HYDROLOGY REPORT

The project site is a bridge located just upstream of the confluence of Broombridge Brook with the Penobscot River. The bridge is subject to backwater flooding from the Penobscot River during high water events on the river. A large swamp or wetland area upstream of the bridge serves as floodplain storage for floodwaters from the river. Flow at the bridge is influenced by runoff from the upstream watershed and backflow/return flow from the Penobscot River during high water.

SUMMARY OF UPSTREAM ELEVATIONS/HYDROLOGY – NO BACKWATER

Frequency	Flow	Existing Bridge	Long Span	Short Span
1.1-yr	54	105.6	105.70	105.70
2-yr	106	106.1	106.10	106.10
10-yr	199	106.9	106.63	106.63
25-yr	261	107.2	106.91	106.91
50-yr	296	107.4	107.06	107.05
100-yr	346	107.7	107.25	107.25
500-yr	454	108.2	107.62	107.62

SUMMARY OF UPSTREAM ELEVATIONS – WITH BACKWATER

Frequency	Existing Bridge	Long Span	Short Span
1.1-yr	110.12	110.25	110.30
2-yr	112.10	112.20	112.27
10-yr	120.00	120.00	120.00
25-yr	122.00	122.00	122.00
50-yr	123.60	123.60	123.60
100-yr	125.00	125.00	125.00
500-yr	128.50	128.50	128.50

See Appendix E for the “Preliminary Design Hydrology and Hydraulic Report” as prepared by Northstar Hydro, Inc.

Reported by: E. O’Brien
Date: May 24, 2017

Note: All elevations based on North American Vertical Datum (NAVD) of 1988.

HYDRAULIC REPORT

The hydraulic analysis has shown that the existing bridge is likely overtopped by floodwaters from the Penobscot River during low frequency events, with estimated overtopping occurring for floods above the 10-year level. The bridge is significantly larger than required for conveyance of upland flows, but allows floodwaters from the Penobscot River to fill the upstream wetland area. As the entire road and bridge would need to be raised more than is practicable, the intent of the proposed bridge spans was to duplicate or increase the existing opening area, eliminate the bridge piers, and improve the alignment of the abutments to the flow. The two proposed span options are not projected to increase flood levels and are of similar size to the existing, allowing backflow and velocity similar to existing. See Appendix E for the complete “Preliminary Design Hydrology and Hydraulic Report” as prepared by Northstar Hydro, Inc.

Appendix E

Hydraulics Data

Preliminary Design Hydrology and Hydraulics Report

Boombridge Road - Bridge # 3587, Greenbush, Maine

1.0 Introduction.

This report details work on hydrologic and hydraulic evaluation of Bridge #3587 for the replacement of Route 2 over Boombridge Brook in Greenbush, Maine. The work was prepared for CLD as part of their preliminary design work for the Maine DOT on a replacement bridge. Figure 1 is the topographic map of the project site.

Figure 1. Boombridge Brook Bridge, Greenbush

The bridge is located just upstream of the confluence of Boombridge Brook with the Penobscot River. The bridge and surrounding area is shown in figures 2-5. The bridge is subject to backwater flooding from the Penobscot River during high water events on the river. A large low swamp or wetland area upstream of the bridge serves as floodplain storage for floodwaters from the river. Flow at the bridge is influenced by runoff from the upstream watershed and backflow/return flow from the Penobscot River during high water.

Figure 2. Boombridge from downstream at Penobscot River

Figure 3. Looking downstream at Penobscot River from bridge. Photo taken during fall 2016 drought.

Figure 4. Penobscot River from Bridge, facing north.

Figure 5. Looking upstream from Bridge.

2.0 Existing Data Review

Existing data related to the project site was compiled and reviewed including:

- FEMA Flood Insurance Study Data: FEMA published a Flood Insurance Study for the Town of Greenbush in September of 1987. The study included flood elevations for the 100-year flood on the Penobscot River but no detailed information for Boombridge Brook. The study map is shown in figure 6.

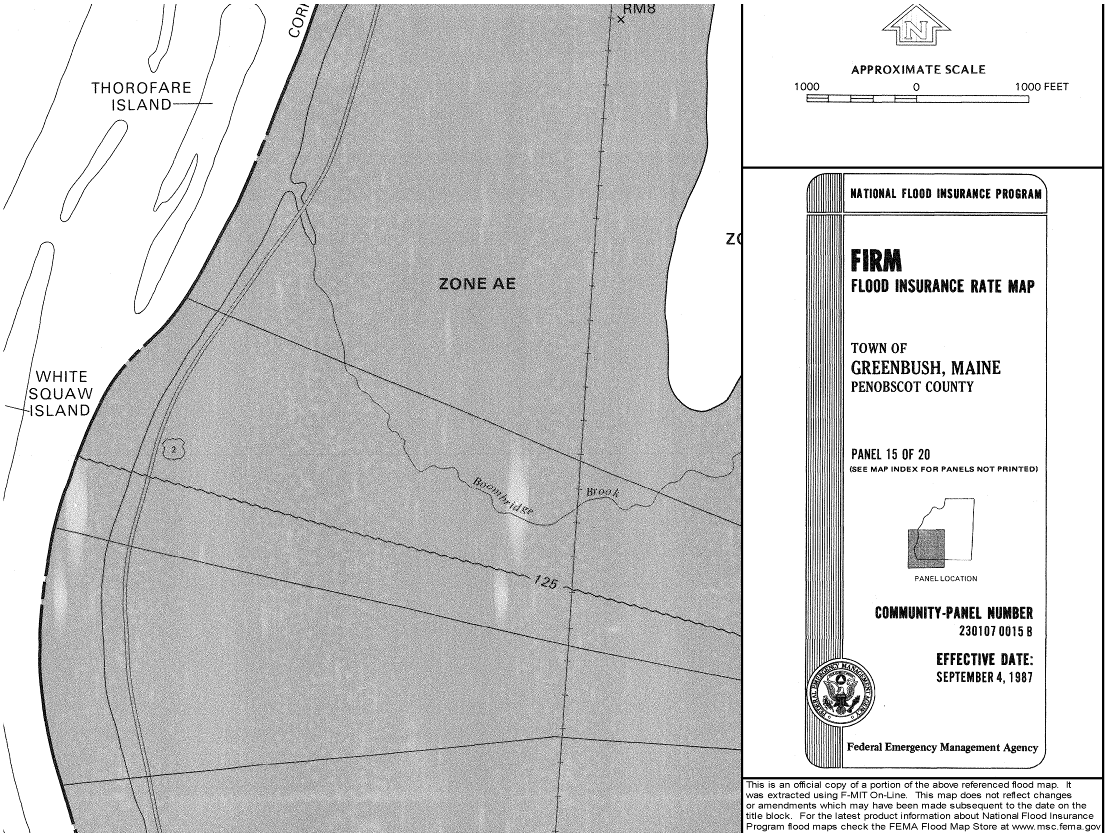

Figure 6. FEMA FIS map of Boombridge Brook

- USGS gaging station data for the Penobscot River, including gages at West Enfield, # 01034500, and Eddington, # 01036390
- USGS data on historical floods on the Penobscot River including the 1987 flood
- GIS database of information for the Boombridge Brook watershed, including soils data, elevation data, land use data, and hydrologic network.
- Maine DOT 1938 bridge plans and bridge inspection files.

