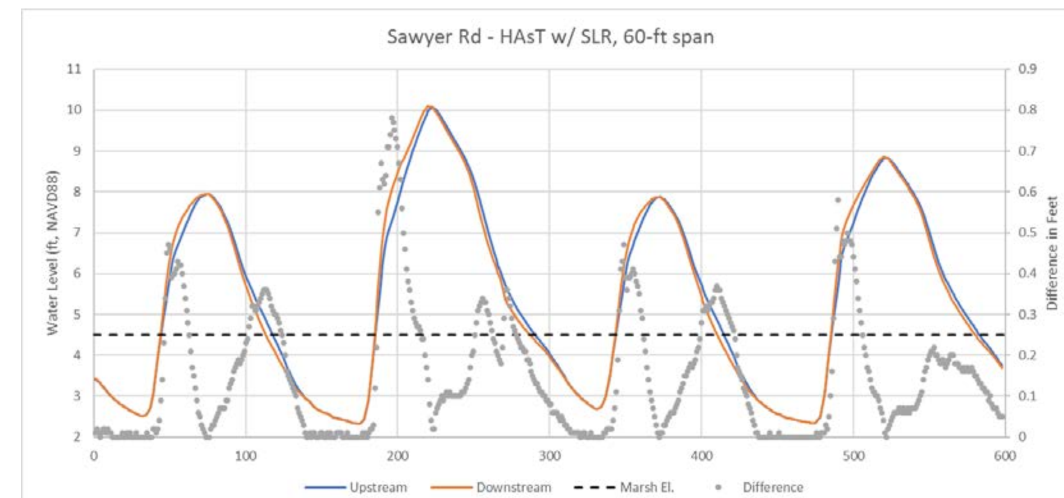
Site 5 – Sawyer Rd / Spurwink Marsh

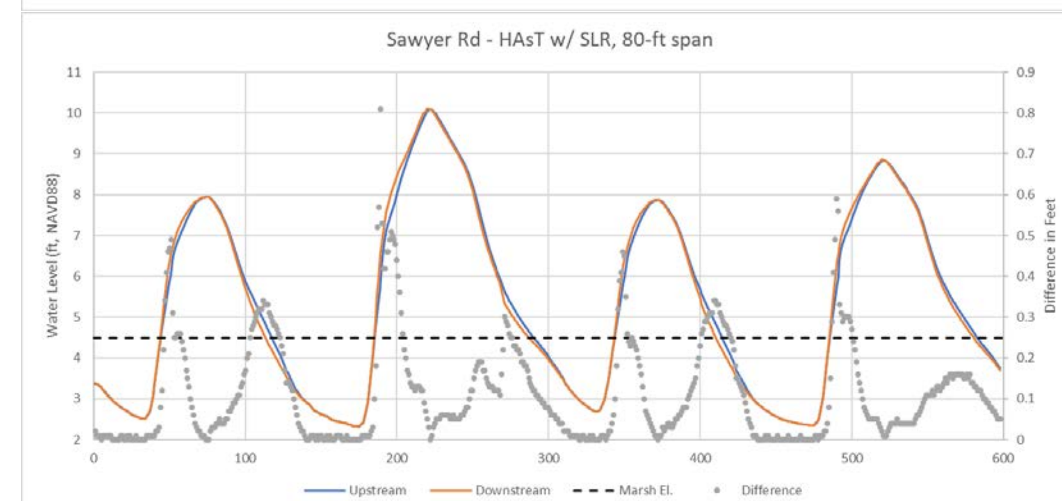


1-D HEC-RAS Model

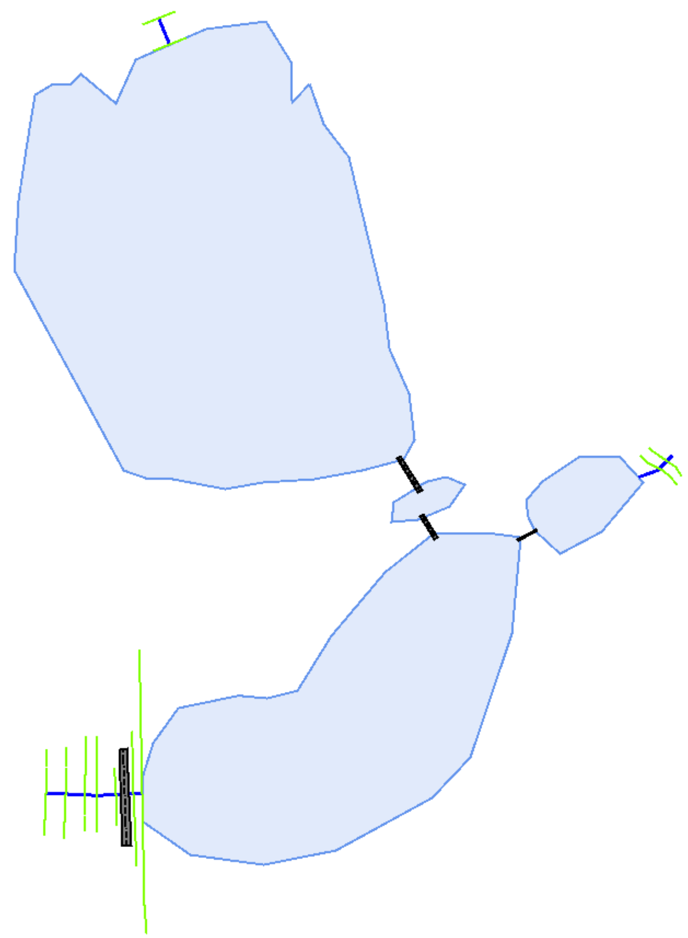
Existing 12-ft span culvert structure





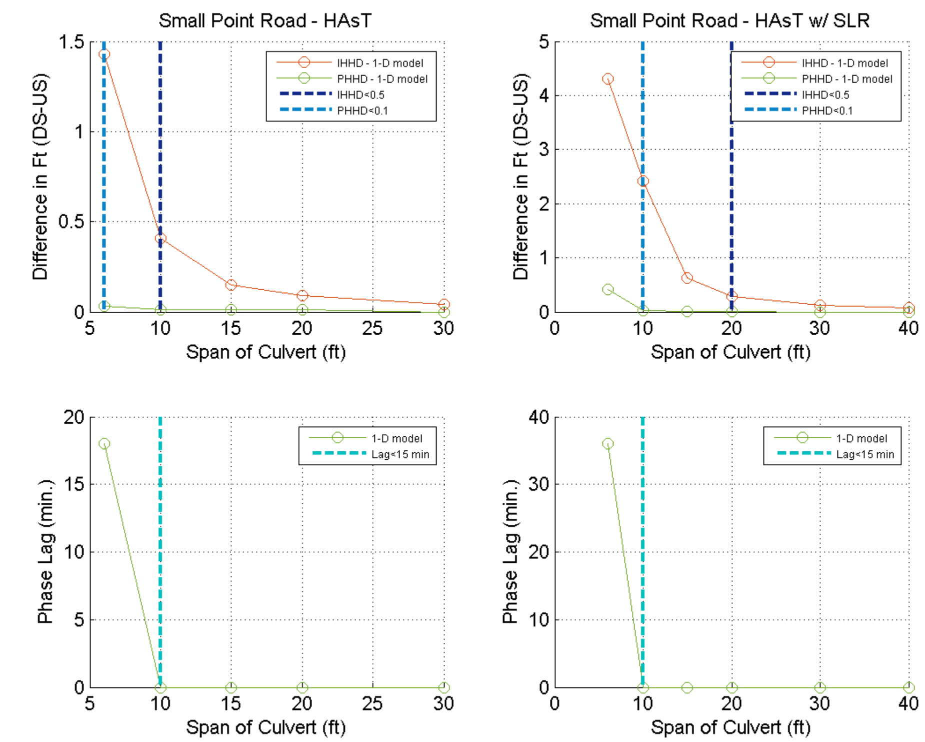


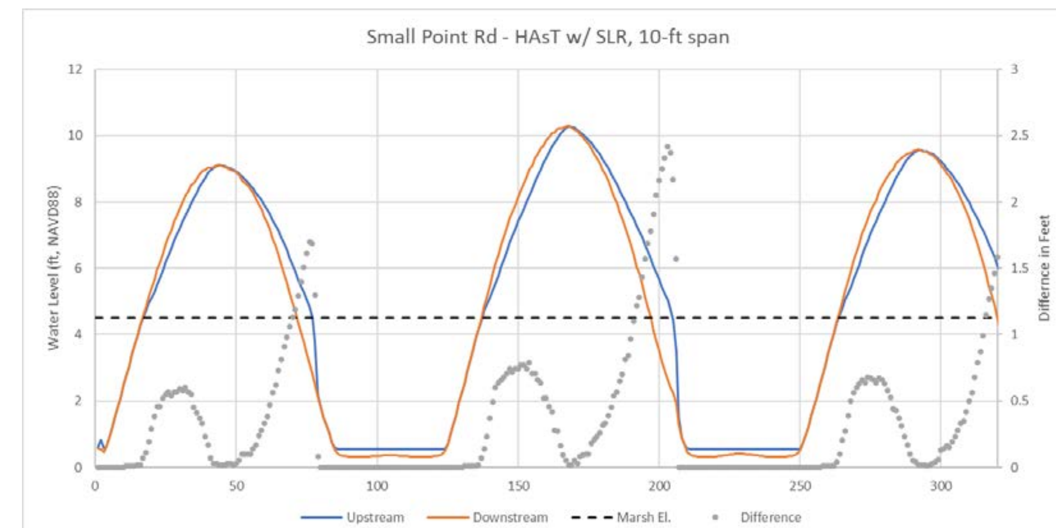
Site 6 – Small Point Rd, Phippsburg, ME

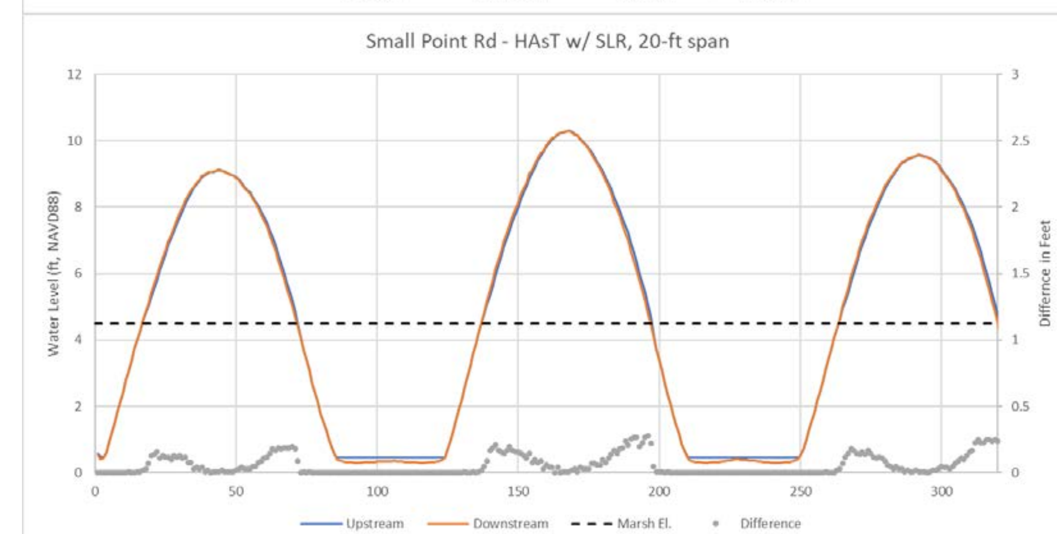


1-D HEC-RAS Model

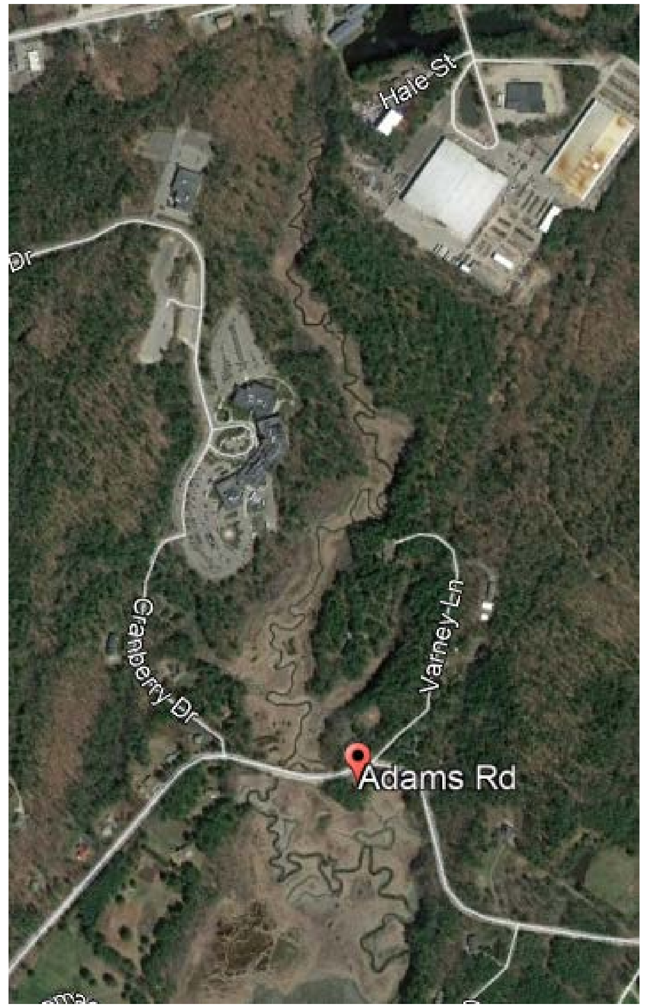
Existing ~2-ft span culvert structure



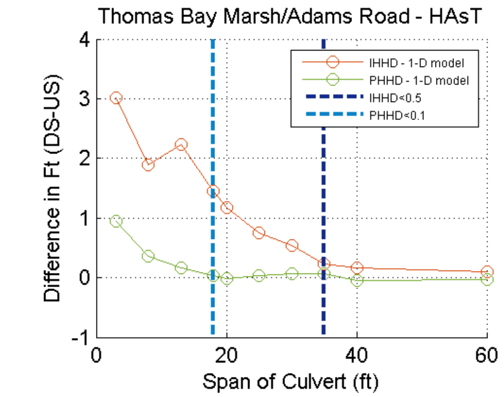


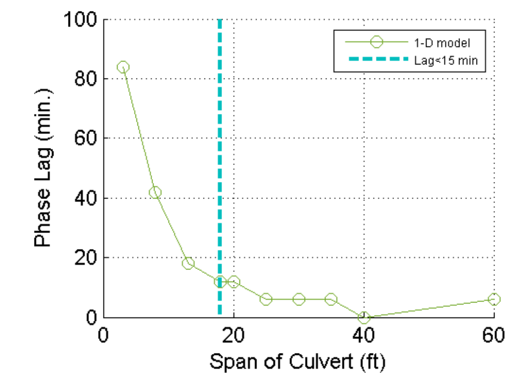


