COLUMBIA COUNTY
WEST END FLOOD MITIGATION STUDY
FINAL REPORT

ADDENDUM NO. 1
2-DIMENSIONAL HYDRAULIC MODELING ANALYSIS

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SECTION 1 – INTRODUCTION

1.1. Purpose and Goals

The overall purpose and goals of the West End Flood Mitigation Study are described in Section 1.3 of the Columbia County West End Flood Mitigation Study Final Report, Volume I, dated June 2022 hereinafter referred to as the Final Report.

This hydrologic and hydraulic (H&H) report is an addendum to the Final Report. In the initial phase of the study, Fishing Creek hydraulics were evaluated utilizing a 1-Dimensional (1D) hydraulic analysis. During that study, it became evident that the complexity of the hydraulics exceeded the capability of 1D analysis. Due to the size and breadth of the floodplain including the regulated floodway, multiple occurrences of split flow and flow junctions, density of development in the floodplain, and superelevated water surfaces around channel bends, a 2-Dimensional (2D) model was created for analysis of existing and proposed hydraulic conditions related to the recommended flood mitigation project for the West End of the Town of Bloomsburg.

The Final Report outlines the recommendations for a levee/floodwall system to mitigate flood risk from Fishing Creek and the Susquehanna River. The purpose of this supplemental 2D hydraulic analysis of Fishing Creek was to accurately determine the hydraulic impacts of a proposed levee on neighboring municipalities and residents and to evaluate the viability of various solutions to minimize or eliminate those impacts. The 2D hydraulic analysis included:

1) Model Development
2) Model Calibration
3) Existing Conditions Analysis
4) Proposed Conditions Analysis
5) Induced Flooding Mitigation Alternatives Analysis

1.2. Project Area & Description

The study area and description are presented in Section 1.2 of the Final Report. Refer to Figure 1.1 on the following page for a map of the study area.

The study area is comprised of approximately five hundred (500) parcels and three hundred fifty (350) structures.

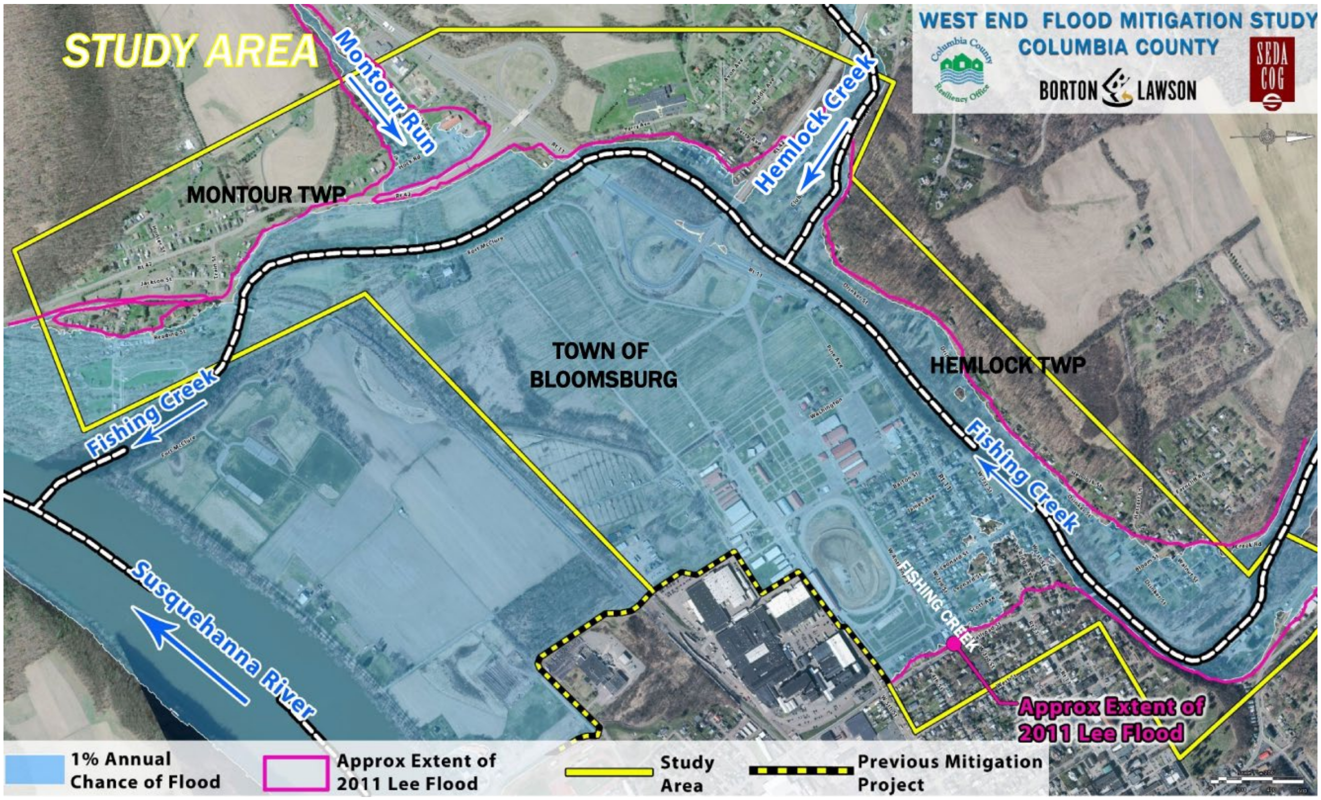

Figure 1.1 – Study Area Map

SECTION 2 – HYDROLOGIC ANALYSIS

The 1D hydraulic analysis performed as part of the West End Flood Mitigation Study assumed a constant flow in Fishing Creek with no flow changes along the studied reach of the creek. When creating the 2D model for this supplemental study in the same manner, the nature of the output appeared incomplete with tributaries within the study area not producing flow. To model Hemlock Creek and Montour Run, flows were added to these tributaries. Fishing Creek flows were then adjusted accordingly to ensure the peak discharge at the confluence with the Susquehanna River remained consistent. This action resulted in a reduction in peak flows on Fishing Creek upstream of Hemlock Creek relative to the 1D model.

The coincident recurrence intervals for Hemlock Creek, Montour Run, and the Susquehanna River corresponding to the base flood (100-Yr flood) on Fishing Creek were determined by applying drainage area ratios per Figure 2.1 for determining relationships between tributaries and a main stem.

	50-year design		100-year design	
	main stream	tributary	main stream	tributary
10,000:1	2	50	2	100
	50	2	100	2
1,000:1	5	50	10	100
	50	5	100	10
100:1	10	50	25	100
	50	10	100	25
10:1	25	50	50	100
	50	25	100	50
1:1	50	50	100	100
	50	50	100	100

Figure 2.1 – Frequencies of Coincidental Occurrence
Pennsylvania Department of Transportation (PennDOT) Publication 584, Chapter 7

Brief hydrologic summaries are provided below for each watercourse within the study area. Tables 3.1 and 3.2 summarize the design flows used for each condition relative to the original 1D hydraulic model.

Fishing Creek

Fishing Creek is a major tributary to the Susquehanna River within Columbia County and has a total drainage area of 385 square miles above its confluence with the Susquehanna River. Fishing Creek discharges were obtained using a combination of a United States Army Corps of Engineers (USACE) Study, dated June 2012, which incorporated data from the Tropical Storm Lee event of 2011 and the United States Geological Survey (USGS) Scientific Investigations Report (SIR) 2019-5094 for estimation of flood flows at ungauged sites.

The 2012 USACE study determined flows at the project site by applying a ratio of the drainage area to the gauged flow. USGS SIR 2019-5094 presents a newer method for transposing flows from a nearby stream gauge to a project site using a drainage area characteristic exponent in the regional regression equation. Applying the USGS method to the Tropical Storm Lee event results in a lower flow rate compared to the method utilized in the USACE report, 72,500 cubic feet per second (CFS) vs. 78,700 CFS. The lesser flow is within the standard 90% confidence interval for an event with a 350-year recurrence interval.

To calibrate the model for the Tropical Storm Lee Event, the flows calculated following the USGS method were chosen as the target flows at the Susquehanna River confluence and adjusted to the upper boundary of Fishing Creek by subtracting the tributary inflows at Hemlock Creek and Montour Run.

Hemlock Creek

Hemlock Creek is a tributary to Fishing Creek with a drainage area of 16.6 square miles; the confluence occurs within the study area immediately upstream of the US Route 11 and PA Route 42 Interchange. Hemlock Creek is a Federal Emergency Management Agency (FEMA) detailed study watercourse with a regulatory floodway. Water surface elevations (WSELs) and peak discharges on Hemlock Creek were obtained from the Preliminary Flood Insurance Study (FIS) dated August 28, 2020.

Montour Run

Montour Run is a tributary to Fishing Creek with a drainage area of 4.6 square miles. The confluence occurs downstream of US Route 11 within the Township of Montour. Montour Run is an approximate study stream with no predetermined WSELs or peak discharges. Because no peak discharges are available from FEMA, PA StreamStats was used to obtain peak flows for various recurrence interval events. StreamStats is a web-based application created and managed by USGS and utilizes hydrologic regression equations to estimate flows. StreamStats data for Montour Run is included in Appendix A.

Susquehanna River

Susquehanna River flows used in modeling the base flood on Fishing Creek were taken from the 2020 Preliminary FEMA Flood Insurance Study (FIS). When calibrating the model for Tropical Storm Lee, the coincident discharge recorded by the USGS Susquehanna River gauge at Bloomsburg coinciding with the peak flow recorded on the USGS Fishing Creek gauge was used. These flows are recorded in Tables 3.1 and 3.2.

SECTION 3 – 2D HYDRAULIC MODEL DEVELOPMENT

3.1. Model Selection & Justification

The Hydrologic Engineering Center-River Analysis System (HEC-RAS) version 6.2 program, developed by the U.S. Army Corps of Engineers, was used to perform the hydraulic analysis of the study area using the Two-Dimensional modeling capabilities of the software. Two-Dimensional modeling produces detailed and accurate representations of complex flow path conditions including wide floodplains, sinuous channels, multiple channels, bends and confluences, bridge/roadway crossings, lateral hydraulic structures, roadway overtopping, levees, and heavily developed urban settings among other conditions. The West End of the Town of Bloomsburg contains several of these features in existing conditions and several more are introduced in proposed conditions and for mitigation. The complex nature of the study area justifies using 2D analysis which is critical to support the decision making of engineers, stakeholders, and local elected officials.

Two-Dimensional models can enhance communication with stakeholders and the public with presentation of realistic, easy to interpret graphics and videos produced by the model. These models also provide more accurate representations of flow and velocity distribution, water surface elevation, backwater, velocity magnitude and direction, flow depth, shear stress and many other parameters which may be of interest to the modeler or stakeholders.

3.2. Assumptions & Limitations

The current limitations of the HEC-RAS 2D hydraulic modeling software includes an inability to perform water quality modeling in 2D flow areas, account for steep slopes above 10% inside the model, or allow a straightforward coupling to an 2D dynamic stormwater analysis. None of these current software limitations are present or relevant to the objectives of this study.

3.3. 2D Model Domain

The HEC-RAS 2D model domain was defined to encompass the extent of the Preliminary FEMA 500-Year floodplain and include the upstream and downstream boundaries of all modeled watercourses a sufficient distance from the study area to stabilize the computations.

A single HEC-RAS 2D flow area was created for the entire domain, and a 2D computational mesh was generated at a nominal grid cell spacing of 40’ X 40’.