3.0 Hydrology:

The site is impacted by flows from Boombridge Brook and backwater flow from the Penobscot River. Upland flows were calculated by MaineDOT as follows:

Drainage Area, 4.81 Sq. mi.	**Flow, cfs**
Wetland Area, 1.1 square miles	
Q25	261
Design Discharge (Q50)	296
Check Discharge (Q100)	346
Scour Check Discharge (Q500)	454
Ordinary High Water (Q1.1)	54
Flood of Record, April 1987	Unknown flow – elevation due to Penobscot River

Frequency, Years	Flow, cfs
Q1.1	54
Q 2	106
Q10	199
Q25	261
Q50	296
Q100	346
Q500	454

Table 2. Additional Hydrologic Data

The drainage basin to the site is shown in Figure 7.

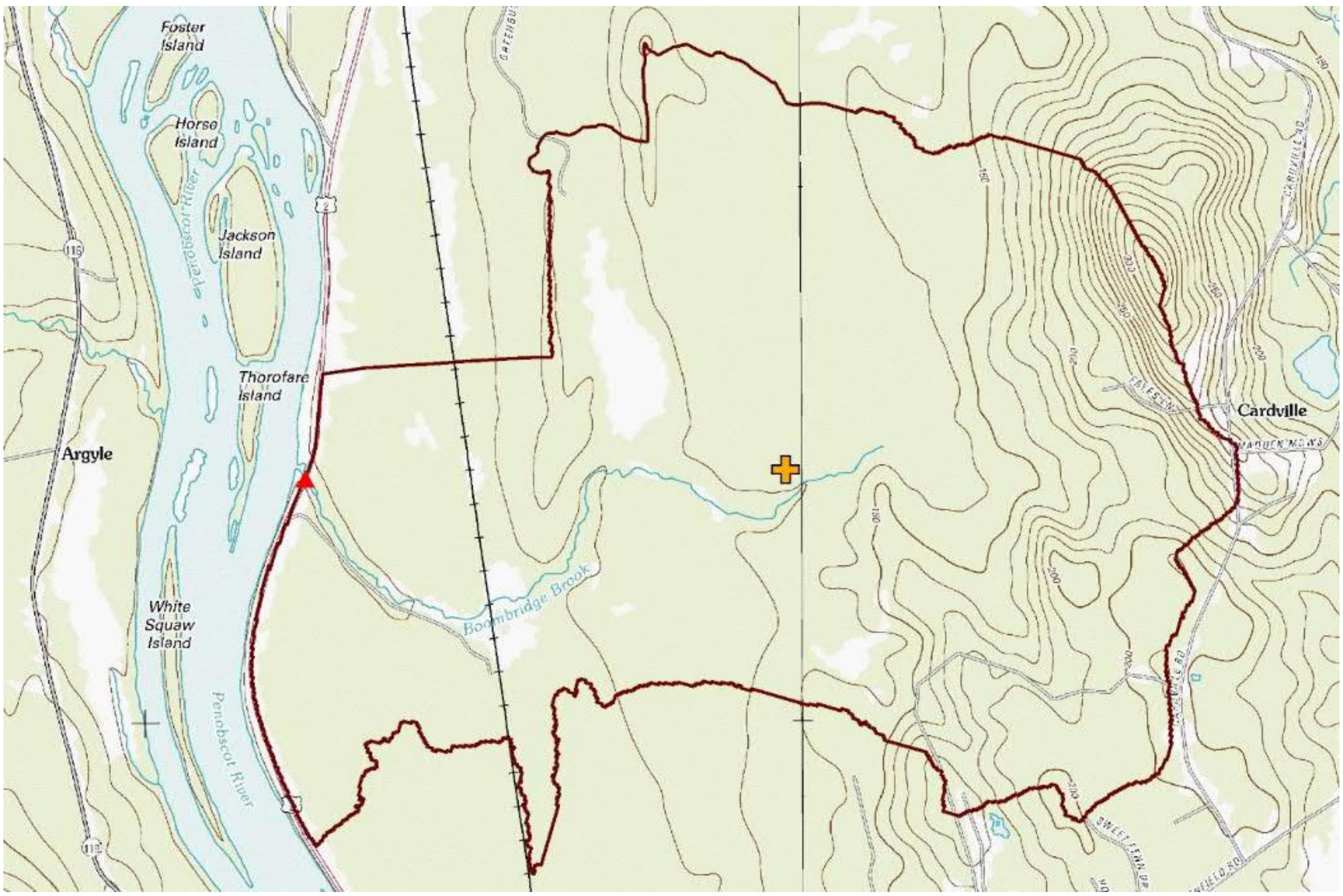

Figure 7. Drainage area to Bridge 3587

The Penobscot River flows past the site and rises to levels at or above the level of Route 2. During high water, the river flows upstream through and over the bridge filling the large wetland area upstream of the bridge. Data for the Penobscot River is based on FEMA Flood Insurance Studies and USGS gages at West Enfield (upstream) and Eddington (downstream). Flow data is summarized in table 3. No new hydraulic analyses of the Penobscot River were done for this bridge study.

	USGS Regression Report - West Enfield Gage	FEMA FIS data, Greenbush	1987 Flood Data at West Enfield Gage		1987 Flood at Eddington Gage		StreamStats at Greenbush
Drainage Area, mi2	6677.8	7094-7170	6671		7764		7193
Frequency, yrs	Flow, cfs	Flow, cfs	Flow, cfs	Elev, ft NGVD	Flow, cfs	Elev, ft NGVD	Flow, cfs
2	61400.34						57800
5	84690.12						73300
10	99863.77						83600
25	119271.9						95500
50	133739.8						104000
100	148207.7	156000-158000					113000
500	182083.8						134000
1987			147000	149.2	159000	30.7	
1923			153000				
1984					136000		

Table 3. Summary of Hydrologic Calculations, Penobscot River

Flood levels on the Penobscot River at the project site were estimated using a combination of the FEMA FIS flood profile for the Penobscot River in Greenbush and West Enfield, and recorded flood levels at the West Enfield Gage. Estimated backwater elevations for the Penobscot River at the project site are listed below in table 4.

Return Interval	FEMA elevation at W Enfield,	FEMA Elev at Greenbush	Estimated Elevation at Greenbush
10-yr	144		120
50-yr	147.6		123.6
100-yr	149	125	125
500-yr	152.5		128.5

Table 4. Summary of Flood Levels, Penobscot River. Elevations are Feet, NGVD

FEMA flood profiles are included in the appendix and show flood elevations at the West Enfield gage and projected at Greenbush.

Additional Penobscot River data was generated using a recorded hydrograph of flood elevations at West Enfield for the April 1987 flood, a rating curve of flow vs elevation at West Enfield, and estimating the levels downstream at Greenbush for the 1987 flood. The flow hydrograph at west

Enfield with flood levels is shown in figure 8. The rating curve at the gage is included in the appendix.