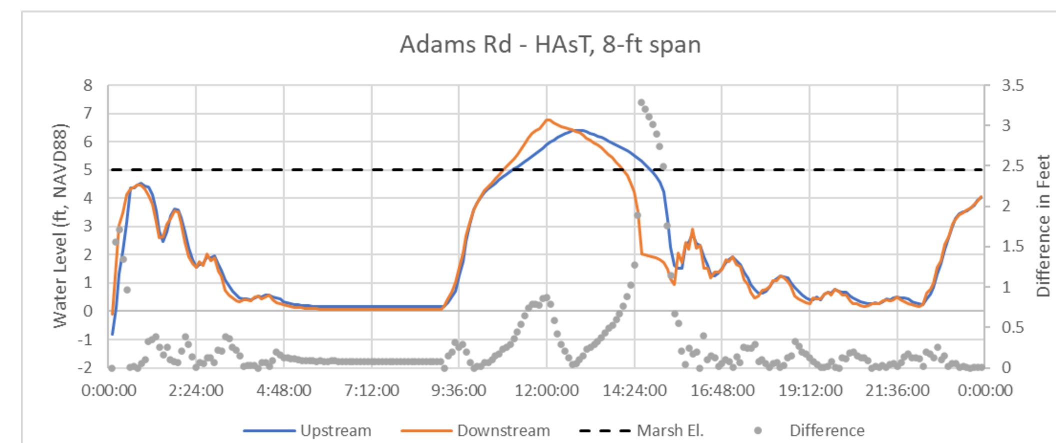
Site 7 – Adams Rd / Thomas Bay Marsh

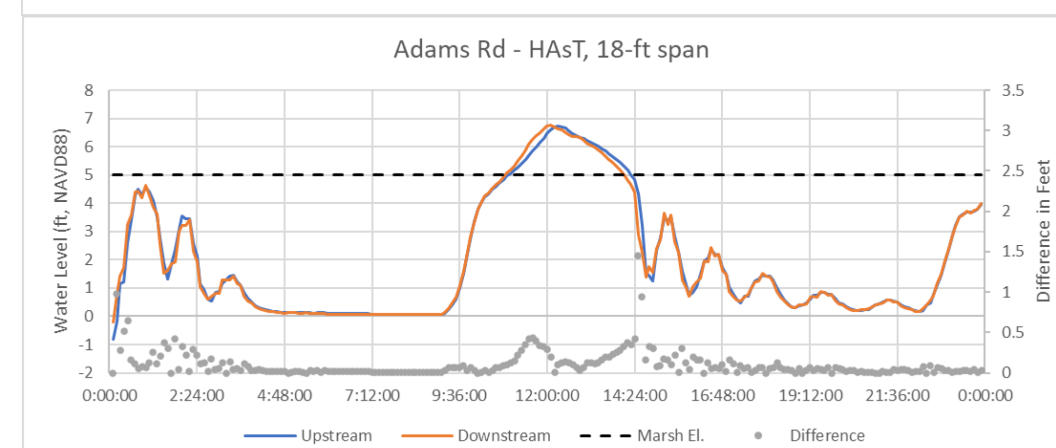


Existing 13’x8’ ft arch culvert

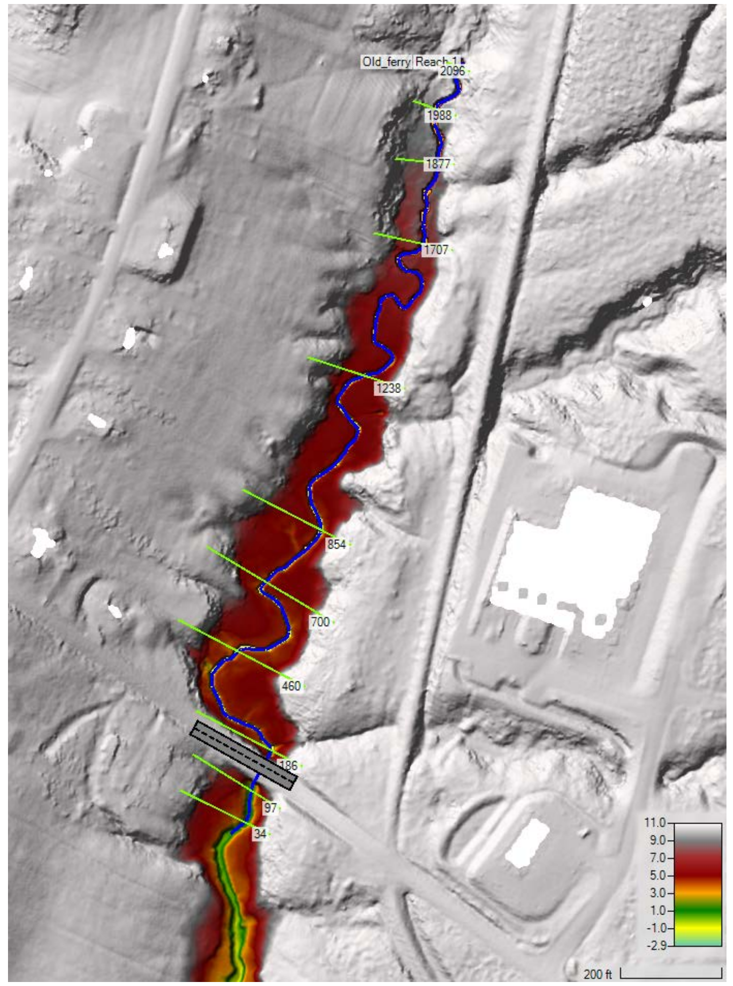






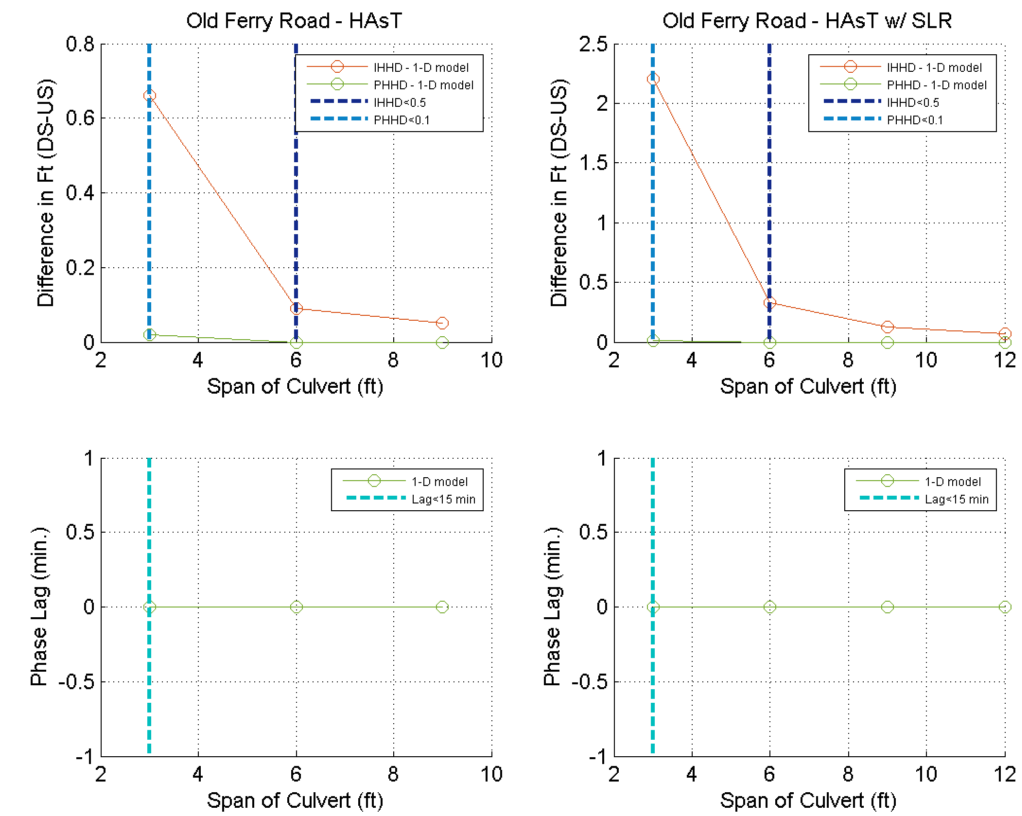


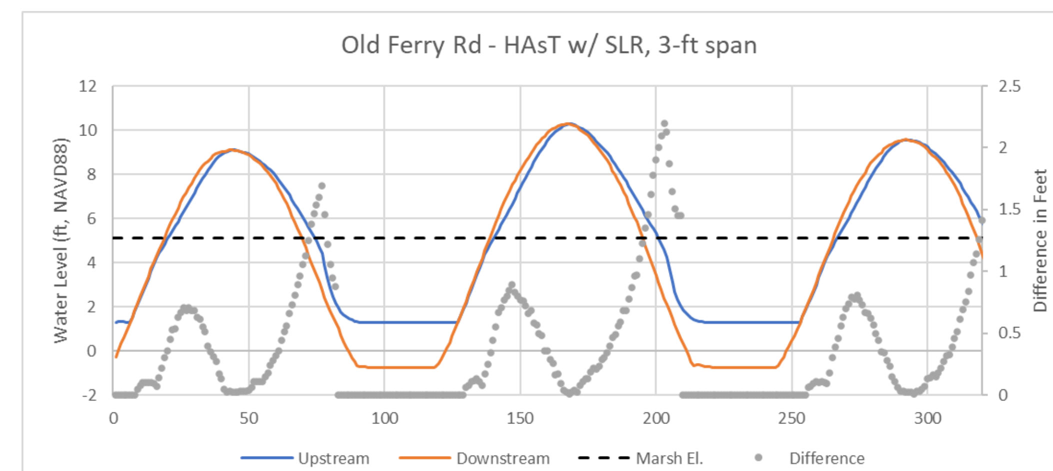
Site 8 – Old Ferry Rd, Wiscasset, ME

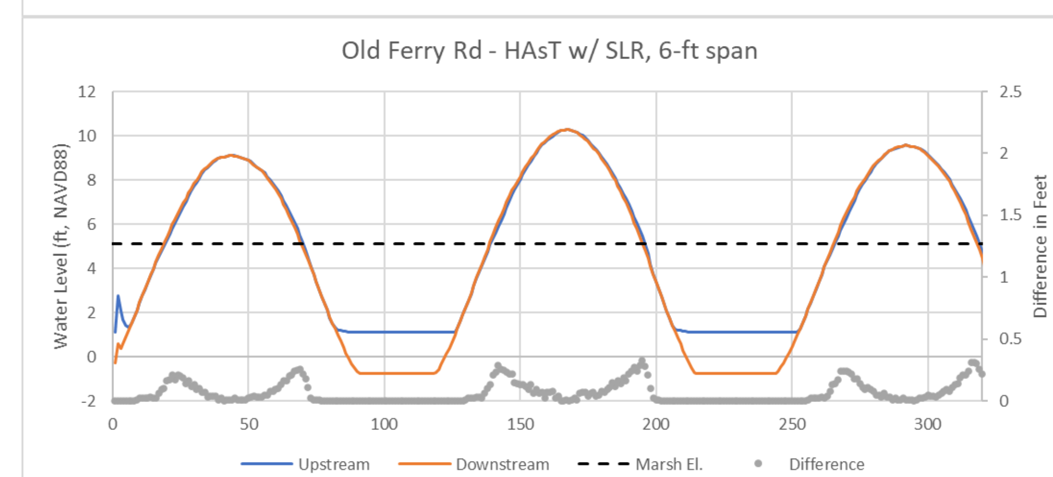


1-D HEC-RAS Model

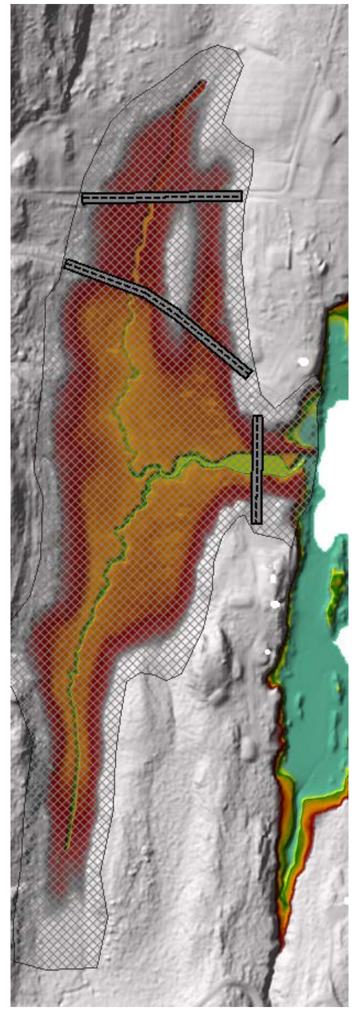
Existing 3-ft diameter culvert





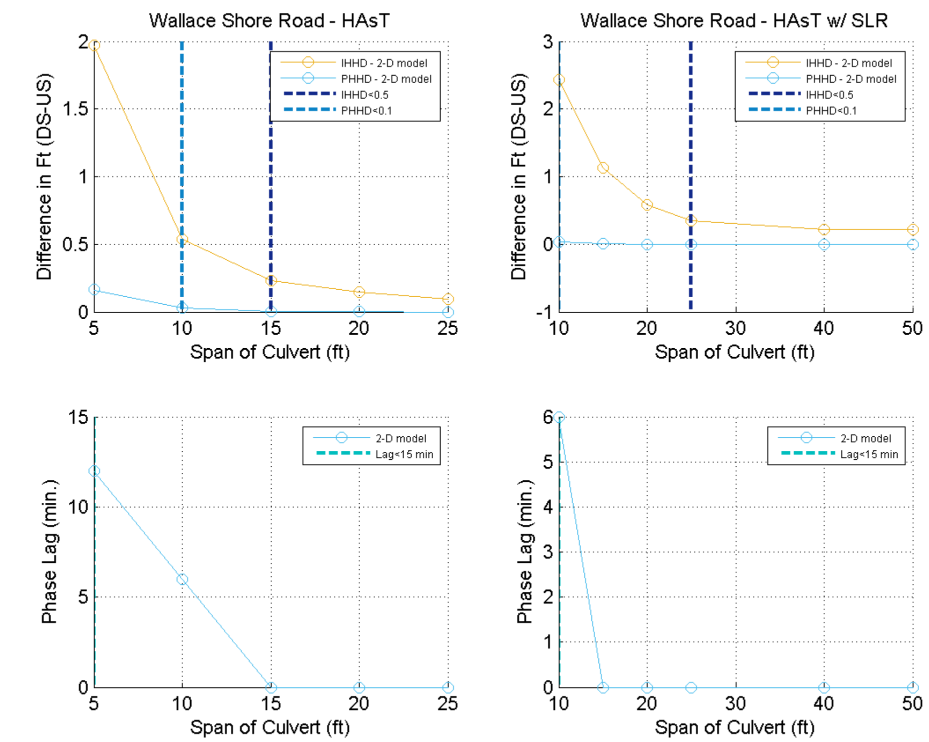


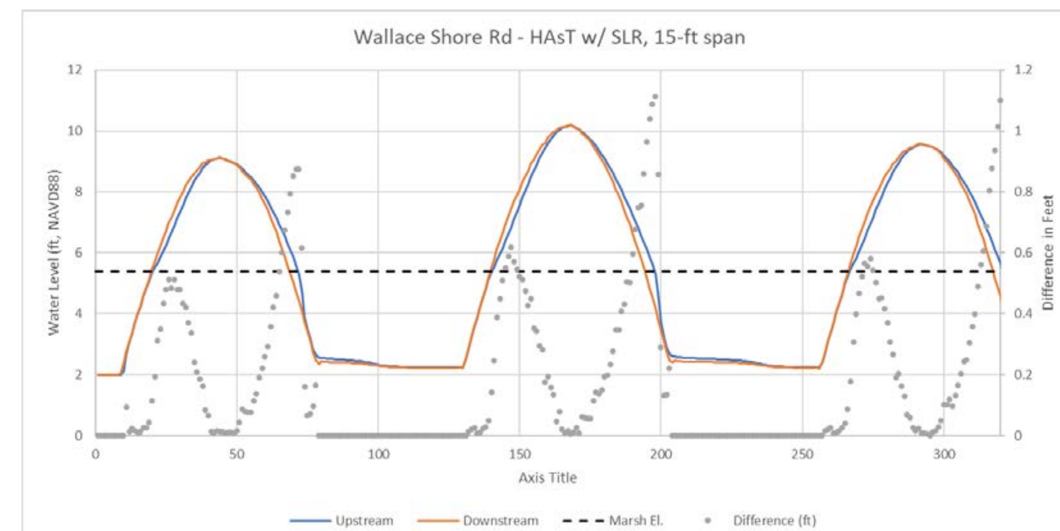
Site 9 – Wallace Shore Rd, Harpswell, ME