The final computational mesh contains approximately 177,300 cells with an average cell size of about 5,370 square feet. The model domain covers approximately 16,095 linear feet (3.0 miles) of Fishing Creek and approximately 1,063.5 acres of floodplain.

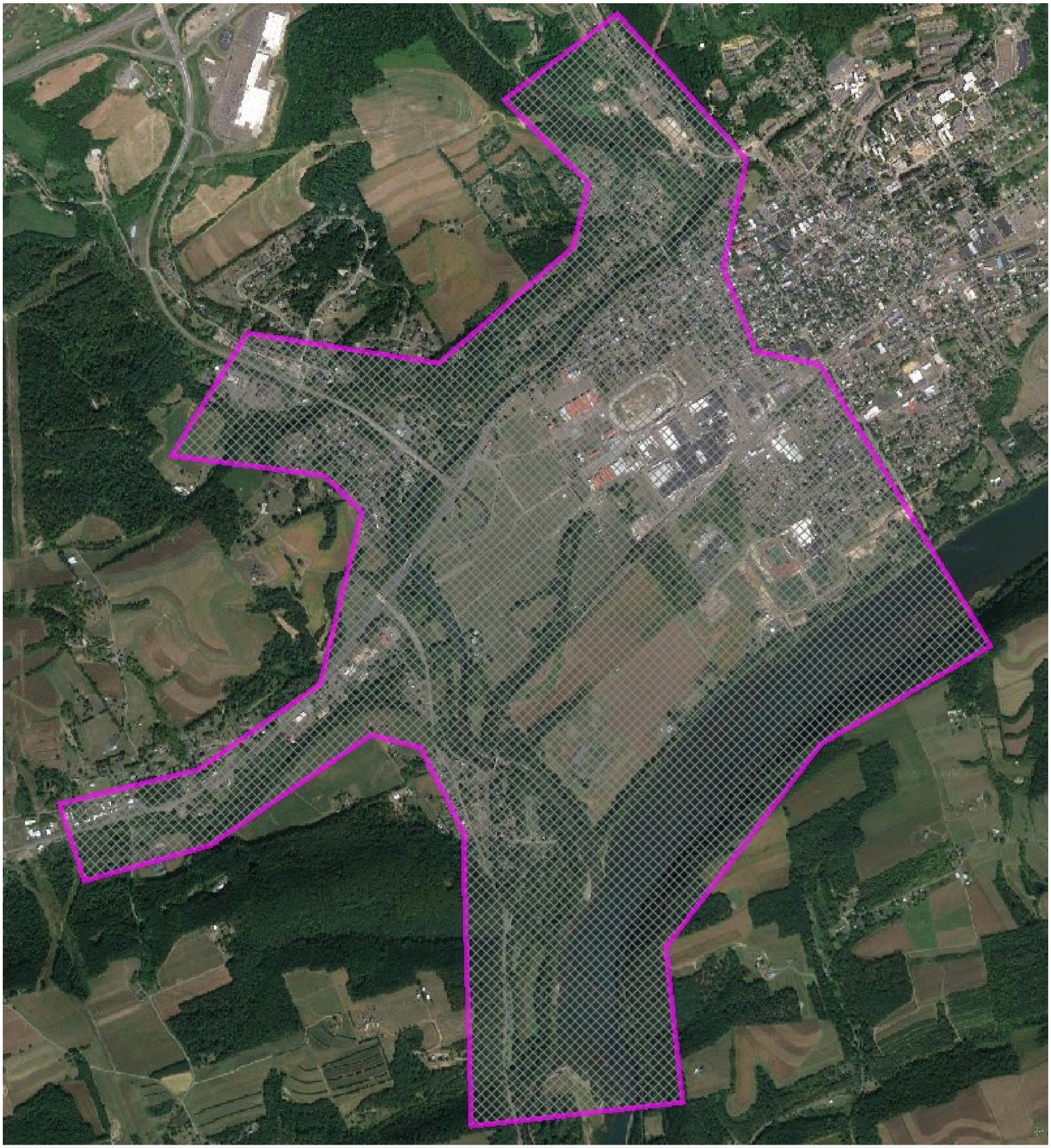

Figure 3.1 – 2D Hydraulic Model Domain Limits

3.4. Terrain Data Sources

Horizontal projection and Vertical Datum

The horizontal coordinate system is set to Pennsylvania Sate Plane North American Datum of 1983 (NAD83) North FIPS 3701 Feet. The vertical datum is referenced to the North American Vertical Datum of 1988 (NAVD88).

Data Sources

The surface terrain data used in the modeling effort is a combination of topographic data from the following sources:

- PA State LIDAR (Light Detecting and Ranging) – Obtained from Pennsylvania Spatial Data Access (PASDA) and collected under the Pennsylvania Department of Conservation and Natural Resources (DCNR) PAMAP Program in 2008.
- Detailed topographic survey - performed by The Thrasher Group in the Spring of 2021 via airplane and LIDAR.
- Bathymetric Survey of Fishing Creek - Performed by Borton-Lawson, May/June 2022.
- Supplemental topographic survey – Performed by Borton-Lawson, May/June 2022.
- Bathymetry data segments from the upstream boundary for Fishing Creek to the beginning of the bathymetry field survey, and from the end of the bathymetric field survey to the mouth of the Susquehanna River were generated from FEMA cross sections.
- Bathymetric data for Hemlock Creek were generated from FEMA cross sections.
- Bathymetry data for Susquehanna River derived from 2013 HEC-RAS Model developed by the USACE.
- As-Built survey and design surface data for formerly completed Phase 1 and Phase 2 Levee systems.

Considering the density of development present within the floodplain, building footprint data was extruded 20 feet above existing grade and made part of the final merged terrain. The initial building footprint Geographic Information Systems (GIS) shape file was obtained from Columbia County, GIS Department.

In areas where data sources overlap, sources were layered in order from lowest precision to highest precision when merging the final terrain file.

3.5. Boundary Conditions

The boundary conditions for the hydraulic models are summarized in Table 3.1 and Table 3.2 for the 1% annual exceedance probability (AEP) Base Flood and for the 2011 Lee Flood Event, respectively. The boundary values for the 2011 Lee Flood Event were used to calibrate the model for the Existing Conditions, Proposed Conditions, and Mitigation Alternatives analyses.

Table 3.1
Boundary Conditions for 1% AEP Base Flood

Boundary	Type	Peak Value (CFS)	Return Period (Years)	Reference/Source
Inflow Fishing Creek	Inflow Hydrograph	54,363	100	2012 USACE Report
Inflow Susquehanna River	Inflow Hydrograph	155,100	10	Preliminary FIS 2020
Inflow Hemlock Creek	Inflow Hydrograph	3,800	25	Interpolated from Preliminary FIS 2020
Inflow Montour Run	Inflow Hydrograph	737	25	USGS PA StreamStats
Downstream Susquehanna River	Normal Depth	0.001	-	(100-Year) Flow gradient @ FEMA Cross-section: BH

Table 3.2
Boundary Conditions for 2011 Lee Flood Event

Boundary	Type	Peak Value (CFS)	Return Period (Years)	Reference/Source
Inflow Fishing Creek	Inflow Hydrograph	63,064	350	USGS SIR 2019-5094 & 2012 USACE Report
Inflow Susquehanna River	Inflow Hydrograph	141,501	10	Susquehanna River Gauge at Bloomsburg
Inflow Hemlock Creek	Inflow Hydrograph	8,500	100	Preliminary FIS 2020

Inflow Montour Run	Inflow Hydrograph	935	50	USGS PA StreamStats
Downstream Susquehanna River	Normal Depth	0.001	-	(100-Year) Flow gradient FEMA @ Cross-section: BH

The return period for tributaries was determined according to PennDOT Pub584/ Frequencies for Coincidental Occurrence.

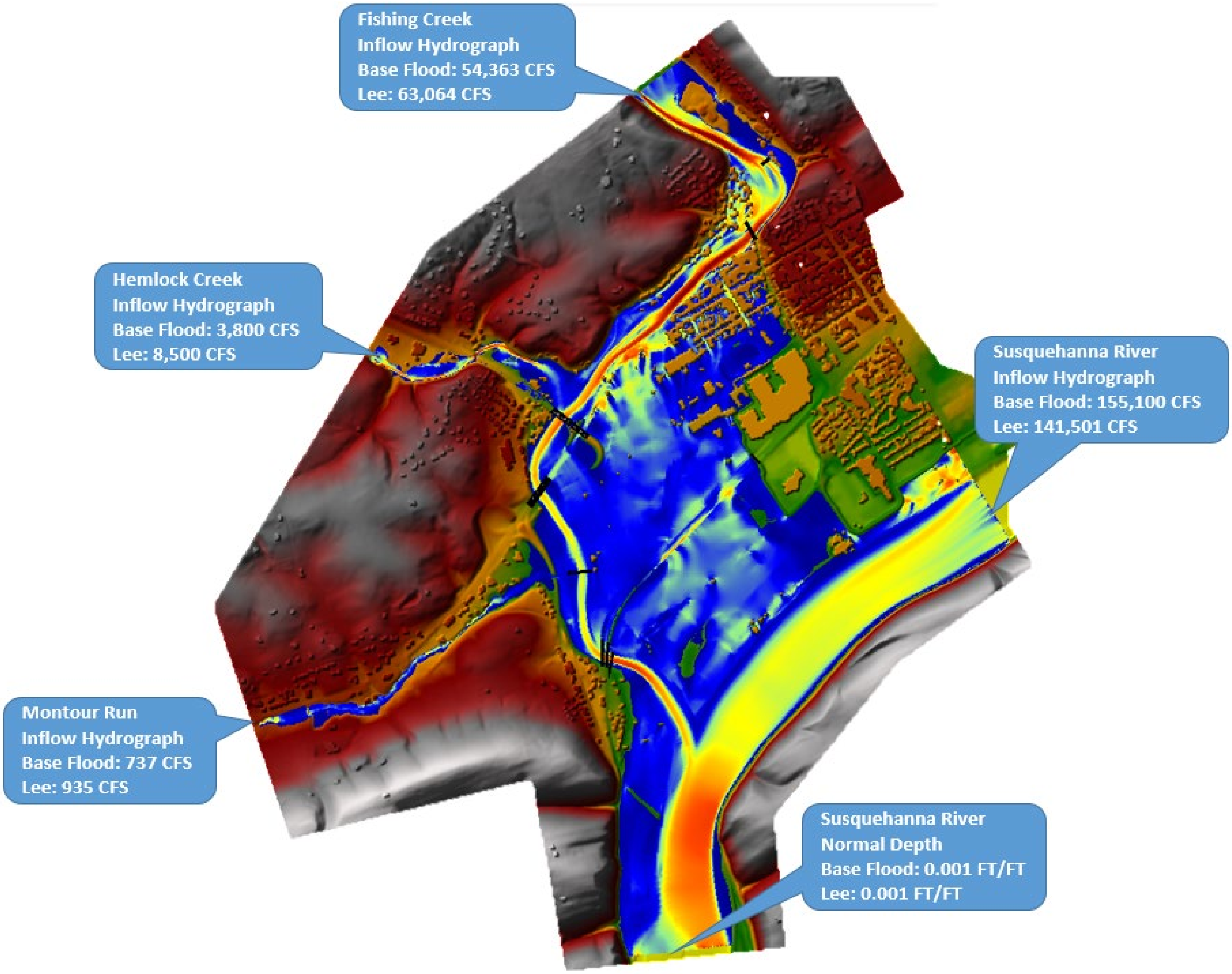

Figure 3.2 - Annotated Plot of Boundary Conditions

3.6. Breaklines and Refinement Regions

The 2D domain mesh was adjusted extensively using refinement regions and 2D breaklines in areas with complex topography and along elevated terrain features that would otherwise be missed by the uniform rectilinear grid.