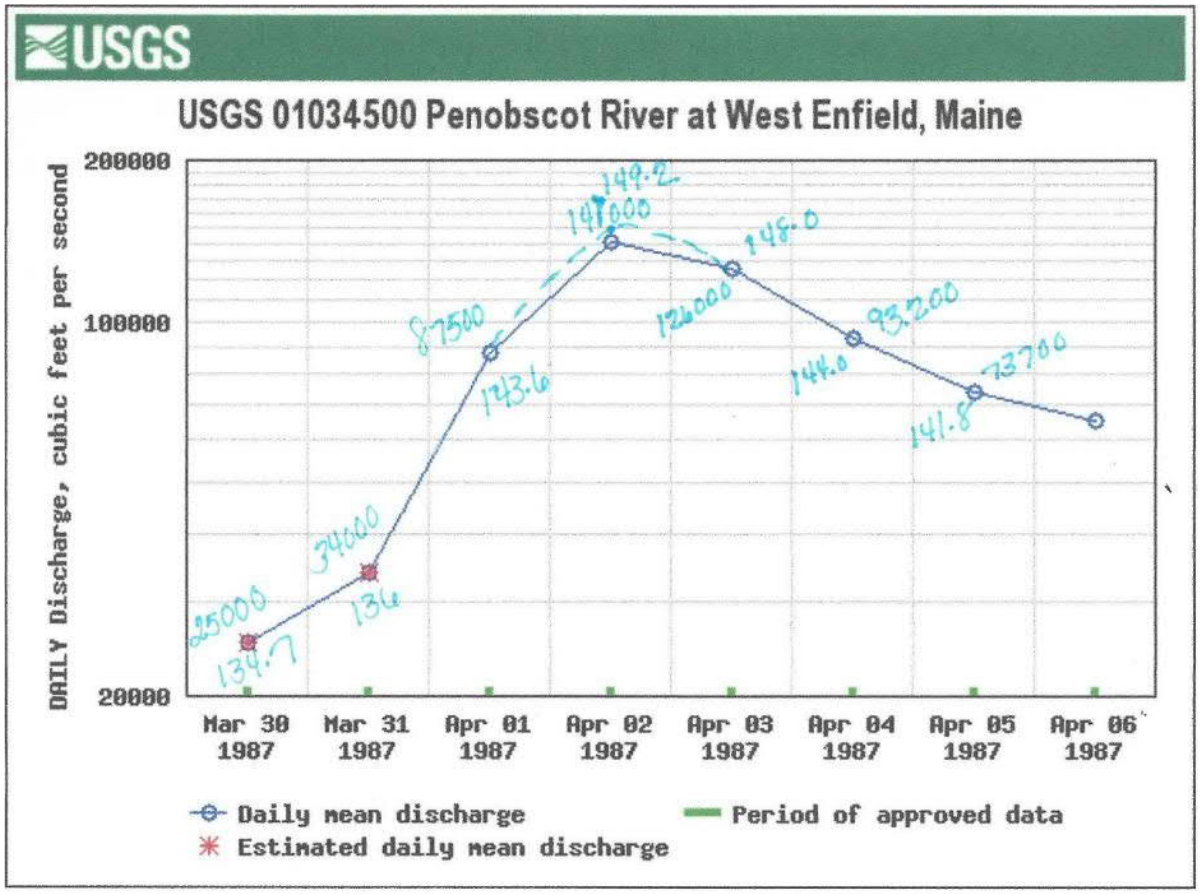

Figure 8. Flood hydrograph with elevations at West Enfield gage, April 1987 flood.

The hydrograph elevations are shown in Table 4 below.

Date	April, 1987 Storm at West Enfield Elev NGVD	Greenbush at Boombridge Brook FEMA section E-F Elev-subtract 24'	Estimated Depth over road	Flow rate at West Enfield Average Daily, cfs
Mar 30	134.7	110.7	-9.3	25000
Mar 31	136	112	-8	34000
Apr 1	143.6	119.6	-0.4	87500
Apr 2	149.2	125.2	5.2	147000
Apr 3	148	124	4	126000
Apr 4	144	120	0	93200
Apr 5	141.8	117.8	-2.2	73700

Table 4. Penobscot River Flood hydrograph, estimated at Boom Bridge. April 1987 storm, approximately a 100-year flood.

4.0 Hydraulics:

The existing bridge piers are aligned with the stream flow, but are not perpendicular to the road. The abutments and piers are skewed to the road but not to flow. The bridge has two piers with the center channel being deepest and the two side areas being less deep. Figure 9 is a photo of the bridge from downstream during very low water in October of 2016. The upstream side of the bridge has some blockage due to a beaver dam and is shown in figure 10.

Figure 9. Boom Bridge from downstream

Figure 10. Upstream face of bridge from south side.

CLD provided drawings for two proposed bridge replacement options including a long span of 125' and a shorter option with a span length of 74'. For the long span, proposed abutments will be placed outside of the existing abutments. The shorter span includes new abutments inside of the existing abutments. Neither proposed option has piers. Because the bridge has two-way flow, CLD has provided dimensions designed to replicate existing hydraulic opening as closely as possible. The two options are shown in Figures 11 and 12.