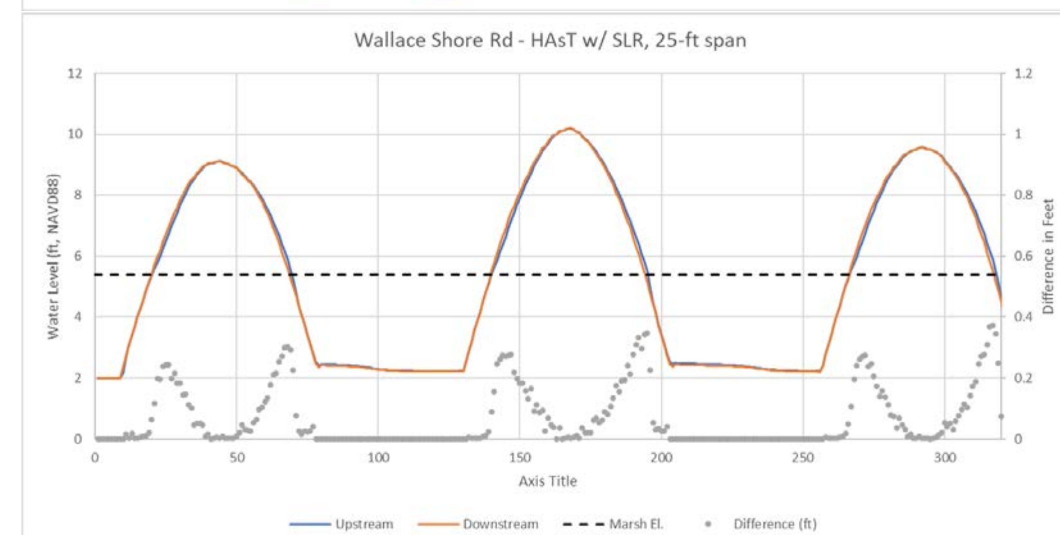


2-D HEC-RAS Model

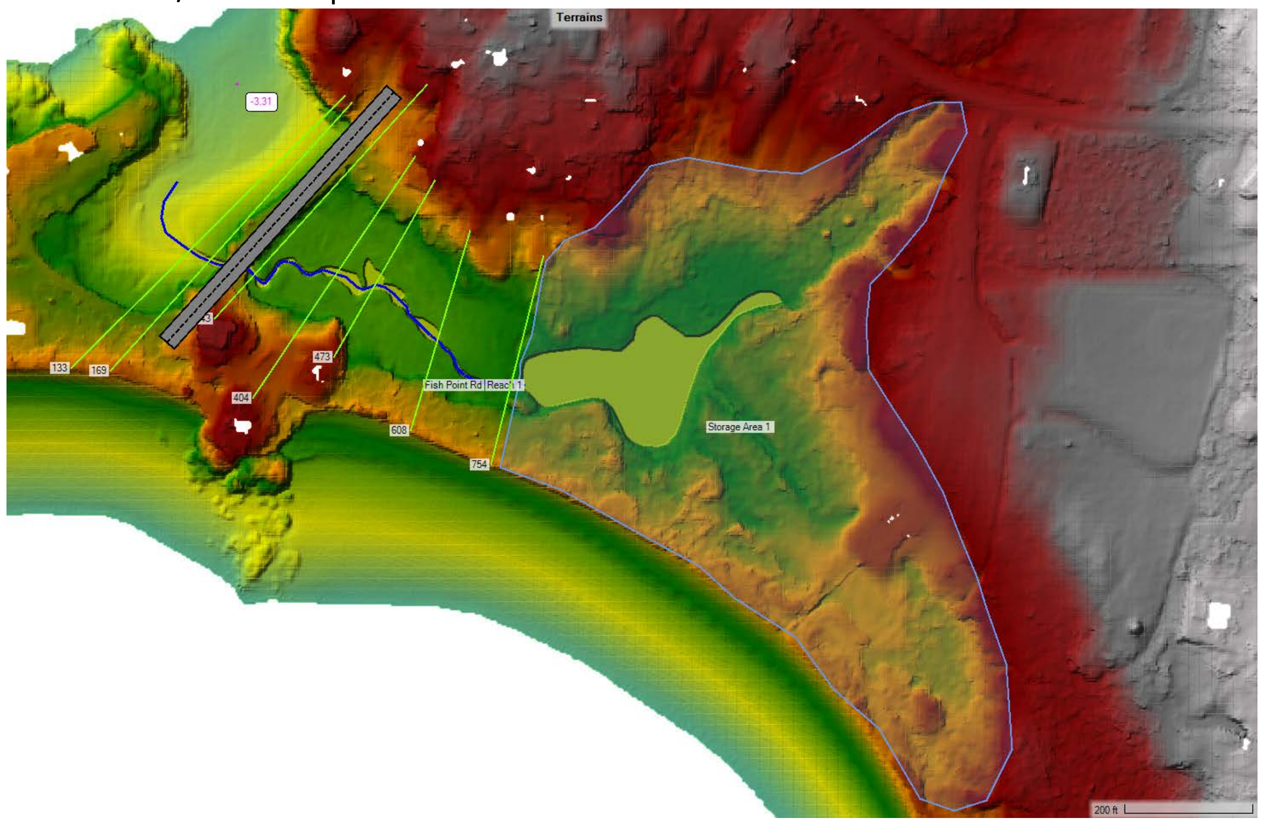
4’ x 2’ box culvert (Existed prior to Dec. 2014)





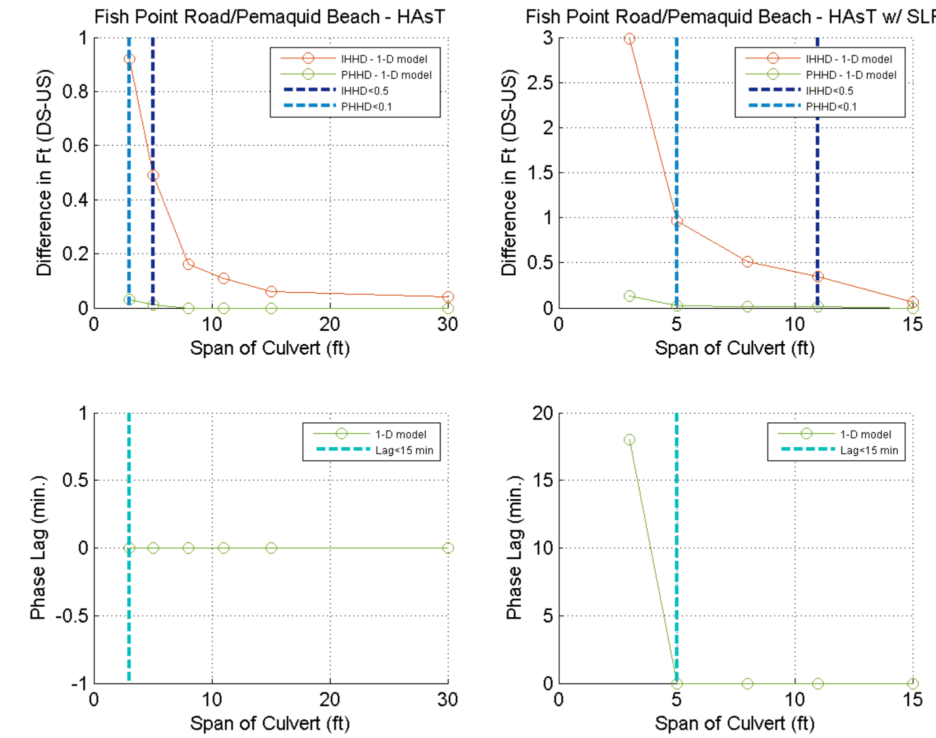


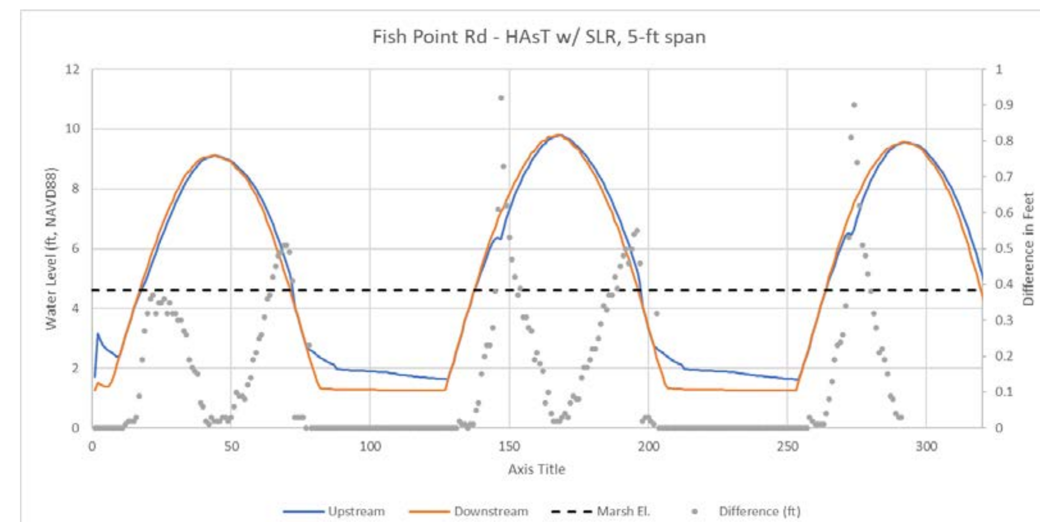
Site 10 – Fish Point Rd / Pemaquid Marsh