Breaklines were created along channels, riverbanks, roadways, levees, and other areas of high ground. These breaklines and refinement regions were enforced within the 2D flow area at a nominal grid cell spacing of 20' x 20'. The breaklines along levees alignments were enforced with 10'x10' grid spacing. The SA/2D connections at dams and bridges were enforced as breaklines with 10'x10' spacing.

3.7. Hydraulic Structures

Multiple structures exist along Fishing Creek within the model domain including eight (8) bridges and two (2) dams. The modeled structures are listed in Table 3.3 below.

Table 3.3 – Existing Structures

Station (ft)	Designation
2366.2	Dam_1 (Near water authority plant)
3986.3	Railroad Street Bridge
8826.0	SR42 Mall Blvd Bridge over Fishing Creek
8826.0	SR42 Mall Blvd Bridge over SR 11
10308.6	US Route 11 Bridge North Bound over Fishing Creek
10365.1	US Route 11 Bridge South Bound over Fishing Creek
12020.3	Dam_2 (Boone's Dam)
13696.9	Railroad Bridge (abandoned)
13786.6	Railroad Bridge
13862.8	Covered Bridge #56

3.8. Manning's Roughness Coefficients

Manning's roughness coefficients are used to quantify a surface's resistance to flow. The assignment of these values to channels and floodplain is critical in determining channel and overbank velocities and is a crucial step in successful implementation of the hydraulic model. Manning's roughness coefficients are typically denoted by the variable "n."

As an initial approach, land cover information was extracted from the 2019 National Land Cover Database. The land cover polygons were verified using Columbia County parcel data and land use depicted on the ortho-imagery to create Manning's n polygons.

The Manning's n values were based on land cover descriptions and defined within recommended ranges from the USACE Hydrologic Engineering Center (HEC).

The land cover descriptions and corresponding initial Manning's N value are shown in Table 3.4.

Table 3.4 - Land Coverages & Initial Manning's n Values

Reference Identifier	Description	Manning's n Values
0	No Data	
1	Water	0.035
2	Deciduous	0.15
3	Shrub	0.12
4	Developed Open Space	0.04
5	Low Intensity Developed	0.09
8	Medium Intensity Developed	0.12
9	High Intensity Developed	0.16
7	Roads	0.025
6	Cultivated Land	0.035
10	Bare Land	0.027

3.9. Computation and Run Control Parameters

The following computation & run control parameters used in the hydraulic model are as follows:

- Computation Equation SW-ELM, Variable Time Step, Initial value = 5 seconds
- Run Time = 24 hours
- Simulation Time
  - Start Date & Time: 01JAN2023 00:00:00
  - End Date & Time: 01JAN2023 24:00:00
- Computation Settings:
  - Computation Interval: 5 seconds
  - Hydrograph Output Interval: 30 minutes
  - Mapping Output Interval: 30 minutes
  - Detailed Output Interval: 30 minutes

The model was reviewed for mesh quality and other errors and troubleshooted to ensure that the model did not experience mathematical instability where significant oscillations or mass balance errors could occur.

SECTION 4 – MODEL CALIBRATION

Calibration is performed to establish the accuracy of a model, typically by simulating a historic flow with well-established high-water marks.

4.1. Historical Event Selection

The West End Flood Mitigation model was calibrated to the 2011 Tropical Storm Lee flood event. This historical event was selected for it being the flood of record and for the quantity of high-water marks (HWMs) recorded after the event. The majority of HWMs for the 2011 Lee event were recorded by USGS. Detailed information on location, type, and quality of the HWMs are provided in Table 4.1 below and in Appendix B.

Multiple HWMs shown in the study area on Figure 4.1 (not labeled) were set by backwater from the Susquehanna River the day after Fishing Creek crested. These HWMs are not useful for calibration of Fishing Creek.

One additional HWM was collected from a tree along the left bank of Fishing Creek. While not displayed on the USGS map below, it is included in the comparison provided in Table 4.5.

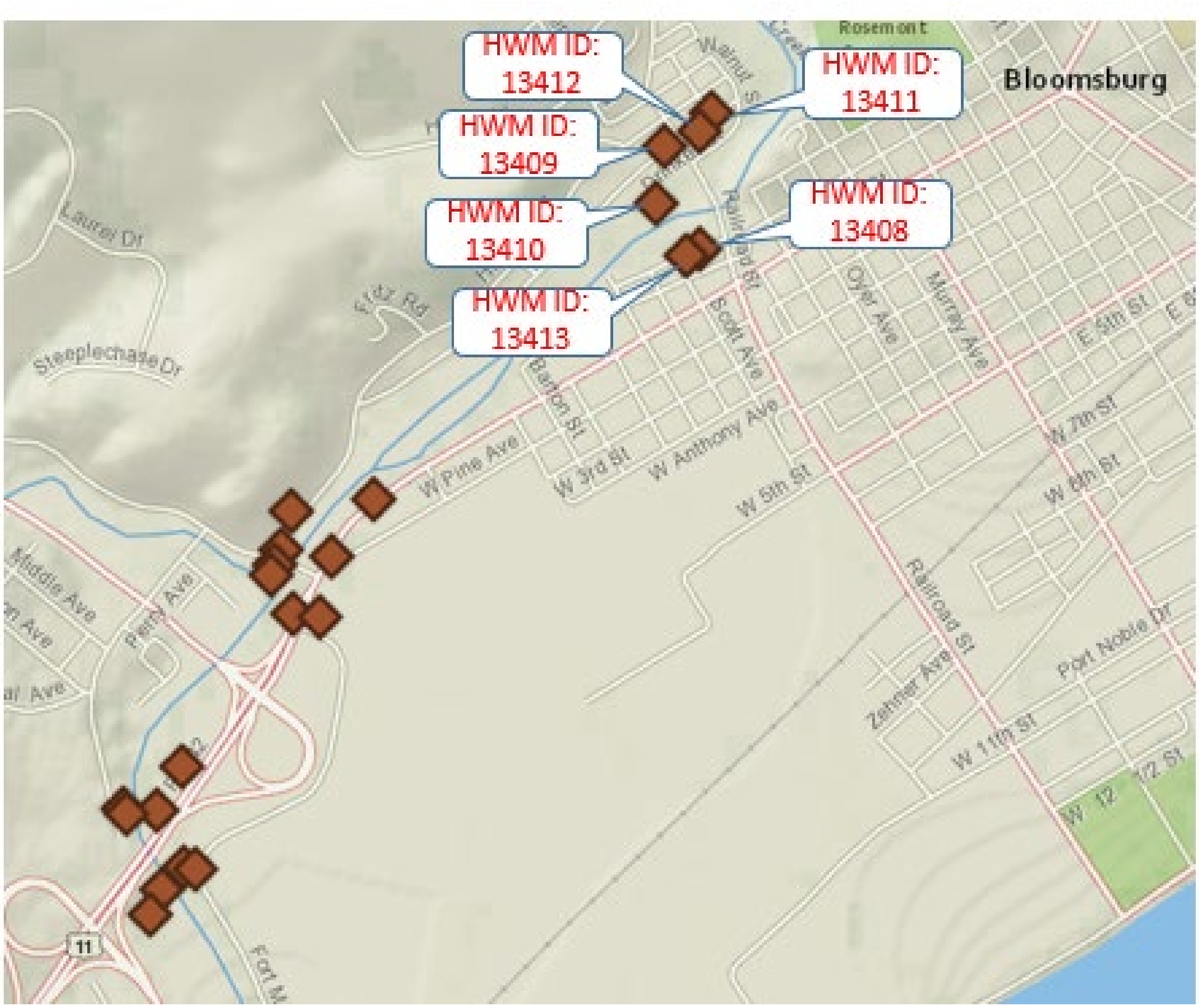

Figure 4.1. – USGS High Water Mark Locations

Table 4.1. – USGS High Water Marks

HWM ID	Site ID	HWM Type	HWM Quality	LOCATION	Survey Date	Elevation (feet NAVD88)
13408	16098	Mud	Good: +/- 0.10 ft	HWM transferred from small garage with grey vinyl siding at 435 West First St. Transferred to telephone pole 63 ft bankward across street and 65 ft upstream.	5/31/2012	485.8
13409	16098	Debris	Fair: +/- 0.20 ft	HWM is debris in shrubs just downstream of house number 139. Mark was transferred to telephone pole ID 35479/N30746 49 ft upstream on same roadside.	5/31/2012	486.4
13410	16098	Seed Line	Fair: +/- 0.20 ft	HWM was seed line on door jamb of garage. Mark transferred to tree 90 ft streamward.	5/31/2012	483.5*
13411	16098	Mud	Fair: +/- 0.20 ft	Located at house address 49 Drinker St. Transferred HWM to telephone pole from door 75 ft downstream on same side of road. Pole Id 35520/N30772	5/31/2012	488.4
13412	16098	Mud	Fair: +/- 0.20 ft	HWM found on siding of house number 87 on Drinker St. Transferred to telephone pole ID N30759/35510 downstream and across road from house.	5/31/2012	487.9
13413	16098	Mud	Good: +/- 0.10 ft	HWM is transferred from house #441 on West First St to telephone pole directly across street, distance from house to telephone pole =36 ft.	5/31/2012	484.9*

*No elevation given. Height Above Ground was provided and used to approximate elevation.

4.2. Discharge Flows

The discharge flows used for the 2011 Tropical Storm Lee event conditions were developed in similar fashion as the flows used for the base flood event modeling. The June 2012 USACE report titled *Bloomsburg, PA Flood Risk Management Study (FMRS) Update of Hydrology and Hydraulics for Inclusion of Tropical Storm Lee Event* (Appendix C) analyzed a full range of recurrence intervals from 99% to 0.2% annual exceedance probabilities. Following Tropical Storm Lee, the USGS determined the peak discharge of Fishing Creek at the confluence with the Susquehanna River to be 78,700 CFS. USACE used this discharge value and calculated 90% confidence limits between approximately 63,000 and 100,000 CFS. This corresponds to a recurrence interval of 350 years or an annual exceedance probability of 0.3% for Tropical Storm Lee. The flows applied to the calibration model were calculated using an updated USGS procedure outlined in SIR 2019-5094 as covered in the hydrologic section of this report.

Coincident tributary flows on Hemlock Creek and Montour Run were set to 100-year and 50-year recurrence intervals, respectively. Tributary flows were determined in the same manner as for modeling of the Base Flood condition using drainage area ratios to make assumptions for lagging peak discharges.

Coincident flow on the Susquehanna River was determined by identifying the time at which peak flow occurred at the USGS Fishing Creek gauge 01539000 located on the Bowman's Mill Bridge 5.5 miles north of Bloomsburg and retrieving the concurrent flow at the USGS Susquehanna River gage 01538700 located immediately upstream of the SR 0487 Bridge in Bloomsburg. Some uncertainty exists in this approach because of the lag time required for flow to travel 5.5 miles from the Fishing Creek gauge to the study area and because the gauge on Fishing Creek failed near the peak of the event.