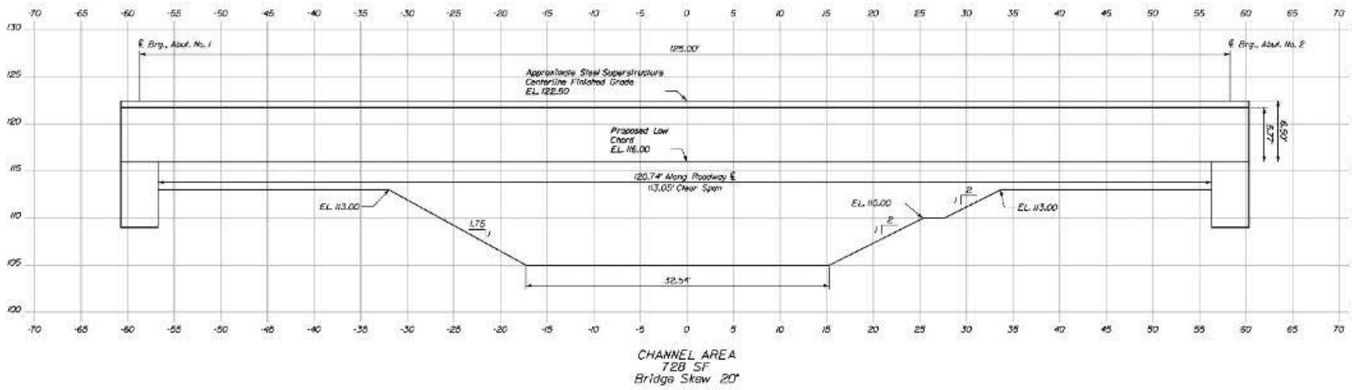

Figure 11. Long span option

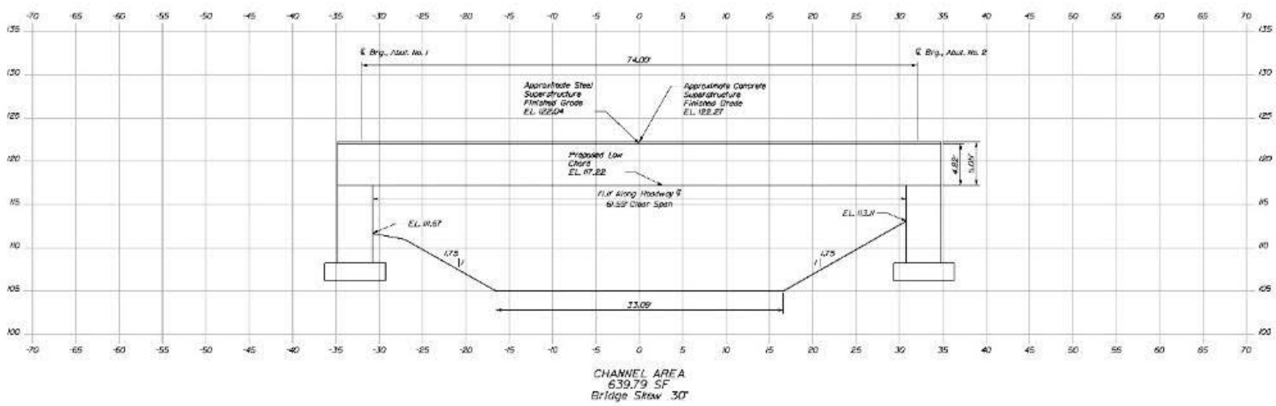

Figure 12. Short Span option

The existing bridge conveys water from the upland drainage area to the Penobscot River. Flood flows are not large compared to the bridge opening size. The bridge also conveys Penobscot River water into the drainage basin upstream of the bridge, either through the bridge, possibly through other bridges and rarely over the top of Route 2. The existing bridge was analyzed to evaluate flow capacity relative to upland flows and in relation to potential flow conditions when the Penobscot River flows into the bridge and/or over Route 2.

A HECRAS model of the bridge site, the upland wetland storage basin and the Penobscot River connection was constructed and was run in both steady flow and unsteady flow modes to understand how the bridge functions during upland floods with low or high water downstream and during upland floods where the "swamp" upstream is draining out after a road overtopping type of event from the Penobscot River. Model runs, historic data and interviews with road maintenance personnel indicate that Route 2 does occasionally overtop. The "swamp" or wetland area upstream of the bridge likely fills with water from the Penobscot River. Based on potential flooding scenarios, the following steady flow options were developed to model conditions at this bridge:

- Bridge Geometry:
  - Existing bridge
  - long span,
  - short span
- Penobscot River Backwater
  - Backwater
  - No Backwater
- Flows:
  - Upland flows for Boombridge Brook
  - Wide flow range to develop rating curve for bridge opening and overtopping

These combinations allow modeling of flow during low water on the Penobscot River and allow evaluation of worst case conditions for potential scour as the wetland area behind the bridge drains after overtopping or backflow from the Penobscot River. Due to overtopping and uncertainties in the extended roadway profile, the unsteady flow option was not utilized. Basic routing techniques were utilized to evaluate estimated rate of overtopping and rate of draining of "swamp" area upstream of bridge.

Rating curves for each bridge option for upland flows were developed using model HECRAS. Figure 13 shows flow vs elevation for selected flow rates at each bridge option under conditions of no backwater on river and backwater on river. Figure 14 and 15 show water surface elevation profiles through the bridge for each bridge option under no backwater and backwater conditions for predicted upland runoff rates.

Figure 16 shows bridge rating curves for a wide range of flows assuming backflow from the Penobscot River. The plot shows rating curves for existing and long and short options, assuming that return flow happens under backwater conditions, and no backwater conditions. Flow profiles for selected high flows representing worst case backflow rates are shown in figures 17 and 18.

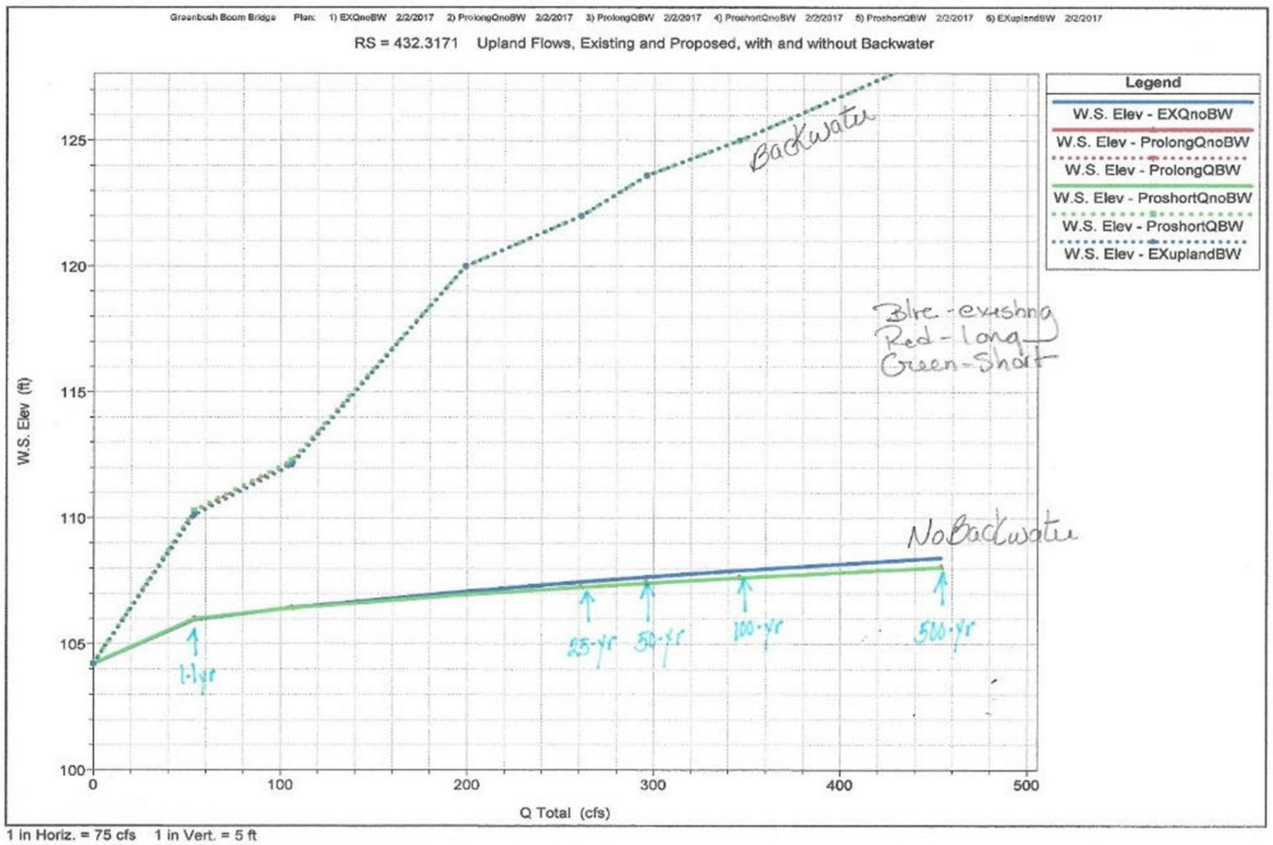

Figure 13. Rating curves for existing, long and short span options. Shown with and without backwater from Penobscot River.