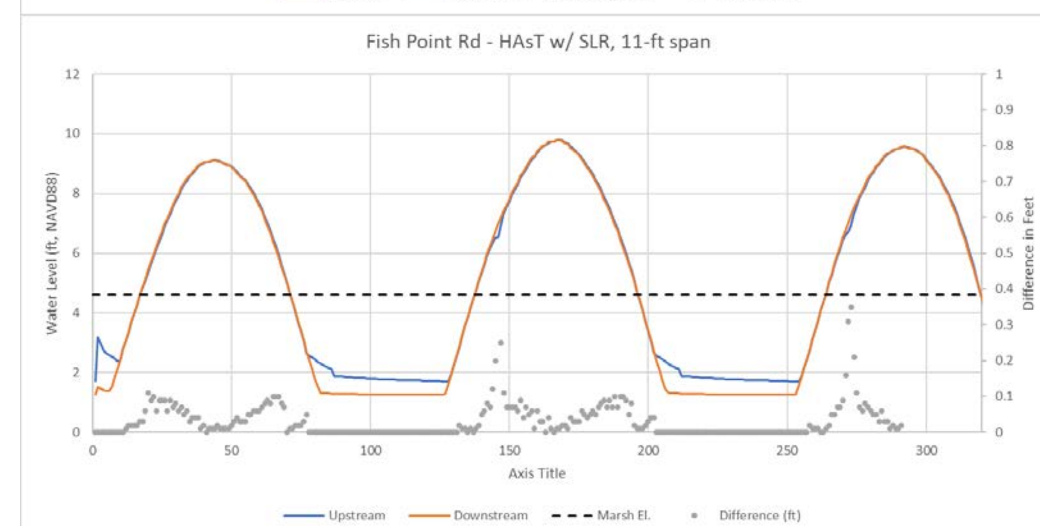


1-D HEC-RAS Model

Existing 10' x 5' box culvert

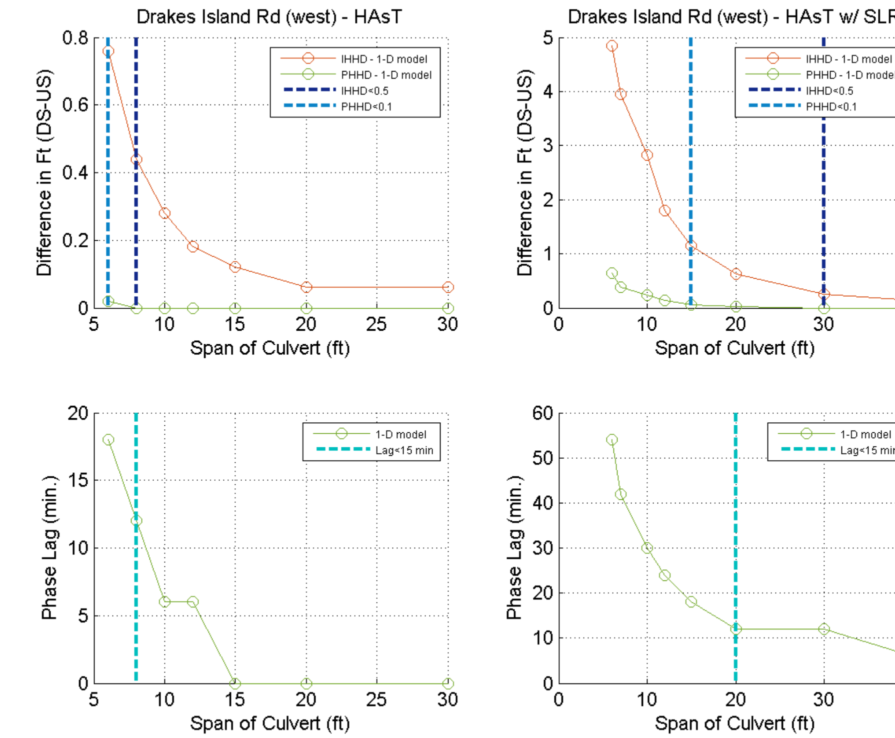


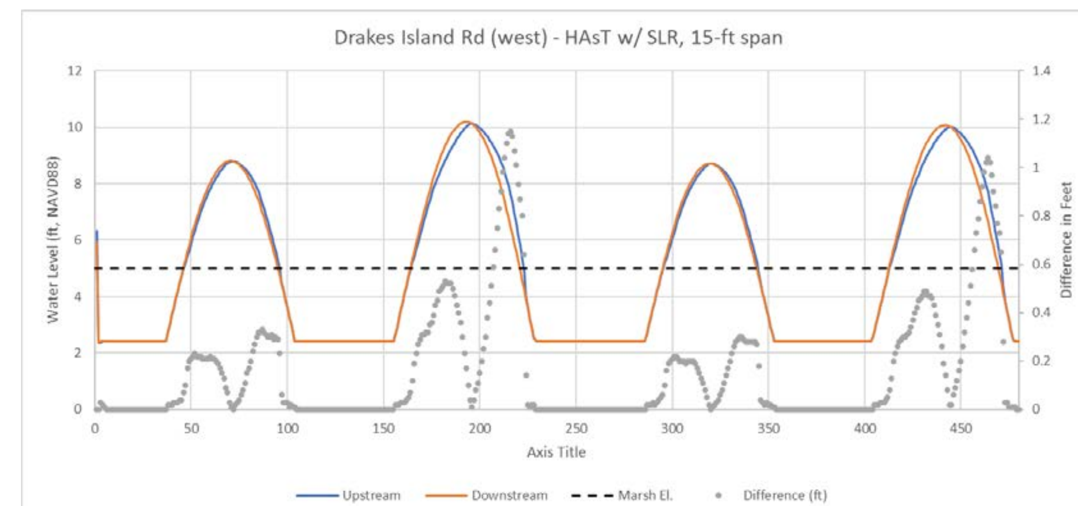


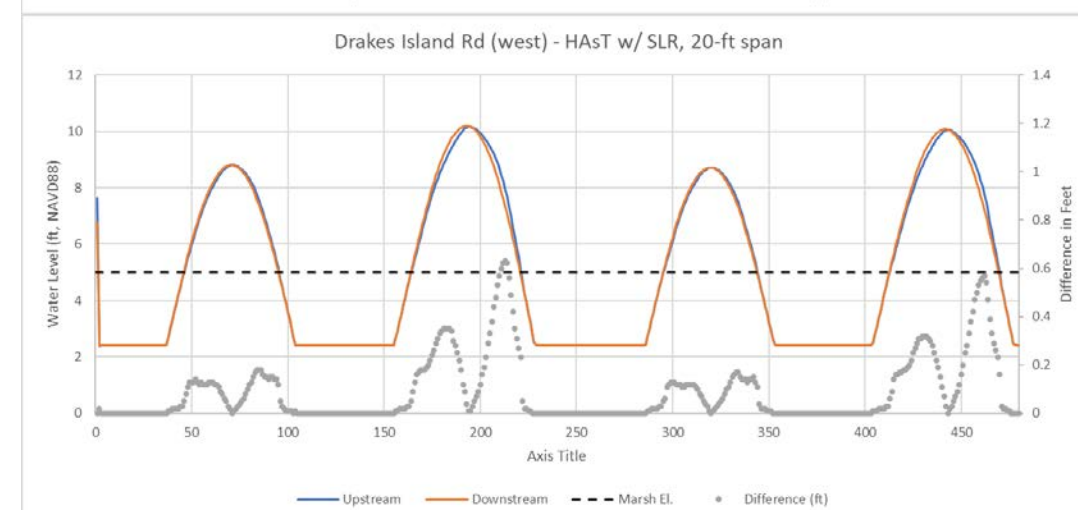


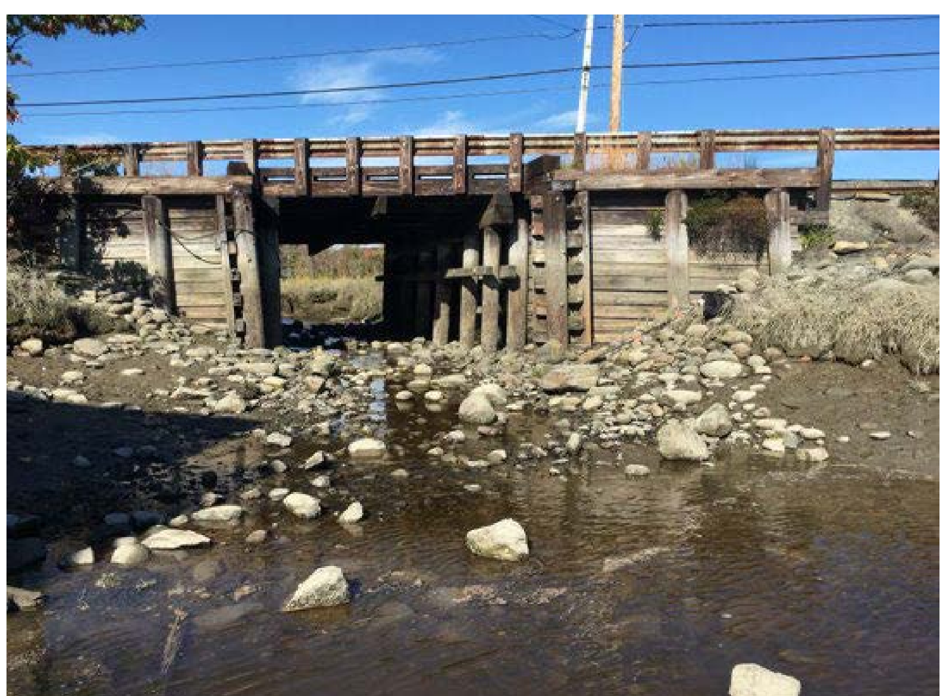
Site 11 – Drakes Island Rd (west)

1-D HEC-RAS Model



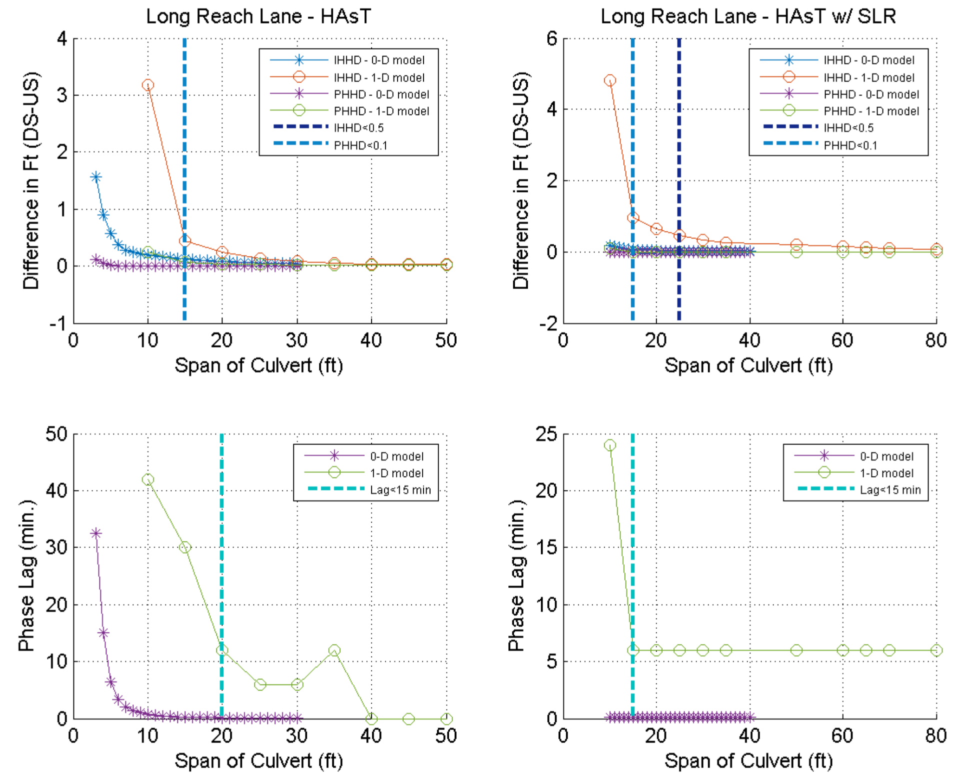


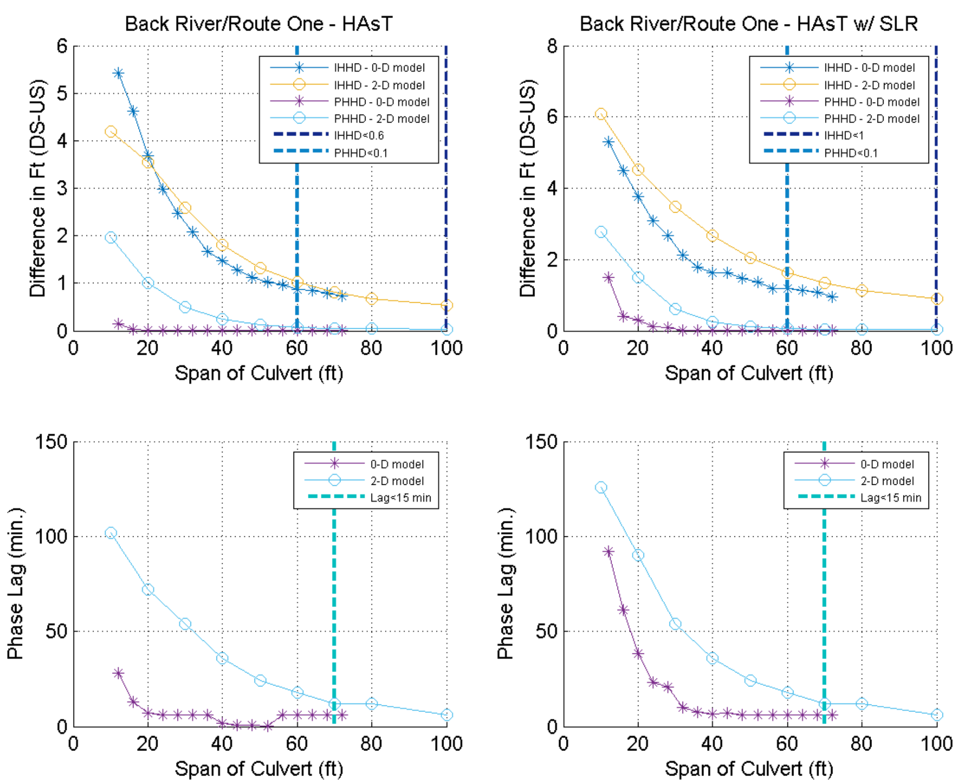


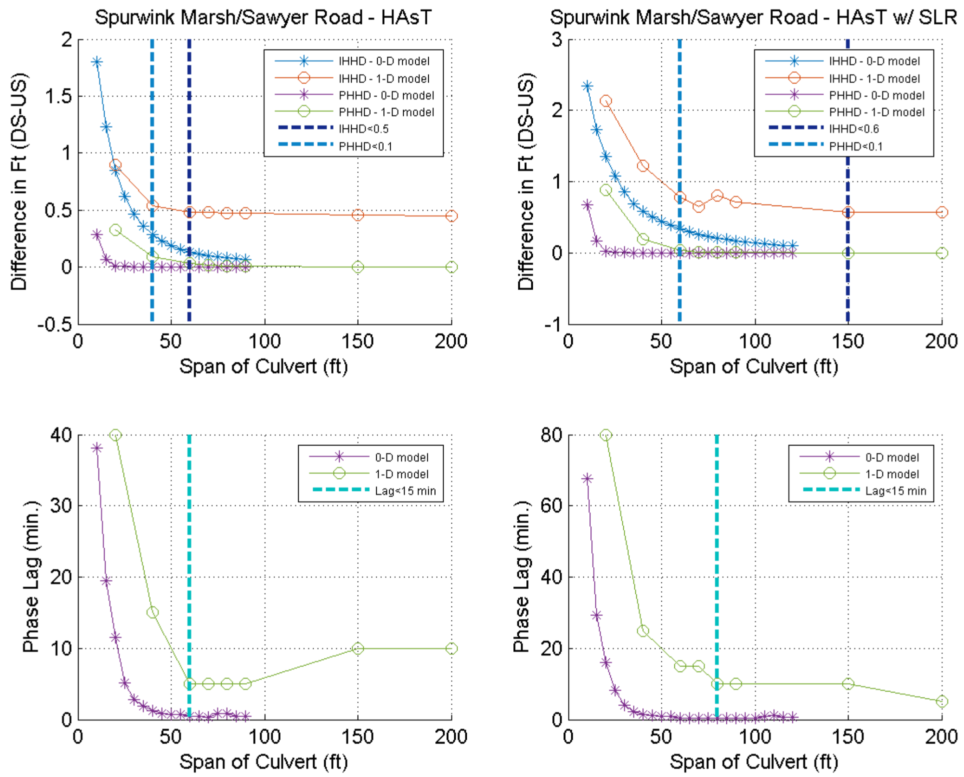


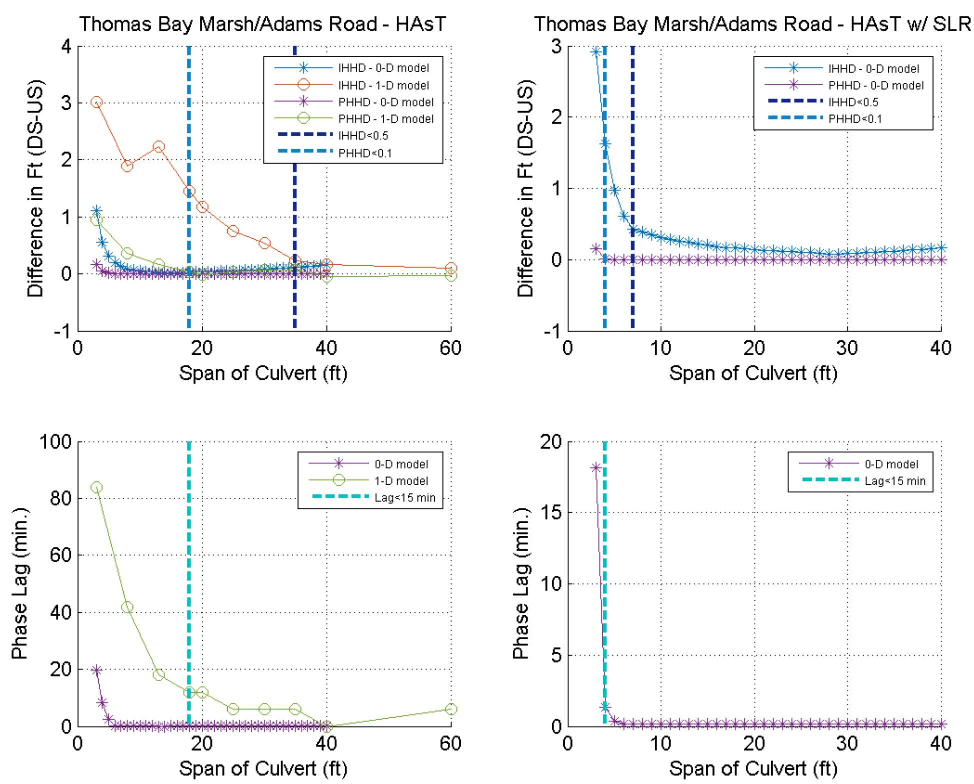
Existing bridge span opening (~15-ft span)