Peak discharges applied to the Tropical Storm Lee calibration model are provided in Table 3.2.

4.3. Terrain Data Adjustments

In order to recreate the topographic conditions at the time of the 2011 Tropical Storm Lee Event, several modifications were made to the final terrain file. Several property acquisition/demolition projects have occurred within the floodplain since Tropical Storm Lee. With this knowledge, historical imagery was used to add structures to the terrain surface which do not currently exist or appear in the Columbia County GIS dataset.

Additionally, neither the Phase 1 levee system around Autoneum nor the Phase 2 levee system around the Bloomsburg High School existed in 2011. These features were removed from the 2011 calibration terrain file.

Some factors are either impossible or exceedingly difficult to replicate for the 2011 event such as bathymetric data, geomorphology of stream banks, and conditions which developed mid-event which would have impacted peak WSELs (i.e., debris jams, erosion, structure movement).

4.4. Hydraulic Structures

The structures listed in Table 4.2 were modeled under 2011 Storm Lee flood event conditions. Notably included in the calibration model is the Red Mill Road Bridge which once connected Red Mill Road to US Route 11. The structure was erected in 1923 and demolished in 2012; a photo of the structure during the Tropical Storm Lee event is shown in Figure 4.2. Due to the age of the structure, little information was available for coding the bridge into the calibration model except for a 1937 sketch of the bridge and the 2011 PennDOT demolition plan, both provided in Appendix D.

Table 4.2 – 2011 Tropical Storm Lee Hydraulic Structures

Rank	Station (ft)	Designation
1	2366.2	Dam_1
2	3986.3	Railroad Street Bridge
3	7947.0	Red Mill Road Bridge
4	8826.0	SR42 Mall Blvd over Fishing Creek
5	8826.0	SR42 Mall Blvd over SR 11
6	10308.6	US Route 11 Bridge North Bound over Fishing Creek
7	10365.1	US Route 11 Bridge South Bound over Fishing Creek
8	12020.3	Dam_2 (Boone's Dam)
9	13696.9	Railroad BR (abandoned)
10	13786.6	Railroad Bridge
11	13862.8	Covered Bridge #56

Figure 4.2 – Red Mill Road Bridge (2011 Event Facing Upstream)

4.5. Manning's Roughness Coefficients

The initial Manning's n roughness values were further refined through model calibration to result in closer agreement between calculated WSELs and recorded HWMs set during the 2011 Tropical Storm Lee event. It is important to understand that general descriptions are given to land uses that are comprised of subsets of smaller land uses; for example, a manning's value for high intensity residential land use considers a proportion of lawn, impervious area, and physical obstructions inherent to that weighted roughness value.

When creating the hydraulic model, the physical obstructions in the floodplain were integrated into the terrain itself; therefore, it would be considered a form of "double counting" to also account for these obstructions in the Manning's coefficient. Likewise, roadways and other large impervious areas were assigned unique Manning's coefficients and should not factor into the weighted value assigned to high intensity residential values.

When these areas are accounted for elsewhere in the model parameters for low, medium, and high intensity residential land uses, the primary land use remaining may be considered as developed open space. This was the logic applied in determining the Manning's n values reflected in Table 4.3.

Table 4.3 - Final Manning's n Values Derived from Calibration

Reference Identifier	Description	Manning's n Values
0	No Data	
1	Water	0.027
2	Deciduous	0.10
3	Shrub	0.08
4	Developed Open Space	0.03
5	Low Intensity Residential	0.03
8	Medium Intensity Residential	0.03
9	High Intensity Residential	0.03
7	Roads	0.02
6	Cultivated Land	0.03
10	Bare Land	0.03

4.6. Calibration Results

The calibration model run consisted of performing a simulation of the hydraulic model with known variables to ensure the accuracy of subsequent model runs. For this project, the model was calibrated using information from the 2011 Tropical Storm Lee Flood. This was a record flood event that is well documented with many sources of information available for reference.

Results of the initial run showed that the model was significantly overestimating WSELs relative to recorded HWMs throughout the study area. In subsequent calibration runs, the initial roughness values were adjusted incrementally lower until reaching the values recorded in Table 4.3. During calibration, it was clear that adjusting Manning's coefficients alone would not bring the model into agreement with the recorded HWMs. Other parameters altered include boundary condition inflows and the bridge modeling approach at the Railroad Street Bridge.

Boundary condition inflows on Fishing Creek were adjusted lower by increasing the coincident recurrence interval of Hemlock Creek and Montour Run to 100-year peak discharges as discussed in Section 4.2. The peak discharge at the confluence with the Susquehanna River remained constant through all calibration runs.

Calculated WSELs in the Fernville area of Hemlock Township remained particularly high relative to surveyed HWMs. Because the Railroad Street Bridge is a major structure in this reach of Fishing Creek, further evaluation of the modeling approach at the structure occurred and led to switching the high flow modeling approach from pressure/weir to energy only. Although the flow does hit the low chord of the bridge, the parapet and bridge deck are not overtopped and the ratio of the hydraulic open area to the area obstructed by the bridge deck is relatively small.

Table 4.4. presents the calibration results by comparing the predicted WSELs against the high-water marks from the September 2011 Lee flood Event. The results show close agreement between the model and the surveyed values generally within 0.6 feet with two outliers. The differences, while not large, are likely due to a combination of three factors. First, the exact location of the surveyed high-water mark is difficult to pinpoint based on the available information. Second, the slope of the water surface profile is steep for a distance of approximately 1,000 feet upstream of the Railroad Street Bridge, changing by more than 3.5 feet between Station 2900 and STA 3950. Lastly, because this study area is in an ungauged location, flow values are statistical estimates based upon a stream gauge located 5.5 miles upstream which malfunctioned near the peak of the 2011 event. As a result, the location of the reading and the selected boundary condition flows will influence the water surface elevation value retrieved from the model.

Table 4.4 - Comparison of HWMs to Modeled WSELs

HWM ID	2011 High Water Marks (Feet NAVD88)	Model Elevation* (Feet NAVD88)	Difference (feet)
13408	485.8	485.45	-0.35
13409	486.4	487.00	0.60
13410	483.5**	485.32	1.82
13411	488.4	489.42	1.02
13412	487.9	488.09	0.19
13413	484.9**	485.21	0.31
Surveyed HWM on Tree (2006 – 482.19')	483.23	482.63	-0.60

*Elevation taken at approximate location of HWM as described in Table 4.1.
**No elevation given. Height Above Ground was provided and used to approximate elevation.

SECTION 5 – EXISTING CONDITIONS HYDRAULIC ANALYSIS

Upon completion of the model calibration, the final parameters were copied to the existing conditions model to be evaluated under a 100-year (Base Flood) condition. The results of the existing conditions model run were used as a base for comparison to the proposed levee condition and mitigation alternative runs.

The 100-year base flood discharge flows used in the existing conditions model are shown in Table 3.1 in Section 3.5. The terrain and structure footprint data included in the existing conditions surface reflect the conditions at the time this study was completed.

SECTION 6 – PROPOSED CONDITIONS HYDRAULIC ANALYSIS

The proposed conditions model was derived from the existing conditions model with identical discharge flows, hydraulic structures, and Manning's n roughness values. The only change from the existing conditions model was the incorporation of the proposed levee system shown in Figure 6.1 into the terrain surface. The proposed levee system is discussed in greater detail in the Final Report.

Minor terrain modifications were required on the proposed levee surface to correct model output/data issues resulting from conflict between the terrain and the mesh grid. These corrections were primarily required where the levee type transitions or where the surface is much narrower than the mesh grid spacing. In these locations, the terrain was widened toward the protected side of the levee to ensure model results are not influenced.

The large floodway of Fishing Creek in the West End study area is situated such that a proposed levee system would be constructed entirely within the regulatory floodway. Results of the 2D proposed conditions modeling show that the WSELs of the base flood increase with the proposed levee shown in Figure 6.1, creating what is referred to as induced flooding. The induced flooding with the proposed levee causes a WSEL increase of the base flood on Fishing Creek up to 2.1 feet. The residential areas in Hemlock Township adjacent to and upstream of the proposed levee would experience a greater risk of flooding because these areas would not be protected by the proposed levee. Figure 6.2 presents the WSEL profiles of the base flood on Fishing Creek with existing conditions as compared to the proposed condition with a levee.

A comparison of Fishing Creek Existing Conditions WSELs and Proposed Conditions WSELs for the base flood is also presented in Table 6.1.

Figure 6.1 – Proposed Conditions Levee Alignment

Table 6.1 - Existing & Proposed Conditions - WSEL Comparisons

2D Modeled Base Flood Flows (100-yr)

#	Designation/Location	Station/ River Feet	WSEL Existing	WSEL Proposed	Change in WSEL (Feet)
1	Dam_1 - Upstream	2330	489.84	490.61	0.77
2	Dam_1 - Centerline	2370	489.80	490.59	0.79
3	Dam_1 - Downstream	2400	489.84	490.62	0.78
4	Railroad Street - Upstream	3950	486.32	488.08	1.76
5	Railroad Street - Centerline	3985	485.75	487.72	1.97
6	Railroad Street - Downstream	4025	484.96	487.04	2.08
7	Leonard Street	4900	483.07	484.45	1.38
8	Barton Street	5800	481.51	482.70	1.19
9	Hemlock Creek	8160	479.67	480.15	0.48
10	SR 42 Mall Blvd - Upstream	8760	479.21	479.65	0.44
11	SR 42 Mall Blvd - Centerline	8840	478.79	479.16	0.37
12	SR 42 Mall Blvd - Downstream	8900	477.95	478.14	0.19
13	SR 11 - Upstream	10240	477.74	477.92	0.18
14	SR 11 - Centerline	10320	477.56	477.70	0.14
15	SR 11 - Downstream	10400	477.38	477.49	0.11
16	Dam_2_: Fishing - Upstream	11980	477.24	477.36	0.12
17	Dam_2_: Fishing - Centerline	12020	477.21	477.33	0.12
18	Dam_2_: Fishing - Downstream	12060	477.20	477.32	0.12
19	Railroad BR Abandoned - Upstream	13650	476.08	476.17	0.07
20	Railroad BR Abandoned - Centerline	13700	475.85	475.93	0.08
21	Railroad BR Abandoned - Downstream	13730	475.67	475.74	0.07
22	Railroad Bridge - Upstream	13750	475.61	475.68	0.07
23	Railroad Bridge - Centerline	13790	475.18	475.23	0.05
24	Railroad Bridge - Downstream	13810	474.44	474.46	0.02
25	Covered BR #56 - Upstream	13840	474.50	474.52	0.02
26	Covered BR #56 - Centerline	13860	474.38	474.39	0.01
27	Covered BR #56 - Downstream	13900	473.95	473.94	-0.01

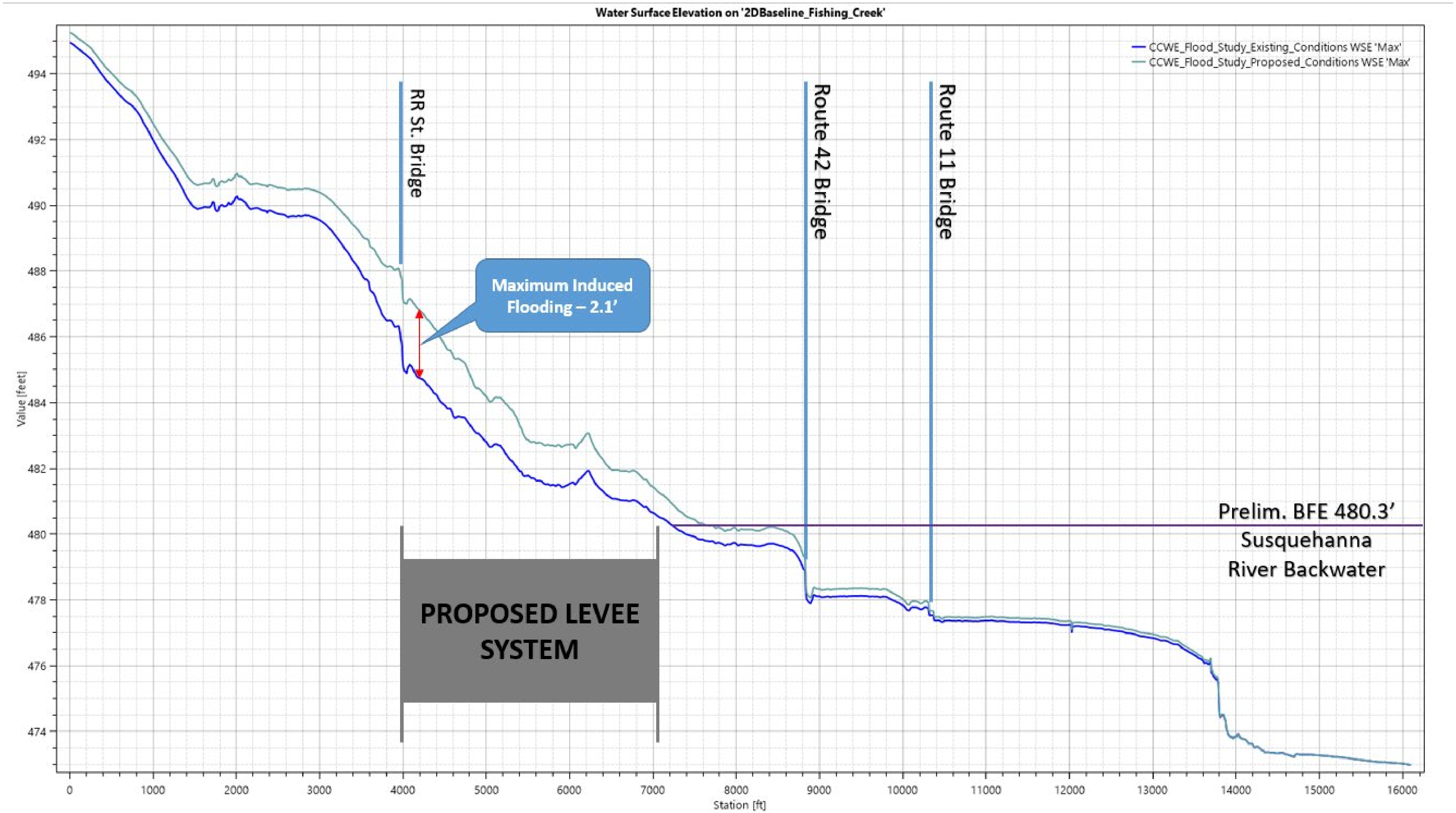

Figure 6.2 – WSEL Profiles of Existing & Proposed Conditions, 2D Modeled Base Flood Flows (100-yr)

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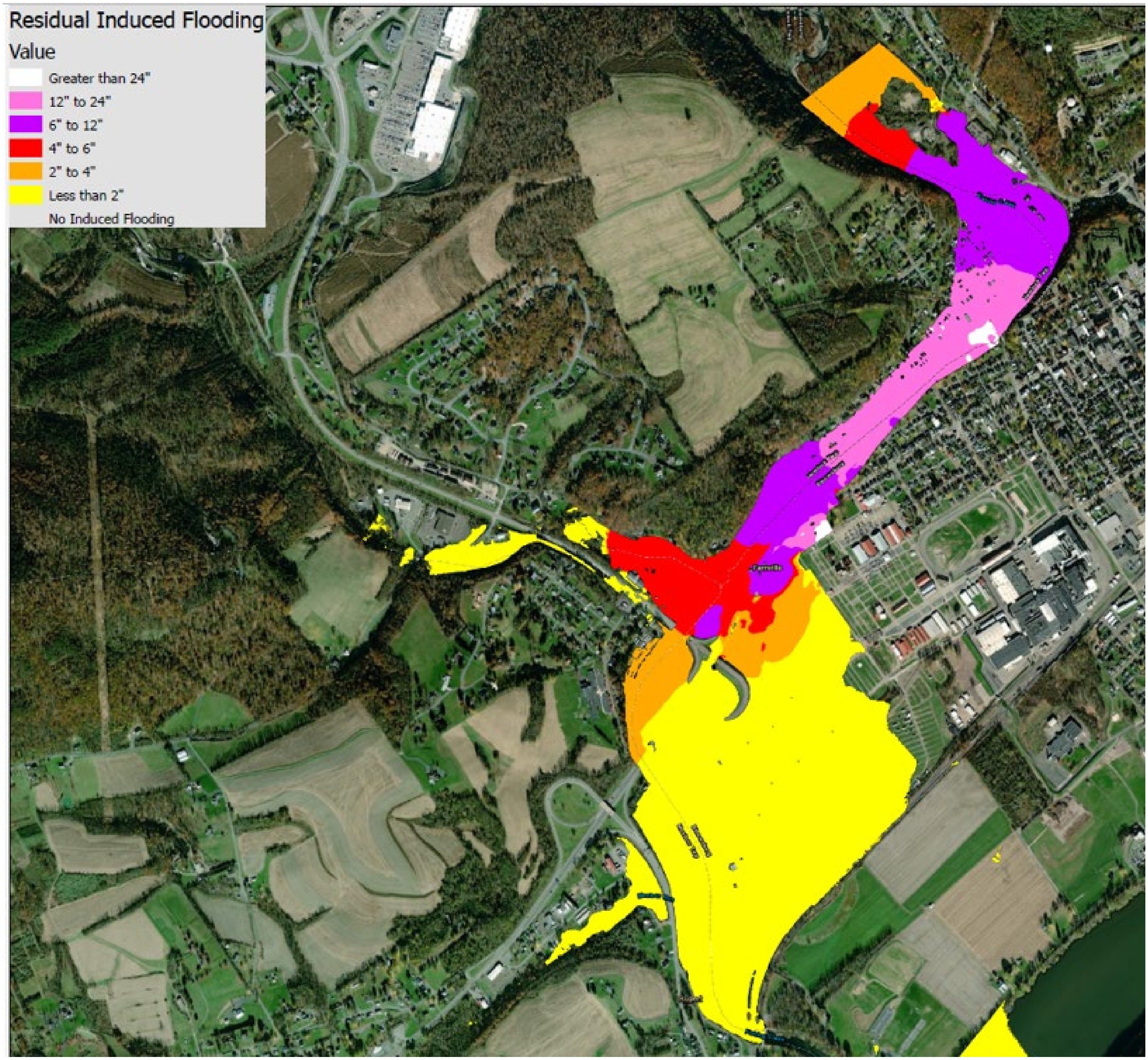

Figure 6.3 – Induced Flooding (Without Mitigation)

SECTION 7 – MITIGATION ALTERNATIVES

In order to analyze mitigation actions required to lower the induced flooding to zero, several alternatives were simulated.

A brief description of each mitigation alternative is provided below.

Mitigation Alternative No. 1

Alternative 1 includes a benched floodplain along the right bank of Fishing Creek and an additional span on the Railroad Street Bridge matching the width of the benched floodplain through the structure. This alternative consists of several sub-alternatives ranging from Alternatives 1B-1F which were created to gauge sensitivity of the model to changes in bridge span length and benched floodplain extents.

A benched floodplain is a term used to describe an area where an elevated streambank has been excavated to provide a bench closer to the channel bottom that will flood more frequently. This feature provides more channel conveyance during flood events and can reduce impacts to the developed floodplain. Figure 7.1 includes an example of a typical benched floodplain and a cross section of Fishing Creek showing proposed conditions grading. The location and extents of the benched floodplain are depicted in Figure 7.4.

Initial iterations of Alternative 1 demonstrated a sizable reduction in induced flooding in the area adjacent to the levee system and significant reduction (up to 1') below existing conditions upstream of the Railroad Street Bridge. Later iterations of Alternative 1 revealed that expansion of the Railroad Street Bridge is not required because presence of the benched floodplain downstream of the Railroad Street Bridge is sufficient in mitigating induced flooding in the vicinity of and upstream of Railroad Street.

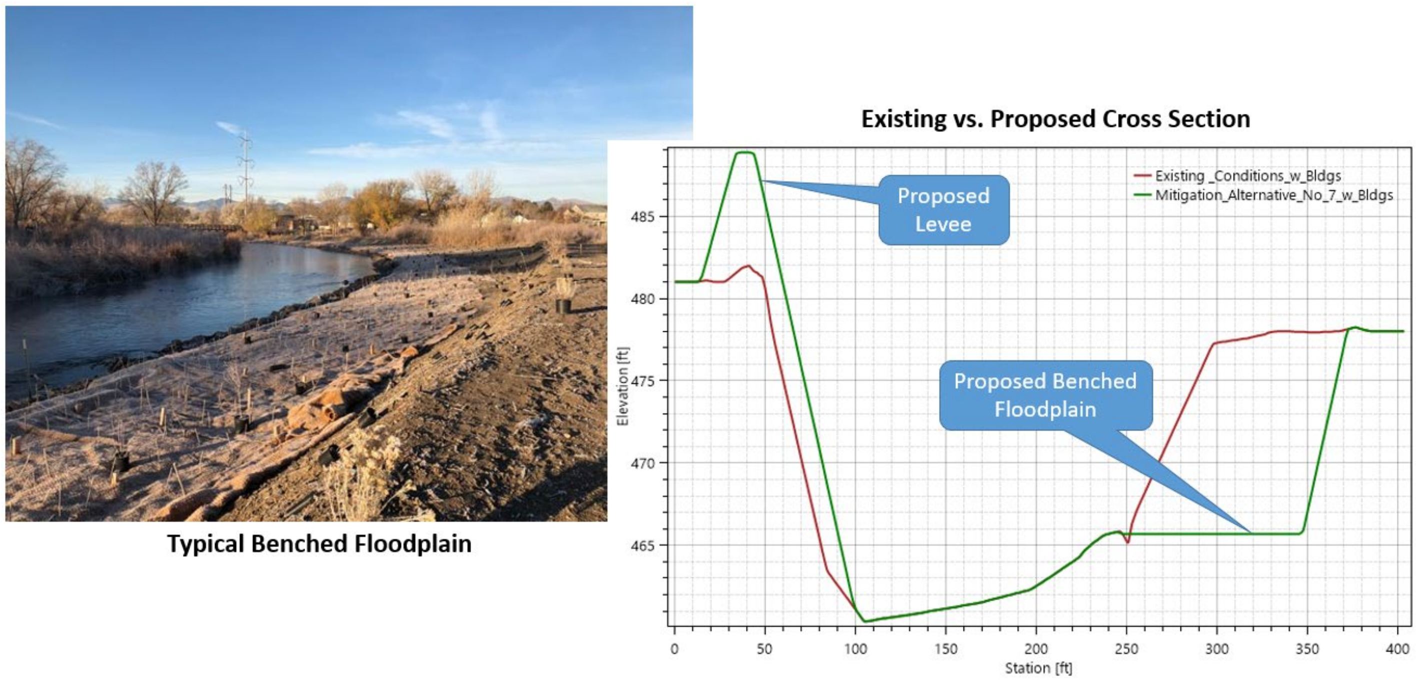

Figure 7.1 – Benched Floodplain

Mitigation Alternative No. 2

Alternative 2 was modeled to determine the effects of minimizing encroachment into the regulated floodway by replacing the 90 degree turn in the alignment of the proposed levee with a smoothed radius alignment. Other minor modifications to the levee alignment were also evaluated as Alternative 2A.

Alternative 2A produces a modest decrease in induced flooding with a correspondingly small cost of implementation. A simple change in the proposed levee alignment, while negatively impacting a portion of fairgrounds, aids in meeting the ultimate goal of no induced flooding. Comparison of the alternative alignment vs. the proposed alignment presented in the Final Report is provided in Figure 7.2.

Figure 7.2 – Levee Alignment Modifications

Mitigation Alternative No. 3

Alternative 3 was created to evaluate the benefit of constructing culverts under US Route 11 to reconnect Fishing Creek flows to the floodplain. Alternative 3 consists of seven (7) 4'x30' low-profile concrete arch culverts oriented to the direction of overbank flow. The final shape, span, and configuration of the structures beneath US Route 11 will likely be modified during design to balance hydraulic effectiveness vs. cost vs. reduction in induced flooding.

US Route 11 parallels Fishing Creek downstream of where the proposed levee along the left bank of Fishing Creek turns inland. The location of the culverts was chosen based on the high velocities in this area predicted by the model and because of the historical damages that occurred to homes at this location during Tropical Storm Lee which led to their demolition in 2012. This Alternative serves to mitigate induced flooding between benched floodplain and the PA Route 42 Bridge by increasing conveyance from Fishing Creek to the floodplain. See Figure 7.3 below.

The concept employed by Mitigation 3 has been used in flood mitigation projects elsewhere in the United States, notably the USACE Old River Control Structure on the Mississippi River in Louisiana and the Yolo Bypass on the Sacramento River in California.

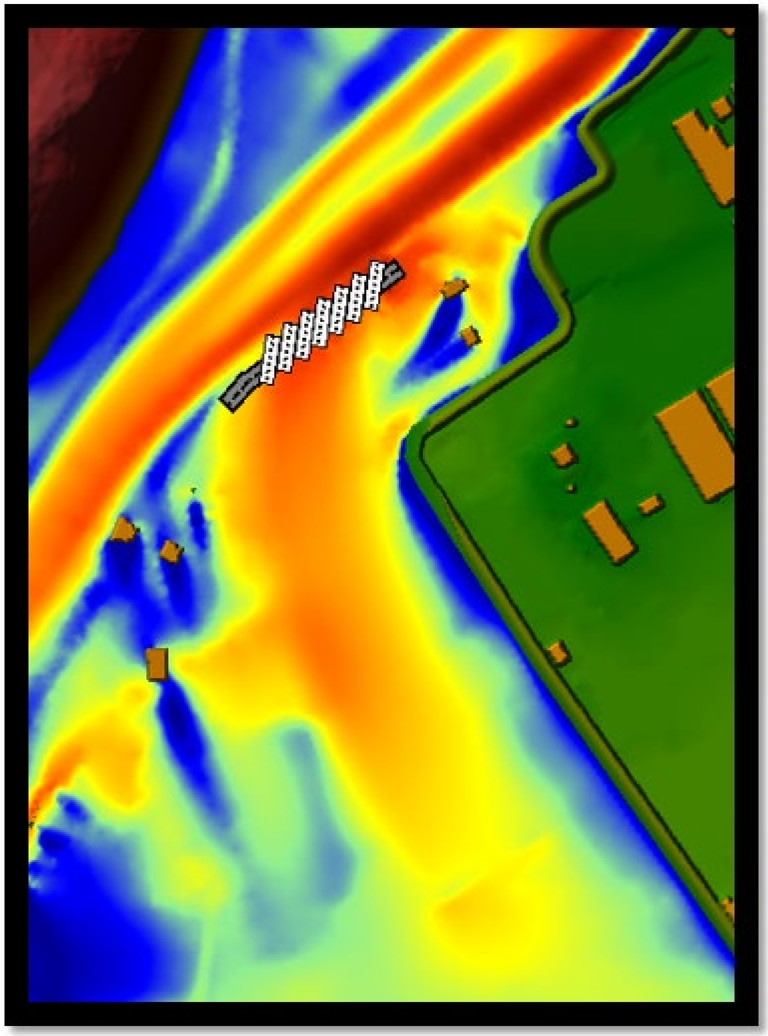

Figure 7.3 – Relief Culverts Beneath Route 11

Mitigation Alternative No. 4

Mitigation Alternative 4 consists of combining Alternatives 1, 2, & 3 to determine potential compounding benefits of mitigation features.

The benched floodplain and floodplain reconnection utilizing relief culverts under US Route 11 operate in tandem to largely mitigate induced flooding to homes and structures in Hemlock Township. The benched floodplain increases conveyance capacity of Fishing Creek in the area where the Creek overtops its bank into the West End of Bloomsburg; this flow is then conveyed downstream to be released back into the floodplain by the proposed relief culverts described in Mitigation Alternative 3.

Upon review of Alternative 4 results, several structures in Hemlock Township remained impacted by induced flooding. Additional evaluation of mitigation alternatives was performed.

Mitigation Alternative No. 5

Alternative 5 evaluated the impact of adding an additional span on the left side of the PA Route 42 Bridge. Alternative 5A evaluated additional spans on both sides of the structure and included a benched floodplain beginning upstream of the bridge and extending downstream through the structure past the existing mobile home park. Alternative 5A produced noticeably more reduction in induced flooding compared to Alternative 5. Significant increases in water surface elevation downstream at the US Route 11 Bridge together with the excessive cost and scheduling implications of modifying a large state bridge prevented further consideration of this alternative.

Mitigation Alternative No. 6

Alternative 6 is a refinement of Alternative 4 created by including the least restrictive levee alignment from Alternative 2A, eliminating the additional span on the Railroad Street Bridge (Alt 1F), and improving the transitional grading from the relief culverts into the floodplain. Results of this alternative were positive and offered confirmation that the mitigation concepts were heading in the right direction. Six (6) structures, all located along Drinker Street in Hemlock Township, remained impacted by induced flooding of between 2” to 6” under base flood conditions. Note that existing structures scheduled for acquisition/demolition are not included in this number.

Mitigation Alternative No. 7

Alternative 7 is the final alternative completed under the scope of this study and builds upon Alternative 6 by including adjustments to the proposed levee alignment along West 1st Street which runs parallel to the left bank of Fishing Creek and by lowering and widening the benched floodplain along the right bank (opposite the proposed levee). The purpose of this alternative is to reduce channel constrictions and maximize conveyance capacity within the channel of Fishing Creek.

Alternative 7 provides the most promising results of all those evaluated resulting in just two (2) structures with residual induced flooding of approximately 4” under base flood conditions. Both structures are located along Drinker Street which runs parallel to Fishing Creek in Hemlock Township. Figures 7.4 through 7.6 include graphics of the final proposed levee and mitigation features, water surface elevation profiles along Fishing Creek, and graphical extents of expected residual induced flooding in Hemlock Township for the base flood. Figures 7.7 and 7.8 illustrate modeled velocities in Fishing Creek main channel and floodplains under existing conditions and proposed (with Mitigation Alternative 7 conditions) for the base flood. Velocities are slightly reduced in Fishing Creek’s channel with proposed conditions, as compared to existing conditions, likely due to the proposed benched floodplain. Velocities are slightly increased down gradient of the proposed relief culverts in the open field area of the Bloomsburg Fairgrounds; this is due to intentional diversion of flows to this area from Fishing Creek under high flow/flood conditions on the creek.

No additional alternatives were modeled as part of this flood mitigation study. Additional sensitivity analysis can be completed during the design phase of a future project. Successful mitigation of the residual induced flooding is likely with refinement of the levee alignment along the left bank of Fishing Creek and with final design of a culvert system beneath US Route 11.

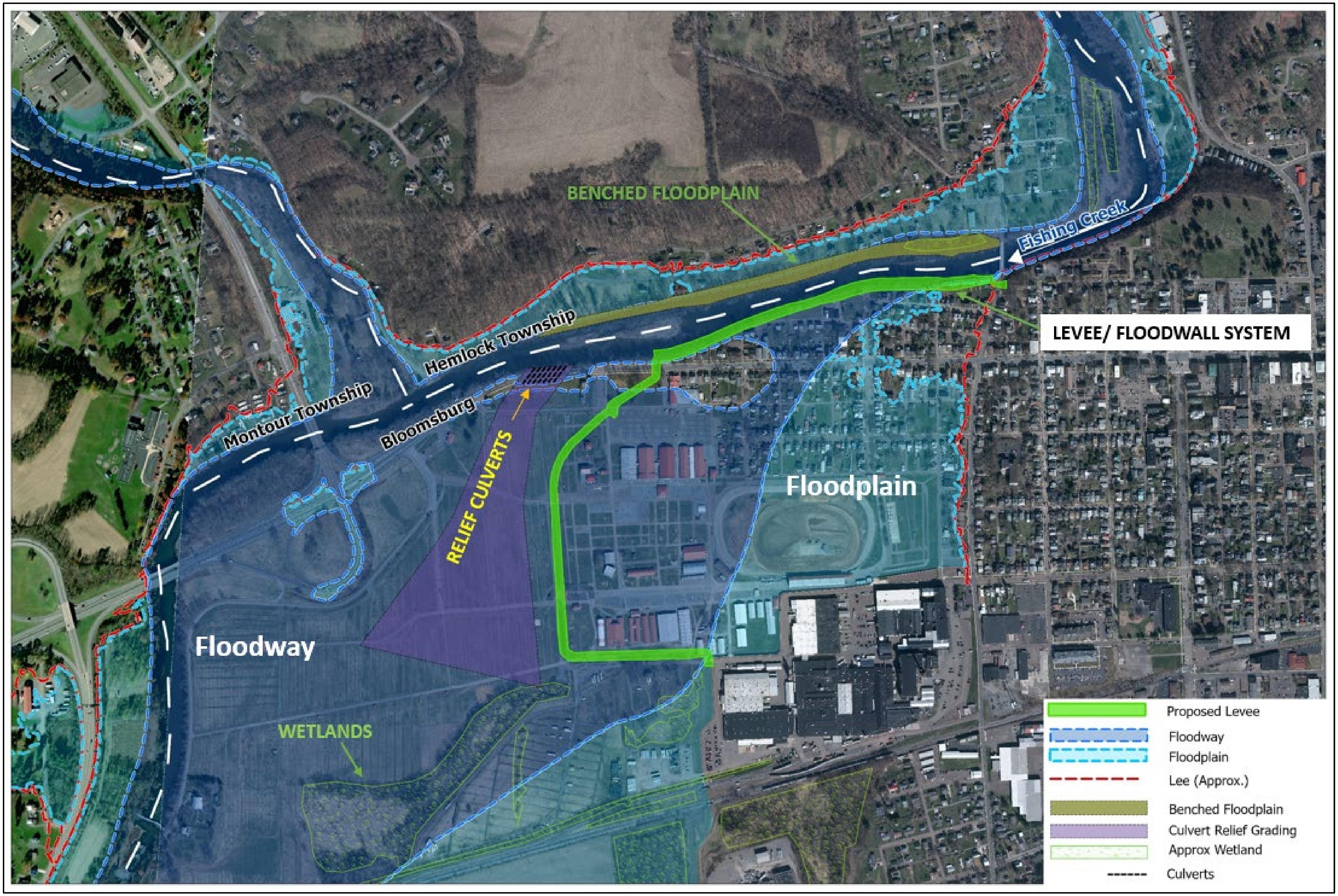

Figure 7.4 – Final Proposed Levee Alignment with Mitigation Features (Mitigation Alternative 7)

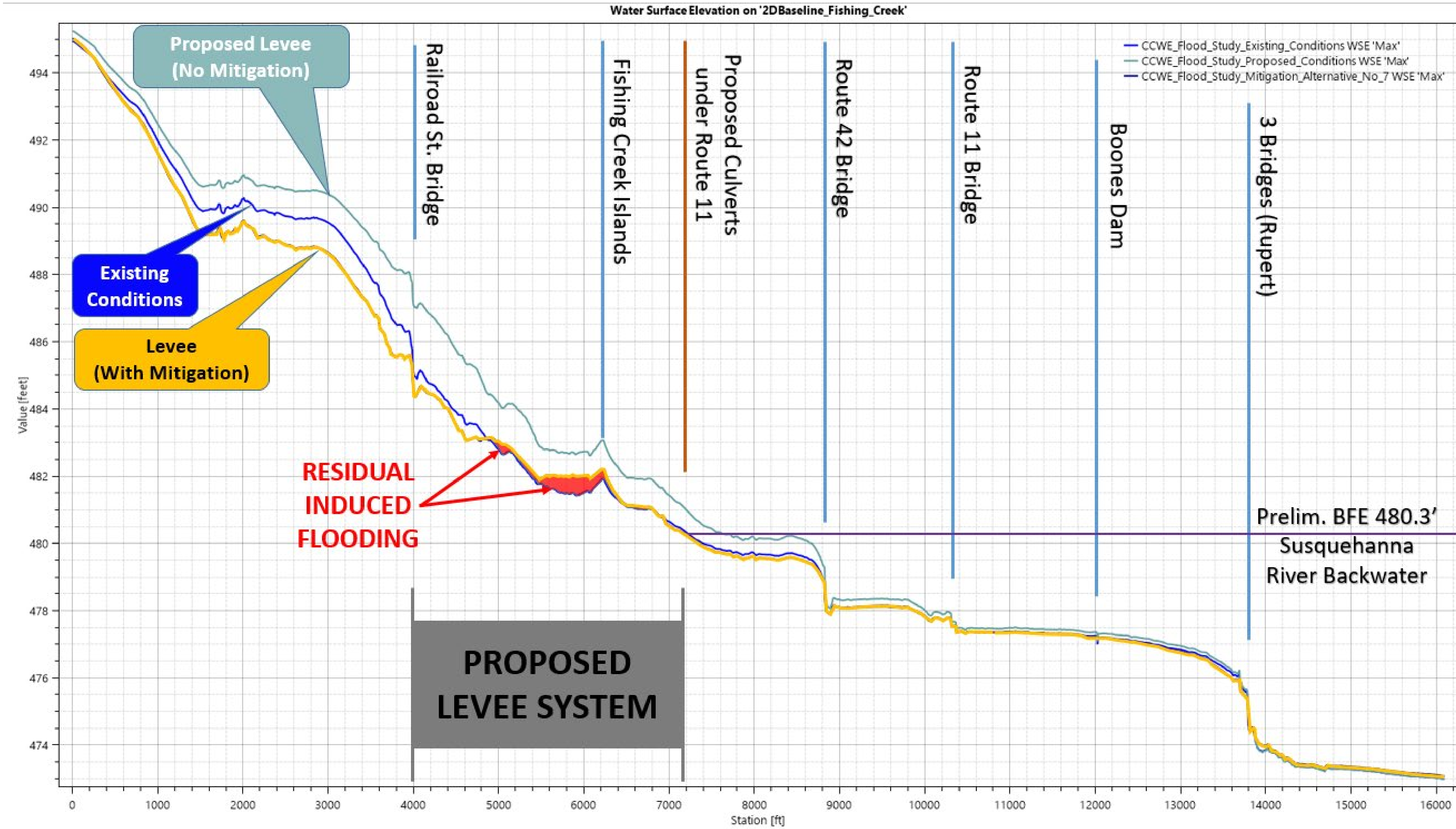

Figure 7.5 – WSEL Profiles - Existing, Proposed, and Mitigation Alternative 7

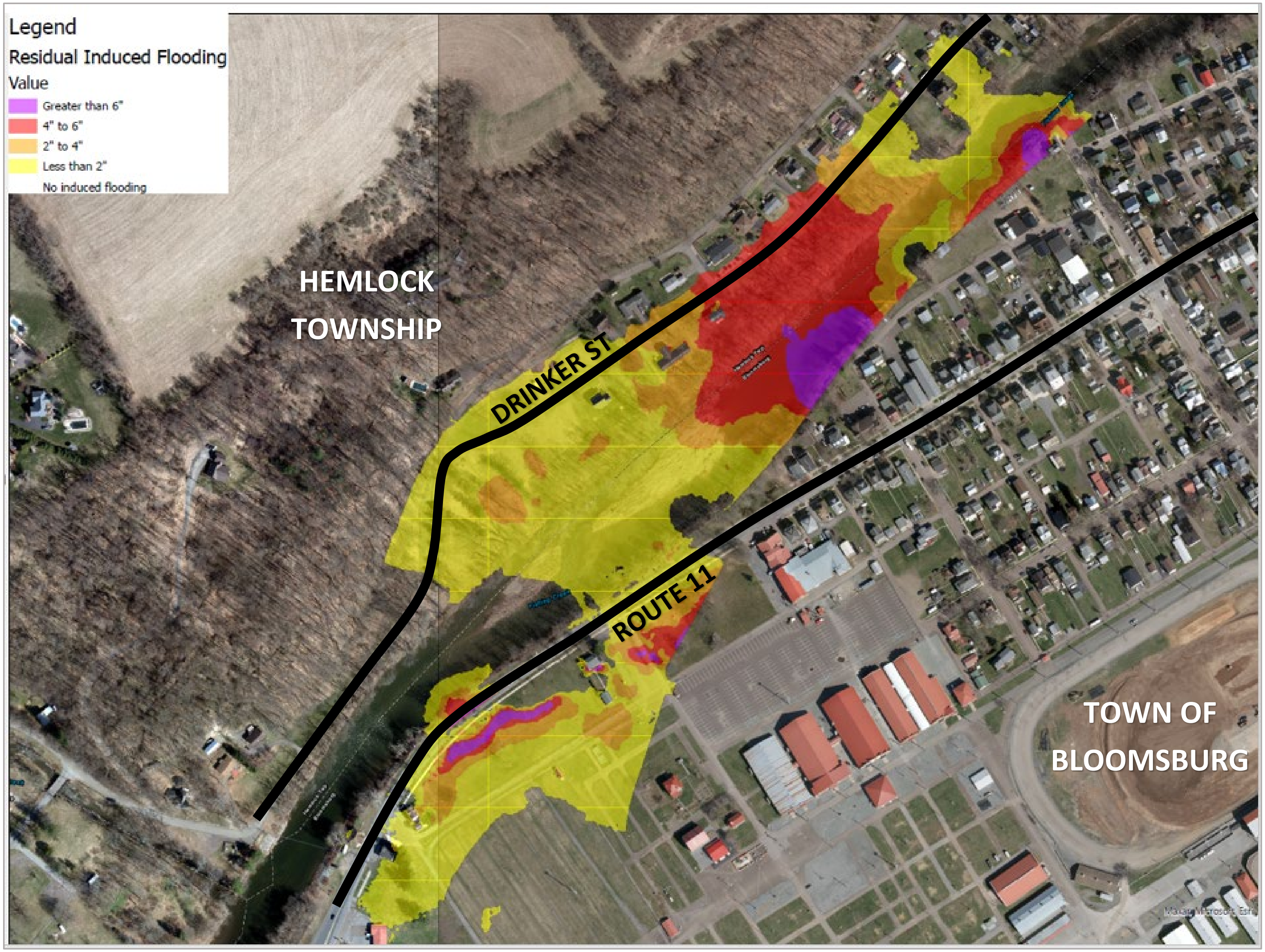

Figure 7.6 – Residual Induced Flooding (After Mitigation)

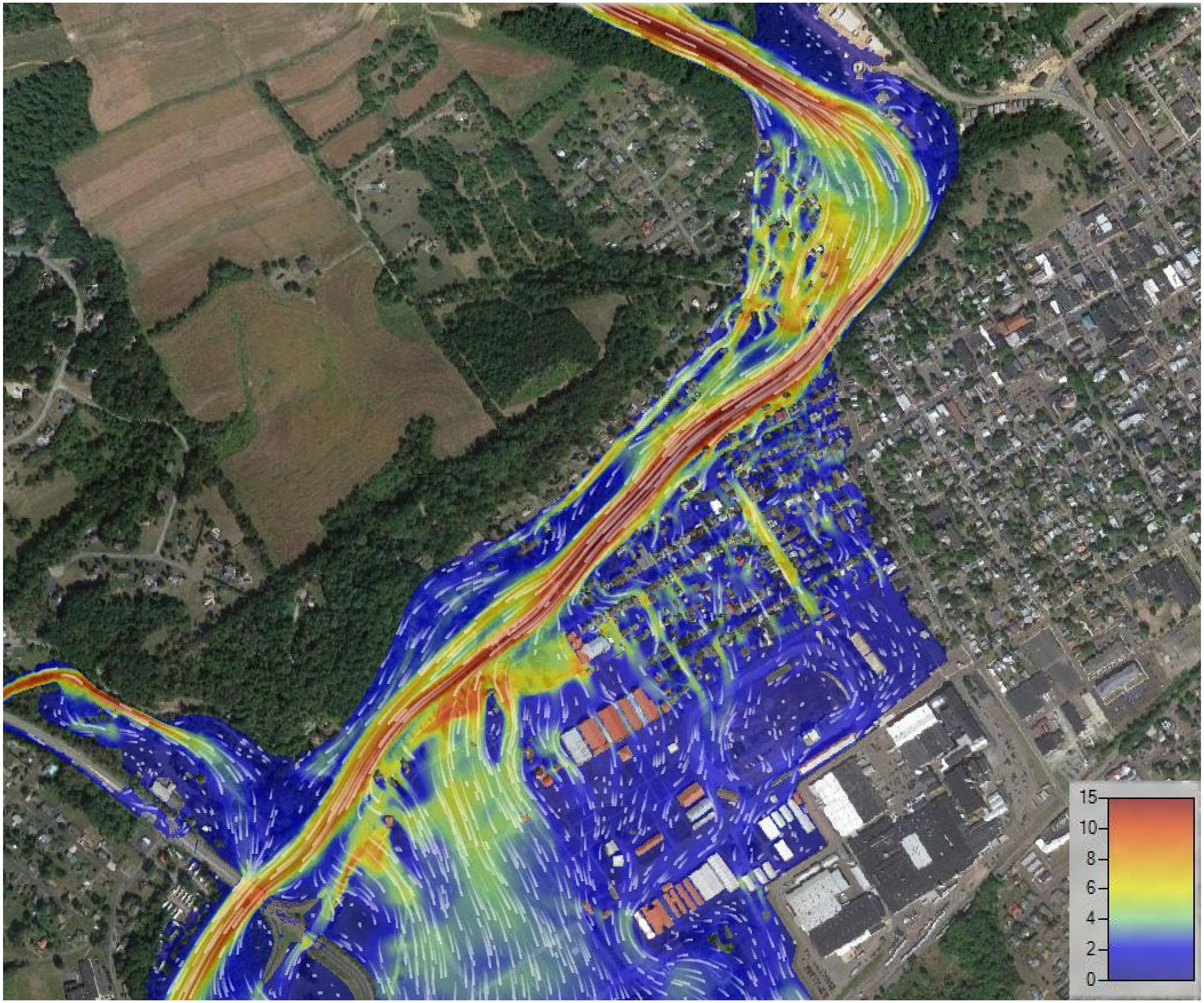

Figure 7.7 – Modeled Velocities (feet per second) along Fishing Creek, Base Flood - *Existing Conditions*

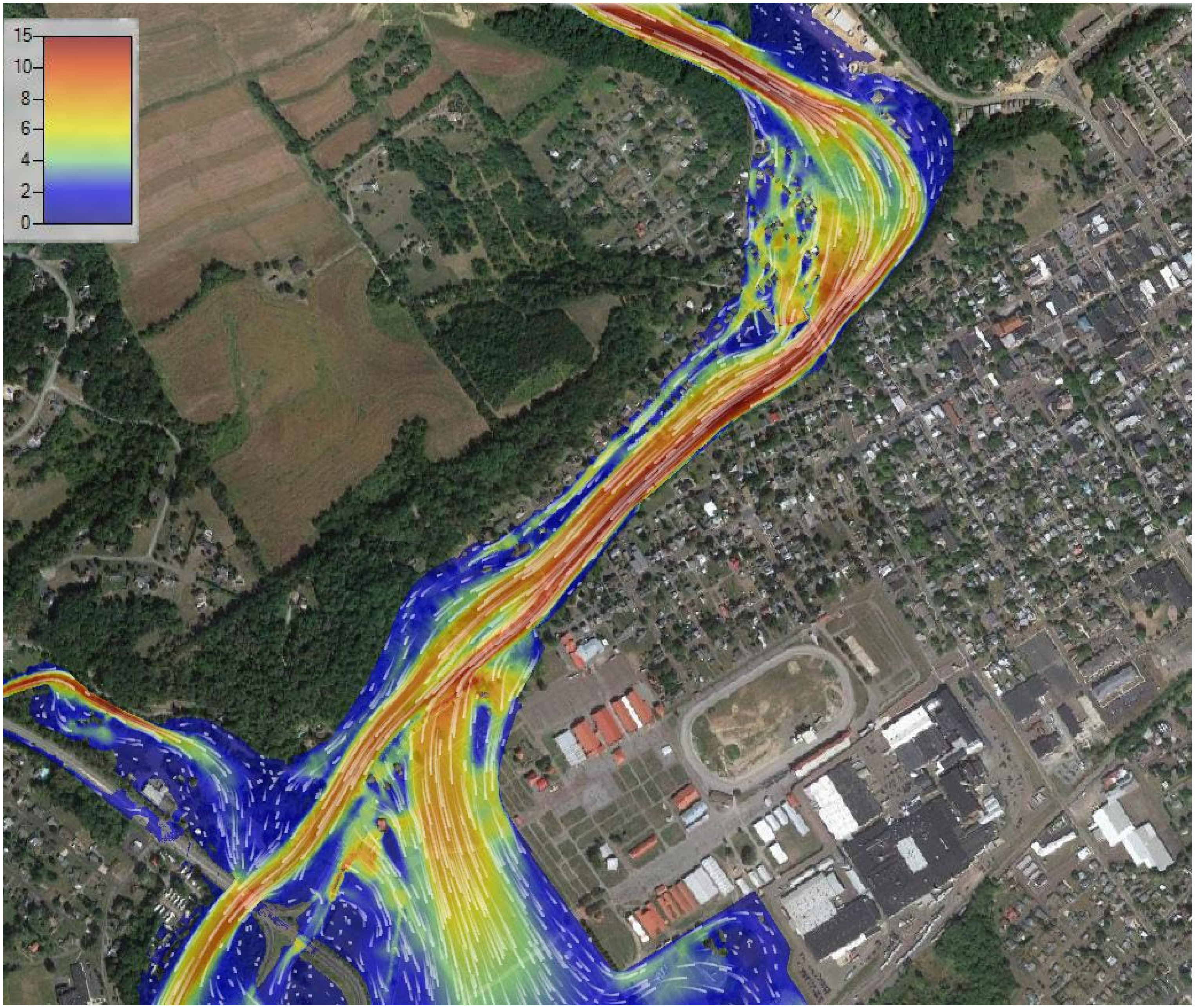

Figure 7.8 – Modeled Velocities (feet per second) along Fishing Creek, Base Flood
Final Proposed Conditions – Mitigation Alternative 7 (Levee, Benched Floodplain, Relief Culverts)

The WSEL comparisons for Mitigation Alternatives are shown in Table 7.1.

Table 7.1 - WSEL Comparisons for Mitigation Alternatives

#	Designation/Location	Station / River Feet	WSEL (feet NAVD 88)						
			Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
1	Dam_1 - Upstream	2330	489.32	488.82	490.50	488.76	490.59	489.24	489.01
2	Dam_1 - Centerline	2370	489.26	488.74	490.47	488.70	490.56	489.20	488.97
3	Dam_1 - Downstream	2400	489.31	488.80	490.50	488.75	490.60	489.22	488.99
4	Railroad Street - Upstream	3950	486.42	486.24	487.90	486.09	488.03	486.24	485.53
5	Railroad Street - Centerline	3985	486.19	486.09	487.68	485.87	487.76	486.08	485.21
6	Railroad Street - Downstream	4025	485.33	485.31	486.89	485.17	486.96	485.04	484.30
7	Leonard Street	4900	483.15	482.95	484.24	482.77	484.36	482.60	483.08
8	Barton Street	5800	482.58	482.33	482.29	482.05	482.58	481.90	481.90
9	Hemlock Creek	8160	480.14	479.99	479.79	479.75	479.74	479.54	479.49
10	SR42 Mall Blvd - Upstream	8760	479.77	479.64	479.44	479.41	479.49	479.18	479.14
11	SR42 Mall Blvd - Centerline	8840	478.31	478.34	478.15	478.22	478.67	478.01	478.02
12	SR42 Mall Blvd - Downstream	8900	478.17	478.19	478.02	478.06	478.66	477.94	477.95
13	US Route 11 BR - Upstream	10240	477.95	477.93	477.86	477.89	478.00	477.73	477.75
14	US Route 11 BR - Centerline	10320	477.72	477.70	477.66	477.69	477.72	477.53	477.55
15	US Route 11 BR - Downstream	10400	477.53	477.53	477.48	477.51	477.49	477.35	477.38
16	Dam_2_: Fishing– Upstream*	11980	477.39	477.38	477.31	477.37	477.37	477.15	477.20
17	Dam_2_: Fishing– Centerline*	12020	477.38	477.38	477.31	477.36	477.28	477.15	477.20
18	Dam_2_: Fishing– Downstream*	12060	477.38	477.38	477.31	477.36	477.33	477.15	477.19
19	Railroad BR Abandoned - US	13650	476.32	476.32	476.16	476.29	476.19	475.84	475.93
20	Railroad BR Abandoned - CL	13700	476.14	476.15	475.96	476.11	476.02	475.72	475.90
21	Railroad BR Abandoned - DS	13730	475.94	475.94	475.74	475.92	475.80	475.50	475.52
22	Railroad Bridge - Upstream	13750	475.87	475.88	475.68	475.85	475.76	475.41	475.46
23	Railroad Bridge - Centerline	13790	475.47	475.48	475.26	475.44	475.56	475.02	474.98
24	Railroad Bridge - Downstream	13810	474.69	474.73	474.48	474.71	474.57	474.45	474.46
25	Covered BR #56 - Upstream	13840	474.74	474.74	474.53	474.74	474.57	474.57	474.53
26	Covered BR #56 - Centerline	13860	474.62	474.62	474.40	474.62	474.45	474.56	474.51
27	Covered BR #56 - Downstream	13900	474.21	474.23	473.96	474.24	473.98	474.18	474.14

*Dam 2 (Boone's Dam) is scheduled for removal and was not included in the mitigation analyses.
**WSELs given are from the most favorable iteration of each individual alternative.
***All WSELs are taken along

SECTION 8 - OPINION OF PROBABLE CONSTRUCTION COST

Alternative 7 involves construction of a benched floodplain along the right descending bank of Fishing Creek in Hemlock Township, a system of culverts under US Route 11 just upstream of the PA Route 42 Bridge in Bloomsburg, and grading of a portion of the Fairgrounds parking area in Bloomsburg to provide an efficient flow path for higher level floods which flow through this area under existing conditions.

An opinion of probable construction costs for the mitigation features was developed utilizing cost data from recent levee construction projects in Bloomsburg, PA. The detailed construction cost estimate is included in Appendix E.

A cost summary is provided below:

1.	General Grading	$200,000
2.	Benched Floodplain	$1,800,000
3.	Culverts under US Route 11	$2,000,000
	TOTAL	**$4,000,000**

SECTION 9 – ANALYSIS SUMMARY

Fishing Creek in the West End of the Town of Bloomsburg is a hydraulically complex stream. Hydraulic modeling with 2D software offers powerful computational methods to better understand the behavior of flows under existing conditions and to predict flows under proposed conditions. This facilitates a better understanding of the movement of floodwaters in Fishing Creek and adjacent floodplains.

The large floodway of Fishing Creek in the West End study area is situated such that a proposed levee system would be constructed entirely within the regulatory floodway. Results of the 2D proposed conditions modeling show that the water surface elevation (WSEL) of the base flood increases by a maximum of 2.1 feet when a levee is constructed along the bank of Fishing Creek. The residential areas in Hemlock Township adjacent to and upstream of the proposed levee would experience a greater risk of flooding because these areas would not be protected by the proposed levee.

Several mitigation alternatives were evaluated with the goal of eliminating all induced flooding to structures/homes. Mitigation alternative 7 was chosen as the preferred alternate. It includes a benched floodplain to increase conveyance capacity parallel to the levee and a series of culverts under US Route 11 to encourage flow back into the floodplain west of the proposed levee alignment. The proposed culverts are located in the floodway in an area where, during the Tropical Storm Lee Flood of 2011, several homes were destroyed by overbank flows. The intent of this mitigation alternative is to return the flow where it originally went in existing conditions as efficiently as possible.

At the conclusion of this study, the initial 2.1 feet of induced flooding was mitigated to just 4 inches of residual induced flooding realized by two (2) structures along Drinker Street in Hemlock Township. It is possible that further refinement of the selected mitigation features during design could eliminate all the residual induced flooding; however, if not, acquisition/demolition or structure elevations at these properties remain as options that would be acceptable to both FEMA and the Pennsylvania Department of Environmental Protection (PADEP). In fact, the cost of further structural mitigation may outweigh the cost of elevating or acquiring the structures which remain impacted by induced flooding.

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