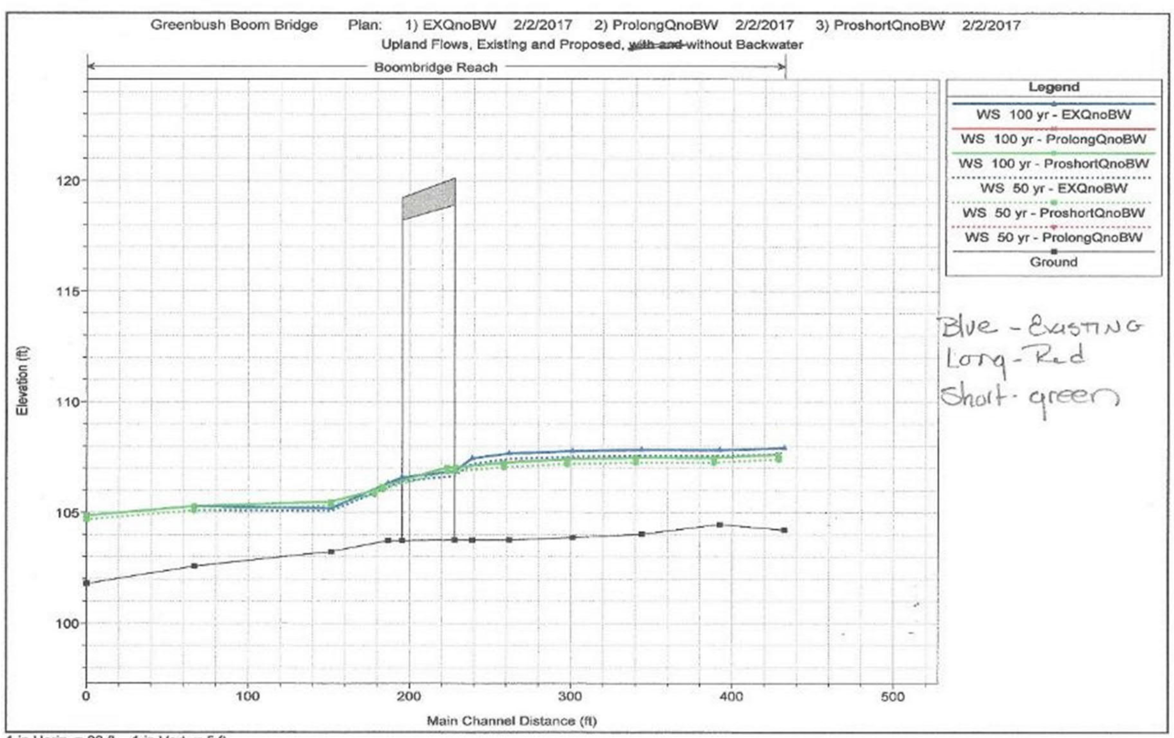

Figure 14. Flood profiles for existing and long and short options without backwater, 50- and 100-year profiles.

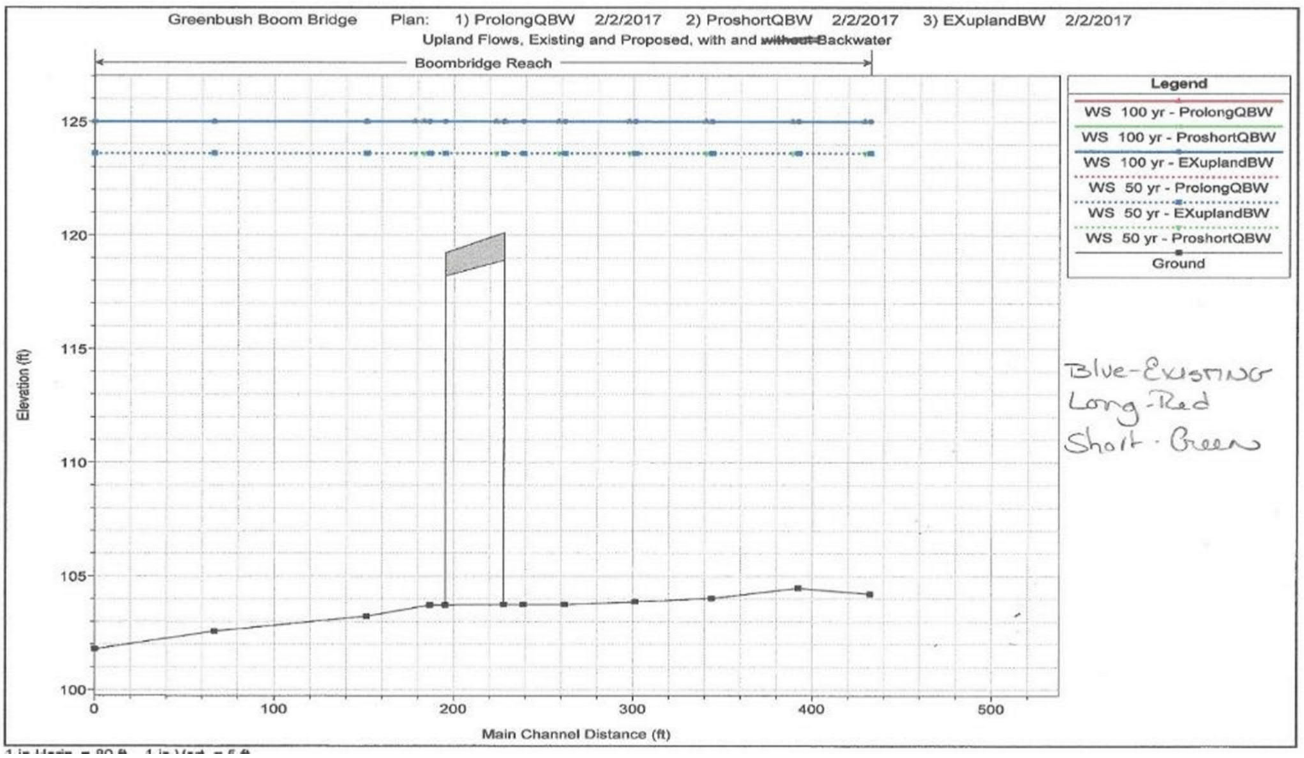

Figure 15. Flood profiles, existing and long and short span options, with backwater. 50- and 100-year profiles.