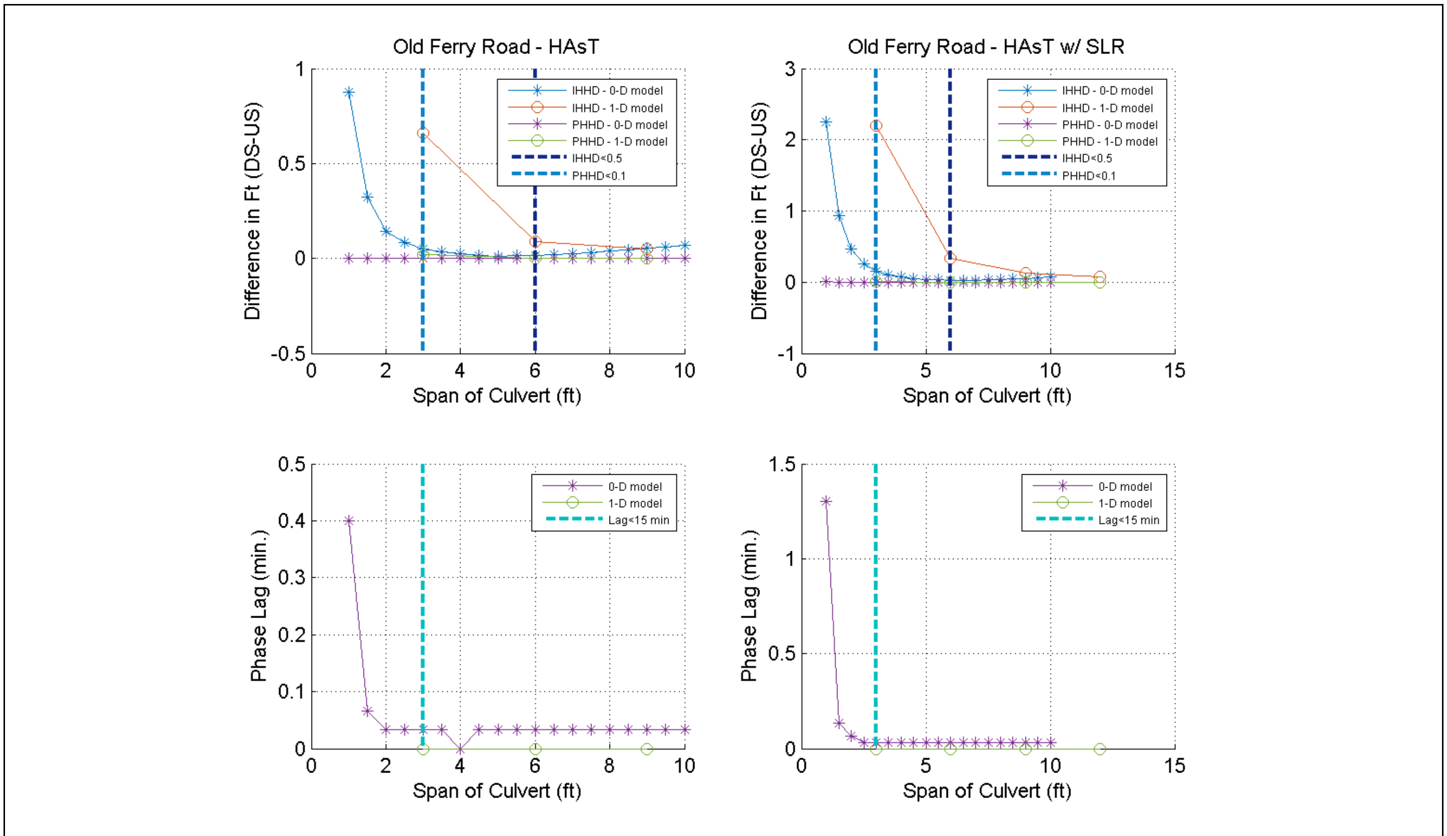
Appendix C – Model Simulation Approach Sensitivity Figures

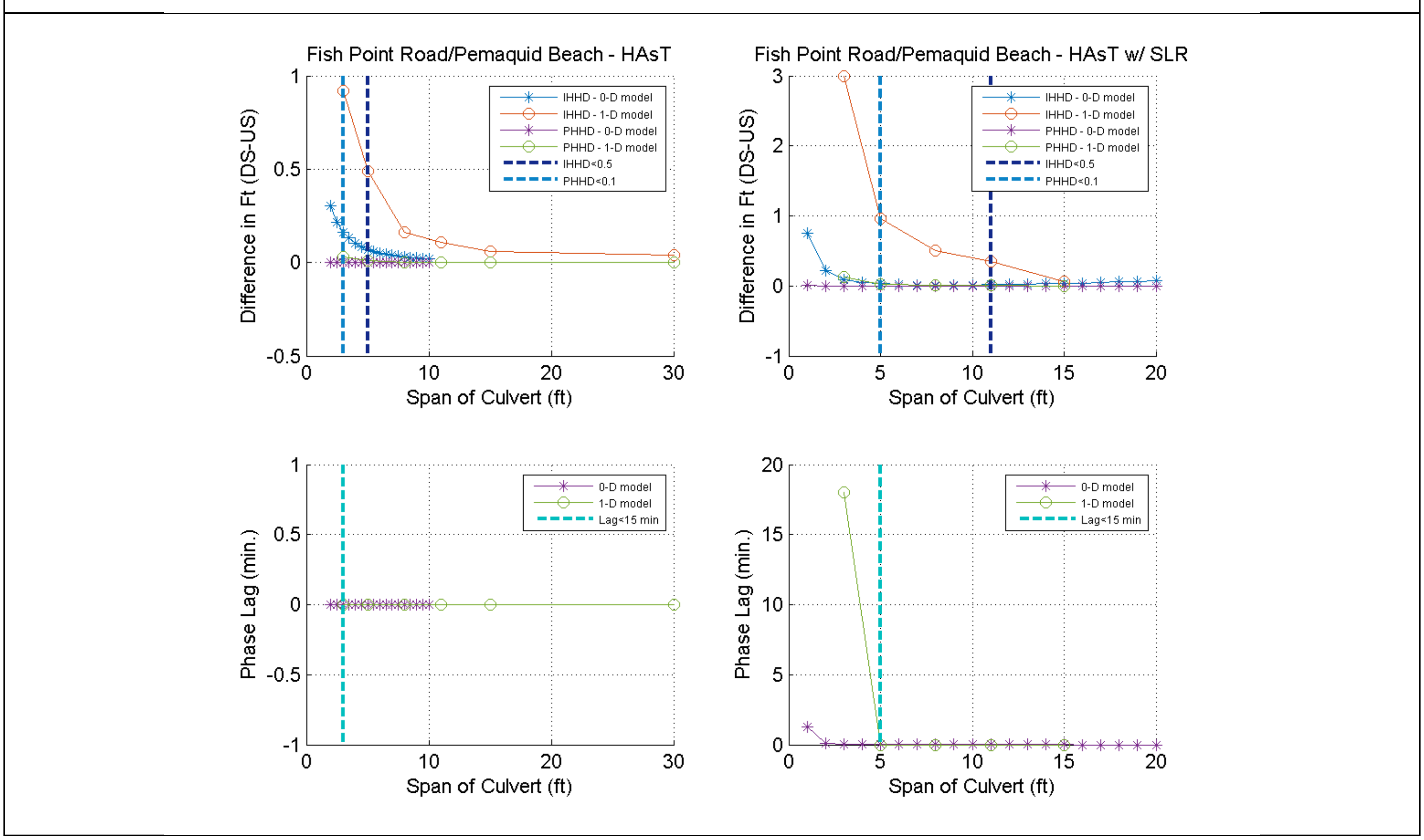


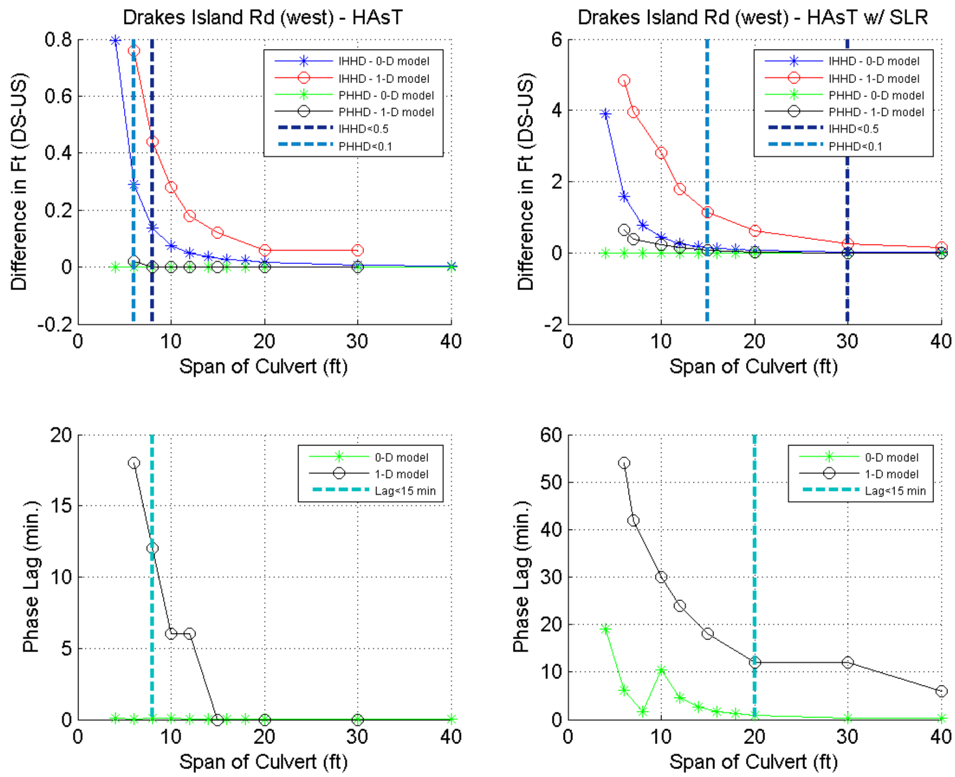



Spurwink Marsh/Sawyer Road - HAsT
Difference in Ft (DS-US)
Span of Culvert (ft)
IHHD - 0-D model
IHHD - 1-D model
PHHD - 0-D model
PHHD - 1-D model
IHHD<0.5
PHHD<0.1
Spurwink Marsh/Sawyer Road - HAsT w/ SLR
IHHD<0.6
Phase Lag (min.)
0-D model
1-D model
Lag<15 min

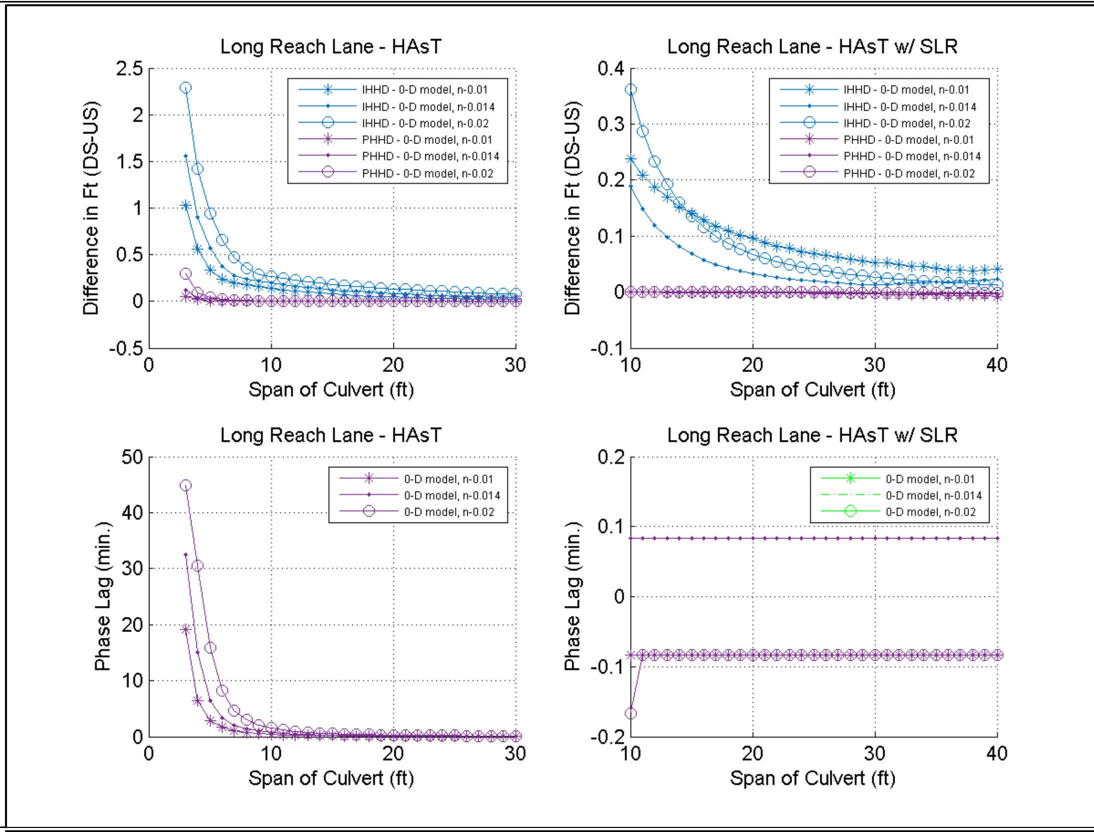

Thomas Bay Marsh/Adams Road - HAsT
Difference in Ft (DS-US)
Span of Culvert (ft)
IHHD - 0-D model
IHHD - 1-D model
PHHD - 0-D model
PHHD - 1-D model
IHHD<0.5
PHHD<0.1
Thomas Bay Marsh/Adams Road - HAsT w/ SLR
Phase Lag (min.)
0-D model
1-D model
Lag<15 min

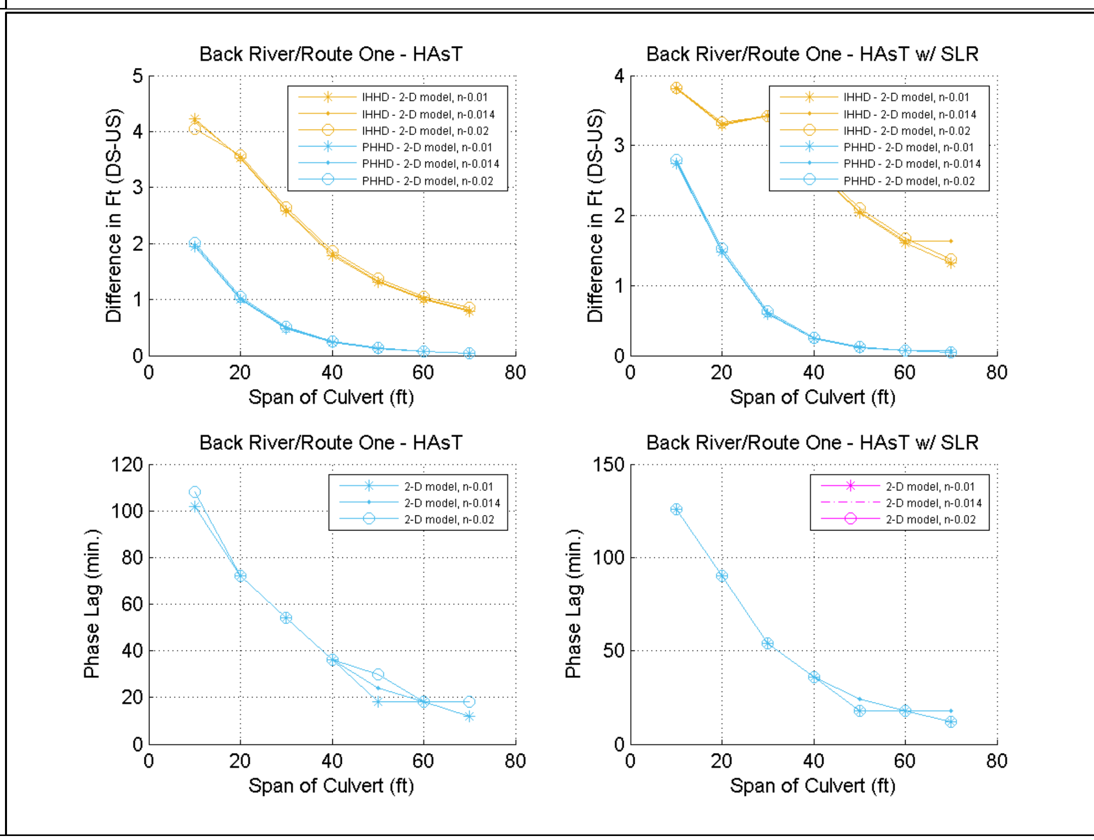

Old Ferry Road - HAsT
Old Ferry Road - HAsT w/ SLR
Difference in Ft (DS-US)
Phase Lag (min.)
Span of Culvert (ft)
IHHD - 0-D model
IHHD - 1-D model
PHHD - 0-D model
PHHD - 1-D model
IHHD<0.5
PHHD<0.1
0-D model
1-D model
Lag<15 min

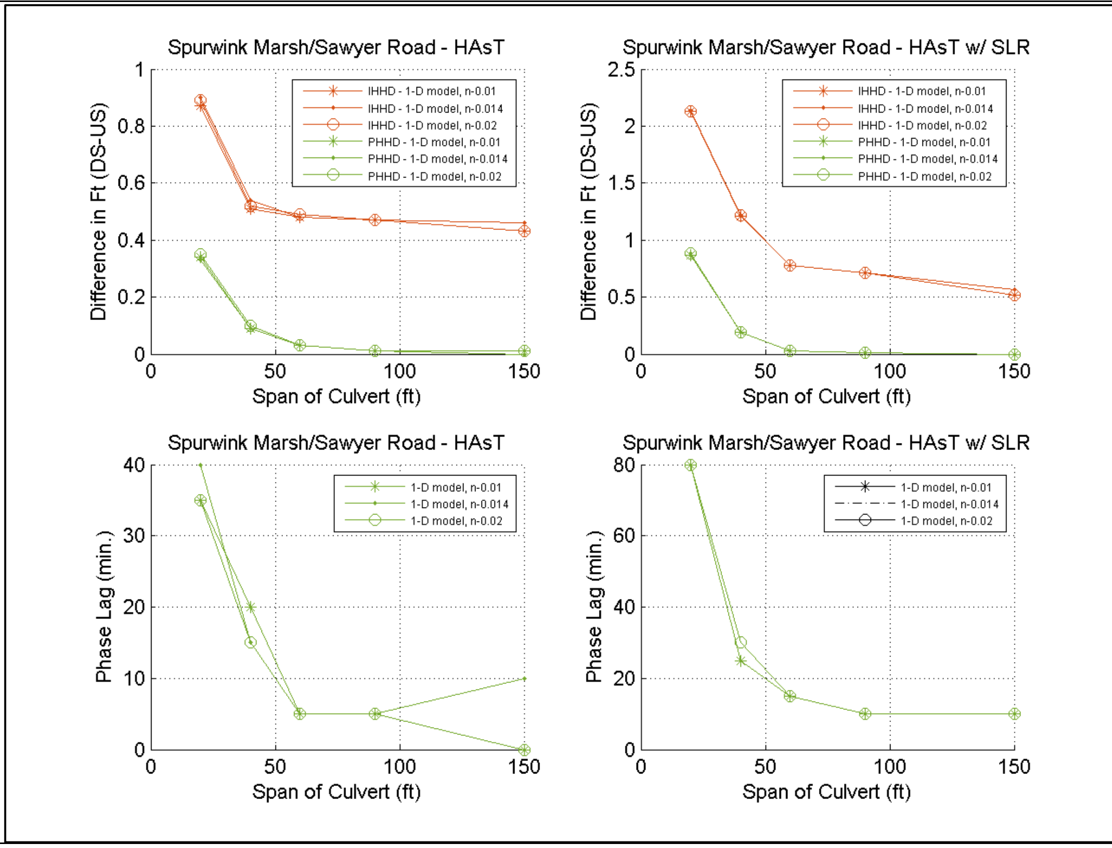

Fish Point Road/Pemaquid Beach - HAsT
Fish Point Road/Pemaquid Beach - HAsT w/ SLR
Difference in Ft (DS-US)
Phase Lag (min.)
Span of Culvert (ft)
IHHD - 0-D model
IHHD - 1-D model
PHHD - 0-D model
PHHD - 1-D model
IHHD<0.5
PHHD<0.1
0-D model
1-D model
Lag<15 min


Drakes Island Rd (west) - HAsT
Drakes Island Rd (west) - HAsT w/ SLR
IHHD - 0-D model
IHHD - 1-D model
PHHD - 0-D model
PHHD - 1-D model
IHHD<0.5
PHHD<0.1
Difference in Ft (DS-US)
Span of Culvert (ft)
0-D model
1-D model
Lag<15 min
Phase Lag (min.)

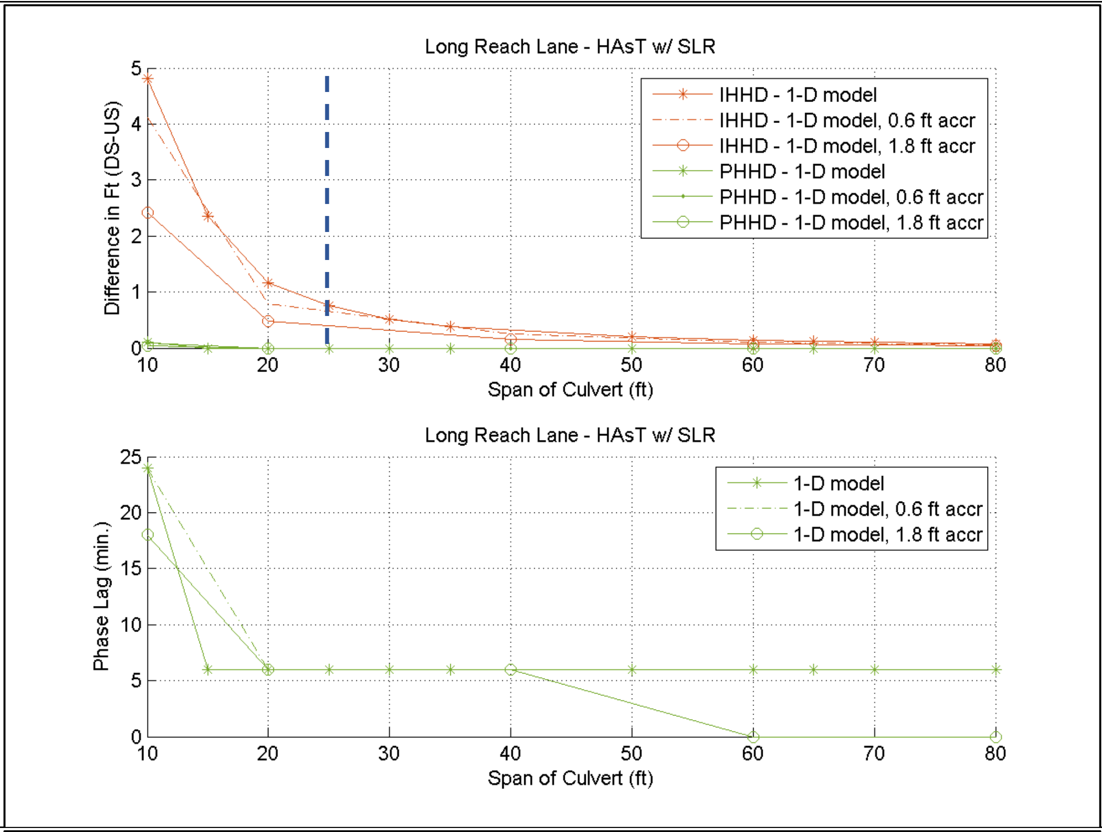
Appendix D – Model Parameter Sensitivity Figures

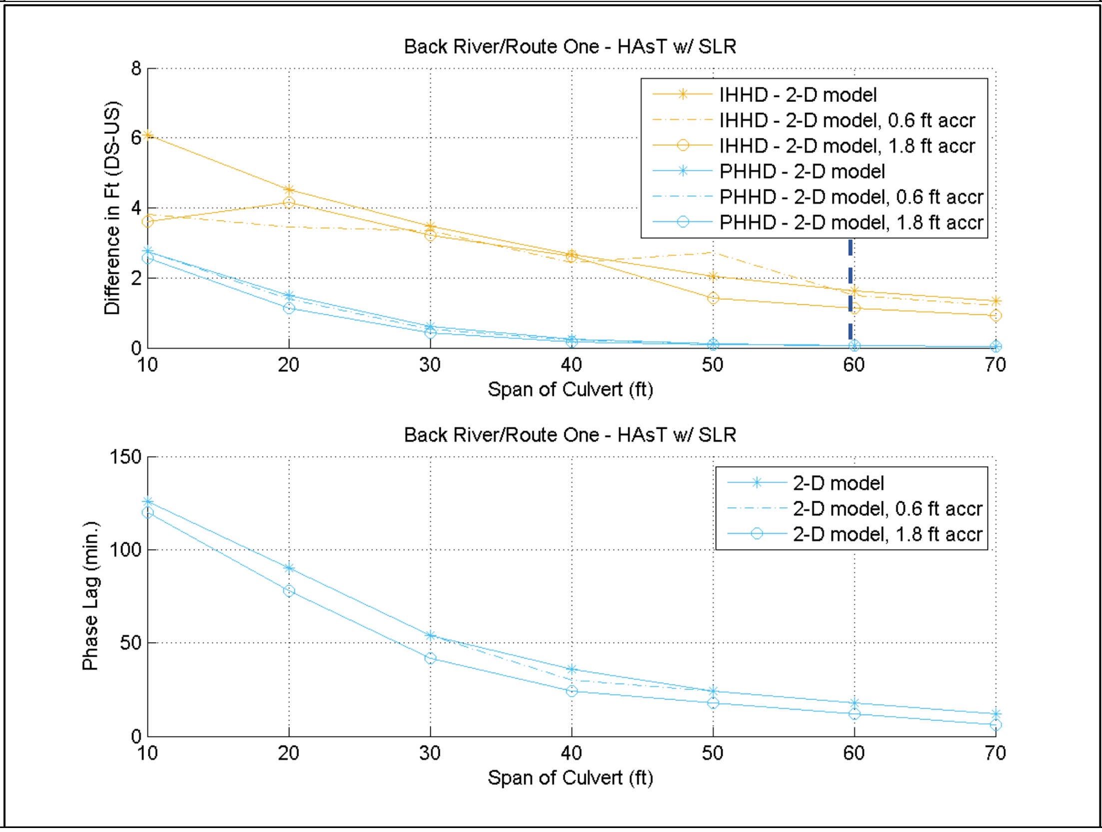


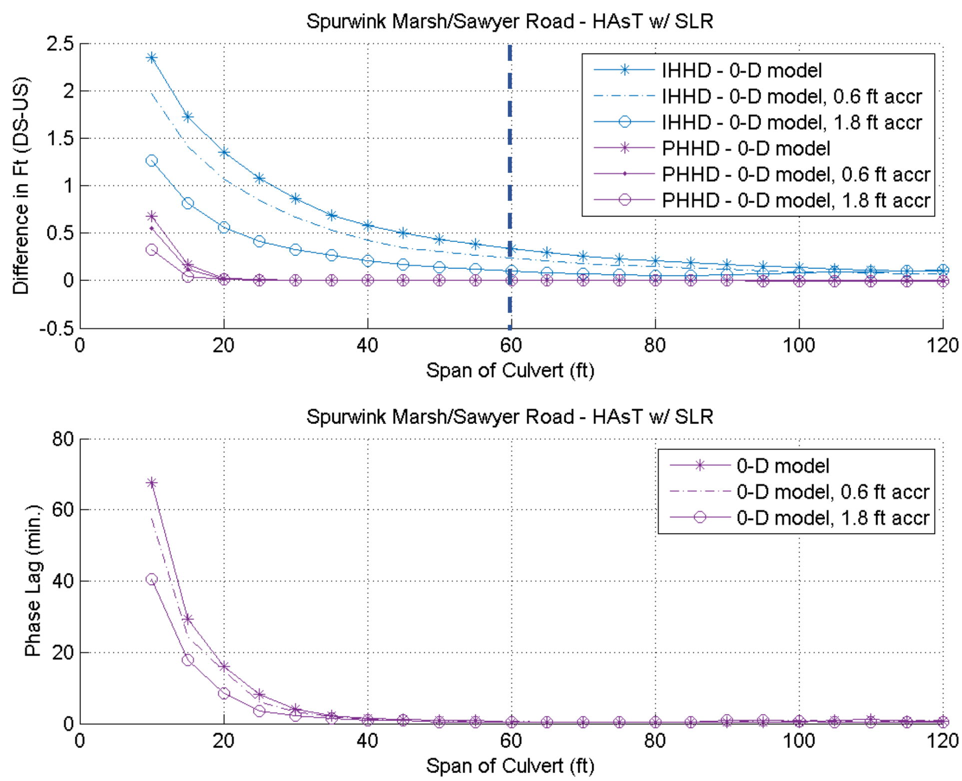



Spurwink Marsh/Sawyer Road - HAsT
Difference in Ft (DS-US)
Span of Culvert (ft)
IHHD - 1-D model, n-0.01
IHHD - 1-D model, n-0.014
IHHD - 1-D model, n-0.02
PHHD - 1-D model, n-0.01
PHHD - 1-D model, n-0.014
PHHD - 1-D model, n-0.02
Spurwink Marsh/Sawyer Road - HAsT w/ SLR
Difference in Ft (DS-US)
Span of Culvert (ft)
Spurwink Marsh/Sawyer Road - HAsT
Phase Lag (min.)
Span of Culvert (ft)
1-D model, n-0.01
1-D model, n-0.014
1-D model, n-0.02
Spurwink Marsh/Sawyer Road - HAsT w/ SLR
Phase Lag (min.)
Span of Culvert (ft)

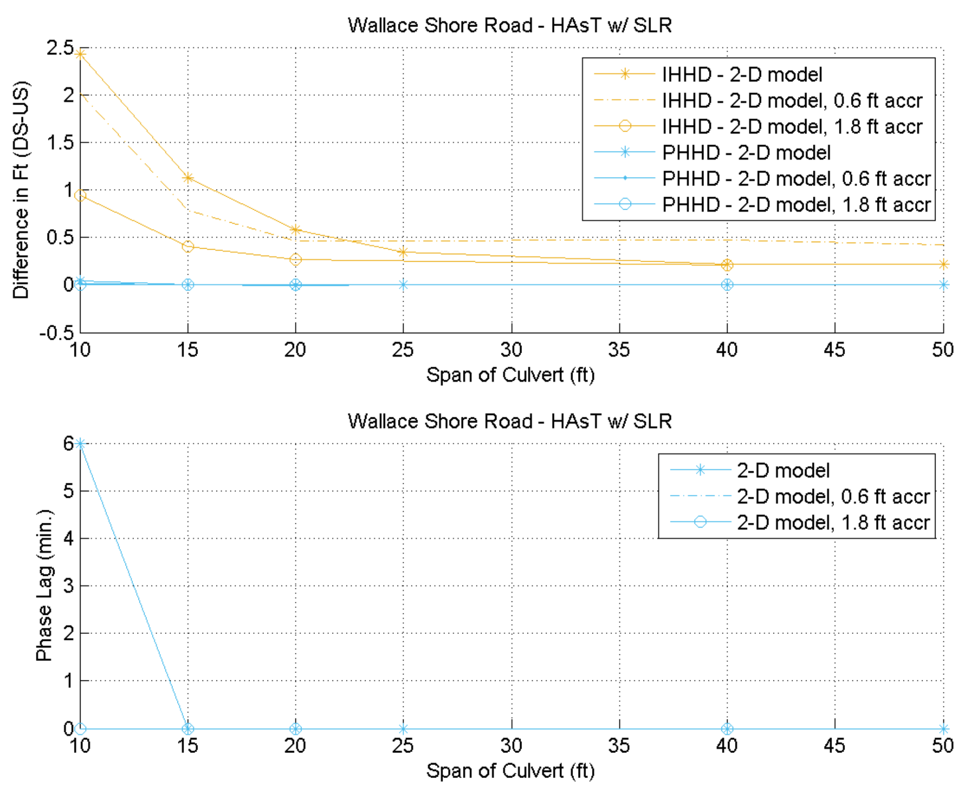
Appendix E – Future Accretion Sensitivity Figures





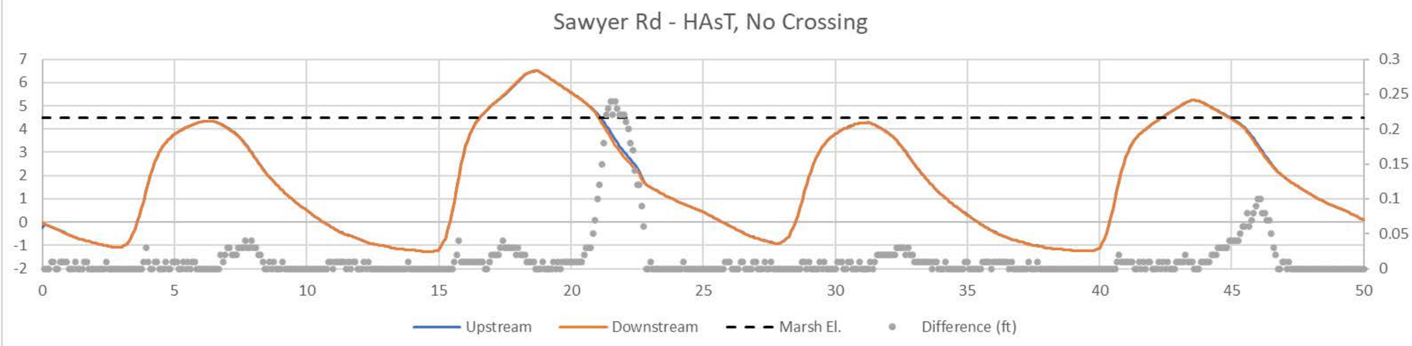


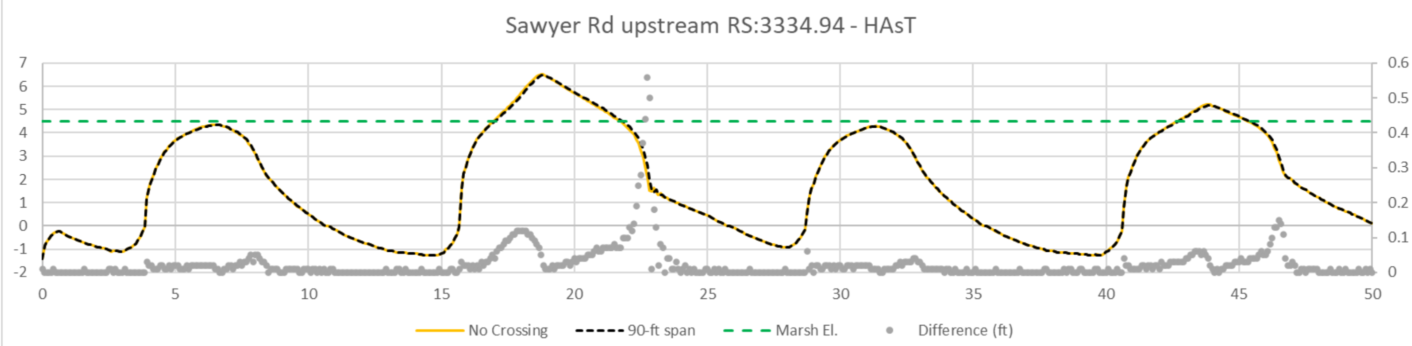
Spurwink Marsh/Sawyer Road - HAsT w/ SLR
IHHD - 0-D model
IHHD - 0-D model, 0.6 ft accr
IHHD - 0-D model, 1.8 ft accr
PHHD - 0-D model
PHHD - 0-D model, 0.6 ft accr
PHHD - 0-D model, 1.8 ft accr
Difference in Ft (DS-US)
Span of Culvert (ft)
Spurwink Marsh/Sawyer Road - HAsT w/ SLR
0-D model
0-D model, 0.6 ft accr
0-D model, 1.8 ft accr
Phase Lag (min.)
Span of Culvert (ft)

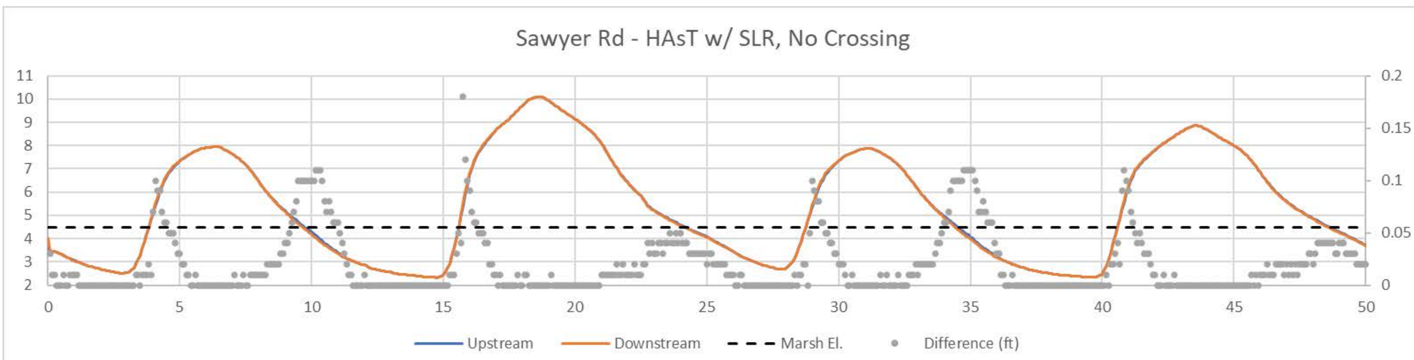


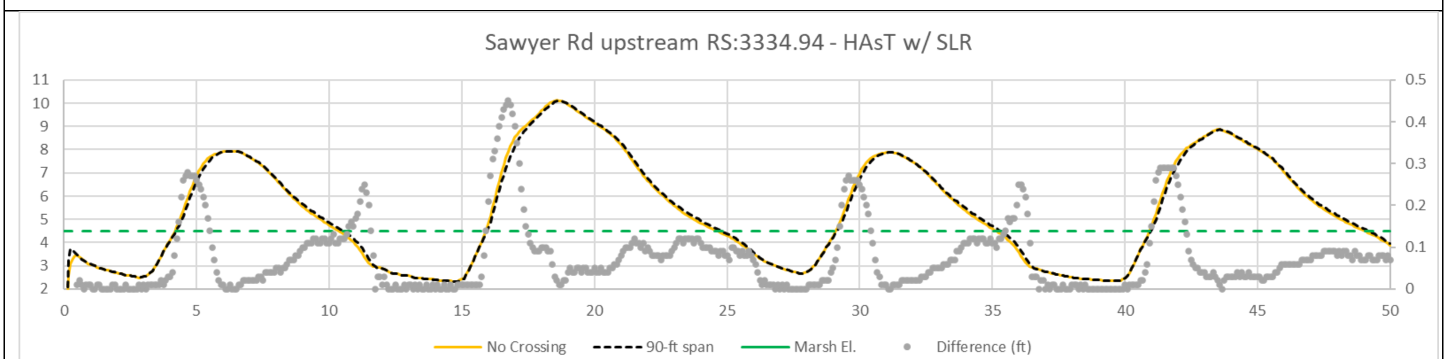
Wallace Shore Road - HAsT w/ SLR
IHHD - 2-D model
IHHD - 2-D model, 0.6 ft accr
IHHD - 2-D model, 1.8 ft accr
PHHD - 2-D model
PHHD - 2-D model, 0.6 ft accr
PHHD - 2-D model, 1.8 ft accr
Difference in Ft (DS-US)
Span of Culvert (ft)
Wallace Shore Road - HAsT w/ SLR
2-D model
2-D model, 0.6 ft accr
2-D model, 1.8 ft accr
Phase Lag (min.)
Span of Culvert (ft)

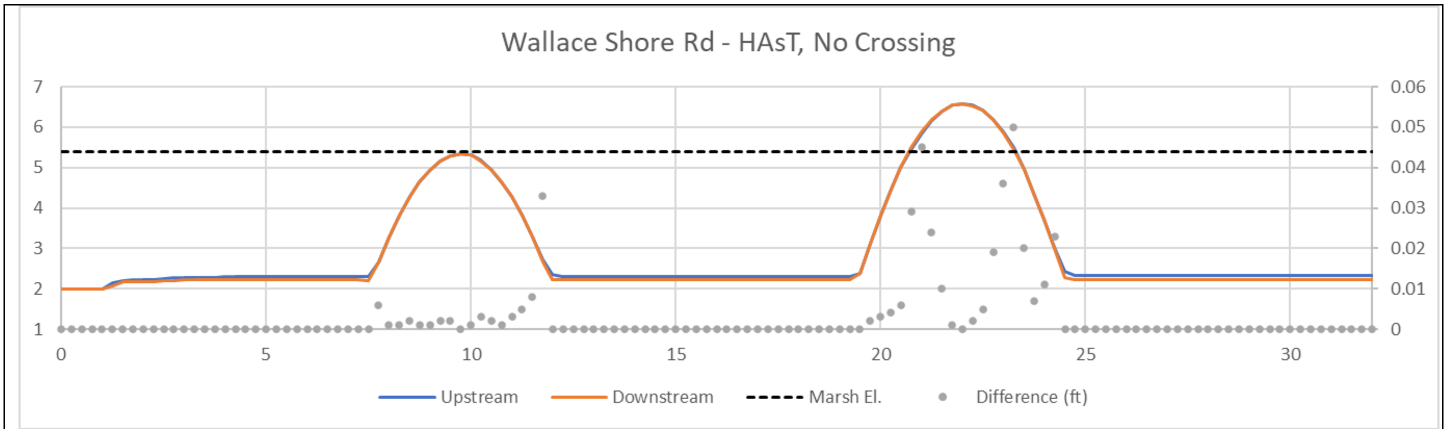
Appendix F – Upstream Tidal Patterns Time Series Figures

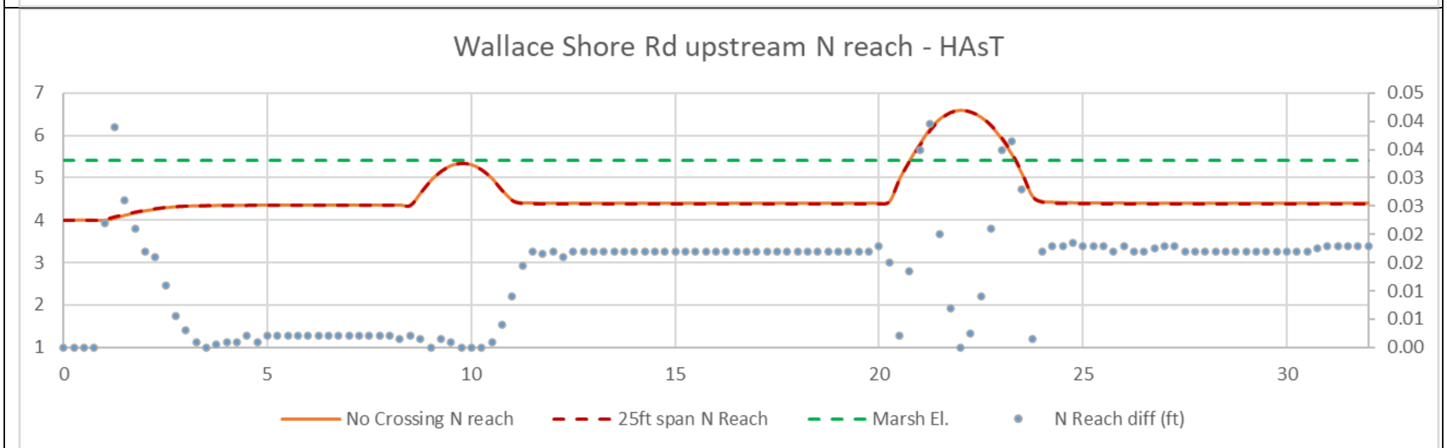


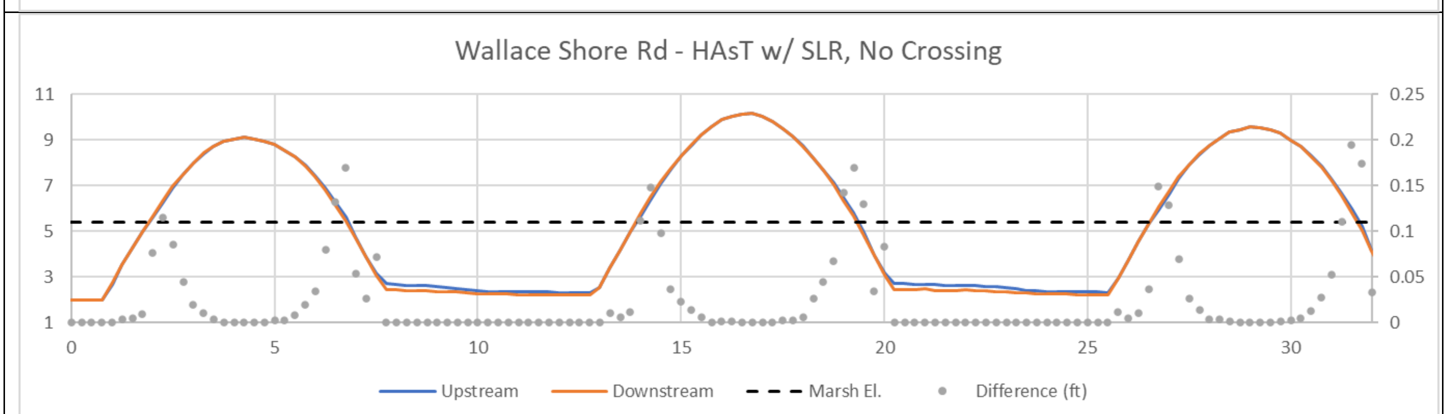


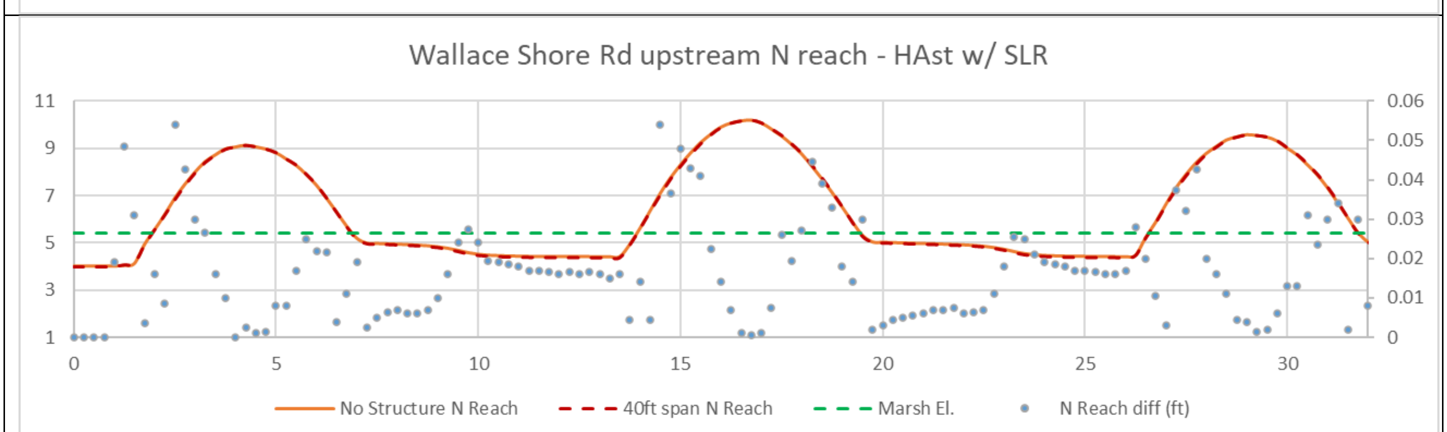


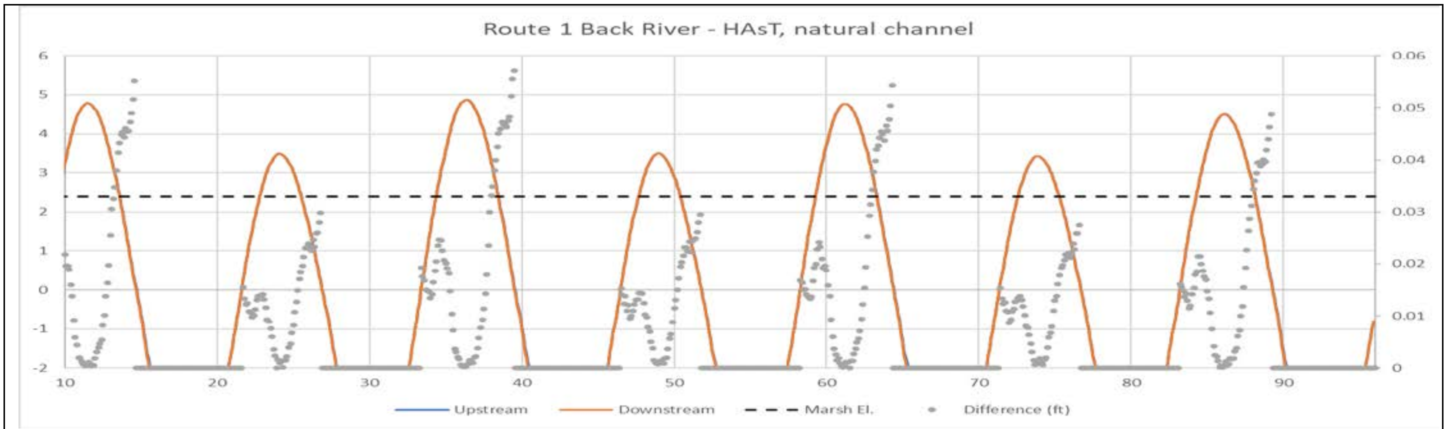


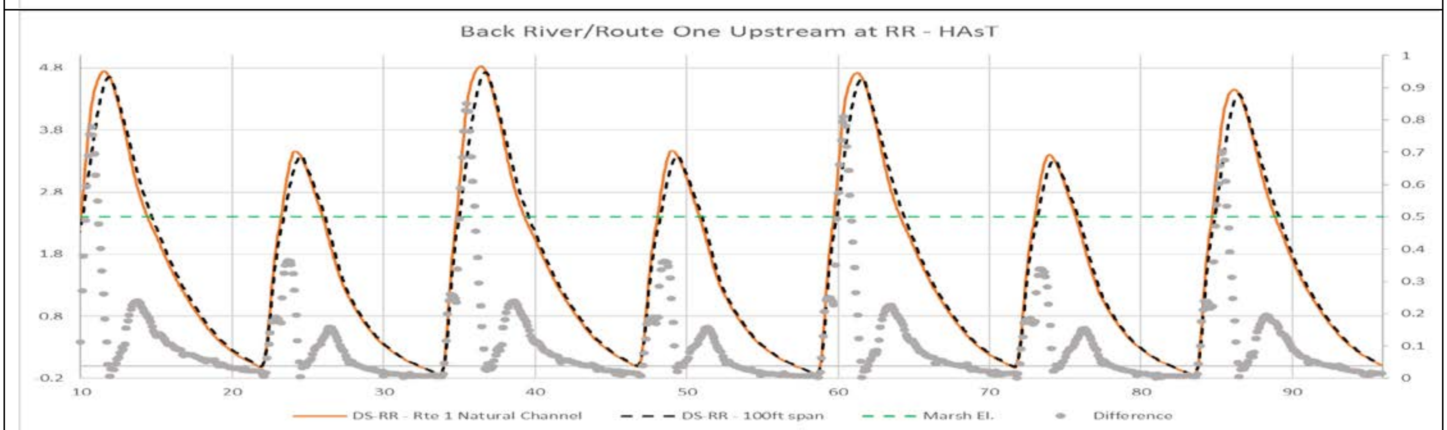

Wallace Shore Rd - HAsT, No Crossing
Upstream
Downstream
Marsh El.
Difference (ft)

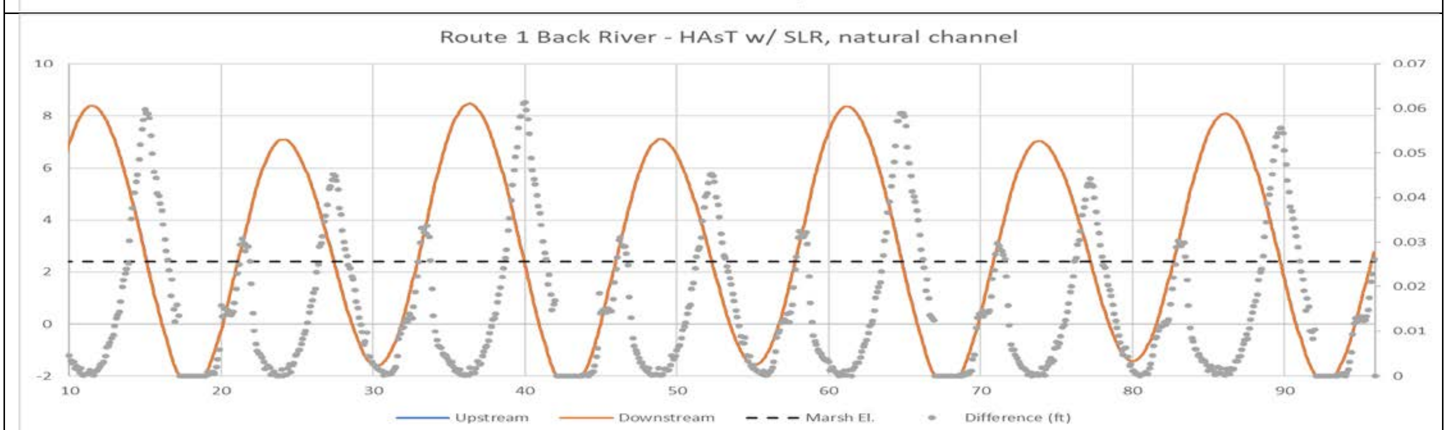

Wallace Shore Rd upstream N reach - HAsT
No Crossing N reach
25ft span N Reach
Marsh El.
N Reach diff (ft)

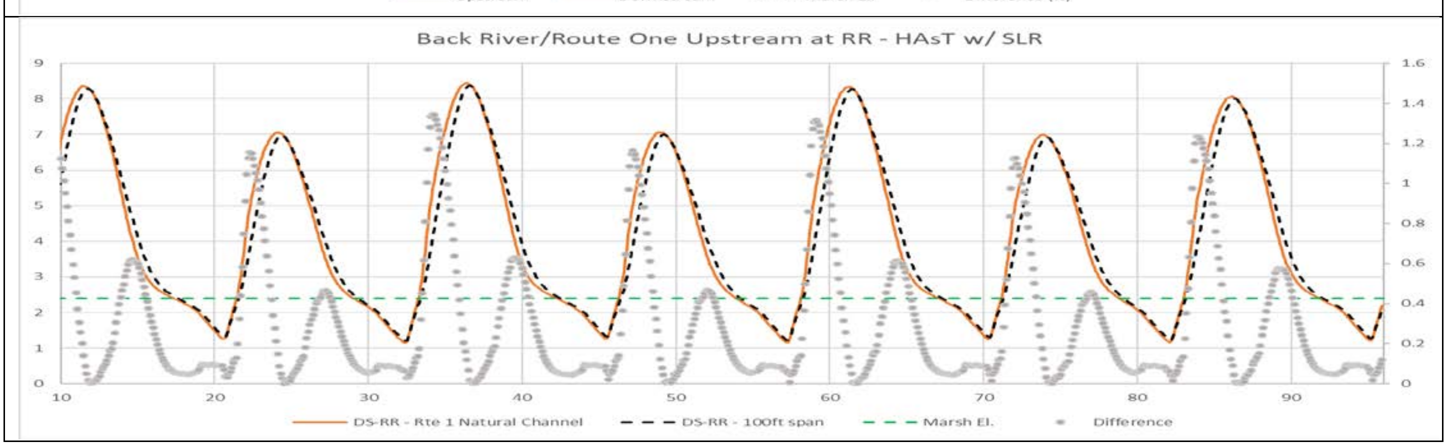

Wallace Shore Rd - HAsT w/ SLR, No Crossing
Upstream
Downstream
Marsh El.
Difference (ft)


Wallace Shore Rd upstream N reach - HAst w/ SLR
No Structure N Reach
40ft span N Reach
Marsh El.
N Reach diff (ft)


Route 1 Back River - HAsT, natural channel
Upstream
Downstream
Marsh El.
Difference (ft)


Back River/Route One Upstream at RR - HAsT
DS-RR - Rte 1 Natural Channel
DS-RR - 100ft span
Marsh El.
Difference


Route 1 Back River - HAsT w/ SLR, natural channel
Upstream
Downstream
Marsh El.
Difference (ft)


Back River/Route One Upstream at RR - HAsT w/ SLR
DS-RR - Rte 1 Natural Channel
DS-RR - 100ft span
Marsh El.
Difference

Appendix H – Glossary of Terms

Design tides – tidal elevations used to evaluate tidal crossings and the sizing of a hydraulic structure opening. For example, a selected design tide may be the highest astronomical tide (HAsT) or mean high water spring (MHWS).

Hydraulic head differential (HHD) –difference in water surface elevation between two selected locations, one downstream and one upstream of a crossing

Hydroperiod – average length of time that a wetland area is inundated. For tidal systems, typically calculated over a lunar month.

Instantaneous Hydraulic head differential (IHHD) –instantaneous difference in water surface elevation during running tides between two selected locations, one downstream and one upstream of a crossing

Peak Hydraulic head differential (PHHD) –difference in peak water surface elevation reached during a tidal cycle between two selected locations, one downstream and one upstream of a crossing

Phase lag - difference in timing of peak water surface elevations reached during a tidal cycle between two selected locations, one downstream and one upstream of a crossing

Tidal transparency – tides are not restricted by the crossing (equivalent water surface elevation between locations downstream and upstream of a crossing)

Tidal synchrony – match in timing and elevations of peaks (highs and lows) between locations downstream and upstream of a crossing

Unrestricted tidal flow condition – SEE Tidal transparency

Wetland resilience – ability of a wetland to adapt and withstand disturbance. In particular for this study, the ability for a salt marsh to accrete and persist with rising tides/sea level.