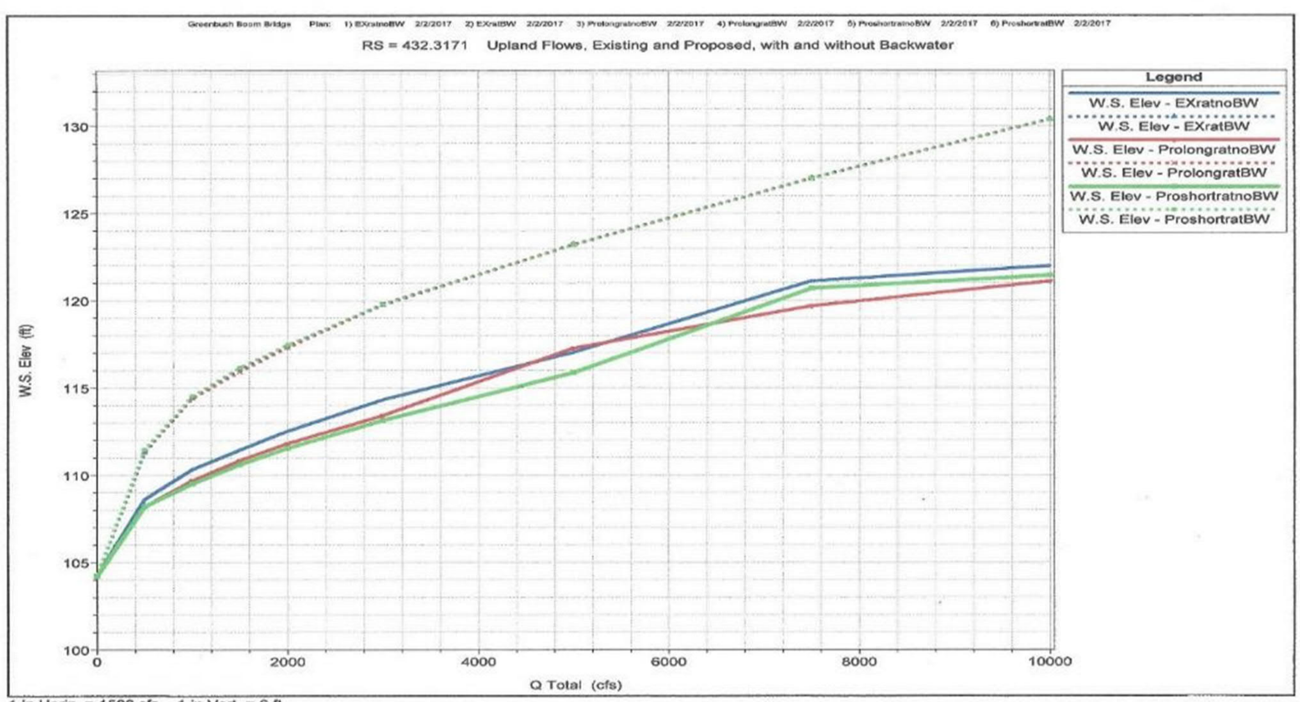

Figure 16. Rating curves for high flows, existing, long and short options, with and without backwater.

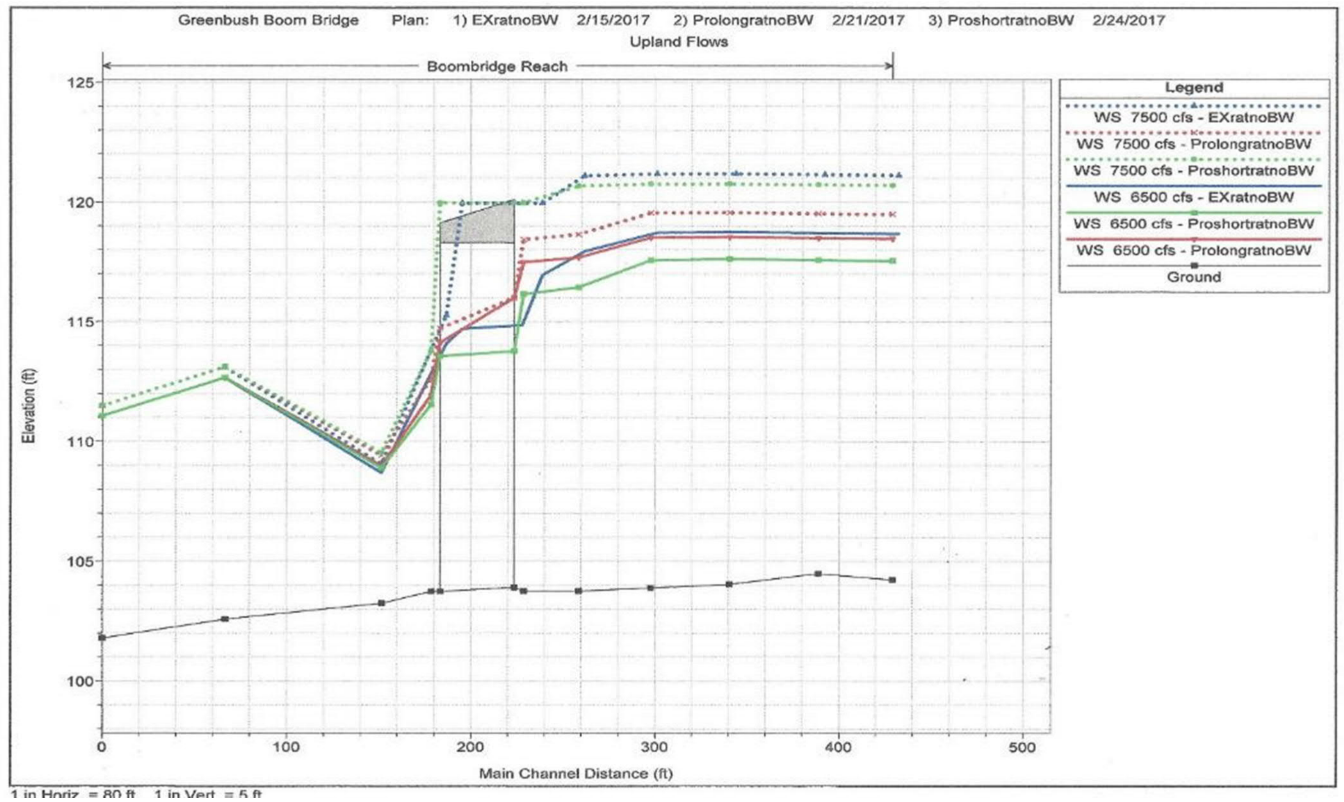

Figure 17. High return flow for existing, short and long span options. 6500 and 7500 cfs without backwater.

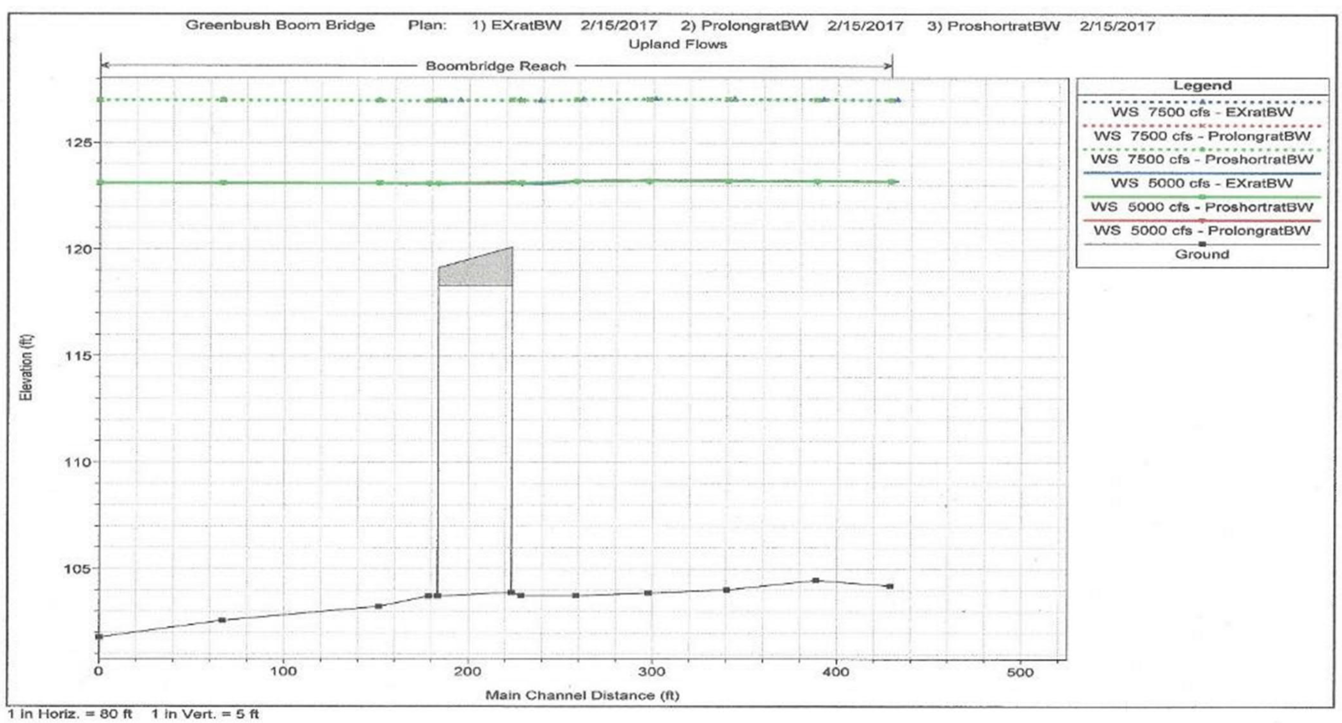

Figure 18. Flood profiles for existing, long and short options with backwater. 5000 and 7500 cfs.

Flow through each bridge is summarized in tables 5-8, including upland flows with and without backwater and elevations for a range of flows that may represent backflow.

Frequency	Existing Bridge	Long Span	Short Span
1.1-yr	105.6	105.70	105.70
2-yr	106.1	106.10	106.10
10-yr	106.9	106.63	106.63
25-yr	107.2	106.91	106.91
50-yr	107.4	107.06	107.05
100-yr	107.7	107.25	107.25
500-yr	108.2	107.62	107.62

Table 5. Summary of Upstream Elevations, no backwater, upland flows only

Frequency	Existing Bridge	Long Span	Short Span
1.1-yr	110.12	110.25	110.30
2-yr	112.10	112.20	112.27
10-yr	120.00	120.00	120.00
25-yr	122.00	122.00	122.00
50-yr	123.60	123.60	123.60
100-yr	125.00	125.00	125.00
500-yr	128.50	128.50	128.50

Table 6. Summary of Upstream Elevations, with backwater and upland flows.

Elevation	Existing Bridge	Long Span	Short Span
105	50	50	50
110	400	400	400
115	1200	1200	1200
120	3200	3200	3200
121	3700	3700	3700

Table 7. Summary of flow rates for headwater elevation, assuming Penobscot River is still at flood stage (backwater).

Elevation	Existing Bridge	Long Span	Short Span
105	100	100	100
110	900	1200	1250
115	3600	3800	4400
120	6800	7200	8000
121	7500	8000	10000

Table 8. Summary of flow rates for headwater elevation, assuming Penobscot River flood hydrograph has passed. (no backwater).

Routing computations illustrate that the existing bridge would allow the swamp area to drain from elevation 120 to elevation 110 in about 14 hours at the rate of flow that is projected to occur with backwater from the Penobscot River. The hydrograph on the Penobscot River for the 1987 storm (approximately 100-year) shows that the river drops about 2 feet per 24 hour period on the trailing side of a storm hydrograph. Therefore, appropriate flow rates at this bridge would use the “with backwater” flow rates. The “swamp” upstream of the bridge is projected to drain at a similar rate to the river, so flow rates will not have dramatic drops in elevation through the bridge. Table 9 summarizes routing computations for “draining the swamp” assuming the bridge is flowing at rates dictated by backwater.

Wetland Elevation	Flow through Existing Bridge, Ac-Ft per hour	Storage, ac-ft	Elevation	Time/Hours
120	264.5	1778.3	119.2	0.0
119.2	243.8	1534.5	118.6	1
118.6	234.0	1300.5	118.2	2.0
118.2	225	1075.5	117.5	3
117.5	200.0	875.5	116.6	4.0
116.6	155.0	720.5	116.2	5.0
116.2	135.0	585.5	115.4	6.0
115.4	110.0	475.5	114.8	7.0
114.8	85.0	390.5	114.5	8.0
114.5	82.0	308.5	113.9	9.0
113.9	70.0	238.5	113.5	10.0
113.5	67.0	171.5	112.7	11.0
112.7	58.0	113.5	112.4	12.0
112.4	54.0	55.5	111.4	13.0
111.4	43.0	12.5	110.2	14.0

Table 9. Estimated rate of outflow from upstream assuming river backwater. Note that river level only drops about 2 feet in 24 hours. Therefore, upstream area water levels will drop at about the same rate as the Penobscot River.

Ice jams are known to have occurred both upstream and downstream of the project site according to the CRREL website. It is assumed that the apparently conservative flood elevations reported by FEMA reflect ice jams as part of the overall flood elevations on the Penobscot River.

Based on the potential rates of flow shown in table 9 above, maximum flow rates and velocities through the bridge are most likely to reflect the “with backwater” flow rates shown in Table 7 above. It is not likely that the full flow from the swamp area would drain without the river in a backwater condition. Table 10 summarizes hydraulic data for the bridge.

Summary of Hydraulic Data Boom Bridge Bridge # 3587, Greenbush, Maine	Existing Bridge	Proposed Bridge – Long Span	Proposed Bridge – Short Span
Low Chord	118.2	116	118.3
Elevation of Top of Road	120	120	120
Flood of Record, 1987, approx. 100 year- estimated elevation from gage and FEMA	125	125	125
Headwater at Q25, ft, w/o backwater	107.2	106.9	106.9
Q25 estimated elevation on Penobscot River	122	122	122
Headwater at Q50, ft, w/o backwater	107.4	107.1	107.1
Q50 estimated elevation on Penobscot River	123.6	123.6	123.6
Headwater at Q100, ft, w/o backwater	107.7	107.3	107.3
Q100 estimated elevation on Penobscot River	125	125	125
Discharge Velocity at Q25, fps- no backwater	5.7	5.1	5.0
Discharge Velocity at Q50, fps – no backwater	6.0	5.4	5.3
Discharge Velocity at Q100, fps – no backwater	6.3	5.7	5.7
Discharge Velocity, Backflow @ Pressure flow, between 7500 and 10000 cfs with backwater from river.	4.2	4.5	4
Ordinary High Water Elevation (Q1.1), no backwater	105.2	105.6	105.6
Discharge Velocity at Q1.1, fps	3.1	2.7	2.7
Clearance @ Q25, ft	11.0	9.1	11.1
Clearance @ Q50, ft	10.8	8.9	10.9
Clearance @ Q100, ft	10.5	8.7	10.6
Bridge Opening Area, ft^2	712.8	744.6	713.2

Table 10. Summary of Hydraulic Data

5.0 Scour Analysis:

Preliminary design scour analysis was performed for the two single span bridge options. Scour computations were based on guidance in FHWA HEC 18, Evaluating Scour at Bridges. Long term, contraction and local scour components were estimated. At this stage of design, geotechnical data was not available.

This bridge is not typical of bridges where maximum flow occurs due to runoff from the watershed. Rather, flood flows are a combination of upland flows and backflow from Penobscot River high water.

Therefore, scour was computed for worst case potential scour. The computed scour is based on an unlikely hydraulic combination, but will assist designers in selection of foundation components. Assumed D50 of 5 mm was used for scour computations. This value will be updated when geotechnical data is received. Note that large riprap or natural boulders were noted in the three flow channels.

Site evidence indicates rapid flow through the bridge. The three channels under the bridge appear to have ongoing scour holes near piers and show sorting of bed material with largest material remaining in the channel and finer material being washed away.

Figure 19. South channel of bridge (looking upstream). Note large rocks and erosion near pier.

Figure 20. Center channel of existing bridge looking downstream from beaver dam. Note large stones in channel and erosion near piers.

Figure 21. Center channel. Note scour hole along center of pier.

Figure 22. Center channel. Note large stones and scour along pier.

Long Term Bed Changes: Comparison with 1939 plans indicates that current bottom levels are very similar to those shown in 1939 plans. The river provides some control on the stream bed level as well. The bed and stream appear generally geomorphically stable based on field observation. A conservative value of 2’ of additional degradation is assumed to account for long term bed changes.

Contraction Scour: Scour computations were run for the potential worst case flow of low backwater on the Penobscot River and floodwater draining back to the river from the upstream swamp at about 6500 cfs, or pressure flow through the bridge (lower than overtopping, but higher than the low chord). This flow scenario is not likely to occur as discussed in the section above on hydraulics. However, evaluating the worst case scenario provides outside guidance to the bridge designers for foundation components. Potential contraction scour was estimated as follows:

Bridge Span	Short Span			Long Span		
Overbanks and/or Channel	Left	Center	Right	Left	Center	Right
Contraction	0	12.9	0	1.1	8.1	1.1
Abutment	9.3		9.1	8.3		7.5
Long Term Bed	2	2	2	2	2	2
Total	11.3	14.9*	11.1	11.4	10.1	10.6

Table 11. Summary of Scour Computations. Note that the short span eliminates modeled "overbank" areas in the bridge, so no scour is predicted at "left and right overbank".

- Note that HECRAS indicates possible overlap of abutment and contraction scour for short span bridge for total scour of 22' center channel. Bedrock is at about 15' below ground in center channel, so scour would only occur to bedrock.

These results indicate potential for scour to bedrock with the short span, but generally about 10' of scour for the longer span.

Properly designed scour protection (see FHWA HEC 23) on the abutments should eliminate or minimize potential for abutment scour, but contraction scour is still possible.

Flow scenarios can be revised and scour computations updated as bridge components are refined with continued design. It is recommended that the bridge designers confer with NHI to review factors that affect scour as final design options are evaluated.

7.0 Summary and Recommendations:

- BoomBridge is subject to flow from upland runoff and backwater from the Penobscot River.
- FEMA lists the 100-year flood elevation from the Penobscot River at 125' NGVD at the project location. FEMA did not study Boombridge Brook.
- 100-year upland flow is computed to be 346 cfs for the 4.8 square mile drainage basin.
- The drainage area includes 1.1 square miles of wetlands which provide flood storage for upland flows and overflow from the Penobscot River.
- USGS maintains two stream gages on the Penobscot River, upstream at West Enfield and downstream at Eddington.
- The bridge is likely overtopped by floodwaters from the Penobscot River during low frequency events, with estimated overtopping occurring for floods above a 10-year level.

This analysis is based on estimated water levels for the Penobscot River using data generated by FEMA and the USGS gaging station at West Enfield.

- Road maintenance personnel did not recall frequent overtopping.
- FEMA and gage data were combined to estimate elevation and duration of flood hydrographs on the Penobscot River.
- The existing bridge and two span options (74' and 125') were evaluated using hydraulic model HECRAS.
- The bridge area is significantly larger than required for conveyance of upland flows.
- The bridge allows floodwaters from the Penobscot River to fill the upstream wetland area.
- Hydraulic models included upland flows, backwater and no-backwater conditions as well as general rating curves for each option.
- The bridge allows drainage back to the river at a rate higher than the river would be expected to recede, so the bridge does not cause a constriction in terms of draining of floodwaters.
- Road maintenance personnel did not recollect frequent overtopping events, so the FEMA elevations and flood levels estimated in this report for the Penobscot River are likely conservative.
- Recommendations for replacement based on hydraulic analysis include
  - Duplication of existing bridge open area as much as possible.
  - Elimination of bridge piers.
  - Alignment of abutment with flow
- The two bridge options are not projected to increase flood levels and are of similar size to existing, allowing backflow and velocities to be similar.
- Elimination of piers provides improved hydraulic function, with lower velocities but similar hydraulic opening for both options.
- Either option provides improved function over the existing bridge. Hydraulically, both are similar. Of the two options, either choice would provide adequate passage for design flood waters within the limitations of this site (i.e. overtopping will occur due to backwater from the Penobscot River). Scour estimates are deeper for the shorter span and may affect final design parameters for substructures.
- The bridge functions hydraulically somewhat similar to a tidal bridge in that upstream flood elevations are impacted by the bridge opening. The amount of water that can flow UPSTREAM during a flood event on the Penobscot River depends on bridge opening and road elevation.
- The beaver dam in the bridge should be eliminated during construction to allow a more open waterway.
- The Penobscot River is recorded to have had ice jams both upstream and downstream of the project site in the past.
- The existing bridge shows evidence of local scour at piers.
- Proposed bridge options do not include piers.

- Worst case scour estimates calculated about 11-15’ of potential scour for the short span and 10-11’ of scour for the long span.
- Scour protection is recommended at abutments. This would reduce scour potential at abutments, but contraction scour is still possible.
- Scour computations should be reviewed for final design based on:
  - Site geotechnical data (none available for preliminary design)
  - Refined design of abutments, channel and bridge deck.
  - Carefully consider most likely flow/backwater combination

8.0 References:

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Appendix: