



Prepared for:
**NIAGARA PENINSULA
CONSERVATION AUTHORITY**

Attention: Brendan Buggeln, P.Eng.
Project Manager
E: bbuggeln@npca.ca

Carly Mason, P.Eng.
Project Lead
E: cmason@npca.ca

Upper Welland River Tributaries Floodplain Mapping Hydraulic Modelling Report

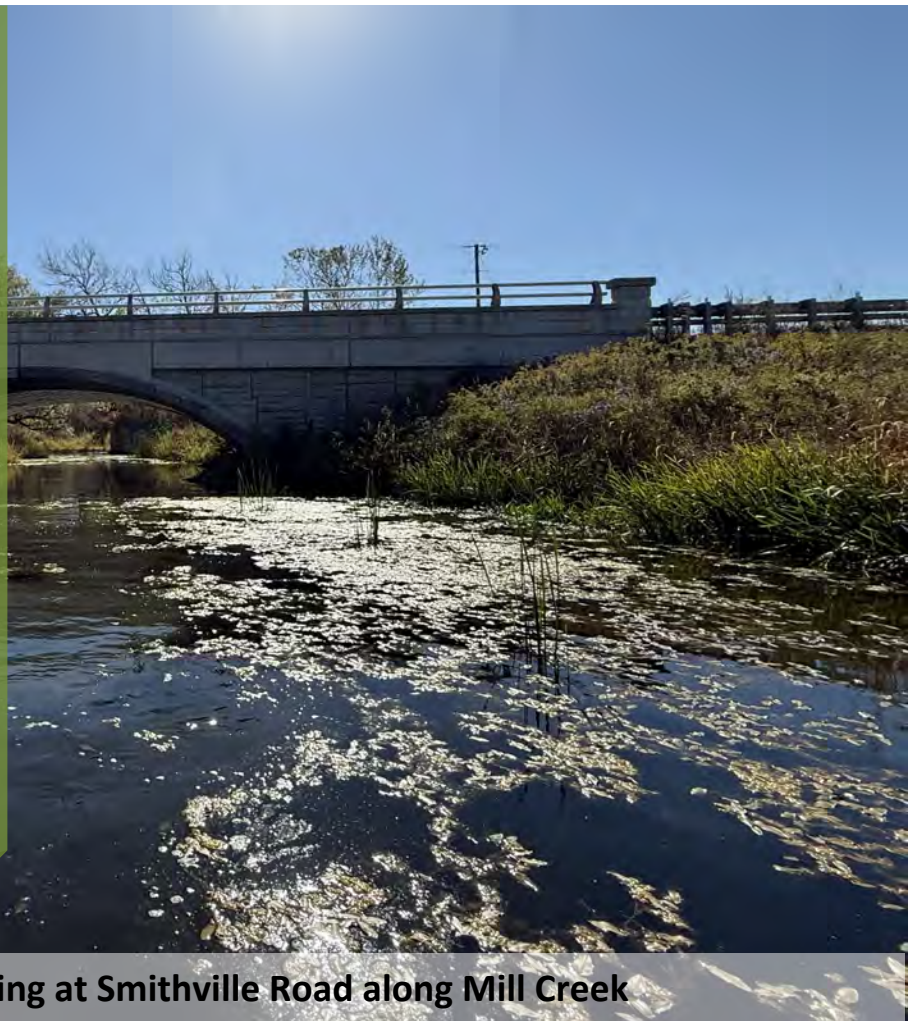
Submitted by:
**Aquafor Beech
Limited**

September 18, 2026

Contact:
Rob Amos, MAsC, P.Eng
Aquafor Beech Limited

amos.r@aquaforbeech.com
5405 Eglinton Avenue West
Suite 106
Toronto, ON M9C 5K6
Tel: 416.705.2367

Aquafor Beech Reference:
68031



Bridge Crossing at Smithville Road along Mill Creek

ACKNOWLEDGEMENTS

Aquafor Beech Limited gratefully acknowledges the efforts and contributions of the following partners and individuals participating in the funding, project management, technical analysis, and detailed hydraulic modelling of the Upper Welland River Tributaries Floodplain Mapping study. This document has been prepared by Aquafor Beech Limited for the Niagara Peninsula Conservation Authority in September 2026.

Federal and Provincial Partners

This project is funded in part by the Government of Canada

Canada

This project was made possible in part by the Province of Ontario

Ontario

Niagara Peninsula Conservation Authority:

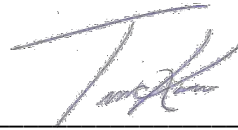
Brendan Buggeln – Manager, Natural Hazard Management and Resiliency
Carly Mason – Water Resources Engineer

Aquafor Beech Limited:

Prepared by:



Natalie Connell, P.Eng.
Water Resource Engineer



Tim Koen, P.Eng.
Senior Water Resource Engineer



Rob Amos, M.A.Sc., P.Eng.
CEO and Project Manager



Meaghan Dustin, M.Sc., P.Eng.
Project Coordinator

EXECUTIVE SUMMARY

Aquafor Beech Limited (Aquafor) was retained by the Niagara Peninsula Conservation Authority (NPCA) to establish updated regulatory floodplain mapping for 19 tributaries to the Upper Welland River through detailed hydrologic and hydraulic modelling, and flood hazard analyses. These tributaries include the Little Forks Creek, Buckhorn Creek, Elsie Creek, Little Wolf Creek, Mill Creek, Moores Creek, Black Creek Drain, Wilson Creek, Wolf Creek, and West Wolf Creek, as well as 9 unnamed tributaries. Together, these watercourses drain a total area of 212.7 km².

The 100-year flood event has been adopted by the NPCA to regulate development within the floodplain and to identify risks to properties and roads within the study area. The NPCA received funding to conduct this study, partnering with the Government of Canada (Natural Resources Canada) and the Province of Ontario (Ministry of Natural Resources) as part of the Flood Hazard Identification and Mapping Program (FHIMP) to develop flood hazard maps for municipalities and territories.

As part of the hydraulic component of the study, Aquafor developed a 1-D HEC-RAS hydraulic model (US Army Corps of Engineers HEC-RAS software, version 6.4.1). Preliminary peak flow inputs were determined using the HEC-HMS hydrologic model outputs completed as part of this study. A digital terrain model (DTM) having a 0.5 m resolution, produced by NRCan based on LiDAR data collected in 2021 was used in conjunction with field survey data to define stream and crossing structure geometries and to establish flood hazard mapping. In total, 197 km of creek, 3066 cross-sections and 167 hydraulic structures were modelled in 1-D. The Regulatory 100-year flood hazard mapping was subsequently developed for Upper Welland Tributaries located within the study area. Additional flood events were mapped; the 50-year event, as well as the 200 and 350-year flood events which serve as proxy events to estimate the impacts of climate change.

In addition to the 1-D hydraulic model, a 2-D HEC-RAS model was developed for a small portion of the study area, in the Black Creek Drain sub-watershed. Very flat topography that generally slopes away from the watercourses in question, combined with a high railway embankment, produced unrealistic 1-D model simulations and results. The 2-D model was therefore built to better understand the direction of flow away from the defined watercourses, and to avoid over-estimation of the flood extents by applying unsteady flow conditions. The 2-D 100-year floodline has therefore been included in the mapping. The approximate area included in the 2-D model extent was 1,500 ha, accounting for approximately 5 km of watercourse defined in the initial study scope.

Following the completion of the flood hazard mapping, road crossing and building analyses were completed to better define flood risks. While a lack of historical or gauge data was available on the subject watercourses, a detailed model sensitivity analysis was completed to provide additional confidence in the model's setup and parameterization.

The approach used for hydraulic modelling and flood line delineation was consistent with the HEC-RAS User's Manual (US Army Corps of Engineers, 2023), the Technical Guide for River & Stream Systems: Flooding Hazard Limit (OMNR, 2002), the Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation (NRCan,

2023), the Technical Guidelines for Flood Hazard Mapping (EWRG et al., 2017), the 2023 MNR Technical Bulletin – Flood Hazard: Data Survey and Mapping Specifications, and the 2024 FHIMP Program Guide.

Table of Contents

1	INTRODUCTION	1
1.1	Study Objective.....	1
1.2	Study Area	2
2	BACKGROUND REVIEW AND SITE RECONNAISSANCE	6
2.1	Background Data Review	6
2.2	Coordinate System and Vertical Datum.....	6
2.3	LiDAR-Derived DTM	6
2.4	Structure Inventory and Survey	6
2.5	Cross-Section Survey	10
3	1-D HYDRAULIC MODEL DEVELOPMENT	10
3.1	Model Software and Platform	10
3.2	Channel Network and Cross-Sections.....	10
3.3	Low-Flow Channel	11
3.4	Hydraulic Structures	15
3.5	Ineffective Flow Areas and Levees.....	16
3.6	Manning’s Roughness Coefficients.....	17
3.7	Contraction and Expansion Coefficients.....	20
3.8	Conveyance Obstructions (Buildings)	20
3.9	Steady-State Flow Rates	20
3.10	Boundary Conditions	31
3.10.1	Tailwater Scenario A: 2-yr Q with 100-yr TWC	31
3.10.2	Tailwater Scenario B: 100-yr Q with 2-yr TWC	32
3.10.3	Tailwater Sensitivity Comparison	34
3.10.4	Tailwater in Minor Flood Events.....	37
3.10.5	Flood Hazard Mapping Scenario Boundary Conditions	38
3.11	Spill Flow Balancing	38
4	2-D HYDRAULIC MODEL DEVELOPMENT – BLACK CREEK.....	47
4.1	2-D Hydraulic Model Platform	49
4.1.1	Building Obstructions	49
4.1.2	Channel Improvements	49
4.2	2-D Flow Area and Perimeter	49
4.3	2-D Breaklines.....	50
4.4	2-D Computation Points	50
4.5	2-D Mesh, Breaklines, Computational Points Visualisation.....	51

4.6	2-D SA/2-D Connections	51
4.7	Terrain Modifications – Hydroburn	51
4.8	2-D Boundary Conditions.....	52
4.8.1	Flow Hydrographs and Upstream Boundary Conditions	52
4.8.2	Downstream Boundary Conditions.....	55
4.9	2-D Computational Settings.....	55
5	MODEL RESULTS AND FLOODPLAIN MAPPING	57
5.1	High Flow Analysis Results and Flood Lines	57
5.2	Flooded Building Assessment	61
5.3	Road Crossing Performance.....	66
5.3.1	Undersized Crossings	72
5.4	Climate Change Assessment.....	73
5.5	Spill Areas	73
5.5.1	Trib 4: 4_1.....	73
5.5.2	Trib 6: 6_1-2.....	74
5.5.3	Trib 6: 6_2-2.....	74
5.5.4	Elsie Creek: Elsie_3	75
5.5.5	Buckhorn Creek: Buckhorn_1	75
5.5.6	Buckhorn Creek: BuckTrib_1.....	76
5.5.7	Buckhorn Creek: BuckTrib_3-2	77
5.5.8	West Wolf Creek: WestWolf_1.....	78
5.5.9	Trib_9: 9_1-3.....	79
5.6	Floodline Validation & Calibration.....	79
5.7	1-D Model Sensitivity.....	79
5.7.1	Mill Creek.....	81
5.7.2	Trib_7.....	88
5.8	Evaluation of 2-D Modelling Stability	92
5.8.1	2-D Un-Steady State Flow Routing	92
5.8.2	Mesh and Time Step Analysis	93
5.8.3	Unsteady Flow Volume Accounting Analysis	94
5.8.4	100-year → 1-D vs 2-D Modelling Results	94
6	UNCERTAINTIES, LIMITS AND RECOMMENDATIONS.....	96
6.1	2-D Hydraulic Modelling	96
7	CONCLUSIONS.....	97
8	REFERENCES.....	99

List of Figures

Figure 1-1. Upper Welland River Tributaries Drainage Network and Reaches to be Mapped - Eastern Subwatersheds	3
Figure 2-1. Location of the Hydraulic Structures Surveyed - Eastern Subwatersheds	7
Figure 2-2. Location of the Hydraulic Structures Surveyed - Central Subwatersheds	8
Figure 2-3. Location of the Hydraulic Structures Surveyed - Western Subwatersheds	9
Figure 3-1. HEC-RAS Model Schematic - Eastern Subwatersheds	12
Figure 3-2. HEC-RAS Model Schematic - Central Subwatersheds	13
Figure 3-3. HEC-RAS Model Schematic - Western Subwatersheds	14
Figure 3-4. Cross-Section Locations at Crossing Structures (US Army Corps of Engineers, 2022)	16
Figure 3-5. Land Cover Upper Welland River Tributaries - Eastern Subwatersheds	18
Figure 3-6. Land Cover Upper Welland River Tributaries - Western Subwatersheds	19
Figure 3-7. HEC-RAS Flow Node Locations – Eastern Watersheds	28
Figure 3-8. HEC-RAS Flow Node Locations – Central Watersheds	29
Figure 3-9. HEC-RAS Flow Node Locations – Western Watersheds	30
Figure 3-10. Estimated Welland River Channel Bottom, 2-Year and 100-Year Profiles	33
Figure 3-11. Tailwater Scenario Comparison for Little Forks Drain	35
Figure 3-12. Tailwater Scenario Comparison for Black Creek Drain	36
Figure 3-13. Tailwater Scenario Comparison for Black Creek Drain	36
Figure 4-1. Black Creek 1-D 100yr Floodplain Extents and Depths	47
Figure 4-2. Black Creek 2-D HEC-RAS Model Extent	48
Figure 4-3. 2-D Mesh Visualization	51
Figure 4-4 Hydro-Burn Scenario – Terrain Modification – Driveway Crossing	52
Figure 4-5 Black Creek – Flow Node Location Plan – 100yr Flows	53
Figure 4-6 Black Creek – Flow Node 10 and 12 Hydrograph Comparison	54
Figure 4-7 Black Creek – 2-D Boundary Conditions	55
Figure 5-1. Overview of the Upper Welland River Tributaries Regulatory Floodplain Mapping - Eastern Subwatersheds	58
Figure 5-2. Overview of the Upper Welland River Tributaries Regulatory Floodplain Mapping - Central Subwatersheds	59
Figure 5-3. Overview of the Upper Welland River Tributaries Regulatory Floodplain Mapping - Western Subwatersheds	60
Figure 5-4. Overview of Flooded Building Locations – Eastern Subwatersheds	63
Figure 5-5. Overview of Flooded Building Locations – Central Subwatersheds	64
Figure 5-6. Overview of Flooded Building Locations – Western Subwatersheds	65

Figure 5-7. Reach 4_1 Spill to Adjacent Welland River Tributary	73
Figure 5-8. Reach 6_1-2 Spill from Channel	74
Figure 5-9. Reach 6_2-2 Spill to Mill Creek.....	75
Figure 5-10. Reach Elsie_3 Spill to Adjacent Welland River Tributary.....	75
Figure 5-11. Reach Buckhorn_1 Spill to Welland River	76
Figure 5-12. Reach BuckTrib_1 Spill to Adjacent Watercourse	77
Figure 5-13. Reach BuckTrib_3-2 Spill to Adjacent Watercourse	78
Figure 5-14. Reach WestWolf_1 Spill to Adjacent Watercourse	78
Figure 5-15. Reach 9_1-3 Spill to Adjacent Watercourse	79
Figure 5-16. Area of Highest Manning’s Sensitivity in the 100-Year Event – Mill Creek (red outline)	82
Figure 5-17. 100-Year Manning’s Sensitivity Flood Extent Comparison for River: Mill Creek, Reach: Mill_1	83
Figure 5-18. 100-Year Manning’s Sensitivity Flood Extent Comparison for River: Mill Creek, Reach: Mill_2	84
Figure 5-19. 100-Year Manning’s Sensitivity Flood Extent Comparison for River: Mill Creek, Reach: Mill_3	85
Figure 5-20. Area of Highest Manning’s Sensitivity in the 100-Year Event – Trib_7 (red outline)	88
Figure 5-21. 100-Year Manning’s Sensitivity Flood Extent Comparison for River: Trib_7, Reaches: 7_1-1 &	89
Figure 5-22. 100-Year Manning’s Sensitivity Flood Extent Comparison for River: Trib_7, Reach: 7_1-2	90
Figure 5-23. 100-Year Manning’s Sensitivity Flood Extent Comparison for River: Trib_7, Reach: 7_1-2 – Area of Largest Top Width Increase.....	92
Figure 5-24. Black Creek 2-D - 100-year Regulatory Courant (Velocity/Length) Map	93
Figure 5-25. Black Creek 1-D vs 2-D - 100-year Floodplain Comparison	94
Figure 5-26. Black Creek 2-D - 100-year Un-Steady vs 12hr Quasi Un-Steady State Comparison	95

List of Tables

Table 3-1. Manning’s Roughness Values Used in the HEC-RAS Model.....	17
Table 3-2. Contraction and Expansion Loss Coefficients used in the HEC-RAS Model	20
Table 3-3. Initial HEC-RAS Flow Configuration based on HEC-HMS Outputs.....	21
Table 3-4. 100-Year Water Surface Elevation in the Welland River at Tributary Outlets (Welland River Floodplain Mapping Update, 2018)	31
Table 3-5. Welland River Depth Gauge Data (Upstream to Downstream).....	32
Table 3-6. Welland River Depth Gauge Data – 2-Year Event.....	33
Table 3-7. Tailwater Sensitivity Analysis Results	34
Table 3-8. Welland River Depth Gauge Data – 20-year Event	37
Table 3-9. Flood Hazard Mapping HEC-RAS Scenario – Downstream Boundary Conditions.....	38
Table 3-10. Peak Flow Balancing Modifications	40
Table 3-11. 1-D HEC-RAS Peak Flow Data used in Flood Hazard Mapping Scenario	41
Table 4-1. 2-D Flow Area Mesh Specifics – Black Creek	50

Table 4-2. 2-D Breakline Attributes	50
Table 4-3. 1-D Boundary Conditions for Downstream Limits of the 2-D model	55
Table 4-4. 2-D Computational Settings.....	56
Table 5-1. Summary of Buildings Located within the 100-Year (Regulatory) Flood Extents	61
Table 5-2. Total of Road Crossing Structures Overtopped and Impassible for the 50-year, 100-year, 200-year and 350-year Flood Events	66
Table 5-3. Roadway Overtopping Depth Conditions for all Roadway Crossings Modelled in 1-D.....	68
Table 5-4. Crossings with Significant Upstream Flood Impacts	72
Table 5-5. Manning’s Roughness Coefficient Variation for Sensitivity Analysis	80
Table 5-6. Manning’s Sensitivity Analysis Results Summary – 100-Year Event - Entire Model	80
Table 5-7. Manning’s Sensitivity Analysis Results – Cross Sections with >0.10 m WSE Increase (+20% Scenario) 100-Year Event	81
Table 5-8. Mill Creek Manning’s Sensitivity Analysis Results for High-Sensitivity Area (100-Year Event).....	85
Table 5-9. Trib_7 Manning’s Sensitivity Analysis Results for High-Sensitivity Area (100-Year Event).....	90
Table 5-10. 2-D Flow Volume Accounting Summary	94

Appendices

- Appendix A – Structure Inventory Sheets
- Appendix B - HEC-RAS Model Output Results
- Appendix C – Model Sensitivity Analyses
- Appendix D – Regulatory Floodplain Mapping
- Appendix E – Climate Change Scenario Floodplain Mapping

1 INTRODUCTION

1.1 Study Objective

Aquafor Beech Limited (Aquafor) was retained by the Niagara Peninsula Conservation Authority (NPCA) to establish updated regulatory floodplain mapping for 19 tributaries of the Upper Welland River. The tributaries to be mapped include the Little Forks Creek, Buckhorn Creek, Elsie Creek, Little Wolf Creek, Mill Creek, Moores Creek, Black Creek Drain, Wilson Creek, Wolf Creek, and West Wolf Creek. Additionally, the study includes 9 unnamed tributaries, herein referred to as Tributaries 1 to 9. The NPCA received funding to conduct this study, partnering with the Government of Canada (Natural Resources Canada) and the Province of Ontario (Ministry of Natural Resources) as part of the Flood Hazard Identification and Mapping Program (FHIMP) to develop flood hazard maps for municipalities and territories. The 100-year flood extent is used by the NPCA to regulate development within the floodplain, as directed by O.Reg. 41/24 under the Ontario Conservation Authorities Act, R.S.O. 1990 (Schedule 1, Table 15).

Aquafor developed a 1-D hydraulic model using the US Army Corps of Engineers HEC-RAS software (Ver. 6.4.1) and the Canadian Geodetic Datum of 2013 (CGVD2013) vertical datum, as opposed to the older CGVD28 vertical datum. The model was developed based on a LiDAR-derived DTM available from the Ontario Land Information GeoHub, topographic field survey data collected by Aquafor in 2025, and flows from the HEC-HMS results completed by Aquafor as part of the hydrologic study included in this assignment. Simulations were performed for the 2-year, 5-year, 10-year, 25-year, 50-year, 100-year (Regulatory), 200-year, 350-year storm events.

In addition to the 1-D model used for the majority of the reaches, a 2-D HEC-RAS hydraulic model was developed to replace 4 reaches in the upstream extents of the Black Creek Drain. The general topography in that area conflicts with the defined flow directions of the assigned watercourses, causing flows to move laterally across a wide area. These conditions made accurate 1-D modelling impossible.

The reaches included in this study are shown in **Figure 1-1**, **Figure 1-2** and **Figure 1-3** below.

The main tasks of the hydraulic component of this study are as follows:

- Review all available background information provided by the NPCA;
- Perform a data gap analysis to identify missing GIS data and road crossing information;
- Identify all watercourse crossing structures along the reaches of interest and complete field surveys;
- Develop a georeferenced 1-D hydraulic model using both the HEC-RAS and GeoHEC-RAS platforms throughout the study area, based upon the LiDAR-derived DTM, which is referenced to the NAD83 (CSRS) UTM Zone 17N horizontal coordinate system and the CGVD2013 vertical datum;
- Develop a georeferenced 2-D hydraulic model using the HEC-RAS platform as-required by limited 1-D modelling conditions;
- Perform a boundary conditions sensitivity analysis;
- Generate riverine flood extents for the 50-year, 100-year (Regulatory), 200-year, 350-year;
- Identify flooding extents;

- Identify areas of potential spills;
- Identify buildings within the regulatory flood hazard extents;
- Complete a road crossing analysis;
- Complete a model parameter sensitivity analysis;
- Provide the regulatory floodplain mapping sheets; and
- Provide the digital flood lines for all events.

1.2 Study Area

The study area includes 19 subwatersheds with a total drainage area of 212.7 km² and a total reach length of 205 km. All subwatersheds drain to the Welland River with the exception of Moores Creek and Little Wolf Creek, which discharge into Mill Creek and Wolf Creek, respectively. The creeks are located throughout the City of Hamilton, Haldimand County and Niagara Region. As illustrated in **Figure 1-1**, **Figure 1-2**, and **Figure 1-3**, the watersheds generally have elongated shapes and are characterized by a main drainage branch. The subwatersheds are predominantly rural and comprised of forests, cultivated lands, and wetlands. Urbanization is concentrated within the community of Binbrook, where Tributary 2 passes through a stormwater management system.

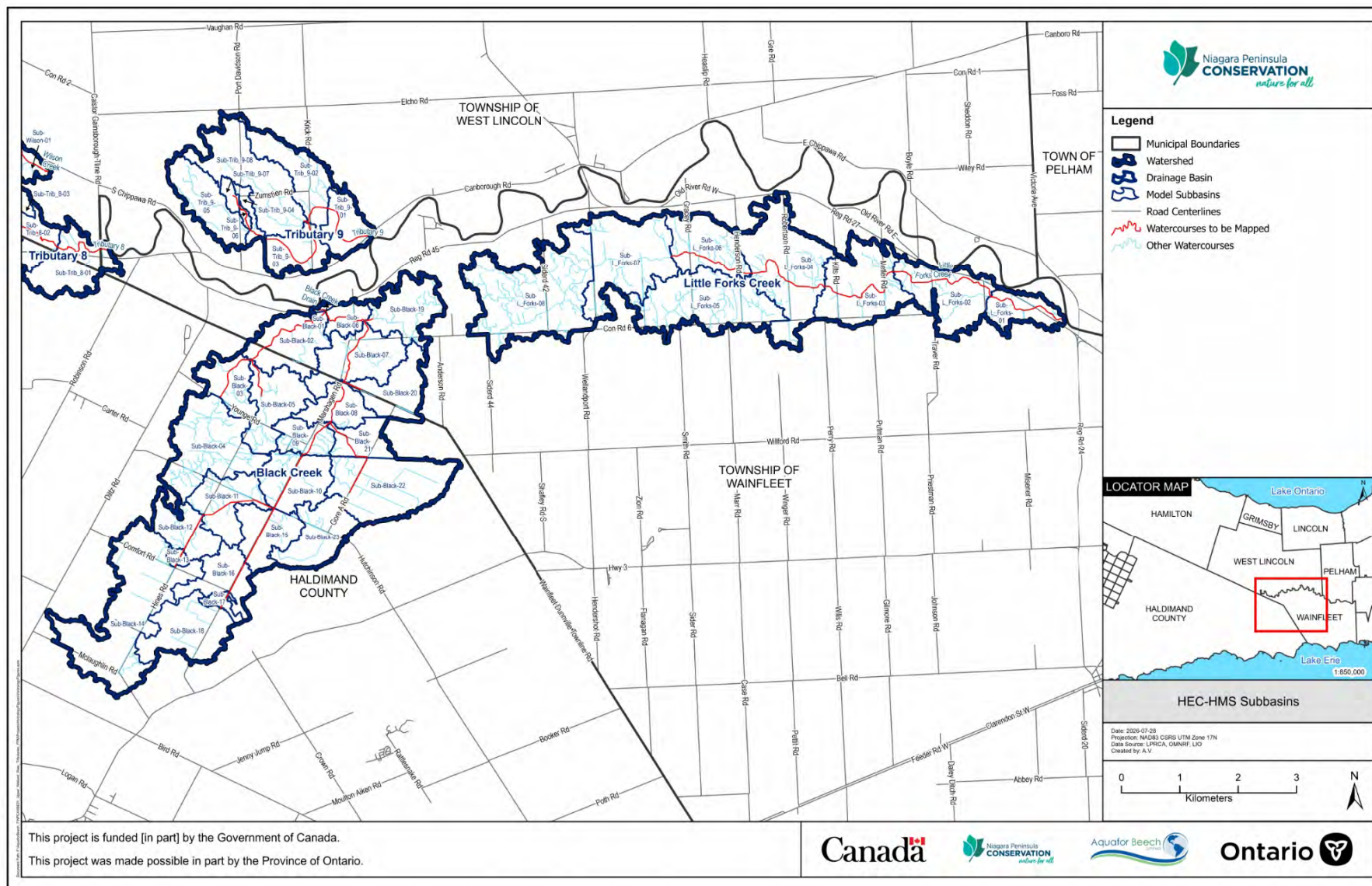


Figure 1-1. Upper Welland River Tributaries Drainage Network and Reaches to be Mapped - Eastern Subwatersheds

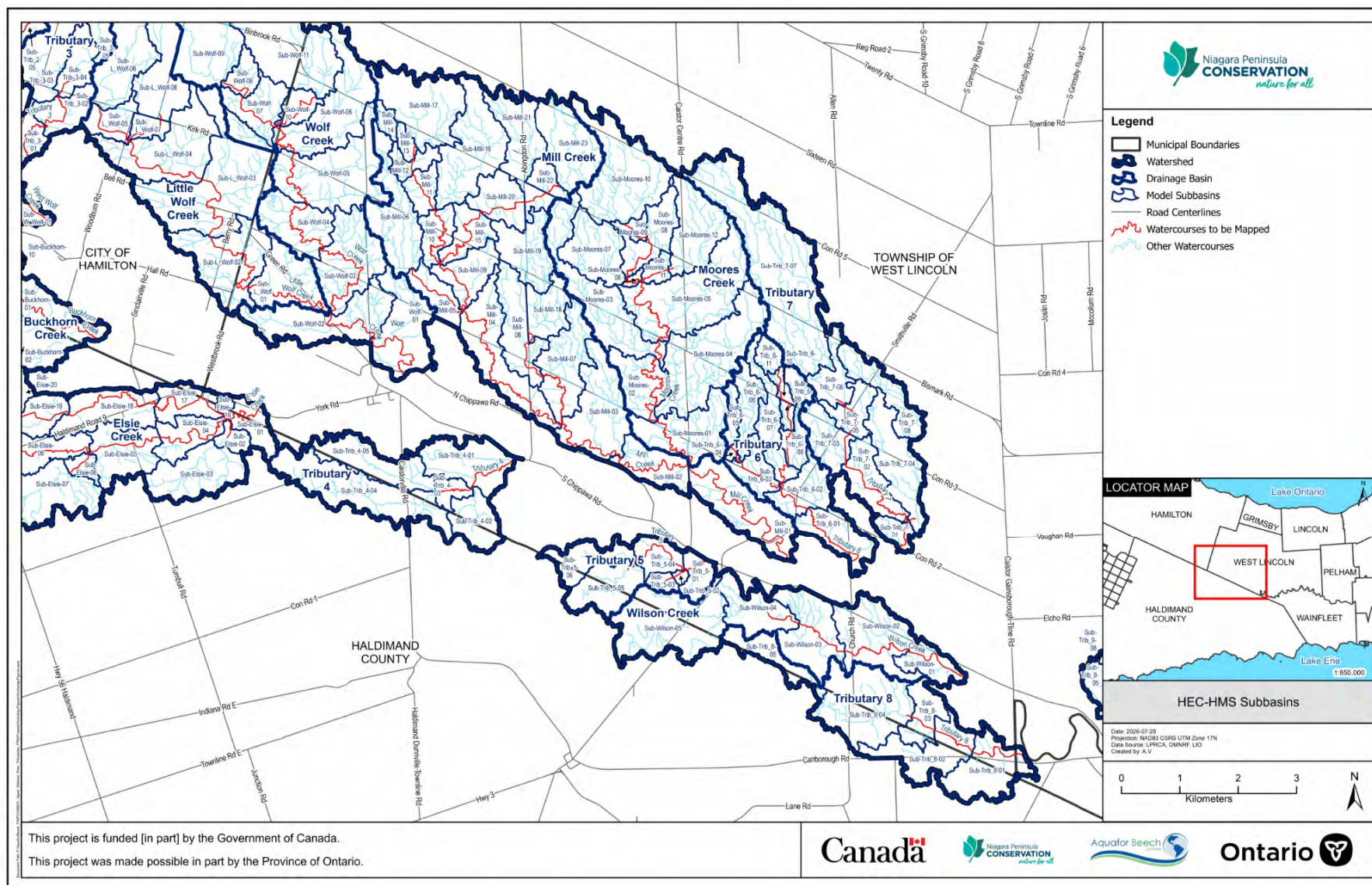


Figure 1-2. Upper Welland River Tributaries Drainage Network and Reaches to be Mapped - Central Subwatersheds

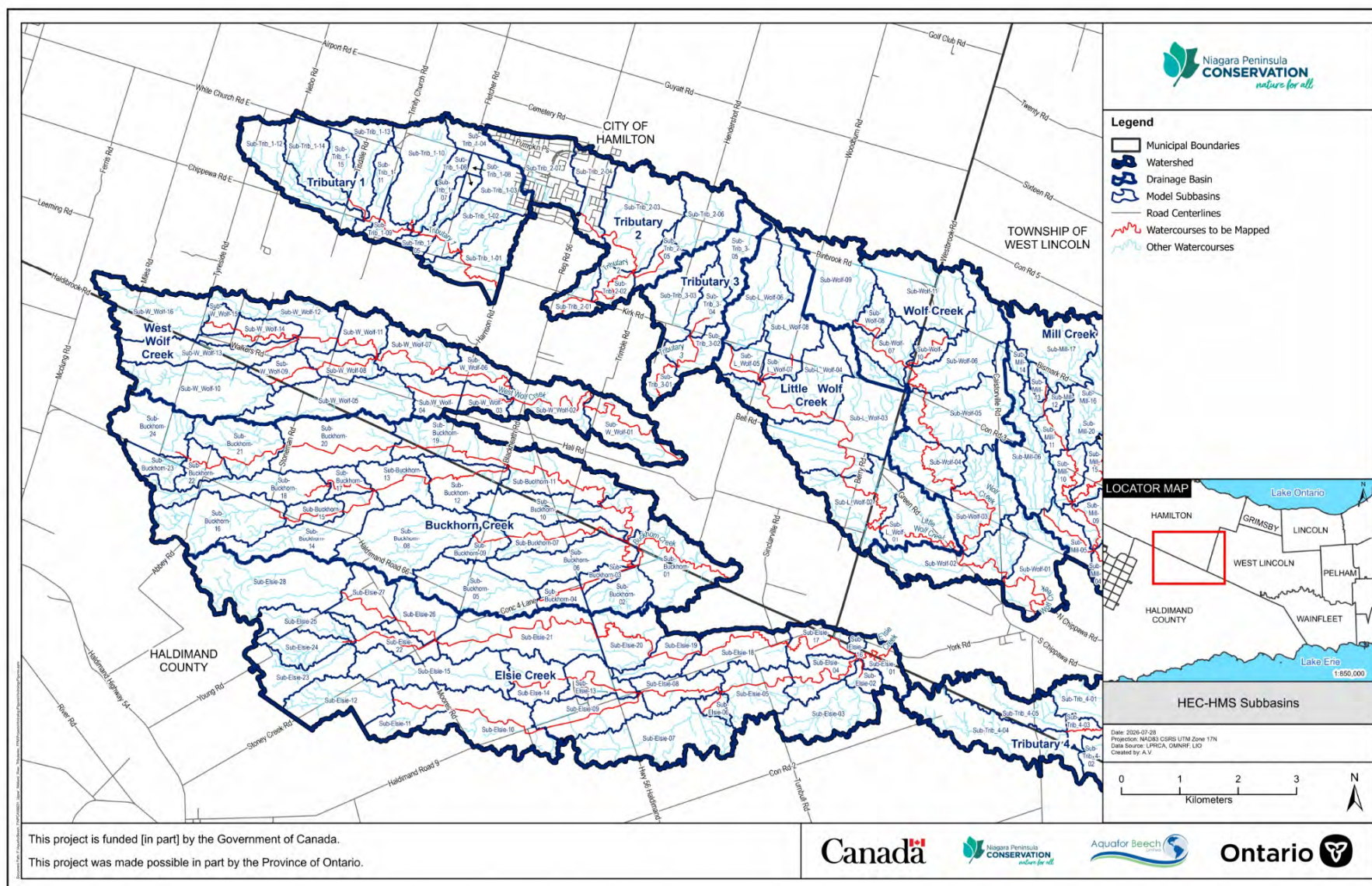


Figure 1-3. Upper Welland River Tributaries Drainage Network and Reaches to be Mapped - Western Subwatersheds

2 BACKGROUND REVIEW AND SITE RECONNAISSANCE

2.1 Background Data Review

At the onset of the hydraulic study, Aquafor collected and compiled all pertinent background information from the NPCA, including:

- A high-resolution DTM that was derived from 2021 LiDAR data
- Flood Plain Mapping Project – Haldimand-Norfolk (M.M. Dillon Limited, 1977)
- Welland River Floodplain Mapping Update (WSP, 2017)
- GIS data layers for existing flood extents, watercourse centrelines, structure locations, and land use.

2.2 Coordinate System and Vertical Datum

As required by FHIMP, the floodplain mapping and associated models must be developed using a specific geospatial reference system. For consistency, all topographic data such as the LiDAR-derived DTM and Aquafor's survey points were referenced to the same horizontal coordinate system and vertical datum as follows:

- Horizontal Datum: North American Datum of 1983 (NAD83), Canadian Spatial Reference System (CSRS)
- Projection: Universal Transverse Mercator, Zone 17 North (UTM Zone 17N)
- Vertical Datum: Canadian Geodetic Vertical Datum of 2013 (CGVD2013)

2.3 LiDAR-Derived DTM

A DTM with a 0.5 m resolution was available for the entire study area. The DTM was produced by Ontario Land Information GeoHub based on LiDAR data collected in 2021 and was used as the primary elevation data source for defining the geometries of hydraulic model components and delineating flood extents. It is referenced to the NAD83 (CSRS) UTM Zone 17N horizontal coordinate system and the CGVD2013 vertical datum.

2.4 Structure Inventory and Survey

Throughout 2025, Aquafor conducted a detailed topographic survey of significant channel crossing structures. Additional topographic survey data was later collected in the spring of 2026. The surveys included structure type and material, location and size of openings and headwalls/wingwalls, heights, depth of embedment, invert and soffit elevations, etc.

A structure tracking sheet and summaries of field inventories at each crossing structure, in the form of structure inventory sheets, are compiled in **Appendix A. Figure 2-1, Figure 2-** and **Figure 2-** illustrate the general location of each hydraulic structure surveyed for the model.

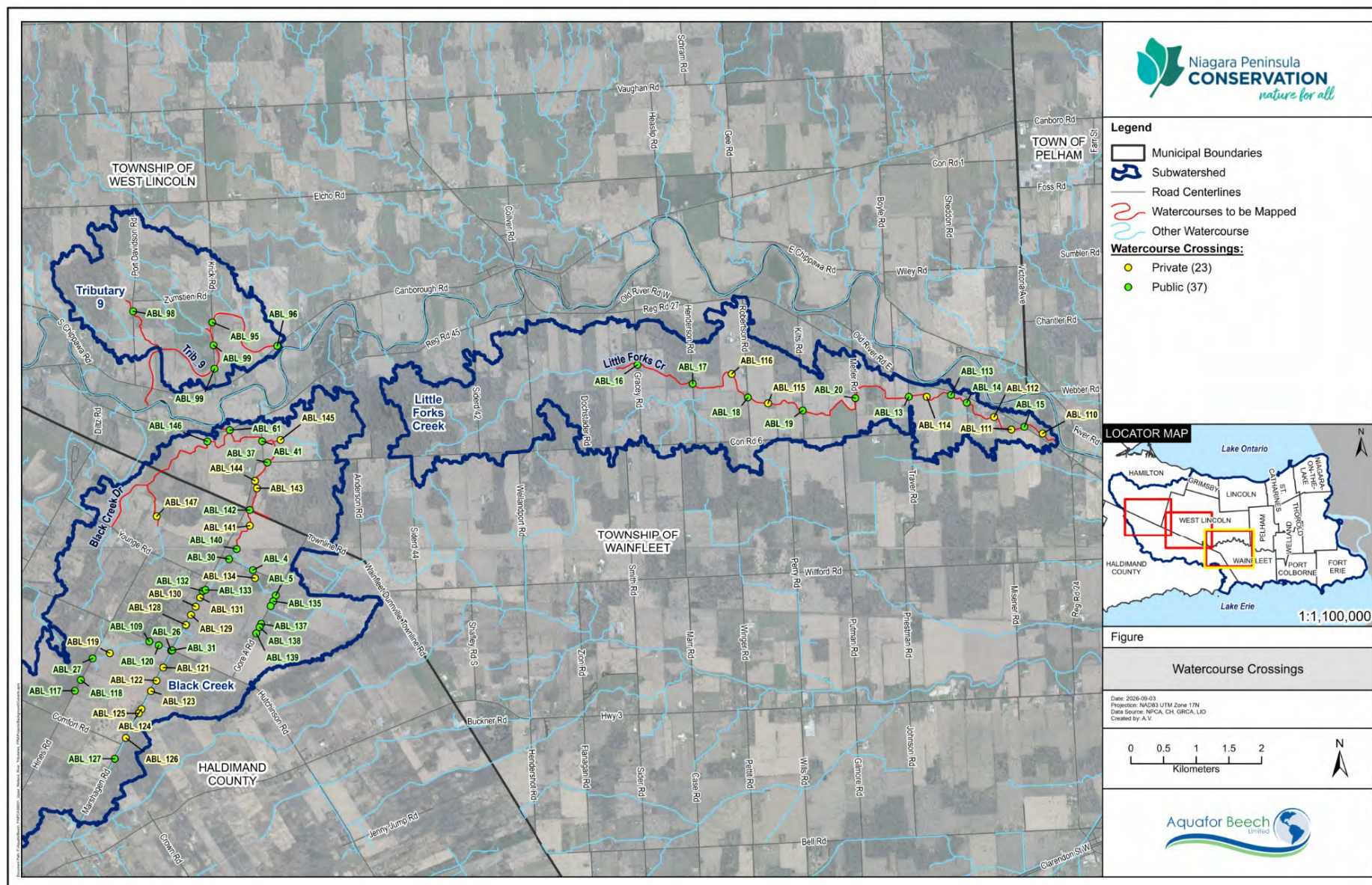


Figure 2-1. Location of the Hydraulic Structures Surveyed - Eastern Subwatersheds

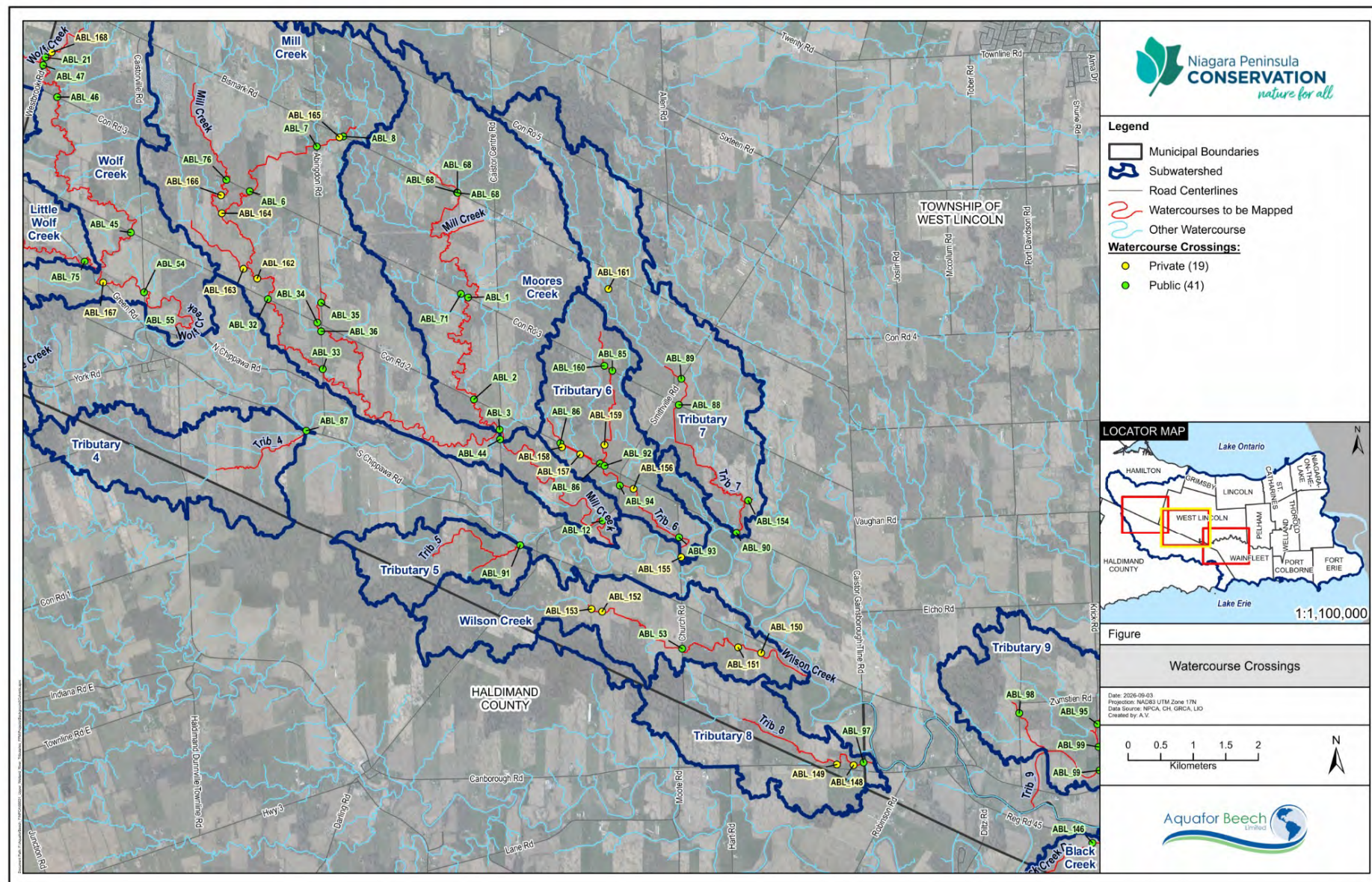


Figure 2-2. Location of the Hydraulic Structures Surveyed - Central Subwatersheds

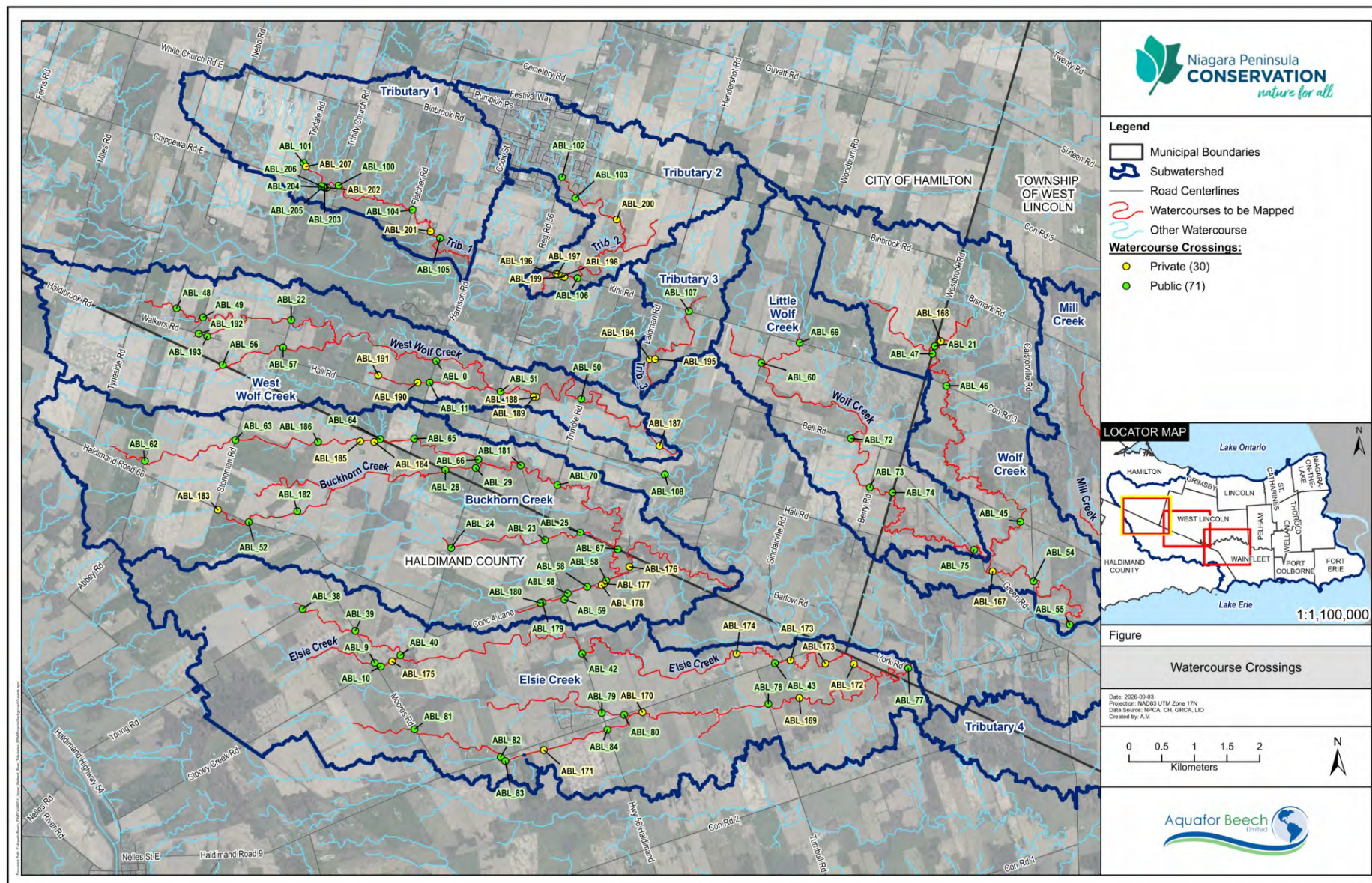


Figure 2-3. Location of the Hydraulic Structures Surveyed - Western Subwatersheds

2.5 Cross-Section Survey

Aquafor undertook a topographic survey of river cross-sections at crossing locations to provide additional detail to the hydraulic modelling geometry. Cross-sections were surveyed throughout the study area, generally consisting of 4 cross-sections at each crossing structure (2 upstream and 2 downstream). The topographic survey of the river cross-sections identified the locations and elevations of the thalweg, streambed geometry, and bottom and top of bank, and overbank topography within the floodplain.

3 1-D HYDRAULIC MODEL DEVELOPMENT

3.1 Model Software and Platform

The Upper Welland River Tributaries 1-D hydraulic model was built using a combination of the HEC-RAS software (ver. 6.4.1) and the GeoHEC-RAS platform, which integrates HEC-RAS modelling directly with various GIS tools and data sources (AutoCAD drawings, elevation rasters, CSV files, ESRI shapefiles, etc.). The model geometry was built using GeoHEC-RAS, with minor edits to edge lines done in HEC-RAS. Flow data was input using HEC-RAS, as the input table allows for much more efficient updates to be made to all reaches. The two platforms allow for seamless transitions between the two.

The 1-D floodplain extents were generated, and refined as shapefiles for mapping, using GeoHEC-RAS based on its HEC-RAS engine results and the LiDAR-derived DTM. The 2-D floodplain extents were generated and refined using HEC-RAS.

3.2 Channel Network and Cross-Sections

The watercourse network to be mapped was determined by NPCA. Aquafor reviewed the centreline of the watercourses during the hydrologic assessment and redefined some lines using the 2021 DTM LiDAR and GeoHEC-RAS software. Within a HEC-RAS hydraulic model, the term “River” refers to a watercourse made of multiple “Reaches”. A total of 205 km of watercourse was initially included in the 1-D hydraulic model as 17 Rivers with 85 Reaches, all ultimately outletting to the Welland River. A schematic of the 1-D HEC-RAS model setup is shown in **Figure 3-1**, **Figure 3-2**, and **Figure 3-3**.

Channel centrelines were provided in a shapefile by the NPCA. One reach was added to the network where Tributary 9 splits to two separate outlets to the Welland River, where previously only the eastern outlet had been identified.

The DTM was used to define channel cross-sections reflecting the channel and floodplain geometry. At select locations where more detailed survey information was obtained through the field investigation, cross-sections were refined with the detailed topographic survey data to refine the channel bed geometry, top of bank, and bottom of bank.

Cross-sections were spaced at minimum every 80-100 m and were located to account for changes in channel geometry and gradient, meanders, roadway crossings, and to account for the narrowest sections of the creek. Additionally, cross-sections were placed close enough to ensure accurate computation of the energy losses around hydraulic structures. In accordance with the HEC-RAS Reference Manual (US Army Corps of Engineers,

2022), cross-sections were extended across the entire floodplain and oriented perpendicular to anticipated flow lines.

3.3 Low-Flow Channel

Where deemed necessary, low-flow channels of modelled cross-sections located near surveyed cross-sections were corrected by using the topographic / bathymetric survey data directly. Generally a cross section was only corrected when the LIDAR-derived cross sectional geometry conflicted completely with the topographic survey of a road crossing structure (ie channel bottom shown above the bridge/culvert obvert). Surveyed cross-sections accounted for all low-flow channel characteristics such as channel bed elevation, water's edge, bottom and top of bank, and slopes. Detailed reach investigations of the low flow channel were not conducted along the entirety of the creeks due to the scale of the study area and because of site access and safety conditions, and the majority of cross sections were not adjusted.

An undefined low-flow channel may increase model uncertainty, especially during base flow and more frequent flood event conditions. However, during the larger flood events targeted as part of this study, the geometry of the low-flow channel bears much less importance, as the overall conveyance area of a cross section greatly exceeds the low-flow area.

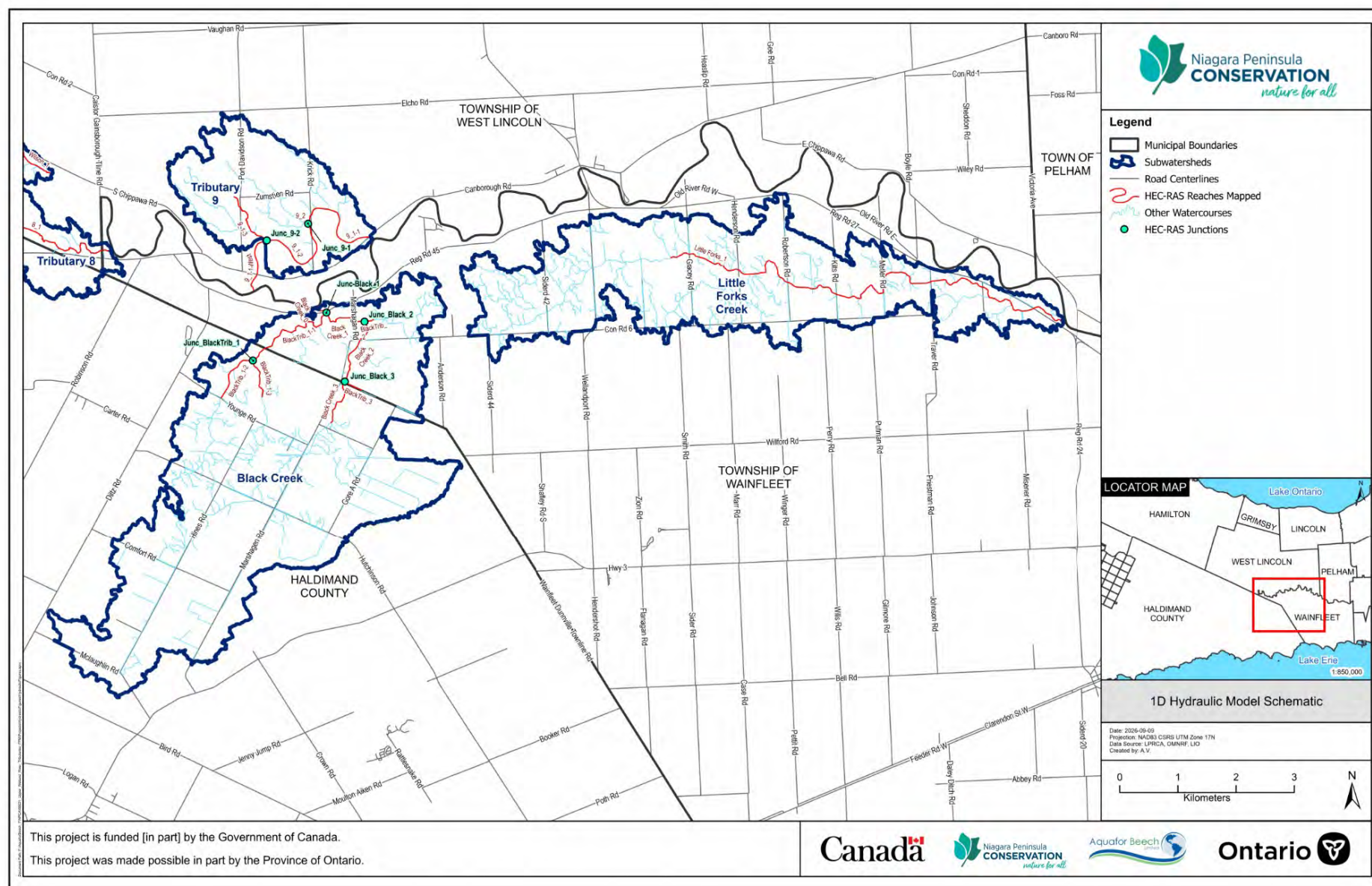


Figure 3-1. HEC-RAS Model Schematic - Eastern Subwatersheds

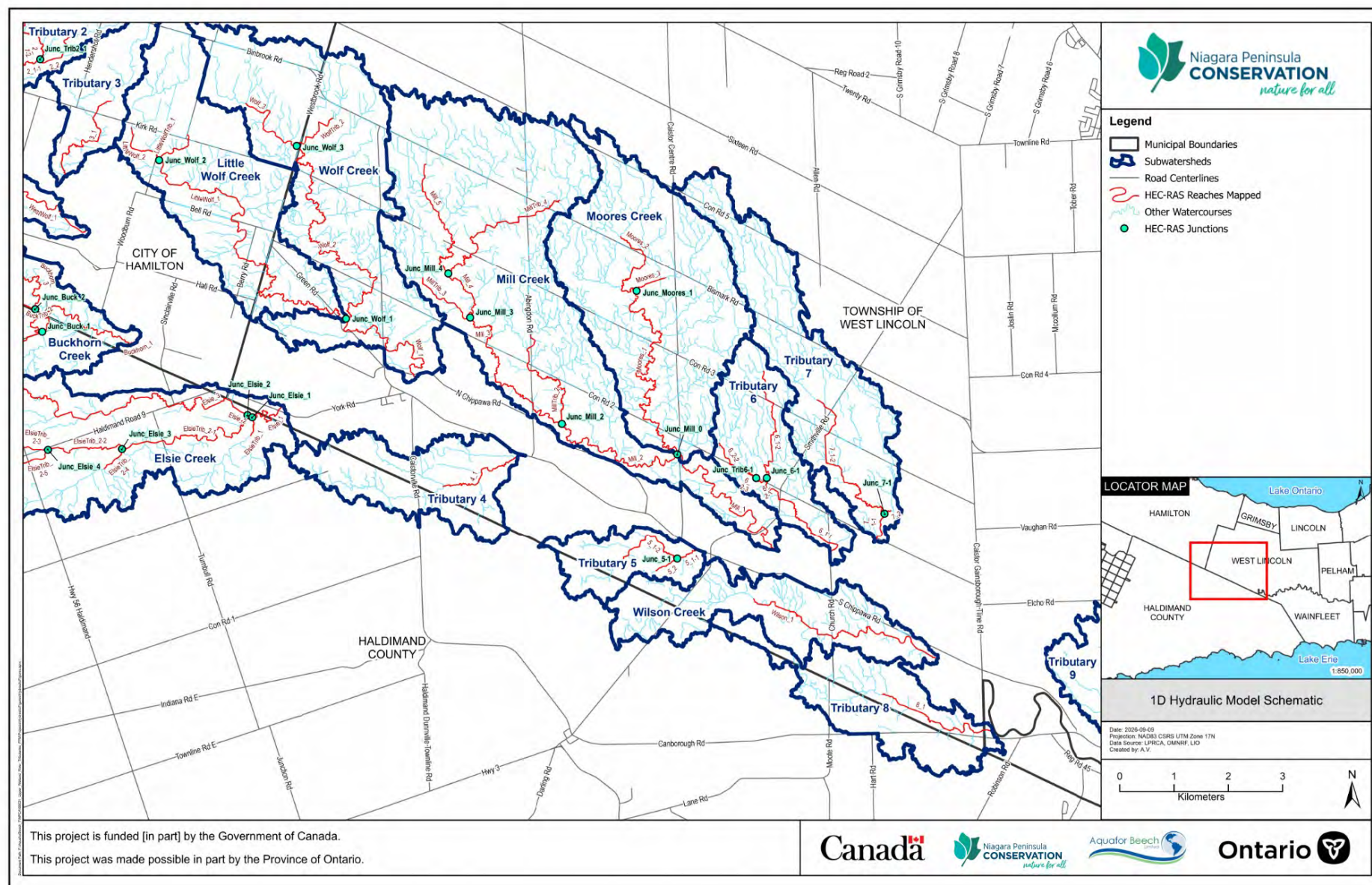


Figure 3-2. HEC-RAS Model Schematic - Central Subwatersheds

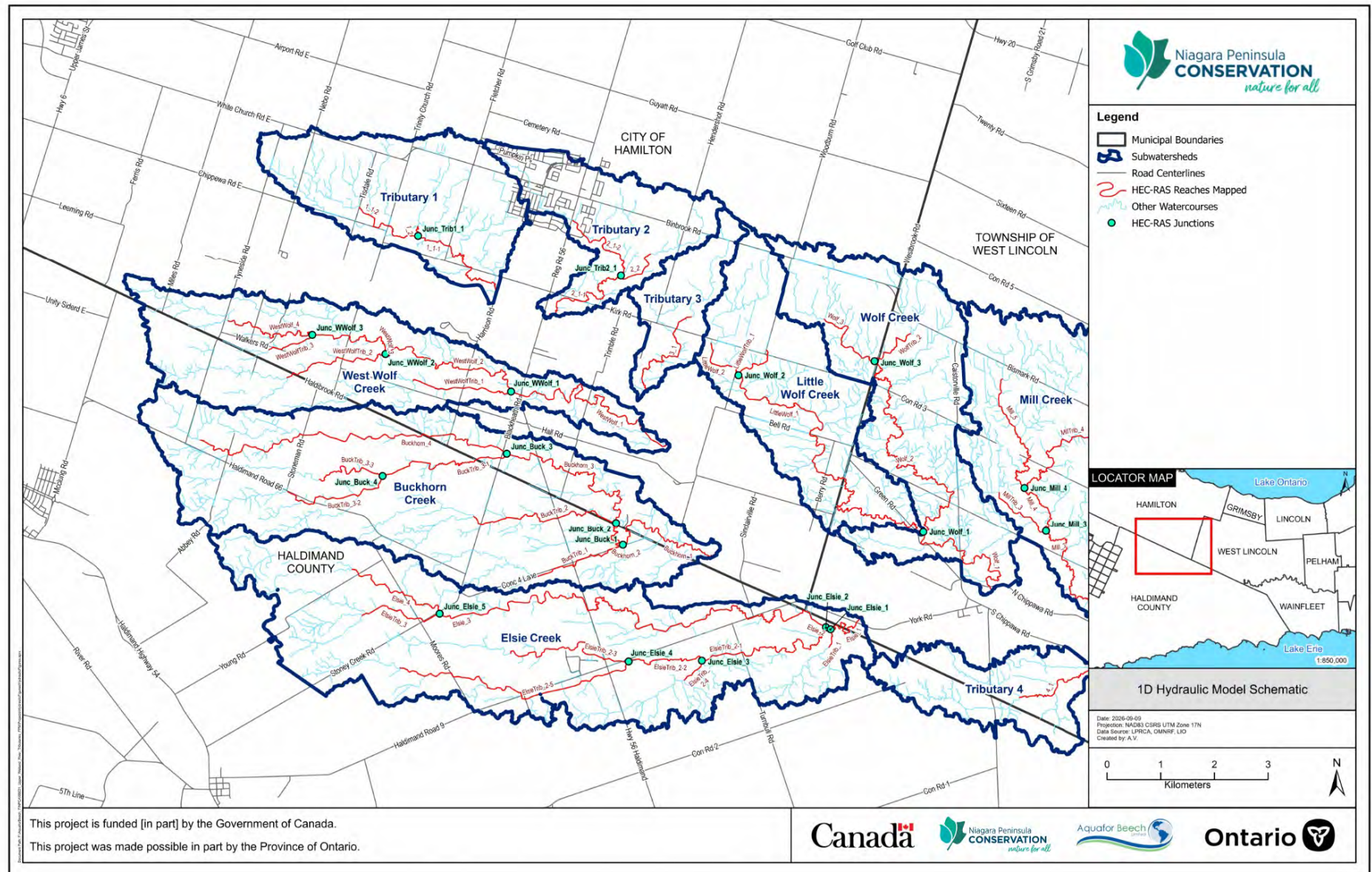


Figure 3-3. HEC-RAS Model Schematic - Western Subwatersheds

3.4 Hydraulic Structures

Hydraulic structures included in this study consisted of bridges, culverts and one stormwater outfall structure. Four cross-sections (i.e., 2 upstream and 2 downstream of each structure) were coded at each crossing structure to define streambed and floodplain geometry in close proximity to the structure, as well as to account for expansion and contraction of flow at these structures.

The spacing of these cross-sections was consistent with the HEC-RAS Reference Manual (US Army Corps of Engineers, 2022), estimated using the recommended flow expansion and contraction ratios. In general, the locations for the upstream cross-sections were selected by assuming a typical flow contraction ratio of 1:1, while the downstream cross-section locations were selected based on expansion ratios that were typically in the range of 2:1 (**Figure 3-4**).

Structure parameters were then coded as per the approach shown in **Figure 3-4**, including the structure material, opening dimensions, invert elevations, skew angles, depth of embedment, etc. Road profiles were mostly defined using LiDAR-derived DTM and cross-referenced with background information. In addition, the height of railing was added to the road profile for certain bridges, where the railing or fencing was anticipated to act as a blockage under high flows. Given the nature and size of debris flow (ie trees) in natural watercourses such as those modelled in this study, a 100% blockage was coded in the model to be conservative.

A coefficient was applied to each culvert crossing to account for the energy loss by the entrance and exit of the culvert. Those entrance and exit loss coefficients depend on the culvert upstream and downstream face characteristics (i.e., projecting, mitered to the slope, wingwalls, etc.,) and were determined based on the field condition (field notes and photos), using values from the HEC-RAS reference manual.

A total of 235 crossings or structures were identified within the 1-D hydraulic study area, and 167 were built into the model. Of the 68 crossings not included in the model, 65 are private crossings not initially identified in the study scope and were inaccessible for survey due to land permission issues. To account for the highly variable condition of these private crossings, 44 cross sections were cut along the laneways. The remaining 21 have been deemed hydraulically insignificant due to their low roadway embankments and high flood flow elevations.

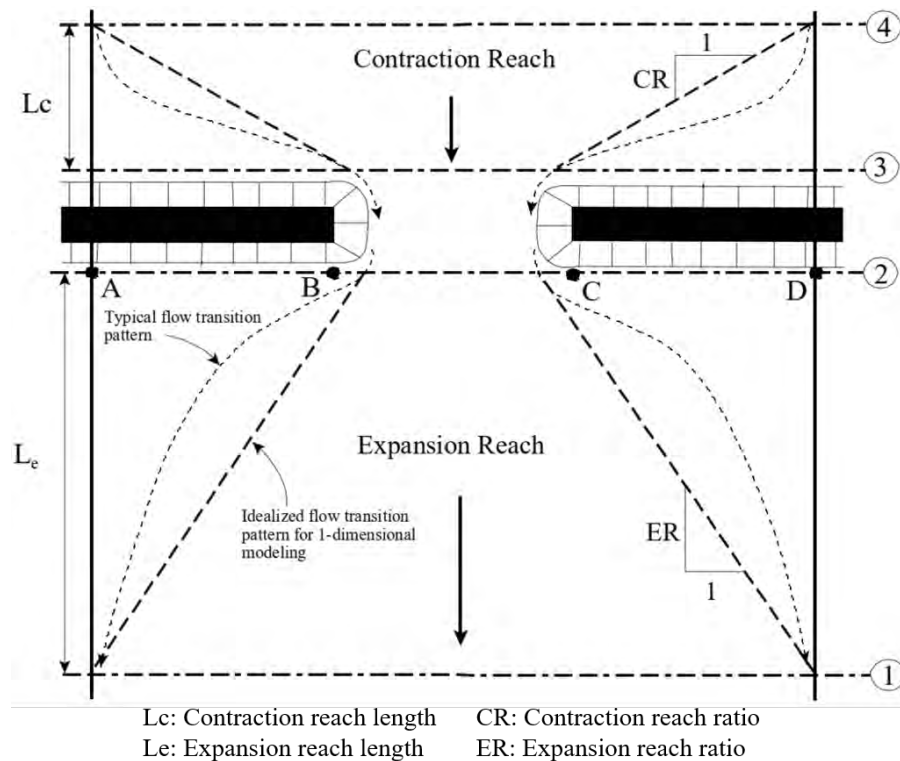


Figure 3-4. Cross-Section Locations at Crossing Structures (US Army Corps of Engineers, 2022)

It is important to note that for computing bridge hydraulics under high flow conditions, the pressure and weir flow calculations were chosen when bridges were under pressure for the Regulatory storm. If the coded bridge was partially under pressure (only the upstream water surface reached the soffit), the applied discharge coefficient was 0.5. When the bridge was fully submerged (both the upstream and downstream faces of the bridge were submerged), the applied discharge coefficient was 0.8.

3.5 Ineffective Flow Areas and Levees

The ineffective flow area option was applied in the model to restrict the flow area to the width of the structure opening until the structure was overtopped and weir flow began over the road structure. Ineffective flow areas were coded in accordance with the HEC-RAS Hydraulic Reference Manual (USACE, 2016) where stations were placed on either side of the structure based on the distance between the bounding cross-sections and structure faces, with a 1:1 contraction ratio upstream and a 2:1 expansion ratio downstream. The ineffective flow elevations upstream were set to the lowest point of the top-of-road (minimum weir elevation), while downstream elevations were set to the average of the soffit and minimum road surface elevations. Refinements were made after the initial run where surface water elevations were confined by the ineffective flow areas.

Levees have been added to the model at some roads and other topographic high points in order to ensure that the estimated water surface elevation remains confined within the channel corridor until the flood flow reaches the levee elevation and enters the floodplain depressions.

3.6 Manning's Roughness Coefficients

Manning's roughness coefficients were assigned to each cross-section based on the land use layer provided by the NPCA for the study. This layer was derived using the Southern Ontario Land Resource Information System (SOLRIS) version 3.0 data layer and grid code classifications. HEC-RAS allows for a maximum of 20 roughness segments per cross section, and the coefficients were assigned to each cross section using the GeoHEC-RAS spatial analysis tool and SOLRIS data layer.

Upper Welland River Tributaries flows through a mix of land uses within the study area, consisting mostly natural coverage (i.e., forest and cultivated crop land). Manning's roughness values were defined as shown in **Table 3-1**, based on the recommendations provided in the Technical Guidelines for Flood Hazard Mapping (EWRG et al., 2017), the MTO Drainage Management Manual (Design Chart 2.01, 1997), and the HEC-RAS reference Manual (US Army Corps of Engineers., 2016). Maps illustrating the different future land uses projected by the official plans of the impacted municipalities within the subwatersheds are shown in **Figure 3-5** and **Figure 3-6**. A sensitivity analysis using the Manning's roughness coefficients was completed as part of this study and is described in Section 5 of this report.

Table 3-1. Manning's Roughness Values Used in the HEC-RAS Model

Classification	Manning's Roughness Value
Forest	0.07
Coniferous Forest	0.07
Mixed Forest	0.07
Deciduous Forest	0.07
Treed Swamp	0.08
Thicket Swamp	0.08
Marsh	0.08
Open Water	0.03
Plantations - Tree Cultivated	0.055
Hedge Rows	0.08
Tilled	0.07
Transportation	0.025
Built-Up Area - Pervious	0.05
Built-Up Area - Impervious	0.025
Extraction - Aggregate	0.05
Undifferentiated	0.05

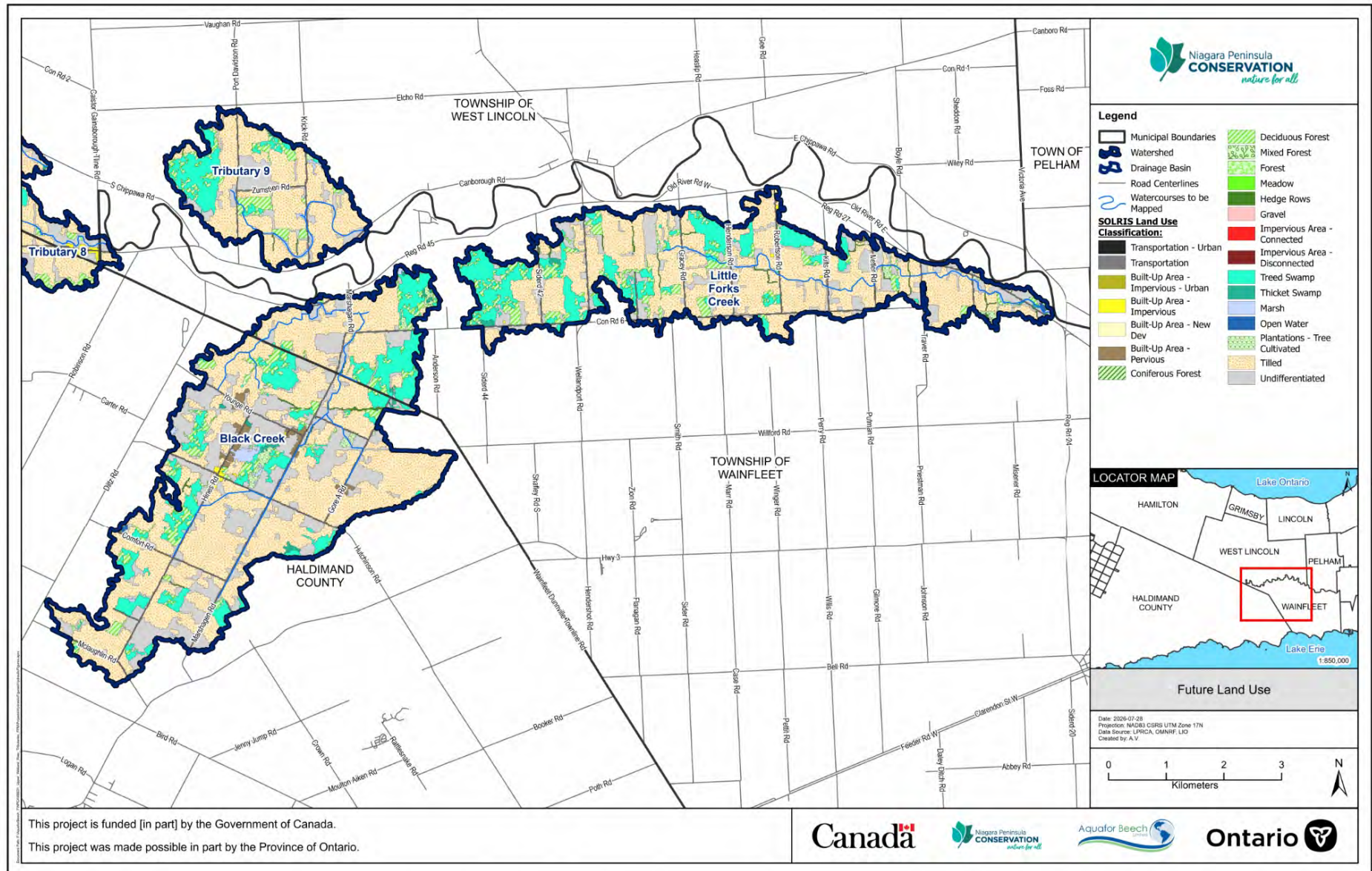


Figure 3-5. Land Cover Upper Welland River Tributaries - Eastern Subwatersheds

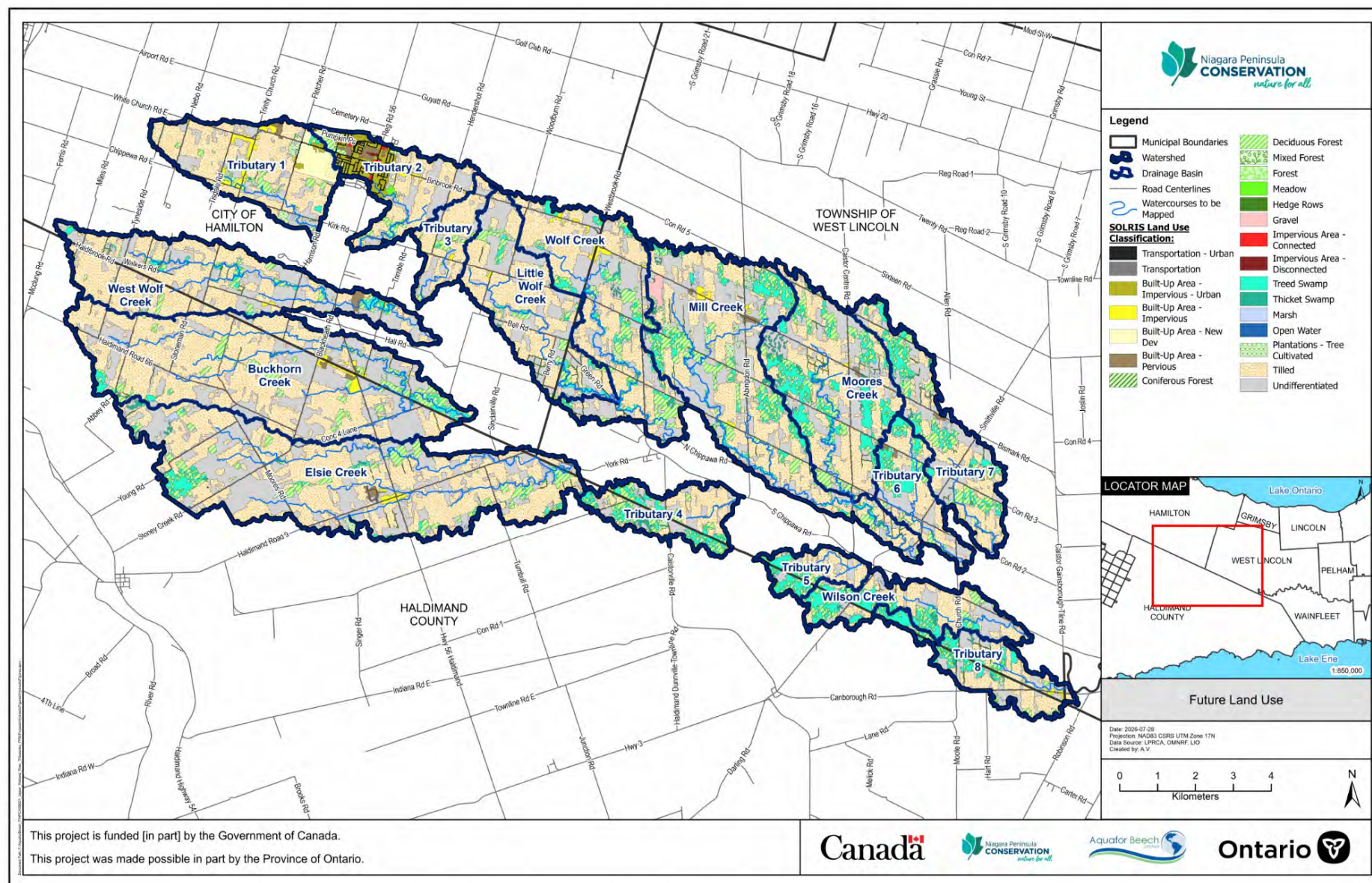


Figure 3-6. Land Cover Upper Welland River Tributaries - Western Subwatersheds

3.7 Contraction and Expansion Coefficients

Contraction and expansion coefficients were coded in the model to evaluate transition loss due to changes of flow between cross-sections. These coefficients were applied differently between regular cross-sections and structure cross-sections based on recommended values, which are summarized in **Table 3-2**.

Table 3-2. Contraction and Expansion Loss Coefficients used in the HEC-RAS Model

	Contraction Coefficient	Expansion Coefficient
Regular Cross-sections	0.1	0.3
Structure Cross-sections	0.3	0.5

3.8 Conveyance Obstructions (Buildings)

Buildings located within the study area were modeled as conveyance obstructions when defining areas of the cross-section that are permanently blocked out. Building footprint data determined using the Buildings Footprint layer provided by the NPCA and aerial photography. It was observed that the Buildings Footprint shapefile is missing several buildings within the study area, and aerial photography was therefore used to supplement the shapefile. Buildings were assigned a height of 3-5 m above the terrain elevation shown on the LIDAR-derived DTM.

3.9 Steady-State Flow Rates

Flow rates for the 2-year, 5-year, 10-year, 25-year, 50-year, 100-year, 200-year, 350-year storm events were completed by Aquafor as part of the hydrologic component of this study using the HEC-HMS modelling platform. The locations of all HEC-RAS flow nodes are provided in **Figure 3-7**, **Figure 3-8**, and **Figure 3-9**, and the associated event-based flow rates initially used in the model are presented in **Table 3-3**.

Table 3-3. Initial HEC-RAS Flow Configuration based on HEC-HMS Outputs

HEC-HMS Junction	ABL HEC-RAS River	Reach	RS	Peak Flow (m ³ /s)							
				2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Jun-Black-09-2	Black Creek Dr	Black Creek_5	7953	1.69	2.93	3.81	4.97	5.86	6.77	7.62	8.25
Jun-Black-07-2	Black Creek Dr	BlackTrib_4	1618	2.27	3.94	5.14	6.71	7.91	9.13	10.27	11.12
Jun-Black-09-1	Black Creek Dr	BlackTrib_5	2340	2.49	4.12	5.37	7.23	8.65	10.1	11.45	12.46
Jun-Black-07-1	Black Creek Dr	Black Creek_4	6022	4.58	7.93	10.21	13.51	15.79	18.4	20.95	22.82
Jun-Black-06-1	Black Creek Dr	Black Creek_3	4066	6.78	11.89	15.37	20.24	23.93	27.57	31.06	33.69
Jun-Black-06-2	Black Creek Dr	BlackTrib_3	309	0.40	0.78	1.05	1.40	1.66	1.92	2.17	2.35
Jun-Black-05-1	Black Creek Dr	Black Creek_2	3333	7.95	14.05	18.19	23.87	28.11	32.48	36.54	39.59
Jun-Black-03-1	Black Creek Dr	BlackTrib_1-2	2904	1.52	2.71	3.56	4.68	5.54	6.41	7.23	7.84
Jun-Black-03-2	Black Creek Dr	BlackTrib_1-3	696	0.61	1.10	1.45	1.90	2.25	2.61	2.94	3.19
Jun-Black-05-2	Black Creek Dr	BlackTrib_2	150	0.55	1.02	1.35	1.78	2.11	2.44	2.75	2.98
Jun-Black-02-2	Black Creek Dr	Black Creek_1	2088	8.60	15.26	19.71	25.93	30.47	35.26	39.69	42.98
Jun-Black-02-1	Black Creek Dr	BlackTrib_1-1	1948	2.91	5.09	6.67	8.82	10.48	12.16	13.73	14.90
Jun-Black-01	Black Creek Dr	Black Creek_0	1219	11.35	20.21	26.10	34.34	40.21	46.61	52.52	56.80
Jun-Buckhorn-14	Buckhorn Creek	BuckTrib_3-2	5216	1.48	2.54	3.28	4.27	5.02	5.80	6.52	7.05
Jun-Buckhorn-13	Buckhorn Creek	BuckTrib_3-2	4877	1.71	2.98	3.89	5.08	6.00	6.93	7.81	8.46
Jun-Buckhorn-12-1	Buckhorn Creek	BuckTrib_3-2	3729	2.88	4.97	6.45	8.41	9.88	11.39	12.81	13.89
Jun-Buckhorn-15	Buckhorn Creek	BuckTrib_3-3	1796	1.01	1.70	2.20	2.85	3.34	3.85	4.33	4.68
Jun-Buckhorn-12-2	Buckhorn Creek	BuckTrib_3-3	1199	1.22	2.07	2.68	3.52	4.17	4.83	5.44	5.90
Jun-Buckhorn-19-1	Buckhorn Creek	Buckhorn_4	16908	1.08	1.78	2.33	3.07	3.64	4.22	4.77	5.19
Jun-Buckhorn-18	Buckhorn Creek	Buckhorn_4	16689	1.96	3.26	4.26	5.61	6.66	7.74	8.76	9.51
Jun-Buckhorn-17	Buckhorn Creek	Buckhorn_4	15741	2.95	4.96	6.44	8.48	10.08	11.72	13.27	14.43
Jun-Buckhorn-16	Buckhorn Creek	Buckhorn_4	14398	4.50	7.60	9.87	12.89	15.26	17.75	20.09	21.84
Jun-Buckhorn-10-2	Buckhorn Creek	Buckhorn_4	12211	5.44	9.26	12.08	15.81	18.73	21.75	24.59	26.71
Jun-Buckhorn-11	Buckhorn Creek	BuckTrib_3-1	2904	4.59	7.96	10.35	13.57	16.02	18.50	20.84	22.62
Jun-Buckhorn-10-1	Buckhorn Creek	BuckTrib_3-1	1745	4.94	8.93	11.65	15.35	18.18	21.04	23.73	25.78
Jun-Buckhorn-09	Buckhorn Creek	Buckhorn_3	9888	9.91	18.47	24.43	32.40	38.51	44.70	50.50	54.85
Jun-Buckhorn-06-2	Buckhorn Creek	Buckhorn_3	6971	10.21	19.38	25.87	34.53	41.17	47.92	54.24	58.97

HEC-HMS Junction	ABL HEC-RAS River	Reach	RS	Peak Flow (m³/s)							
				2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Jun-Buckhorn-07	Buckhorn Creek	BuckTrib_2	3397	2.40	4.04	5.20	6.78	8.01	9.29	10.49	11.38
Jun-Buckhorn-06-1	Buckhorn Creek	BuckTrib_2	2652	3.03	5.31	6.94	9.09	10.75	12.44	14.04	15.25
Jun-Buckhorn-02-1	Buckhorn Creek	Buckhorn_2	5244	11.89	23.22	31.56	42.73	51.33	60.14	68.40	74.57
Jun-Buckhorn-04	Buckhorn Creek	BuckTrib_1	2013	1.71	2.92	3.76	4.88	5.75	6.66	7.50	8.14
Jun-Buckhorn-03-1	Buckhorn Creek	BuckTrib_1	1148	1.88	3.22	4.15	5.37	6.33	7.31	8.24	8.94
Jun-Buckhorn-01	Buckhorn Creek	Buckhorn_1	4320	11.67	23.55	32.57	44.89	54.47	64.36	73.71	80.71
Jun-Elsie-21	Elsie Creek	Elsie_4	16128	2.72	4.74	6.18	8.06	9.50	10.95	12.32	13.33
Jun-Elsie-18-2	Elsie Creek	Elsie_4	14863	3.23	5.74	7.55	9.94	11.76	13.61	15.33	16.60
Jun-Elsie-12	Elsie Creek	ElsieTrib_2-3	8095	1.87	3.25	4.23	5.51	6.49	7.48	8.42	9.11
Jun-Elsie-08-2	Elsie Creek	ElsieTrib_2-3	6912	2.44	4.22	5.48	7.13	8.39	9.68	10.88	11.77
Jun-Elsie-10	Elsie Creek	ElsieTrib_2-5	5060	1.88	3.13	4.06	5.32	6.31	7.33	8.28	9.00
Jun-Elsie-09	Elsie Creek	ElsieTrib_2-5	3906	3.26	5.65	7.33	9.57	11.31	13.10	14.80	16.07
Jun-Elsie-08-1	Elsie Creek	ElsieTrib_2-5	1891	3.97	7.08	9.24	12.26	14.55	16.88	19.05	20.67
Jun-Elsie-19-1	Elsie Creek	ElsieTrib_3	1710	1.19	2.13	2.80	3.68	4.35	5.03	5.66	6.13
Jun-Elsie-18-1	Elsie Creek	ElsieTrib_3	1625	2.17	3.87	5.07	6.64	7.86	9.09	10.24	11.10
Jun-Elsie-06-2	Elsie Creek	ElsieTrib_2-2	5188	6.45	11.80	15.56	20.66	24.58	28.55	32.25	35.00
Jun-Elsie-17	Elsie Creek	Elsie_3	13787	6.26	11.65	15.47	20.46	24.30	28.22	31.87	34.59
Jun-Elsie-16	Elsie Creek	Elsie_3	9809	6.22	11.86	15.94	21.31	25.45	29.69	33.66	36.61
Jun-Elsie-15	Elsie Creek	Elsie_3	7560	6.21	11.92	16.08	21.58	25.85	30.23	34.33	37.40
Jun-Elsie-14	Elsie Creek	Elsie_3	6522	6.15	11.86	16.09	21.79	26.23	30.82	35.16	38.41
Jun-Elsie-04-2	Elsie Creek	Elsie_3	4355	6.09	11.77	16.01	21.72	26.21	30.86	35.25	38.55
Jun-Elsie-06-1	Elsie Creek	ElsieTrib_2-4	521	1.88	3.23	4.18	5.44	6.43	7.46	8.43	9.16
Jun-Elsie-05	Elsie Creek	ElsieTrib_2-1	3508	7.97	15.11	20.25	27.13	32.48	37.90	42.95	46.70
Jun-Elsie-04-1	Elsie Creek	ElsieTrib_2-1	2029	8.08	15.20	20.45	27.51	33.03	38.65	43.89	47.78
Jun-Elsie-02-2	Elsie Creek	Elsie_2	2409	10.50	21.04	29.55	40.85	49.85	59.27	68.24	74.99
Jun-Elsie-02-1	Elsie Creek	ElsieTrib_1	337	1.32	2.20	2.91	3.86	4.60	5.36	6.08	6.61
Jun-Elsie-01	Elsie Creek	Elsie_1	2344	10.20	20.63	28.98	40.31	49.34	58.83	67.88	74.69

HEC-HMS Junction	ABL HEC-RAS River	Reach	RS	Peak Flow (m³/s)							
				2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Jun-L_Forks-05-1	Little Forks Cr	Little Forks_1	9610	3.59	6.64	8.63	10.79	12.04	13.23	14.54	15.81
Jun-L_Forks-04	Little Forks Cr	Little Forks_1	8051	6.45	11.32	14.50	18.96	22.06	25.03	27.74	29.76
Jun-L_Forks-03	Little Forks Cr	Little Forks_1	6302	6.69	11.54	14.83	19.41	22.78	26.09	29.13	31.39
Jun-L_Forks-02	Little Forks Cr	Little Forks_1	4585	6.59	11.58	14.97	19.65	23.21	26.76	30.05	32.50
Jun-L_Forks-01	Little Forks Cr	Little Forks_1	2516	5.00	9.20	12.08	16.09	19.14	22.21	25.11	27.29
Jun-Mill-14	Mill Creek	Mill_5	18634	1.51	2.60	3.35	4.34	5.09	5.85	6.58	7.12
Jun-Mill-12	Mill Creek	Mill_5	18406	2.02	3.41	4.37	5.62	6.56	7.54	8.46	9.16
Jun-Mill-11-1	Mill Creek	Mill_5	18080	2.36	3.99	5.12	6.58	7.69	8.84	9.90	10.69
Jun-Mill-10-1	Mill Creek	Mill_5	17251	4.20	7.13	9.21	11.92	14.00	16.13	18.08	19.53
Jun-Mill-18	Mill Creek	MillTrib_4	3796	1.11	2.01	2.65	3.49	4.12	4.77	5.38	5.83
Jun-Mill-17	Mill Creek	MillTrib_4	3459	2.12	3.77	4.93	6.44	7.59	8.75	9.84	10.65
Jun-Mill-16	Mill Creek	MillTrib_4	2950	2.57	4.57	6.00	7.89	9.33	10.79	12.14	13.16
Jun-Mill-10-2	Mill Creek	MillTrib_4	2045	2.77	5.01	6.71	8.87	10.52	12.20	13.76	14.93
Jun-Mill-05-2	Mill Creek	Mill_4	15310	7.18	12.70	16.81	22.08	26.09	30.17	33.98	36.80
Jun-Mill-05-1	Mill Creek	MillTrib_3	1327	1.26	2.28	3.02	4.03	4.79	5.58	6.31	6.85
Jun-Mill-04-1	Mill Creek	Mill_3	13890	8.27	15.33	20.58	27.54	32.85	38.25	43.30	47.06
Jun-Mill-08	Mill Creek	MillTrib_2	2827	1.48	2.50	3.22	4.20	4.98	5.78	6.54	7.10
Jun-Mill-07	Mill Creek	MillTrib_2	2516	2.31	4.02	5.22	6.81	8.05	9.32	10.52	11.41
Jun-Mill-04-2	Mill Creek	MillTrib_2	1585	3.21	5.67	7.39	9.65	11.37	13.14	14.80	16.04
Jun-Moores-09	Mill Creek	Moores_3	668	1.07	1.81	2.34	3.02	3.55	4.09	4.60	4.98
Jun-Moores-05-2	Mill Creek	Moores_3	597	1.20	2.09	2.72	3.54	4.16	4.79	5.37	5.81
Jun-Moores-07	Mill Creek	Moores_2	9885	1.65	2.88	3.75	4.87	5.73	6.60	7.43	8.06
Jun-Moores-06-1	Mill Creek	Moores_2	9366	2.06	3.72	4.91	6.48	7.68	8.90	10.04	10.88
Jun-Moores-05-1	Mill Creek	Moores_2	8051	2.90	5.27	6.94	9.12	10.80	12.49	14.07	15.24
Jun-Mill-03	Mill Creek	Mill_2	9557	9.55	18.36	25.25	34.70	42.05	49.61	56.68	61.93
Jun-Mill-02-1	Mill Creek	Mill_2	7522	9.34	18.03	25.03	34.54	41.99	49.67	56.89	62.26
Jun-Moores-04	Mill Creek	Moores_1	7593	5.47	10.07	13.29	17.49	20.71	23.99	27.03	29.29

HEC-HMS Junction	ABL HEC-RAS River	Reach	RS	Peak Flow (m³/s)							
				2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Jun-Moores-03	Mill Creek	Moores_1	5228	6.03	11.18	14.84	19.62	23.29	27.02	30.50	33.16
Jun-Moores-02-1	Mill Creek	Moores_1	4616	6.30	11.81	15.74	20.89	24.84	28.86	32.61	35.46
Jun-Moores-01	Mill Creek	Moores_1	1633	7.53	14.47	19.52	26.19	31.32	36.57	41.49	45.24
Jun-Mill-01	Mill Creek	Mill_1	5577	14.43	28.25	39.50	55.15	68.14	81.57	93.98	103.31
Jun-Trib_1-11-1	Trib_1	1_1-2	5492	2.05	3.40	4.38	5.80	6.92	8.05	9.12	9.91
Jun-Trib_1-10	Trib_1	1_1-2	4987	3.57	5.97	7.65	9.95	11.82	13.73	15.54	16.89
Jun-Trib_1-09-1	Trib_1	1_1-2	4614	3.77	6.34	8.17	10.62	12.62	14.64	16.56	17.99
Jun-Trib_1-09-2	Trib_1	1_2	287	1.30	2.18	2.81	3.72	4.43	5.16	5.84	6.36
Jun-Trib_1-07	Trib_1	1_1-1	3795	5.58	9.37	12.04	15.67	18.58	21.59	24.41	26.54
Jun-Trib_1-05	Trib_1	1_1-1	3657	6.00	10.09	13.00	16.90	20.01	23.22	26.24	28.50
Jun-Trib_1-02	Trib_1	1_1-1	3300	7.89	13.20	16.88	21.96	25.95	30.11	34.01	36.95
Jun-Trib_1-01	Trib_1	1_1-1	2556	8.33	14.62	18.78	24.67	29.17	33.78	38.11	41.36
Jun-Trib_2-04	Trib_2	2_1-2	5986	3.34	4.97	6.10	7.58	8.71	9.86	10.93	11.72
Jun-Trib_2-03-2	Trib_2	2_1-2	5328	5.04	7.89	9.92	12.60	14.67	16.78	18.76	20.24
Jun-Trib_2-03-1	Trib_2	2_2	990	1.41	2.35	3.03	3.98	4.71	5.47	6.19	6.73
Jun-Trib_2-02	Trib_2	2_1-1	3778	6.67	10.68	13.55	17.35	20.28	23.29	26.12	28.23
Jun-Trib_2-01	Trib_2	2_1-1	2082	6.98	11.36	14.47	18.54	21.67	24.88	27.89	30.09
Jun-Trib_3-03-1	Trib_3	3_1	3692	1.20	2.01	2.59	3.42	4.07	4.75	5.38	5.86
Jun-Trib_3-02	Trib_3	3_1	3191	2.73	4.59	5.91	7.78	9.26	10.79	12.23	13.31
Jun-Trib_3-01	Trib_3	3_1	2119	3.08	5.19	6.71	8.81	10.46	12.17	13.78	15.00
Jun-Trib_4-02-1	Trib_4	4_1	3005	2.06	3.75	4.96	6.58	7.83	9.10	10.29	11.17
Jun-Trib_4-01	Trib_4	4_1	2171	3.07	5.66	7.58	10.11	12.07	14.08	15.96	17.35
Jun-Trib_5-04-1	Trib_5	5_1-2	3146	0.59	1.12	1.49	1.99	2.36	2.74	3.10	3.36
Jun-Trib_5-02-2	Trib_5	5_1-2	2876	1.32	2.45	3.26	4.35	5.20	6.08	6.89	7.50
Jun-Trib_5-03	Trib_5	5_2	1467	0.16	0.29	0.37	0.49	0.58	0.66	0.75	0.82
Jun-Trib_5-02-1	Trib_5	5_2	1237	0.22	0.38	0.50	0.66	0.77	0.89	1.00	1.09
Jun-Trib_5-01	Trib_5	5_1-1	1543	1.65	3.00	4.02	5.43	6.58	7.71	8.76	9.53

HEC-HMS Junction	ABL HEC-RAS River	Reach	RS	Peak Flow (m³/s)							
				2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Jun-Trib_6-04-1	Trib_6	6_2-2	1402	0.22	0.42	0.55	0.74	0.88	1.03	1.16	1.26
Jun-Trib_6-03-1	Trib_6	6_2-2	1032	1.06	1.93	2.55	3.36	3.97	4.59	5.16	5.59
	Trib_6	6_2-3	551	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Jun-Trib_6-08	Trib_6	6_1-2	6414	0.32	0.58	0.76	1.00	1.17	1.35	1.52	1.64
Jun-Trib_6-07	Trib_6	6_1-2	5664	0.40	0.74	0.98	1.28	1.51	1.74	1.96	2.12
Jun-Trib_6-06	Trib_6	6_1-2	5133	0.87	1.58	2.07	2.71	3.19	3.68	4.14	4.48
Jun-Trib_6-03-2	Trib_6	6_1-2	4427	1.50	2.69	3.51	4.58	5.38	6.20	6.97	7.54
Jun-Trib_6-02	Trib_6	6_1-1	3814	2.91	5.34	7.04	9.38	11.16	12.96	14.62	15.85
Jun-Trib_6-01	Trib_6	6_1-1	2927	3.40	6.12	8.22	10.95	13.04	15.15	17.21	18.69
Jun-Trib_7-02-2	Trib_7	7_2	147	1.64	2.86	3.73	4.87	5.74	6.63	7.46	8.08
Jun-Trib_7-05	Trib_7	7_1-2	5287	2.99	5.29	6.93	9.09	10.74	12.42	13.99	15.15
Jun-Trib_7-04	Trib_7	7_1-2	5084	3.10	5.49	7.20	9.47	11.24	13.09	14.79	16.06
Jun-Trib_7-03	Trib_7	7_1-2	4464	3.35	6.08	7.99	10.59	12.58	14.67	16.57	17.98
Jun-Trib_7-02-1	Trib_7	7_1-2	3923	3.88	7.03	9.21	12.19	14.48	16.89	19.09	20.73
Jun-Trib_7-01	Trib_7	7_1-1	1651	5.54	9.97	13.00	17.17	20.41	23.76	26.93	29.24
Jun-Trib_8-04	Trib_8	8_1	2744	1.38	2.69	3.61	4.78	5.63	6.49	7.30	7.89
Jun-Trib_8-03	Trib_8	8_1	2661	1.76	3.21	4.33	5.82	6.92	8.02	9.04	9.79
Jun-Trib_8-02	Trib_8	8_1	2110	2.47	4.43	5.80	7.69	9.20	10.75	12.25	13.34
Jun-Trib_8-01	Trib_8	8_1	1259	3.27	5.96	7.74	10.19	12.08	14.00	15.84	17.28
Jun-Trib_9-07	Trib_9	9_1-3	4583	0.14	0.24	0.32	0.41	0.49	0.56	0.63	0.68
Jun-Trib_9-06	Trib_9	9_1-3	4369	0.18	0.31	0.41	0.55	0.65	0.75	0.85	0.92
Jun-Trib_9-04	Trib_9	9_1-3	3793	1.01	1.84	2.43	3.23	3.84	4.46	5.03	5.45
Jun-Trib_9-03-1	Trib_9	9_1-2	3443	1.06	2.08	2.84	3.90	4.69	5.48	6.21	6.75
Jun-Trib_9-03-2	Trib_9	9_2	1043	1.51	2.61	3.38	4.39	5.17	5.95	6.69	7.24
Jun-Trib_9-02	Trib_9	9_1-1	1748	3.18	5.91	7.89	10.52	12.55	14.59	16.49	17.89
Jun-Trib_9-01	Trib_9	9_1-1	1322	3.29	6.12	8.22	11.06	13.26	15.50	17.60	19.14
Jun-W_Wolf-12	West Wolf Creek	WestWolf_4	13673	1.50	2.59	3.36	4.37	5.18	6.01	6.79	7.37

HEC-HMS Junction	ABL HEC-RAS River	Reach	RS	Peak Flow (m³/s)							
				2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Jun-W_Wolf-11-2	West Wolf Creek	WestWolf_4	13018	1.92	3.40	4.44	5.81	6.87	7.96	8.98	9.75
Jun-W_Wolf-11-1	West Wolf Creek	WestWolfTrib_3	996	1.00	1.69	2.18	2.83	3.33	3.85	4.33	4.69
Jun-W_Wolf-10	West Wolf Creek	WestWolf_3	11272	3.68	6.56	8.62	11.30	13.35	15.44	17.40	18.87
Jun-W_Wolf-07-2	West Wolf Creek	WestWolf_3	10513	3.79	7.10	9.52	12.64	15.01	17.42	19.67	21.34
Jun-W_Wolf-08	West Wolf Creek	WestWolfTrib_2	2299	2.11	3.55	4.55	5.92	6.97	8.06	9.08	9.85
Jun-W_Wolf-07-1	West Wolf Creek	WestWolfTrib_2	1343	2.58	4.31	5.56	7.27	8.57	9.91	11.17	12.12
Jun-W_Wolf-06	West Wolf Creek	WestWolf_2	9818	6.00	11.34	15.43	20.89	25.02	29.21	33.13	36.05
Jun-W_Wolf-03-2	West Wolf Creek	WestWolf_2	8007	6.07	11.31	15.46	21.07	25.40	29.82	33.95	37.03
Jun-W_Wolf-04	West Wolf Creek	WestWolfTrib_1	2027	1.81	3.18	4.15	5.43	6.40	7.39	8.32	9.01
Jun-W_Wolf-03-1	West Wolf Creek	WestWolfTrib_1	1032	2.08	3.68	4.80	6.28	7.41	8.56	9.64	10.44
Jun-W_Wolf-02	West Wolf Creek	WestWolf_1	6133	7.11	13.24	18.20	25.21	30.77	36.48	41.85	45.86
Jun-W_Wolf-01	West Wolf Creek	WestWolf_1	3699	7.03	13.15	18.08	25.09	30.71	36.54	42.04	46.17
Jun-Wilson-04	Wilson Creek	Wilson_1	5852	1.65	3.17	4.26	5.70	6.79	7.90	8.94	9.71
Jun-Wilson-03	Wilson Creek	Wilson_1	5137	2.32	4.53	6.04	8.10	9.67	11.27	12.76	13.87
Jun-Wilson-02	Wilson Creek	Wilson_1	3979	2.90	5.76	7.79	10.45	12.54	14.66	16.65	18.12
Jun-Wilson-01	Wilson Creek	Wilson_1	2219	3.06	5.96	8.14	10.92	13.14	15.42	17.55	19.14
Jun-Wolf-07-2	Wolf Creek	WolfTrib_2	1198	2.00	3.32	4.31	5.67	6.73	7.82	8.85	9.62
Jun-Wolf-08	Wolf Creek	Wolf_3	13988	1.70	2.90	3.74	4.92	5.83	6.77	7.66	8.33
Jun-Wolf-07-1	Wolf Creek	Wolf_3	13288	2.25	3.98	5.16	6.73	7.96	9.23	10.43	11.33
Jun-Wolf-06	Wolf Creek	Wolf_2	12238	5.74	9.92	12.87	16.75	19.73	22.79	25.68	27.84
Jun-Wolf-05	Wolf Creek	Wolf_2	11107	7.21	12.52	16.29	21.25	25.03	28.89	32.51	35.21
Jun-Wolf-04	Wolf Creek	Wolf_2	9502	7.32	12.95	17.05	22.56	26.78	31.08	35.10	38.10
Jun-Wolf-03-1	Wolf Creek	Wolf_2	7373	7.47	13.49	18.04	24.26	29.06	33.95	38.53	41.93
Jun-L_Wolf-07	Wolf Creek	LittleWolfTrib_1	1002	1.09	1.84	2.37	3.12	3.71	4.32	4.90	5.33
Jun-L_Wolf-05-1	Wolf Creek	LittleWolf_2	9740	1.40	2.51	3.28	4.30	5.07	5.86	6.60	7.15
Jun-L_Wolf-04	Wolf Creek	LittleWolf_1	8699	3.66	6.87	9.12	12.05	14.28	16.55	18.68	20.26
Jun-L_Wolf-03	Wolf Creek	LittleWolf_1	6674	5.55	10.57	13.18	17.83	21.41	24.95	28.24	30.68

HEC-HMS Junction	ABL HEC-RAS River	Reach	RS	Peak Flow (m ³ /s)							
				2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Jun-L_Wolf-02	Wolf Creek	LittleWolf_1	4801	6.22	11.95	15.43	20.19	24.50	28.77	32.73	35.66
Jun-L_Wolf-01	Wolf Creek	LittleWolf_1	2369	6.47	12.25	16.11	21.00	25.37	29.87	34.09	37.24
Jun-Wolf-02	Wolf Creek	Wolf_1	4683	13.41	25.09	33.62	44.94	54.08	63.54	72.47	79.14
Jun-Wolf-01	Wolf Creek	Wolf_1	3130	13.44	25.20	33.88	45.45	54.81	64.14	73.28	80.03

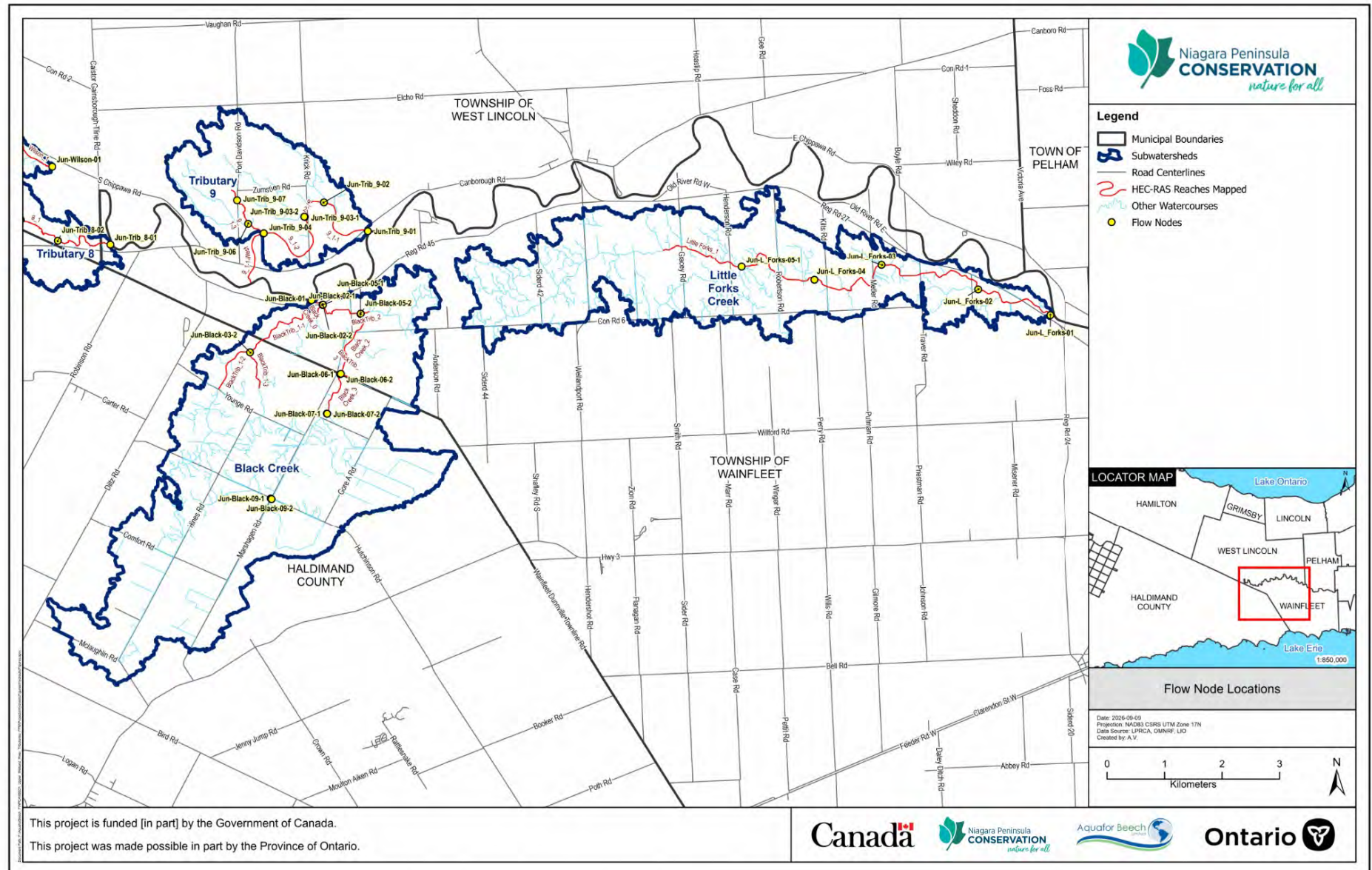


Figure 3-7. HEC-RAS Flow Node Locations – Eastern Watersheds

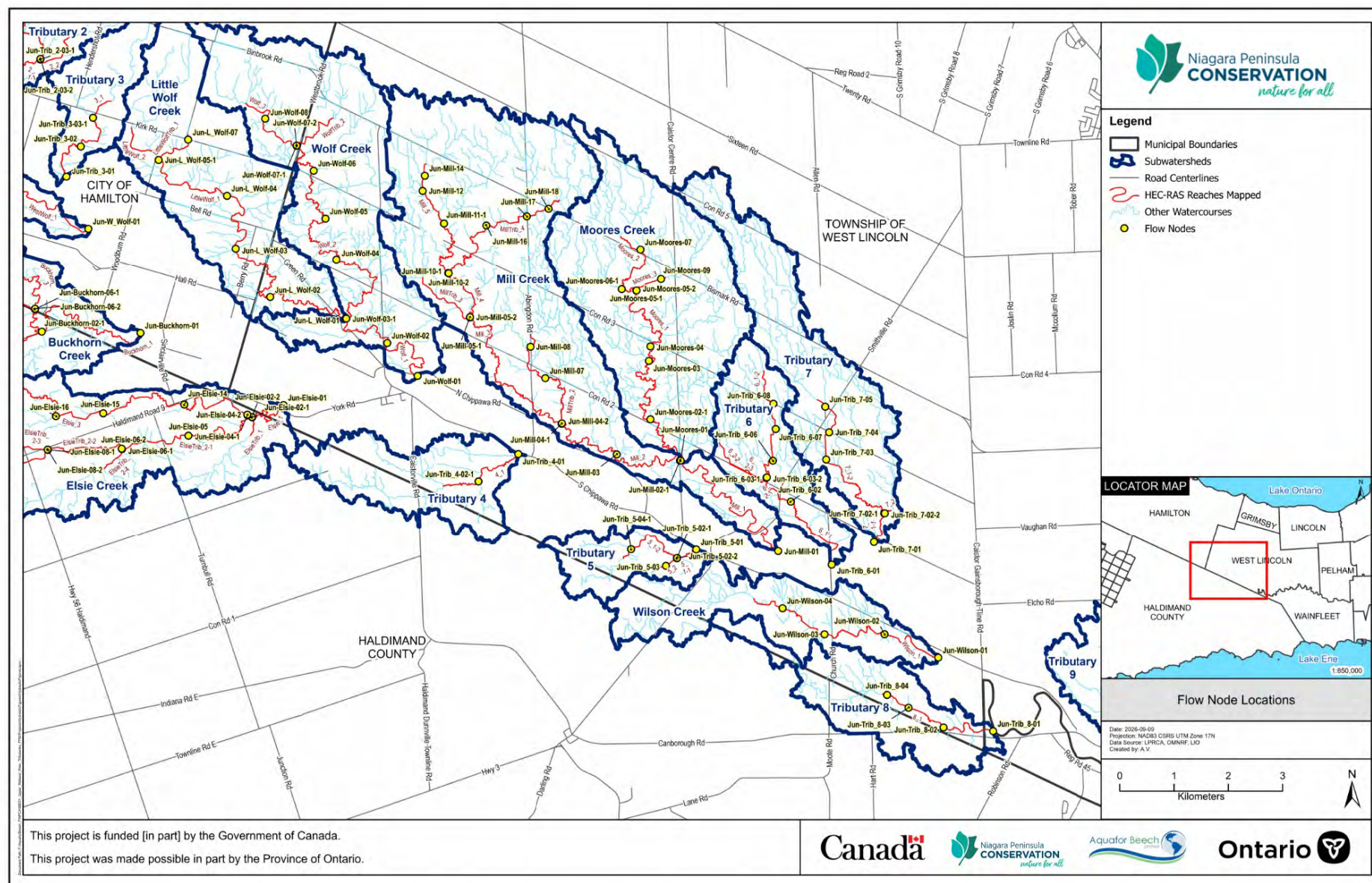


Figure 3-8. HEC-RAS Flow Node Locations – Central Watersheds

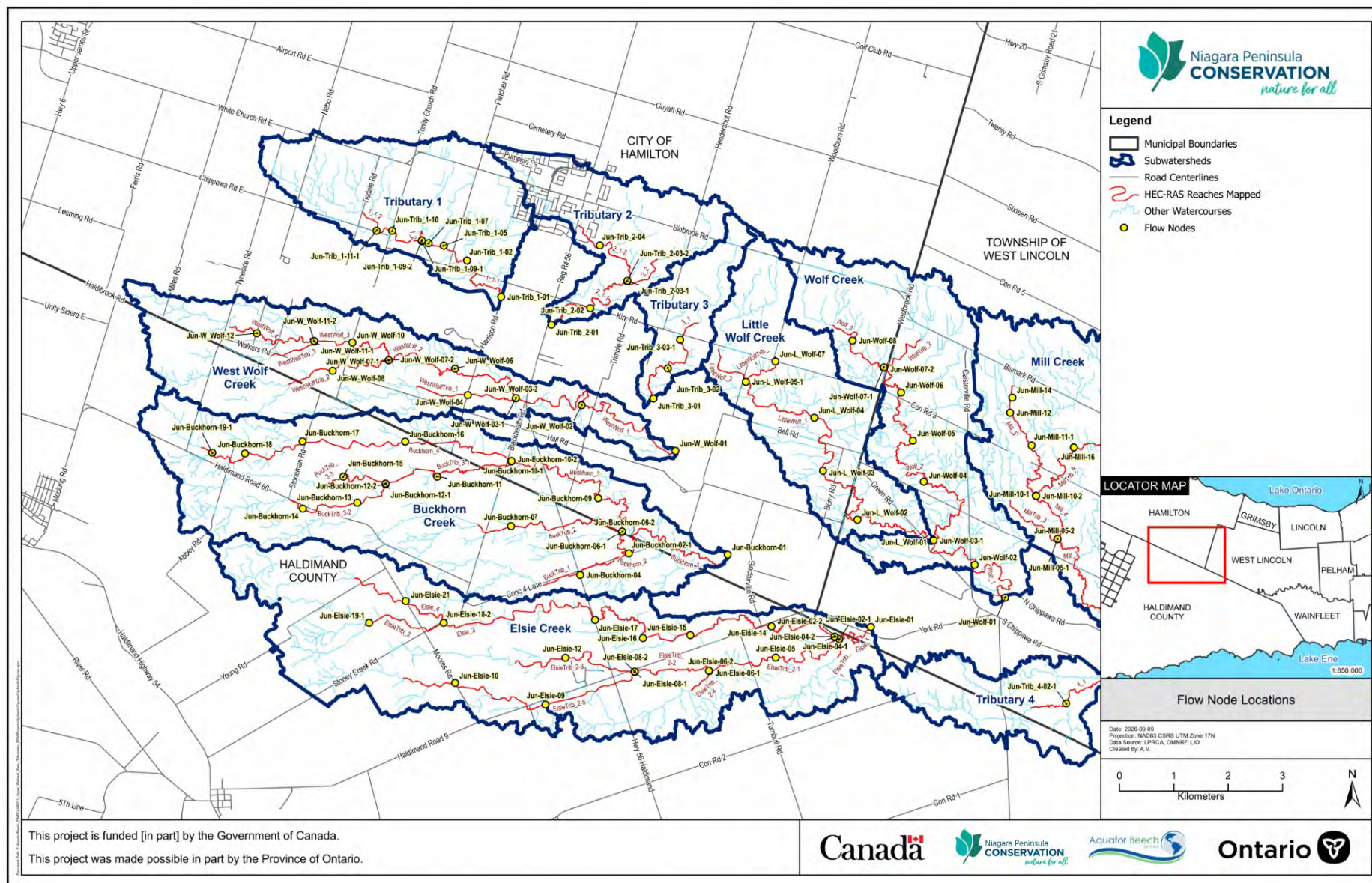


Figure 3-9. HEC-RAS Flow Node Locations – Western Watersheds

3.10 Boundary Conditions

Per the River & Stream Systems: Flooding Hazard Limit MNR guidelines, for rivers flowing into larger receiving watercourses governed by separate and independent flood events, the flood standard should be the higher of:

- A. The mean annual flood level in the smaller river/tributary and the flood hazard limit in the connecting water body; and,
- B. The flood hazard event (100-year) in the river outletting to the mean monthly level in the connecting river.

Aquafor has used this methodology to determine the appropriate downstream boundary condition and flood hazard limit at the various tributary outlets into the Welland River for the 100-year (Regulatory) event. For this study, the 2-year event was used to represent the mean annual flood. Two scenarios were therefore developed and input into the HEC-RAS hydraulic model:

1. **Scenario A (UW FPM – TW A - 2-yrQ with 100yr TWC):** The 2-year flow event in Upper Welland Tributaries outletting to the associated 100-year Welland River flood elevation (CGVD2013);
2. **Scenario B (UW FPM – TW A – 100yrQ with 2yr TWC):** The 100-year Regulatory flow event in Upper Welland Tributaries outletting to a the estimated 2-year Welland River flood elevation (CGVD213).

3.10.1 Tailwater Scenario A: 2-yr Q with 100-yr TWC

To model Scenario A, the 2-year peak flows from the HEC-HMS outputs were copied to the 100-year flow profile in the steady state flow input file for all reaches.

The Welland River Floodplain Mapping Update, 2018, completed by WSP for the NPCA provided the 100-year water surface elevations for the discharge points into the Welland River for all reaches. The report provided the 100-year flood elevation along the river, in what was assumed to be the CGVD 78:28 vertical datum. These elevations were therefore converted to the 2013 datum and applied Scenario A. The water surface elevations applied in Scenario A as the 100-year receiving river boundary conditions for each outlet location are summarized in **Table 3-4**.

All upstream boundary conditions were modelled at normal flow depth at the calculated channel gradient.

Table 3-4. 100-Year Water Surface Elevation in the Welland River at Tributary Outlets (Welland River Floodplain Mapping Update, 2018)

ABL HEC-RAS Reach	100-Year Flood Elevation (CGVD 28:78) (m)	100-Year Flood Elevation (CGVD 2013) (m)	WSP Welland River Flood Figure	WSP Welland River Hydraulic Model XS
Little Forks	174.932	174.526	A31	81840.3
Trib_9 - East Outlet	175.341	174.935	A22	60960.7
Black Creek	175.374	174.969	A21	58785
Trib_9 - West Outlet	175.393	174.988	A20	57290.5
Trib_8	175.551	175.145	A19	53374.1
Wilson_Creek	175.665	175.257	A17	50463.5
Trib_7	175.923	175.514	A15	45281.2
Trib_6	176.026	175.618	A14	43105.1
Mill_Creek	176.363	175.954	A14	41289.6
Trib_5	177.633	177.223	A13	38539

Trib_4	180.659	180.248	A11	32687
Wolf Creek	181.882	181.468	A9	29384.9
Elsie Creek	183.072	182.658	A8	24689.6
Buckhorn Creek	183.94	183.525	A6	18990.9
West Wolf Creek	186.115	185.699	A4	11395.9
Trib_3	186.869	186.453	A3	9588.8
Trib_2	189.367	188.953	A1	3028
Trib_1	190.237	189.822	A1	2588.4

Moore's and Little Wolf Creeks do not outlet into the Welland River but into Mill and Wolf Creeks, respectively. These tributaries have similar sized subwatersheds, and have been modelled assuming coincident flood event timing. They are modelled with a Junction tailwater condition in HEC-RAS.

3.10.2 Tailwater Scenario B: 100-yr Q with 2-yr TWC

To model Scenario B, the 100-year peak flows from the HEC-HMS outputs were maintained in the 100-year flow profile in the steady state flow input file.

The WSP Welland River Floodplain Mapping Update only provided the 100-year water surface elevations in the report. The 2-year river elevations have been estimated using structure data provided in the WSP report and stream gauge data provided by Water Services Canada and the NPCA. Three gauges are maintained on the Welland River within the study limits. A depth-frequency analysis was completed on the data at each gauge to estimate the 2-year flood depth in the Welland River. Details and results of the depth frequency analysis are provided in **Table 3-5**.

Table 3-5. Welland River Depth Gauge Data (Upstream to Downstream)

Depth Gauge	Welland River Hydraulic Model XS (WSP)	Data Source	Years of Water Level Data	Calculated 2-Year WSE (m) (CGVD2013)
Welland River at Southbrook	4850.3	NPCA	13	170.67
02HA007 – Welland River Below Caistor Corners	43105.1	WSC	23	174.75
Welland River at Wellandport Bridge	67147	NPCA	17	188.26

The three data points and their respective 2-year water surface profiles were then interpolated to the approximate outlet locations of the Upper Welland River tributaries in this study to calculate 2-year tailwater elevations for use in Scenario B. There is a small hydraulic structure, the Port Davidson Weir, on the Welland River at Port Davidson. A weir height of 0.5 m has been assumed at the weir, with channel gradients assumed to be equal upstream and downstream of the weir. Channel bottoms in the Welland River were derived from the nearest structure data sheet provided in the WSP report and converted to the CGVD2013 datum.

It was observed that downstream of Caistor Corners, the Welland River channel gradient is much flatter than the upstream portions, with the Caistor gauge located at an inflection point. A schematic of the Welland River channel bottom, as derived from WSP structure data, the 100-year WSE profile and estimated 2-year WSE profile is shown in **Figure 3-10**. When comparing the flood event depths in the river, this inflection results in event depths that are much closer together in the upper reaches (upstream of Caistor) versus downstream in the flatter regions.

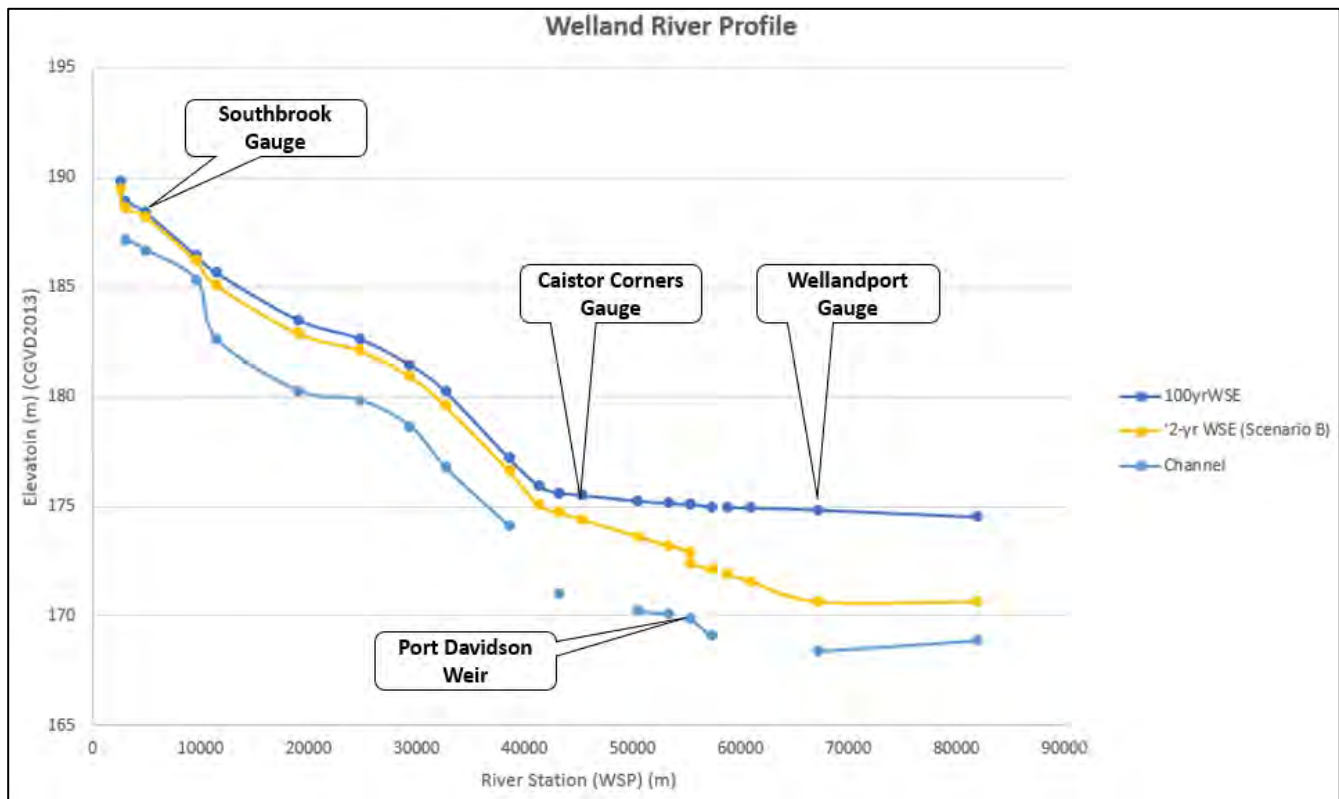


Figure 3-10. Estimated Welland River Channel Bottom, 2-Year and 100-Year Profiles

Upon providing the Southbrook gauge data, the NPCA noted that Welland River levels at the location are heavily influenced by the upstream Binbrook Dam. Interpolation results yielded poor data for the Welland River around the Southbrook Gauge (Trib_3, Trib_2, Trib_1), with water surface elevations calculated as higher than the 100-year known values. The 2-year water surface elevations upstream of Caistor Corners were instead calculated as having a depth of 80% of the 100-year depth. This ratio was calculated based on the Caistor frequency analysis data, and fits well with in the channel bottom and 100-year known profiles in the upstream reaches. Results of the interpolation and ultimate 2-year tailwater elevations used in modelling Scenario B are shown in **Table 3-6**.

Aquafor acknowledges the high degree of uncertainty in the calculation of the 2-year flood depths in the Welland River. However, the use of a lower, yet realistic tailwater condition for the sensitivity analysis at the downstream boundaries is crucial to the study. Details of the analysis are provided in **Appendix E**.

Table 3-6. Welland River Depth Gauge Data – 2-Year Event

Location	100-Yr WSE (m) (CGVD 2013)	Welland River Hydraulic Model XS	Channel Bottom (m) (CGVD2013)	WSP Reference Flood Figure	2-yr WSE (Analysis) (m)	2-yr WSE (Interpolated) (m)	2-yr WSE (Estimated with 0.8*D100) (m)	Used in Scenario B (m)
Little Forks	174.526	81840.3	168.89	A31		170.67		170.67
Wellandport Gauge	174.842	67147	168.405		170.665	170.67		
Trib_9 - East Outlet	174.935	60960.7		A22		171.59		171.59
Black Creek	174.969	58785		A21		171.91		171.91
Trib_9 - West Outlet	174.988	57290.5	169.095	A20		172.13		172.13

Port Davidson Weir D/S	175.107	55389	169.875	A19	172.42	172.42		
Port Davidson Weir U/S	175.107	55372.3		A19	172.918	172.92		
Trib_8	175.145	53374.1	170.115	A19		173.22		0.0003
Wilson_Creek	175.257	50463.5	170.235	A17		173.65		173.65
Trib_7	175.514	45281.2		A15		174.42		174.42
Trib_6	175.618	43105.1		A14		174.75		174.75
Caistor Corners Gauge	175.62	43105.1	170.982	A14	174.75	174.75		
Mill_Creek	175.954	41289.6		A14		175.39	175.08	175.08
Trib_5	177.223	38539	174.105	A13		176.36	176.64	176.64
Trib_4	180.248	32687	176.775	A11		178.43	179.59	179.59
Wolf Creek	181.468	29384.9	178.665	A9		179.60	180.94	180.94
Elsie Creek	182.658	24689.6	179.865	A8		181.25	182.13	182.13
Buckhorn Creek	183.525	18990.9	180.285	A6		183.27	182.92	182.92
West Wolf Creek	185.699	11395.9	182.655	A4		185.95	185.13	185.13
Trib_3	186.453	9588.8	185.325	A3		186.59	186.24	186.24
Southbrook Gauge	188.461	4850.3	186.7	A2	188.26	188.26		
Trib_2	188.953	3028	187.185	A1		188.62	188.62	188.62
Trib_1	189.822	2588.4		A1		189.49	189.49	189.49

3.10.3 Tailwater Sensitivity Comparison

Both tailwater scenarios were run in the HEC-RAS model to determine which tailwater scenario produced the higher water surface elevations and at which point, if any, the scenarios switched. The comparison showed that Scenario A (2yr Q with 100yr TWC) governed in every outlet to the Welland River. The exception to this is Trib_1, which terminates upstream of the confluence with the Welland River. For each of the 17 outlets to the Welland River, the transition point where the Scenario B (100yr Q with 2yr TWC) profile exceeded the Scenario A profile was recorded, including the distance from the outlet. Two additional tributaries on Black Creek (BlackTrib_1, BlackTrib_2) were included in the analysis, as the switch point extended upstream into those reaches. Results of the scenario comparison are provided in **Table 3-7**.

Comparisons of the two tailwater scenarios for the tributaries with the longest distance of Scenario A governance: Little Forks Drain, Black Creek Drain, and Trib_9, are shown in **Figure 3-11**, **Figure 3-12**, and **Figure 3-13**, respectively.

Table 3-7. Tailwater Sensitivity Analysis Results

Tributary	Governing TW Scenario at Outlet	HEC-RAS Station where Scenario B Governs	Distance to Switch (m)
Little Forks	A	3801	2,801
Trib_9 - East Outlet	A	3871	3,843
Black Creek	A	2211	1,211
BlackTrib_1	A	1260	1,201
BlackTrib_2	A	126	96
Trib_9 - West Outlet	A	3871	3,843

Tributary	Governing TW Scenario at Outlet	HEC-RAS Station where Scenario B Governs	Distance to Switch (m)
Trib_8	A	1342	1,280
Wilson_Creek	A	2422	1,422
Trib_7	A	1295	316
Trib_6	A	1543	543
Mill_Creek	A	1272	272
Trib_5	A	1009	11
Trib_4	A	1027	27
Wolf Creek	A	1016	31
Elsie Creek	A	1112	112
Buckhorn Creek	A	1593	593
West Wolf Creek	A	1084	84
Trib_3	A	1189	189
Trib_2	A	1070	70
Trib_1	Road Elev	n/a	n/a

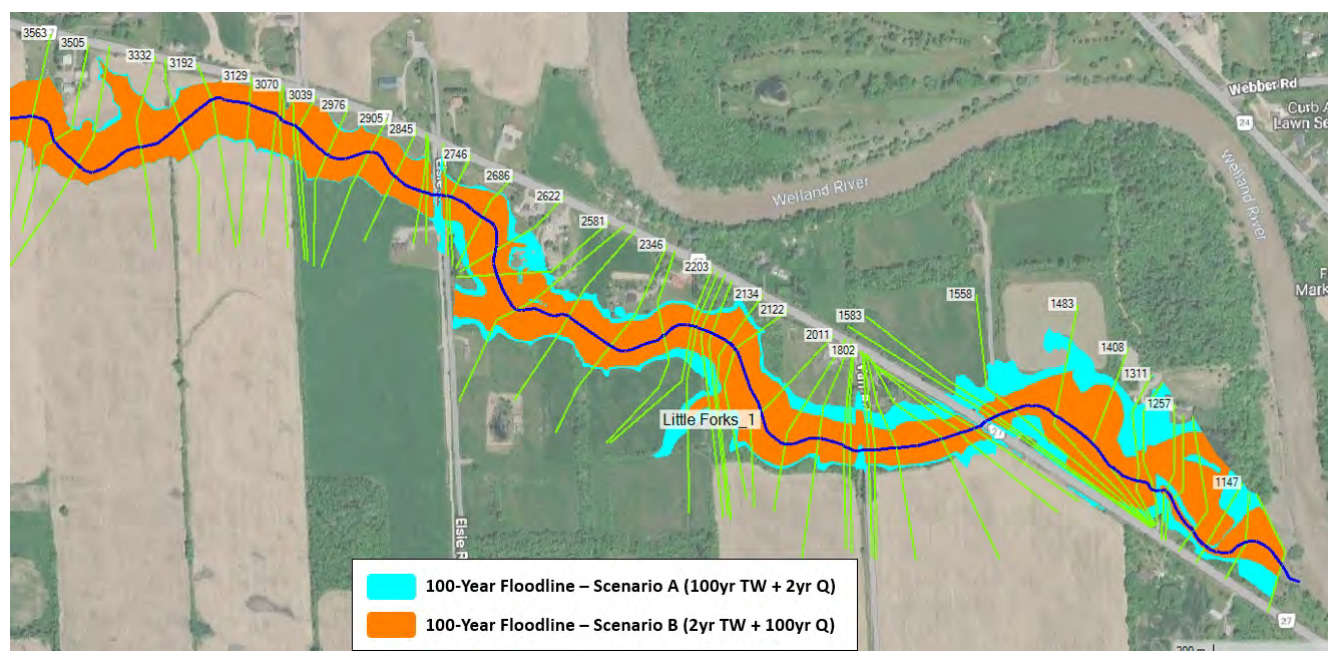


Figure 3-11. Tailwater Scenario Comparison for Little Forks Drain

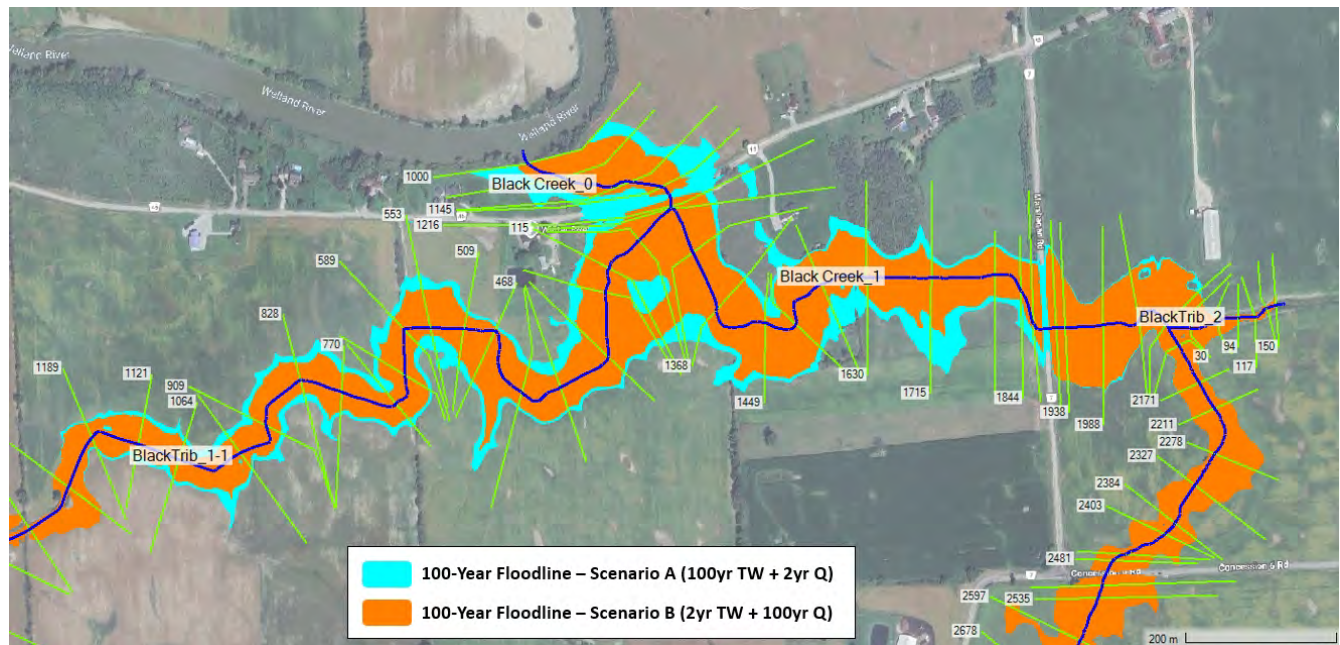


Figure 3-12. Tailwater Scenario Comparison for Black Creek Drain

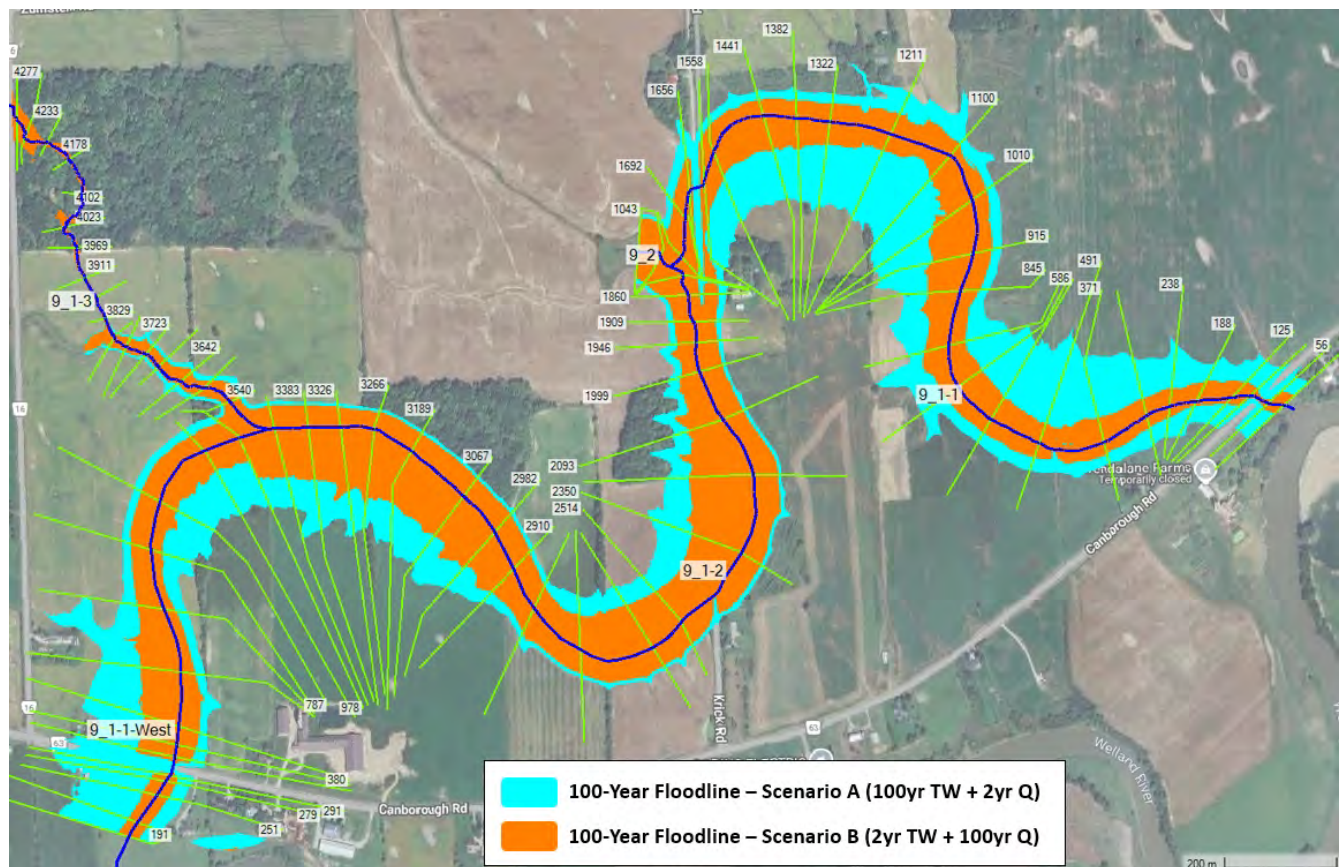


Figure 3-13. Tailwater Scenario Comparison for Black Creek Drain

Generally the eastern tributaries were more sensitive to the high tailwater condition, with Scenario A governing farther upstream. Black Creek Drain, Little Forks Drain, Tributary 8, Tributary 9, and Wilson Creek were all influenced by the 100-year tailwater elevation for more than 1 km upstream. The western reaches, where the

2-year and 100-year tailwater elevations in the Welland River were closer together, showed much less tailwater sensitivity, with the 100-year flow profile governing a short distance upstream of the outlet. Tributaries 2, 4, 5, Wolf Creek and West Wolf Creek all had zones of 100-year tailwater influence of less than 100 m. Detailed results for each tributary are provided in **Appendix C**.

3.10.4 Tailwater in Minor Flood Events

In discussion with NPCA staff, it was determined that the 100-year tailwater condition was overly conservative and unrealistic to model with the 2 through 50-year flood events in the reaches where it holds greater influence in the mapped tributaries. Given the limited data available from the Welland River gauges, a 20-year tailwater profile for the river downstream of the Caistor Corners gauge was developed and applied as the Known Water Surface tailwater condition in the more frequent flood events. The 20-year tailwater profile between Little Forks Drain and Caistor Corners was developed using the same methodology as the 2-year tailwater profile described above. Data from the Southbrook gauge was not applied given the poor quality of data. Instead, the 100-year tailwater elevation was maintained in the model upstream (west) of the Caistor gauge. This is considered acceptable, as the reaches upstream of Caistor Corners are less sensitive to tailwater changes. A summary of the 20-year tailwater elevations used in the HEC-RAS model for the 2, 5, 10, 25 and 50-year flood events is provided in **Table 3-8**.

Table 3-8. Welland River Depth Gauge Data – 20-year Event

Location	100-Yr WSE (m) (CGVD 2013)	Welland River Hydraulic Model XS	Channel Bottom (m) (CGVD2013)	WSP Reference Flood Figure	20-yr WSE (Analysis) (m)	20-yr WSE (Interpolated) Used in Model (m)
Little Forks	174.526	81840.3	168.89	A31		172.55
Wellandport Gauge	174.842	67147	168.405		172.55	
Trib_9 - East Outlet	174.935	60960.7		A22		173.09
Black Creek	174.969	58785		A21		173.28
Trib_9 - West Outlet	174.988	57290.5	169.095	A20		173.41
Port Davidson Weir D/S	175.107	55389	169.875	A19	173.57	
Port Davidson Weir U/S	175.107	55372.3		A19	174.07	
Trib_8	175.145	53374.1	170.115	A19		174.25
Wilson_Creek	175.257	50463.5	170.235	A17		174.50
Trib_7	175.514	45281.2		A15		174.95
Trib_6	175.618	43105.1		A14		175.14
Caistor Corners Gauge	175.62	43105.1	170.982	A14	175.14	
Mill_Creek	175.954	41289.6		A14	100-Year WSE Used Upstream of Caistor Corners	
Trib_5	177.223	38539	174.105	A13		
Trib_4	180.248	32687	176.775	A11		
Wolf Creek	181.468	29384.9	178.665	A9		
Elsie Creek	182.658	24689.6	179.865	A8		
Buckhorn Creek	183.525	18990.9	180.285	A6		
West Wolf Creek	185.699	11395.9	182.655	A4		
Trib_3	186.453	9588.8	185.325	A3		
Southbrook Gauge	188.461	4850.3	186.7	A2		
Trib_2	188.953	3028	187.185	A1		
Trib_1	189.822	2588.4		A1		189.49

3.10.5 Flood Hazard Mapping Scenario Boundary Conditions

The Flood Hazard Mapping Scenario was developed in HEC-RAS using the results of the tailwater sensitivity analysis. With Scenario A governing as the tailwater condition in all reaches assessed, the Known Water Surface tailwater elevation for all outlets has been set to the 100-year Welland River flood elevations for the 100-year (Regulatory), 200-year and 350-year events. For the 100-year event, a flow change node was added at the switch point between Scenarios A and B, and the 2-year peak flow was applied downstream of each switch point to the outlet. For the 200 and 350-year events, to account for event timing variability with climate change, the peak flows were maintained as modelled in HEC-HMS.

For the 2, 5, 10, 25 and 50-year events, the Known Water Surface tailwater elevation was set to the 20-year Welland River flood elevations for all reaches outletting downstream of Caistor Corners, and set to the 100-year river flood elevations upstream. All peak flows remain unchanged from the HEC-HMS outputs for the lower frequency events. A summary of the Flood Hazard Scenario downstream boundary conditions is provided in

Table 3-9. Flood Hazard Mapping HEC-RAS Scenario – Downstream Boundary Conditions

Tributary	2 to 50-Year Flood Events		100-Year (Regulatory), Flood Event		200 and 350-Year Flood Events	
	Tailwater Condition	Elev. (m) (CGVD2013)	Tailwater Condition	Elev. (m) (CGVD2013)	Tailwater Condition	Elev. (m) (CGVD2013)
Little Forks	20-Year Welland River WSE	172.55		174.53		174.53
Trib_9 - East Outlet		173.09		174.94		174.94
Black Creek		173.28		174.97		174.97
Trib_9 - West Outlet		173.41		174.99		174.99
Trib_8	with	174.25	100-Year Welland River WSE	175.15	100-Year Welland River WSE	175.15
Wilson_Creek	Event-Based Peak Flows	174.50		175.26		175.26
Trib_7		174.95		175.51		175.51
Trib_6		175.14		175.62		175.62
Mill_Creek	100-Year Welland River WSE	175.95	with	175.95	with	175.95
Trib_5		177.22		177.22		177.22
Trib_4		180.25		180.25		180.25
Wolf Creek		181.47		181.47	Event-Based Peak Flows	181.47
Elsie Creek	with	182.66	2-Year Peak Flow	182.66		182.66
Buckhorn Creek	Event-Based Peak Flows	183.53		183.53		183.53
West Wolf Creek		185.70		185.70		185.70
Trib_3		186.45		186.45		186.45
Trib_2		188.95		188.95		188.95
Trib_1	Road Elev.	189.49	Road Elev.	189.49	Road Elev.	189.49

3.11 Spill Flow Balancing

Initial runs of the Flood Hazard Scenario in HEC-RAS yielded several locations of poor containment, resulting in spill into adjacent reaches. In the 1-D HEC-RAS environment, flows exceeding the channel cross section are contained vertically, resulting in an overestimation of flood elevations. In locations where the flows exceeded cross sections with adjacent modelled reaches, peak flows for the mapped events were “balanced” by reducing the peak flow in the overflowing reach and applying it at the adjacent cross section in the receiving reach. This

was done iteratively until peak flows were contained in the overflowing reach, or the water surface elevations were equal (within a 0.05 m tolerance) in the adjacent cross sections. The instances where balancing was completed were all within the same HEC-RAS River system, and peak flows were unchanged downstream of the nearest confluence in each instance. In some cases, multiple reaches or flow change nodes were adjusted before the confluence (ie Buckhorn Creek). Balancing was completed for the 50-year, 100-year, 200-year and 350-year flood events. Peak flow balancing locations and changes to the HEC-HMS peak flows are shown in **Table 3-10**.

In addition to the containment balancing, peak flows were also balanced between the Eastern and Western Tributary 9 outlets to the Welland River. With the later addition of the Western outlet, and its overflow nature, no HEC-HMS flows were generated for the reach. Flows were moved from Trib_9-1-1 to 9-1-1-West in all events to match the upstream water surface elevations at the junction. With the observed need for 2-D modelling in the upper Black Creek Drain reaches, Reaches Black_4, Black_5, BlackTrib_4, and BlackTrib_5 have been removed from the 1-D model geometry and peak flow input data.

The final peak flows input into the HEC-RAS 1-D model for the Flood Hazard Mapping Scenario, incorporating the tailwater analysis and flow balancing, are provided in **Table 3-11**.

Table 3-10. Peak Flow Balancing Modifications

River	Overflowing						Receiving					
	Reach	Flow Change XS	Peak Flow Reduction (m³/s)				Reach	XS	Peak Flow Increase (m³/s)			
			50-year	100-year	200-year	350-year			50-year	100-year	200-year	350-year
Buckhorn Creek	BuckTrib_2	196	-5.50	-10.00	-13.50	-15.00	Buckhorn_2	5214	Flows unchanged from HEC-HMS; balancing by-passed Haldibrook Road crossing.			
	Buckhorn_2	5224	-5.50	-10.00	-13.50	-15.00						
Elsie Creek	ElsieTrib_3	391	-6.00	-7.10	-8.00	-8.50	Elsie_4	13921	6.00	7.10	8.00	8.50
Elsie Creek	ElsieTrib_2-3	5723		-0.87	-2.10	-2.90	ElsieTrib_2-5	506		0.87	2.10	2.90
Elsie Creek	ElsieTrib_2-3	5341	-0.50	-2.00	-3.00	-4.00	ElsieTrib_2-2	5145	Flows unchanged from HEC-HMS; balancing by-passed private crossing at 5177.			
	ElsieTrib_2-2	5188	-0.50	-2.00	-3.00	-4.00						

Table 3-11. 1-D HEC-RAS Peak Flow Data used in Flood Hazard Mapping Scenario

ABL HEC-RAS River	Reach	RS	Peak Flow (m³/s)							
			2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Black Creek Dr	Black Creek_3	4066	6.78	11.89	15.37	20.24	23.93	27.57	31.06	33.69
Black Creek Dr	BlackTrib_3	309	0.40	0.78	1.05	1.40	1.66	1.92	2.17	2.35
Black Creek Dr	Black Creek_2	3333	7.95	14.05	18.19	23.87	28.11	32.48	36.54	39.59
Black Creek Dr	Black Creek_2	2211	7.95	14.05	18.19	23.87	28.11	7.95	36.54	39.59
Black Creek Dr	BlackTrib_1-2	2904	1.52	2.71	3.56	4.68	5.54	6.41	7.23	7.84
Black Creek Dr	BlackTrib_1-3	696	0.61	1.10	1.45	1.90	2.25	2.61	2.94	3.19
Black Creek Dr	BlackTrib_2	150	0.55	1.02	1.35	1.78	2.11	2.44	2.75	2.98
Black Creek Dr	BlackTrib_2	117	0.55	1.02	1.35	1.78	2.11	0.55	2.75	2.98
Black Creek Dr	Black Creek_1	2088	8.60	15.26	19.71	25.93	30.47	8.60	39.69	42.98
Black Creek Dr	BlackTrib_1-1	1948	2.91	5.09	6.67	8.82	10.48	12.16	13.73	14.90
Black Creek Dr	BlackTrib_1-1	1260	2.91	5.09	6.67	8.82	10.48	2.91	13.73	14.90
Black Creek Dr	Black Creek_0	1219	11.35	20.21	26.10	34.34	40.21	11.35	52.52	56.80
Buckhorn Creek	BuckTrib_3-2	5216	1.48	2.54	3.28	4.27	5.02	5.80	6.52	7.05
Buckhorn Creek	BuckTrib_3-2	4877	1.71	2.98	3.89	5.08	6.00	6.93	7.81	8.46
Buckhorn Creek	BuckTrib_3-2	3729	2.88	4.97	6.45	8.41	9.88	11.39	12.81	13.89
Buckhorn Creek	BuckTrib_3-3	1796	1.01	1.70	2.20	2.85	3.34	3.85	4.33	4.68
Buckhorn Creek	BuckTrib_3-3	1199	1.22	2.07	2.68	3.52	4.17	4.83	5.44	5.90
Buckhorn Creek	Buckhorn_4	16908	1.08	1.78	2.33	3.07	3.64	4.22	4.77	5.19
Buckhorn Creek	Buckhorn_4	16689	1.96	3.26	4.26	5.61	6.66	7.74	8.76	9.51
Buckhorn Creek	Buckhorn_4	15741	2.95	4.96	6.44	8.48	10.08	11.72	13.27	14.43
Buckhorn Creek	Buckhorn_4	14398	4.50	7.60	9.87	12.89	15.26	17.75	20.09	21.84
Buckhorn Creek	Buckhorn_4	12211	5.44	9.26	12.08	15.81	18.73	21.75	24.59	26.71
Buckhorn Creek	BuckTrib_3-1	2904	4.59	7.96	10.35	13.57	16.02	18.50	20.84	22.62
Buckhorn Creek	BuckTrib_3-1	1745	4.94	8.93	11.65	15.35	18.18	21.04	23.73	25.78
Buckhorn Creek	Buckhorn_3	9888	9.91	18.47	24.43	32.40	38.51	44.70	50.50	54.85
Buckhorn Creek	Buckhorn_3	6971	10.21	19.38	25.87	34.53	41.17	47.92	54.24	58.97
Buckhorn Creek	BuckTrib_2	3397	2.40	4.04	5.20	6.78	8.01	9.29	10.49	11.38
Buckhorn Creek	BuckTrib_2	2652	3.03	5.31	6.94	9.09	10.75	12.44	14.04	15.25
Buckhorn Creek	BuckTrib_2	196	3.03	5.31	6.94	9.09	5.25	2.44	0.54	0.25
Buckhorn Creek	Buckhorn_2	5244	11.89	23.22	31.56	42.73	45.83	50.14	54.90	59.57
Buckhorn Creek	Buckhorn_2	5214	11.89	23.22	31.56	42.73	51.33	60.14	68.40	74.57
Buckhorn Creek	BuckTrib_1	2013	1.71	2.92	3.76	4.88	5.75	6.66	7.50	8.14

ABL HEC-RAS River	Reach	RS	Peak Flow (m³/s)							
			2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Buckhorn Creek	BuckTrib_1	1148	1.88	3.22	4.15	5.37	6.33	7.31	8.24	8.94
Buckhorn Creek	Buckhorn_1	4320	11.67	23.55	32.57	44.89	54.47	64.36	73.71	80.71
Buckhorn Creek	Buckhorn_1	1593	11.67	11.67	11.67	11.67	11.67	11.67	73.71	80.71
Elsie Creek	Elsie_4	16128	2.72	4.74	6.18	8.06	9.50	10.95	12.32	13.33
Elsie Creek	Elsie_4	14863	3.23	5.74	7.55	9.94	11.76	13.61	15.33	16.60
Elsie Creek	Elsie_4	13921	3.23	5.74	7.55	9.94	17.76	20.71	23.33	25.10
Elsie Creek	ElsieTrib_2-3	8095	1.87	3.25	4.23	5.51	6.49	7.48	8.42	9.11
Elsie Creek	ElsieTrib_2-3	6912	2.44	4.22	5.48	7.13	8.39	9.68	10.88	11.77
Elsie Creek	ElsieTrib_2-3	5723	2.44	4.22	5.48	7.13	8.39	8.81	8.78	8.87
Elsie Creek	ElsieTrib_2-3	5341	2.44	4.22	5.48	7.13	7.89	7.68	7.88	7.77
Elsie Creek	ElsieTrib_2-5	5060	1.88	3.13	4.06	5.32	6.31	7.33	8.28	9.00
Elsie Creek	ElsieTrib_2-5	3906	3.26	5.65	7.33	9.57	11.31	13.10	14.80	16.07
Elsie Creek	ElsieTrib_2-5	1891	3.97	7.08	9.24	12.26	14.55	16.88	19.05	20.67
Elsie Creek	ElsieTrib_2-5	506	3.97	7.08	9.24	12.26	14.55	17.75	21.15	23.57
Elsie Creek	ElsieTrib_3	1710	1.19	2.13	2.80	3.68	4.35	5.03	5.66	6.13
Elsie Creek	ElsieTrib_3	1625	2.17	3.87	5.07	6.64	7.86	9.09	10.24	11.10
Elsie Creek	ElsieTrib_3	391	2.17	3.87	5.07	6.64	1.86	1.99	2.24	2.60
Elsie Creek	ElsieTrib_2-2	5188	6.45	11.80	15.56	20.66	24.08	26.55	29.25	31.00
Elsie Creek	ElsieTrib_2-2	5145	6.45	11.80	15.56	20.66	24.58	28.55	32.25	35.00
Elsie Creek	Elsie_3	13787	6.26	11.65	15.47	20.46	24.30	28.22	31.87	34.59
Elsie Creek	Elsie_3	9809	6.22	11.86	15.94	21.31	25.45	29.69	33.66	36.61
Elsie Creek	Elsie_3	7560	6.21	11.92	16.08	21.58	25.85	30.23	34.33	37.40
Elsie Creek	Elsie_3	6522	6.15	11.86	16.09	21.79	26.23	30.82	35.16	38.41
Elsie Creek	Elsie_3	4355	6.09	11.77	16.01	21.72	26.21	30.86	35.25	38.55
Elsie Creek	ElsieTrib_2-4	521	1.88	3.23	4.18	5.44	6.43	7.46	8.43	9.16
Elsie Creek	ElsieTrib_2-1	3508	7.97	15.11	20.25	27.13	32.48	37.90	42.95	46.70
Elsie Creek	ElsieTrib_2-1	2029	8.08	15.20	20.45	27.51	33.03	38.65	43.89	47.78
Elsie Creek	Elsie_2	2409	10.50	21.04	29.55	40.85	49.85	59.27	68.24	74.99
Elsie Creek	ElsieTrib_1	337	1.32	2.20	2.91	3.86	4.60	5.36	6.08	6.61
Elsie Creek	Elsie_1	2344	10.20	20.63	28.98	40.31	49.34	58.83	67.88	74.69
Elsie Creek	Elsie_1	1101	10.20	10.20	10.20	10.20	10.20	10.20	67.88	74.69
Little Forks Cr	Little Forks_1	9610	3.59	6.64	8.63	10.79	12.04	13.23	14.54	15.81
Little Forks Cr	Little Forks_1	8051	6.45	11.32	14.50	18.96	22.06	25.03	27.74	29.76

ABL HEC-RAS River	Reach	RS	Peak Flow (m³/s)							
			2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Little Forks Cr	Little Forks_1	6302	6.69	11.54	14.83	19.41	22.78	26.09	29.13	31.39
Little Forks Cr	Little Forks_1	4585	6.59	11.58	14.97	19.65	23.21	26.76	30.05	32.50
Little Forks Cr	Little Forks_1	3789	6.59	11.58	14.97	19.65	23.21	6.59	30.05	32.50
Little Forks Cr	Little Forks_1	2516	5.00	9.20	12.08	16.09	19.14	5.00	25.11	27.29
Mill Creek	Mill_5	18634	1.51	2.60	3.35	4.34	5.09	5.85	6.58	7.12
Mill Creek	Mill_5	18406	2.02	3.41	4.37	5.62	6.56	7.54	8.46	9.16
Mill Creek	Mill_5	18080	2.36	3.99	5.12	6.58	7.69	8.84	9.90	10.69
Mill Creek	Mill_5	17251	4.20	7.13	9.21	11.92	14.00	16.13	18.08	19.53
Mill Creek	MillTrib_4	3796	1.11	2.01	2.65	3.49	4.12	4.77	5.38	5.83
Mill Creek	MillTrib_4	3459	2.12	3.77	4.93	6.44	7.59	8.75	9.84	10.65
Mill Creek	MillTrib_4	2950	2.57	4.57	6.00	7.89	9.33	10.79	12.14	13.16
Mill Creek	MillTrib_4	2045	2.77	5.01	6.71	8.87	10.52	12.20	13.76	14.93
Mill Creek	Mill_4	15310	7.18	12.70	16.81	22.08	26.09	30.17	33.98	36.80
Mill Creek	MillTrib_3	1327	1.26	2.28	3.02	4.03	4.79	5.58	6.31	6.85
Mill Creek	Mill_3	13890	8.27	15.33	20.58	27.54	32.85	38.25	43.30	47.06
Mill Creek	MillTrib_2	2827	1.48	2.50	3.22	4.20	4.98	5.78	6.54	7.10
Mill Creek	MillTrib_2	2516	2.31	4.02	5.22	6.81	8.05	9.32	10.52	11.41
Mill Creek	MillTrib_2	1585	3.21	5.67	7.39	9.65	11.37	13.14	14.80	16.04
Mill Creek	Moore's_3	668	1.07	1.81	2.34	3.02	3.55	4.09	4.60	4.98
Mill Creek	Moore's_3	597	1.20	2.09	2.72	3.54	4.16	4.79	5.37	5.81
Mill Creek	Moore's_2	9885	1.65	2.88	3.75	4.87	5.73	6.60	7.43	8.06
Mill Creek	Moore's_2	9366	2.06	3.72	4.91	6.48	7.68	8.90	10.04	10.88
Mill Creek	Moore's_2	8051	2.90	5.27	6.94	9.12	10.80	12.49	14.07	15.24
Mill Creek	Mill_2	9557	9.55	18.36	25.25	34.70	42.05	49.61	56.68	61.93
Mill Creek	Mill_2	7522	9.34	18.03	25.03	34.54	41.99	49.67	56.89	62.26
Mill Creek	Moore's_1	7593	5.47	10.07	13.29	17.49	20.71	23.99	27.03	29.29
Mill Creek	Moore's_1	5228	6.03	11.18	14.84	19.62	23.29	27.02	30.50	33.16
Mill Creek	Moore's_1	4616	6.30	11.81	15.74	20.89	24.84	28.86	32.61	35.46
Mill Creek	Moore's_1	1633	7.53	14.47	19.52	26.19	31.32	36.57	41.49	45.24
Mill Creek	Mill_1	5577	14.43	28.25	39.50	55.15	68.14	81.57	93.98	103.31
Mill Creek	Mill_1	1272	14.43	14.43	14.43	14.43	14.43	14.43	93.98	103.31
Trib_1	1_1-2	5492	2.05	3.40	4.38	5.80	6.92	8.05	9.12	9.91
Trib_1	1_1-2	4987	3.57	5.97	7.65	9.95	11.82	13.73	15.54	16.89

ABL HEC-RAS River	Reach	RS	Peak Flow (m³/s)							
			2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Trib_1	1_1-2	4614	3.77	6.34	8.17	10.62	12.62	14.64	16.56	17.99
Trib_1	1_2	287	1.30	2.18	2.81	3.72	4.43	5.16	5.84	6.36
Trib_1	1_1-1	3795	5.58	9.37	12.04	15.67	18.58	21.59	24.41	26.54
Trib_1	1_1-1	3657	6.00	10.09	13.00	16.90	20.01	23.22	26.24	28.50
Trib_1	1_1-1	3300	7.89	13.20	16.88	21.96	25.95	30.11	34.01	36.95
Trib_1	1_1-1	2556	8.33	14.62	18.78	24.67	29.17	33.78	38.11	41.36
Trib_2	2_1-2	5986	3.34	4.97	6.10	7.58	8.71	9.86	10.93	11.72
Trib_2	2_1-2	5328	5.04	7.89	9.92	12.60	14.67	16.78	18.76	20.24
Trib_2	2_2	990	1.41	2.35	3.03	3.98	4.71	5.47	6.19	6.73
Trib_2	2_1-1	3778	6.67	10.68	13.55	17.35	20.28	23.29	26.12	28.23
Trib_2	2_1-1	2082	6.98	11.36	14.47	18.54	21.67	24.88	27.89	30.09
Trib_2	2_1-1	1070	6.98	6.98	6.98	6.98	6.98	6.98	27.89	30.09
Trib_3	3_1	3692	1.20	2.01	2.59	3.42	4.07	4.75	5.38	5.86
Trib_3	3_1	3191	2.73	4.59	5.91	7.78	9.26	10.79	12.23	13.31
Trib_3	3_1	2119	3.08	5.19	6.71	8.81	10.46	12.17	13.78	15.00
Trib_3	3_1	1189	3.08	3.08	3.08	3.08	3.08	3.08	13.78	15.00
Trib_4	4_1	3005	2.06	3.75	4.96	6.58	7.83	9.10	10.29	11.17
Trib_4	4_1	2171	3.07	5.66	7.58	10.11	12.07	14.08	15.96	17.35
Trib_4	4_1	1027	3.07	3.07	3.07	3.07	3.07	3.07	15.96	17.35
Trib_5	5_1-2	3146	0.59	1.12	1.49	1.99	2.36	2.74	3.10	3.36
Trib_5	5_1-2	2876	1.32	2.45	3.26	4.35	5.20	6.08	6.89	7.50
Trib_5	5_2	1467	0.16	0.29	0.37	0.49	0.58	0.66	0.75	0.82
Trib_5	5_2	1237	0.22	0.38	0.50	0.66	0.77	0.89	1.00	1.09
Trib_5	5_1-1	1543	1.65	3.00	4.02	5.43	6.58	7.71	8.76	9.53
Trib_5	5_1-1	1000	1.65	1.65	1.65	1.65	1.65	1.65	8.76	9.53
Trib_6	6_2-2	1402	0.22	0.42	0.55	0.74	0.88	1.03	1.16	1.26
Trib_6	6_2-2	1032	1.06	1.93	2.55	3.36	3.97	4.59	5.16	5.59
Trib_6	6_2-2	362	1.06	1.93	2.55	3.36	2.67	2.29	2.71	2.39
Trib_6	6_2-3	551	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Trib_6	6_2-1	322	1.06	1.93	2.55	3.36	3.97	4.59	5.16	5.59
Trib_6	6_2-1	146	1.06	1.93	2.55	3.36	2.17	2.29	2.21	2.09
Trib_6	6_2-1	103	1.06	1.93	2.55	3.36	3.47	4.59	4.66	5.29
Trib_6	6_1-2	6414	0.32	0.58	0.76	1.00	1.17	1.35	1.52	1.64

ABL HEC-RAS River	Reach	RS	Peak Flow (m ³ /s)							
			2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
Trib_6	6_1-2	5664	0.40	0.74	0.98	1.28	1.51	1.74	1.96	2.12
Trib_6	6_1-2	5133	0.87	1.58	2.07	2.71	3.19	3.68	4.14	4.48
Trib_6	6_1-2	4427	1.50	2.69	3.51	4.58	5.38	6.20	6.97	7.54
Trib_6	6_1-1	3814	2.91	5.34	7.04	9.38	10.66	12.96	14.12	15.55
Trib_6	6_1-1	3732	2.91	5.34	7.04	9.38	11.16	12.96	14.62	15.85
Trib_6	6_1-1	2927	3.40	6.12	8.22	10.95	13.04	15.15	17.21	18.69
Trib_6	6_1-1	1528	3.40	6.12	8.22	10.95	13.04	3.40	17.21	18.69
Trib_7	7_2	147	1.64	2.86	3.73	4.87	5.74	6.63	7.46	8.08
Trib_7	7_1-2	5287	2.99	5.29	6.93	9.09	10.74	12.42	13.99	15.15
Trib_7	7_1-2	5084	3.10	5.49	7.20	9.47	11.24	13.09	14.79	16.06
Trib_7	7_1-2	4464	3.35	6.08	7.99	10.59	12.58	14.67	16.57	17.98
Trib_7	7_1-2	3923	3.88	7.03	9.21	12.19	14.48	16.89	19.09	20.73
Trib_7	7_1-1	1651	5.54	9.97	13.00	17.17	20.41	23.76	26.93	29.24
Trib_7	7_1-1	1295	5.54	9.97	13.00	17.17	20.41	5.54	26.93	29.24
Trib_8	8_1	2744	1.38	2.69	3.61	4.78	5.63	6.49	7.30	7.89
Trib_8	8_1	2661	1.76	3.21	4.33	5.82	6.92	8.02	9.04	9.79
Trib_8	8_1	2110	2.47	4.43	5.80	7.69	9.20	10.75	12.25	13.34
Trib_8	8_1	1342	2.47	4.43	5.80	7.69	9.20	2.47	12.25	13.34
Trib_8	8_1	1259	3.27	5.96	7.74	10.19	12.08	3.27	15.84	17.28
Trib_9	9_1-3	4583	0.14	0.24	0.32	0.41	0.49	0.56	0.63	0.68
Trib_9	9_1-3	4369	0.18	0.31	0.41	0.55	0.65	0.75	0.85	0.92
Trib_9	9_1-3	3871	0.18	0.31	0.41	0.55	0.65	0.18	0.85	0.92
Trib_9	9_1-3	3793	1.01	1.84	2.43	3.23	3.84	1.01	5.03	5.45
Trib_9	9_1-2	3443	0.76	0.38	0.04	0.40	0.19	0.76	0.71	0.25
Trib_9	9_2	1043	1.51	2.61	3.38	4.39	5.17	1.51	6.69	7.24
Trib_9	9_1-1-West	978	0.40	1.80	2.90	3.60	4.60	0.40	5.60	6.60
Trib_9	9_1-1	1748	2.88	4.21	5.09	7.02	8.05	2.88	10.99	11.39
Trib_9	9_1-1	1322	2.99	4.42	5.42	7.56	8.76	2.99	12.10	12.64
West Wolf Creek	WestWolf_4	13673	1.50	2.59	3.36	4.37	5.18	6.01	6.79	7.37
West Wolf Creek	WestWolf_4	13018	1.92	3.40	4.44	5.81	6.87	7.96	8.98	9.75
West Wolf Creek	WestWolfTrib_3	996	1.00	1.69	2.18	2.83	3.33	3.85	4.33	4.69
West Wolf Creek	WestWolf_3	11272	3.68	6.56	8.62	11.30	13.35	15.44	17.40	18.87
West Wolf Creek	WestWolf_3	10513	3.79	7.10	9.52	12.64	15.01	17.42	19.67	21.34

ABL HEC-RAS River	Reach	RS	Peak Flow (m³/s)							
			2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	200-yr	350-yr
West Wolf Creek	WestWolfTrib_2	2299	2.11	3.55	4.55	5.92	6.97	8.06	9.08	9.85
West Wolf Creek	WestWolfTrib_2	1343	2.58	4.31	5.56	7.27	8.57	9.91	11.17	12.12
West Wolf Creek	WestWolf_2	9818	6.00	11.34	15.43	20.89	25.02	29.21	33.13	36.05
West Wolf Creek	WestWolf_2	8007	6.07	11.31	15.46	21.07	25.40	29.82	33.95	37.03
West Wolf Creek	WestWolfTrib_1	2027	1.81	3.18	4.15	5.43	6.40	7.39	8.32	9.01
West Wolf Creek	WestWolfTrib_1	1032	2.08	3.68	4.80	6.28	7.41	8.56	9.64	10.44
West Wolf Creek	WestWolf_1	6133	7.11	13.24	18.20	25.21	30.77	36.48	41.85	45.86
West Wolf Creek	WestWolf_1	3699	7.03	13.15	18.08	25.09	30.71	36.54	42.04	46.17
West Wolf Creek	WestWolf_1	1059	7.03	7.03	7.03	7.03	7.03	7.03	42.04	46.17
Wilson Creek	Wilson_1	5852	1.65	3.17	4.26	5.70	6.79	7.90	8.94	9.71
Wilson Creek	Wilson_1	5137	2.32	4.53	6.04	8.10	9.67	11.27	12.76	13.87
Wilson Creek	Wilson_1	3979	2.90	5.76	7.79	10.45	12.54	14.66	16.65	18.12
Wilson Creek	Wilson_1	2422	2.90	5.76	7.79	10.45	12.54	2.90	16.65	18.12
Wilson Creek	Wilson_1	2219	3.06	5.96	8.14	10.92	13.14	3.06	17.55	19.14
Wolf Creek	WolfTrib_2	1198	2.00	3.32	4.31	5.67	6.73	7.82	8.85	9.62
Wolf Creek	WolfTrib_2	148	2.00	3.32	4.31	5.67	6.73	7.82	8.85	9.62
Wolf Creek	Wolf_3	13988	1.70	2.90	3.74	4.92	5.83	6.77	7.66	8.33
Wolf Creek	Wolf_3	13288	2.25	3.98	5.16	6.73	7.96	9.23	10.43	11.33
Wolf Creek	Wolf_2	12238	5.74	9.92	12.87	16.75	19.73	22.79	25.68	27.84
Wolf Creek	Wolf_2	12157	5.74	9.92	12.87	16.75	19.73	22.79	25.68	27.84
Wolf Creek	Wolf_2	11107	7.21	12.52	16.29	21.25	25.03	28.89	32.51	35.21
Wolf Creek	Wolf_2	9502	7.32	12.95	17.05	22.56	26.78	31.08	35.10	38.10
Wolf Creek	Wolf_2	7373	7.47	13.49	18.04	24.26	29.06	33.95	38.53	41.93
Wolf Creek	LittleWolfTrib_1	1002	1.09	1.84	2.37	3.12	3.71	4.32	4.90	5.33
Wolf Creek	LittleWolf_2	9740	1.40	2.51	3.28	4.30	5.07	5.86	6.60	7.15
Wolf Creek	LittleWolf_1	8699	3.66	6.87	9.12	12.05	14.28	16.55	18.68	20.26
Wolf Creek	LittleWolf_1	6674	5.55	10.57	13.18	17.83	21.41	24.95	28.24	30.68
Wolf Creek	LittleWolf_1	4801	6.22	11.95	15.43	20.19	24.50	28.77	32.73	35.66
Wolf Creek	LittleWolf_1	2369	6.47	12.25	16.11	21.00	25.37	29.87	34.09	37.24
Wolf Creek	Wolf_1	4683	13.41	25.09	33.62	44.94	54.08	63.54	72.47	79.14
Wolf Creek	Wolf_1	3130	13.44	25.20	33.88	45.45	54.81	64.14	73.28	80.03
Wolf Creek	Wolf_1	1000	13.44	13.44	13.44	13.44	13.44	13.44	73.28	80.03

4 2-D HYDRAULIC MODEL DEVELOPMENT – BLACK CREEK

Preliminary 1-D hydraulic modelling for Black Creek was completed for reaches Black Creek_4, Black Creek_5, BlackCreekTrib_4, and BlackCreekTrib_5. The preliminary 100-yr water surface extents and associated floodplain depth have been illustrated in **Figure 4-2**.

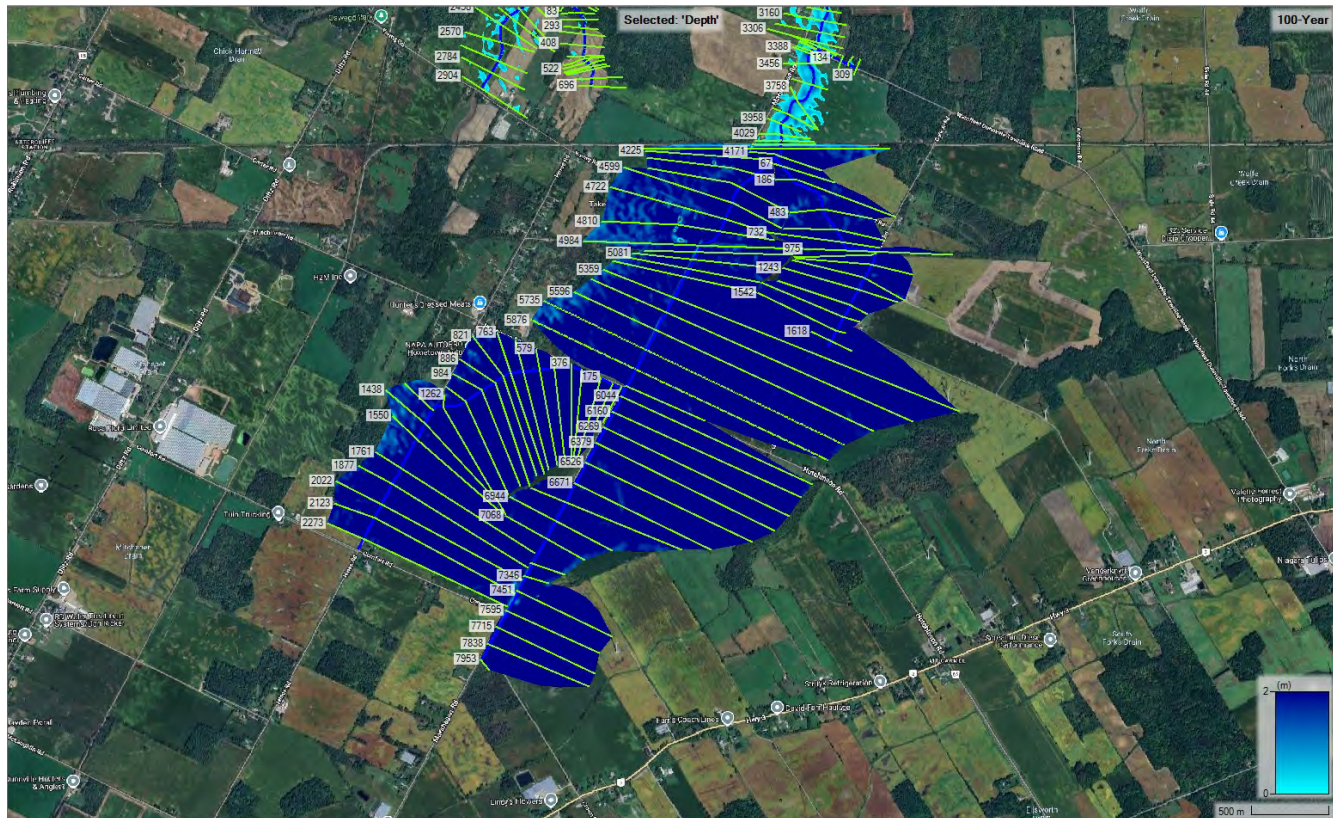


Figure 4-1. Black Creek 1-D 100yr Floodplain Extents and Depths

A detailed review of existing topographic features within the Black Creek floodplain has revealed a number of key hydraulic characteristics including;

- Shallow watercourse profiles ($\leq 0.05\%$);
- Limited bankfull flow capacities;
- Relatively flat floodplains in the direct vicinity of watercourses;

In-lieu of the above, very wide (in excess of 2km) 1-D 100-year floodplain extents have been observed. We further note that 1-D 100-year floodplain depths exceed 2m in many locations. Based on the excessive floodplain width, wide cross sections have not been able to contain the 100-year floodplain extents and has therefore resulted in floodplain depths that would not represent field conditions.

Detailed discussions with the NPCA were held to review the results of the 1-D HEC-RAS modelling results. Based on these detailed discussions, it was mutually agreed between the NPCA and Aquafor, that a 1-D floodplain model was overestimating the Regulatory floodplain in this area. Further, it was mutually agreed between the

NPCA and Aquafor that 2-D Floodplain Hydraulic Modelling was required to refine the Regulatory (100 year) floodlines within the project area. The commentary that follows outlines the methodology and assumptions used in the preparation of the 2-D Hydraulic Modelling and associated floodlines for Black Creek.

The following reaches within Black Creek Drain were incorporated into the 2-D mesh: Black Creek_4, Black Creek_5, BlackCreekTrib_4, and BlackCreekTrib_5. The extent of the 2-D model is shown in **Figure 4-2**.



Figure 4-2. Black Creek 2-D HEC-RAS Model Extent

The orange boundaries illustrated in **Figure 4-2** show the limits of the 2-D modelling extents contained in this report. Generally, the Black Creek 2-D modelling area is bound to the north and west by the existing railway corridor, to the east by Highway 3 and to the south by Comfort Road.

The 2-D floodplain modelling has built on the previously completed 1-D hydraulic modelling for Black Creek as previously noted. Key background information used to construct the 2-D HEC-RAS model has been detailed below;

- **Peak Flows** – peak flow rates have been referenced from the NPCA Upper Welland HEC-HMS Hydrologic Model, completed by Aquafor Beech Ltd 2026. The 50, 100, 200 and 350-year 12hr AES peak flow rates and associated hydrographs have been applied as External and Internal Hydrographs. Internal hydrographs represent the difference in peak flows between flow nodes;
- **Terrain** – MNRF's 2021 LiDAR DTM (Coordinate system NAD83 - UTM Zone 17N, vertical coordinate system CGVD2013). Saved as NPCA Upper Welland DTM CGVD2013.hdf;
- **Land Use** – land use mapping is consistent with the Southern Ontario Land Resource Information System (SOLRIS) version 3.0 data layer and grid code classifications;
- **Roadway Crossings** - are consistent with the 1-D NPCA Upper Welland HEC-RAS hydraulic modelling completed by Aquafor Beech Ltd within this report.

4.1 2-D Hydraulic Model Platform

Detailed 2-D hydraulic modelling of Black Creek was built using the HEC-RAS software (ver. 6.4.1). Preliminary floodplain mapping was also generated using HEC-RAS results and elevation surface data.

4.1.1 Building Obstructions

Primary buildings located within the study area have been identified via aerial imagery and built into the terrain as a polygon modification layer. Primary buildings are classified as the largest residential dwellings, commercial, institutional and industrial buildings located on each parcel within the study area. Smaller buildings such as sheds, storage units, etc have not been added to the terrain. Building heights and elevations have been arbitrarily set in the terrain to an elevation of 3-4 m which above ground surface elevations depending on location.

4.1.2 Channel Improvements

Invert elevations of culvert crossings on multiple roadways have been identified as residing below the LiDAR DTM data. Accordingly, to accurately replicate culvert hydraulics within the 2-D modelling environment, Terrain modifications have been performed along the profile of the existing roadway culverts in the form of a Ground Line Modification. The Lower (Terrain/User) Value option has been selected to provide a nominally lower elevation profile ($\leq 1\text{m}$) through each culvert crossing.

4.2 2-D Flow Area and Perimeter

The 2-D modelling perimeter has been configured with the assumption that Regulatory peak flows may occupy a wide footprint within each of their respective areas of focus. Accordingly, the overall 2-D modelling perimeter has been configured as per **Figure 4-2**.

As noted in the HEC-RAS 2-D User's Manual;

"Assigning an appropriate mesh cell size (or sizes) and computational time step (ΔT) is very important to getting accurate answers with 2-D flow areas."

Accordingly, a generic 30m (X) by 30m (Y) rectangular cell mesh distribution has been used as a mesh default, given the relatively flat sloping grades of the study area and anticipated Regulatory floodplain extents. Additional mesh detail has been provided via breaklines within the model at reduced spacing/intervals to refine the mesh within the banks of the various reaches and within roadway right-of-ways. The 2-D flow area mesh specifics have been provided in **Table 4-1** and **Table 4-2**.

Table 4-1. 2-D Flow Area Mesh Specifics – Black Creek

Number of Cells	Average Face Length (m)	Average Cell Size (m ²)	Maximum Cell Size (m ²)	Minimum Cell Size (m ²)
92419	11	120	1,600	0

4.3 2-D Breaklines

Breaklines have been added to the HEC-RAS hydraulic model to refine the 2-D mesh and provide a higher level of computational detail in key locations including Local and Rural Roadways, Rivers and Stream Corridors and Culvert Crossings.

For rivers and watercourses, breaklines have been strategically placed to identify the centerline of the watercourse between roadway crossings. Breakline attributes for rivers and watercourses have been selected to replicate bank full flow widths and channel depths. Breaklines used to refine the mesh within roadway corridors have been coded to identify the centerline of roadway, driving lane width and roadway embankments. Details surrounding the Near Spacing, Near Repeats and Far Spacing of the 2-D breaklines used in the project area have been identified in **Table 5-4**;

Table 4-2. 2-D Breakline Attributes

	Near Spacing (m)	Near Repeats	Far Spacing (m)
Local Roadways	5	3	15
Rural Roadways	3	3	5
Watercourse	1	3	5

4.4 2-D Computation Points

In addition to the default Computational Points derived by the RAS Mapper, Computational points were added to the 2-D Mesh in the direct vicinity of roadway culvert inlets and outlets. These additional computational points provide an enhanced level of mesh detail at key locations in the hydraulic model to aid in computational

efficiency and accuracy of roadway culvert crossings. Additional computational points have been added, where required, to the mesh to retain a maximum of eight (8) cell sides within in overall 2-D mesh in accordance with the 2-D HEC-RAS Users Manual.

4.5 2-D Mesh, Breaklines, Computational Points Visualisation

To visualise the constructed mesh within the 2-D hydraulic model, **Figure 4-3** has been provided to illustrate the integration of various mesh components including individual mesh cells, breaklines and computational points.



Figure 4-3. 2-D Mesh Visualization

4.6 2-D SA/2-D Connections

Roadway Culvert and Roadway Bridge crossings, at major roadway crossings, have been added to the 2-D HEC-RAS model via SA/2-D Connections. Detailed crossing information was coded to be consistent with the 1-D NPCA Upper Welland hydraulic of Black Creek completed by Aquafor Beech Limited (ABL) as detailed in Section 3 of this report.

4.7 Terrain Modifications – Hydroburn

Roadway conveyance at non-major roadway crossings (i.e. driveway culverts and farm crossings) has been simulated via a Channel Terrain Modification (aka Hydroburn). To complete this scenario, we have cloned the original MNRF's 2021 LiDAR DTM and saved the new Terrain as "NPCA DTM – Modified". Next, rectangular channels have been "burned" into the ground terrain at each non-major roadway crossing location. The channel bottom widths have been set to the width of, or slightly wider than the bottom of, the channel on either side of

the crossing. Side slopes have been set to 0.001:1 with maximum extents generally set to less than 10m depending on location. Invert elevations have simply used the channel inverts of the DTM on each side of the crossing. **Figure 4-4** visually illustrates the “Hydro-Burn” Terrain Modification as noted above.

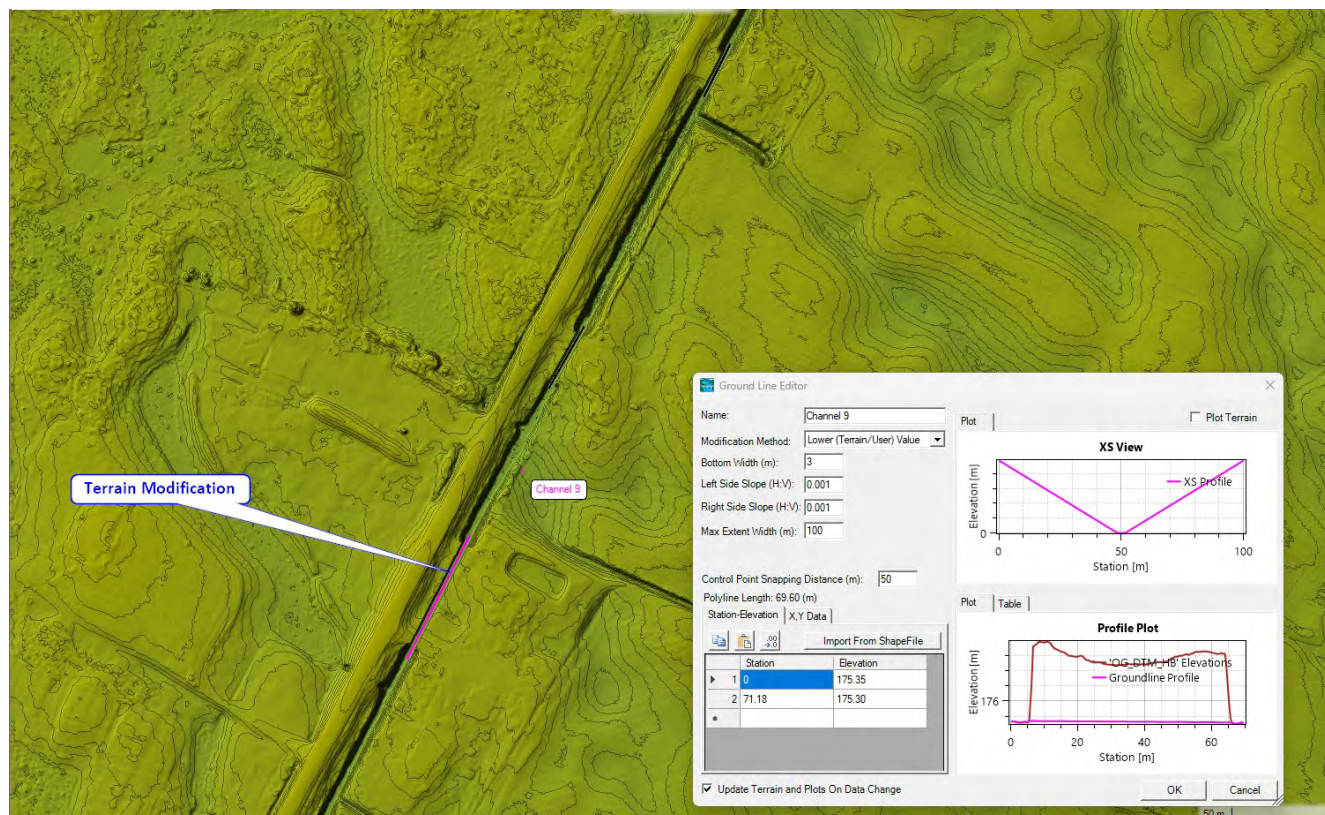


Figure 4-4 Hydro-Burn Scenario – Terrain Modification – Driveway Crossing

This modelling scenario represents a scenario in which the ponded volumes upstream of minor driveway crossings will be minimized (yet still nominally available) and represents a theoretical case for close to or near free flow conditions at each crossing. We note that this scenario has been reserved for the Black Creek 2D modelling area only.

4.8 2-D Boundary Conditions

Two distinct types of boundary conditions have been applied to the Black Creek 2-D HEC-RAS hydraulic model including Flow Hydrographs (Upstream Boundary Conditions) and Normal Depth (Downstream Boundary Conditions). The following details the methodology used in the application of both boundary conditions.

4.8.1 Flow Hydrographs and Upstream Boundary Conditions

As an initial 2d modelling test, the 100yr 12hr AES hydrographs within the NPCA Upper Welland HEC-HMS Hydrologic Model have been exported for use in the 2-D HEC-RAS model. Specifically, Flow Hydrographs have been applied to the 2-D model at the upstream limits of each reach and at key flow node locations within the watershed as applicable. **Figure 4-4** below illustrates the Flow Nodes peak flow magnitudes and locations of each Flow Hydrograph applied to the 2-D HEC-RAS hydraulic model.

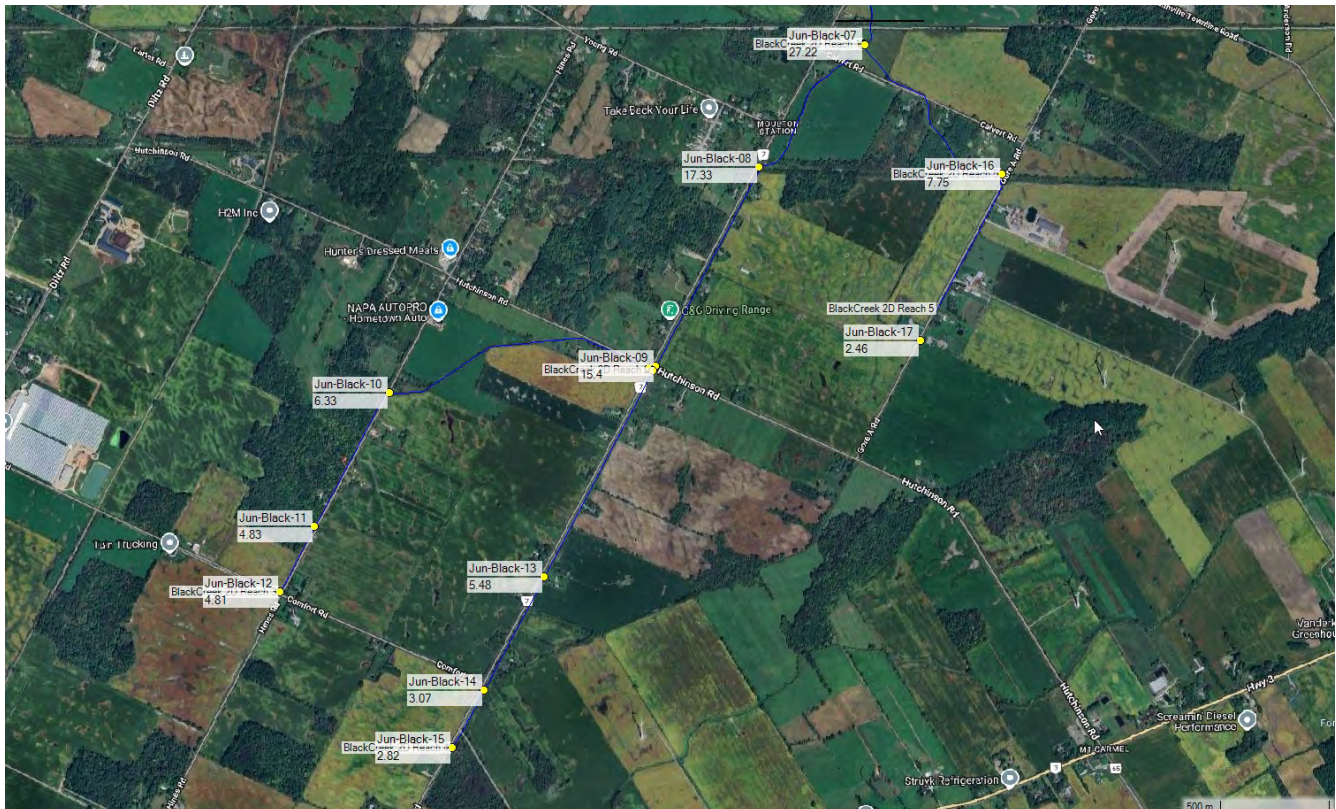


Figure 4-5 Black Creek – Flow Node Location Plan – 100yr Flows

We note the within a 1-D Steady State HEC-RAS hydraulic model, peak flows are applied at cross section locations within the reach. Flows are varied by increasing or decreasing flows at selected cross sections within the reach. This application of peak flows in a one-dimensional environment carries the assumption that peak flows remain constant without the application of time. This basic assumption tied to a one-dimensional hydraulic model also carries the assumption that flood flow volume from a rainfall event is not accounted for.

Peak Flows within a 2-D HEC-RAS hydraulic model may be applied as Flow Hydrographs directly to the 2-D Mesh at key flow node locations throughout the watershed. However, as 2-D HEC-RAS hydraulic modelling requires the input of a flow hydrograph, the element of time is introduced into the modelling environment. This element of time enables the 2-D HEC-RAS hydraulic model to account for both the conveyance and attenuation of flood flow volume within the 2-D mesh of the model. Accordingly, as flood flow volume is accounted for within the 2-D modelling environment, incrementally applying raw hydrographs within the reach may double count (or more) the overall flow volume in the model.

Said another way, peak flood flow volume within a riverine corridor is a function of flow timing of individual catchments within the watershed. Catchments located in the lower limits of the watershed may drain entirely prior to the peak flow from the upper limits of the watershed reaching the outlet. Catchments located in the middle of the watershed may contribute only a portion of their peak flow to the overall flood volume based on this timing effect.

In summary, the peak flood flow magnitude within a watercourse is cumulation of timing of peak flows of individual catchments within a watershed. Accordingly, given the timing effect between flow node locations we have simplified the application of incremental flow hydrographs within the model.

Figure 4-5 provides a direct visual comparison of the 100-year SCS hydrographs for Flow Nodes Jun- 12 and Jun-- 10 for further analysis and discussion.

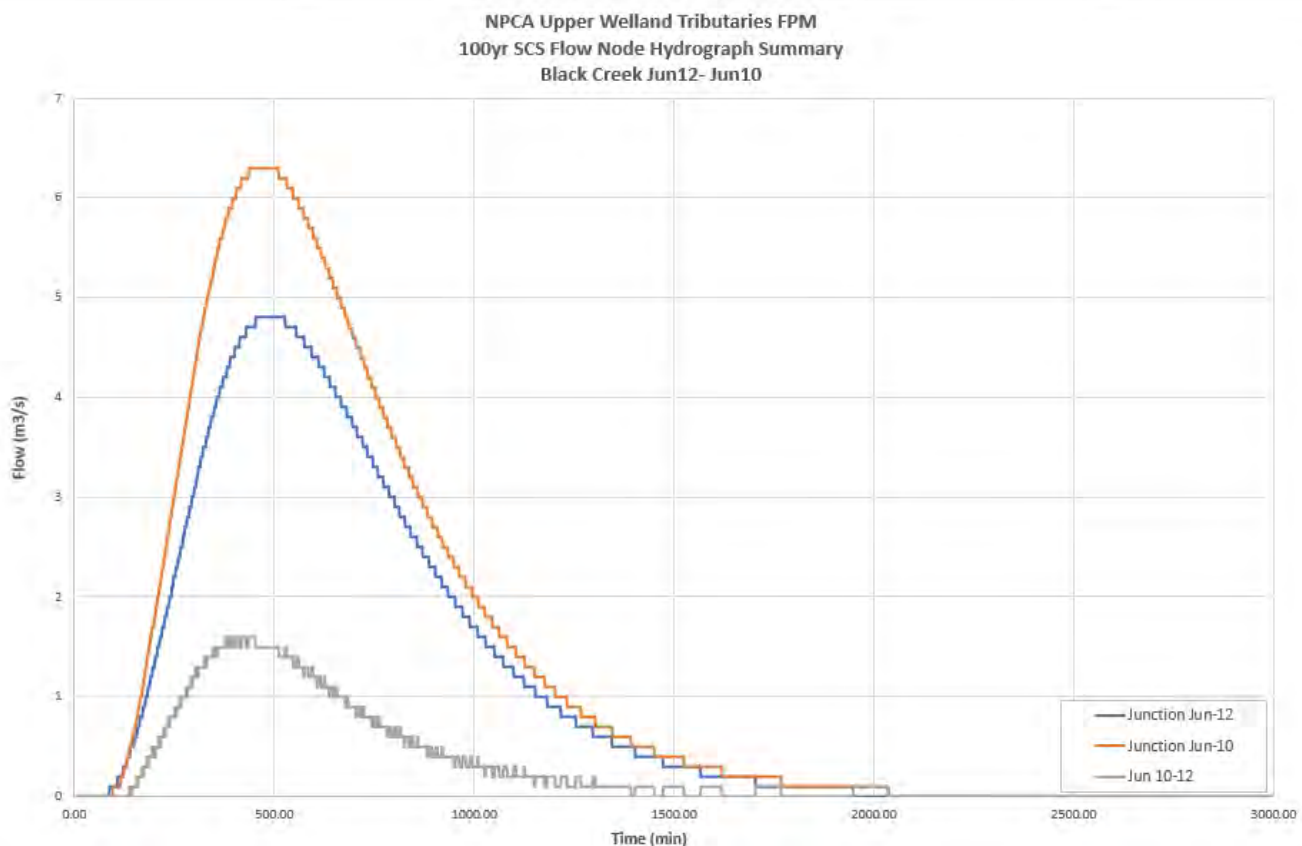


Figure 4-6 Black Creek – Flow Node 10 and 12 Hydrograph Comparison

Focusing in on River: Black Creek, Reach: BlackTrib_5, two flow nodes have been identified, namely Jun- 12 (blue) producing a 100-year peak flow of 4.8 m³/s and Jun- 10 (orange) producing a 100-year peak flow of 6.3 m³/s. The peak flows are 1.5 m³/s (grey) (6.3 m³/s – 4.8 m³/s) higher at Jun-10 given the increase in drainage area associated with this downstream flow node. However, we note two key discussion points. The first is that timing of the peaks of the hydrographs are not the same as there is a channel routing aspect of the hydrographs and therefore a direct subtraction of peak flow values is not applicable as they occur at different times. The second key point is the hydrograph at Jun-10 also contains peak flow volume from Jun-12. To refrain from double counting flow volume within the 2-D HEC-RAS model, we have taken the difference in flow hydrographs (grey) and applied this difference, in this example, at the downstream Flow Node Jun-10. This approach provides the 2-D HEC-RAS model with an incremental flow increase to account for the increased runoff associated with a larger drainage area while recognising only a portion of the flow increase will result in an incremental volume contribution to the overall floodplain.

4.8.2 Downstream Boundary Conditions

To provide a seamless transition between the 2-D 100-year regulatory floodline and the 1-D 100-year regulatory floodline, we have identified the 1-D Cross Sections at the boundary of where both models converge as illustrated below.

Table 4-3. 1-D Boundary Conditions for Downstream Limits of the 2-D model

Modelling Area	River	Reach	1-D Cross Section Location	1-D 100 - Water Surface Elevation (m)
Black Creek	Black Creek	Reach 3	4029	177.13

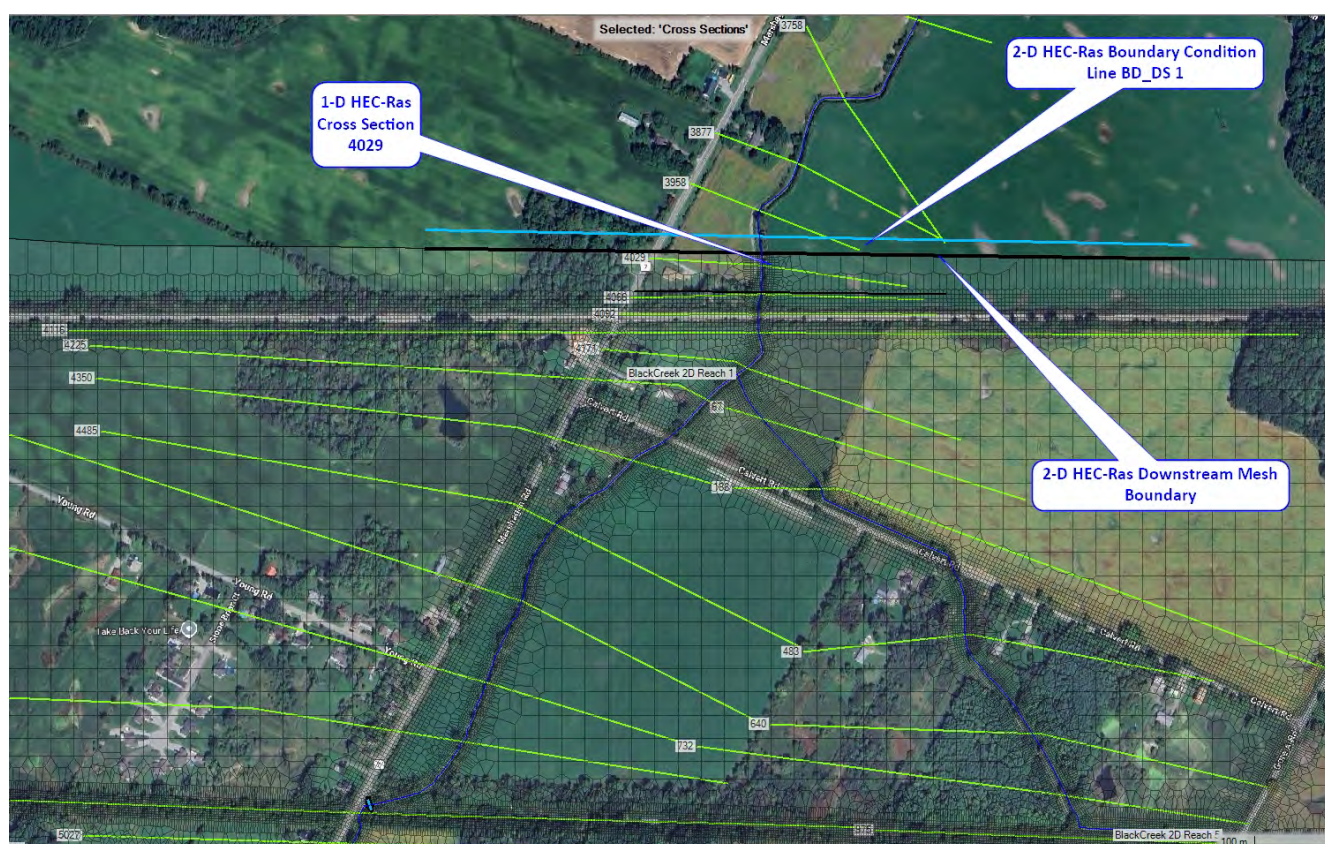


Figure 4-7 Black Creek – 2-D Boundary Conditions

The 1-D Cross Section 4029 produces a 100-year water surface elevation of 177.13 m. To replicate this elevation in the 2-D modelling environment, a stage hydrograph with a peak elevation of 177.13 m has been created. The initial boundary condition of 177.13m has been set to force the 2-D modelling limits to tie into the downstream 1-D model.

4.9 2-D Computational Settings

To provide an accurate representation of all flow events within the 2-D modelling environment, we have selected the following computational settings for each modelling scenario.

Table 4-4. 2-D Computational Settings

Computational Settings - Crossings Scenario				
Computation Interval	→	5 Second		
Mapping Output Interval	→	5 Second		
Hydrograph Output Interval	→	5 Second		
2-D Flow Options	→	Equation Set	→	SWE-ELM
Advanced Time Step Control	→			
		Fixed Time Step Method	→	5 seconds

All other default modelling settings have been maintained.

5 MODEL RESULTS AND FLOODPLAIN MAPPING

5.1 High Flow Analysis Results and Flood Lines

The HEC-RAS hydraulic model for Upper Welland River Tributaries was executed under a mixed flow regime to establish water surface profiles for each of the 2-year to 350-year storm events, with a focus on the 100-year storm, which is considered to be the Regulatory event for this watershed as directed by O.Reg. 41/24 under the Ontario Conservation Authorities Act, R.S.O. 1990 (Schedule 1, Table 15). The presence of steeper channel gradients and potential for super critical flow in some areas of the model warranted the use of a mixed flow regime. Model results for all reaches are presented in **Appendix B**.

Regulatory flood lines were generated using the water surface elevation outputs from the HEC-RAS model under the 100-year event and current land use. The flood lines were mapped based on the intersection between the predicted water surface elevation and the LiDAR-derived DTM, as well as engineering judgement to extend flood lines according to topography where they intersect the HEC-RAS edge lines (limits of computed inundation mapping). Regulatory floodplain mapping for the 100-year event is included in **Appendix D**. A comparison of all flood events mapped, including the Climate Change scenarios, is included in **Appendix E**. **Figure 5-1, Figure 5-2 and Figure 5-3** provide an overview of the regulatory floodplain mapping. The following are notable components of the flood hazard mapping exercise:

- The hydraulic model was built using a combination of topographic data (DTM and field survey), both referenced to the CGVD2013 vertical datum.
- The hydraulic model was run under mixed flow for all storm events. The 2 through 25-year storms were simulated for hydraulic results only; flow balancing was not completed on these events, and the results only provide insight into the approximate behaviour of the river for events having a lower magnitude than the 50-year, 100-year, 200-year and 350-year storms.
- The 100-year Welland River WSE as established by WSP in 2018, combined with the 2-year peak flow rate, was applied as the downstream boundary condition for the 100-year flood events. The 20-year Welland River WSE, combined with event-based HEC-HMS peak flow rates was applied as the downstream boundary condition to the 2 through 50-year flood events. The 100-year Welland River WSE and peak 200 and 350-year flow rates applied for their respective events.
- Smoothing of flood lines and full manual inspection of the flood lines for all storms was performed.
- Where the automatically-generated flooding extents were cut off, the flooding boundary was filled-in by extending it to an appropriate contour elevation.
- Islands were manually filled and isolated areas of flooding (hydraulically disconnected from main reach) were removed, as deemed appropriate.

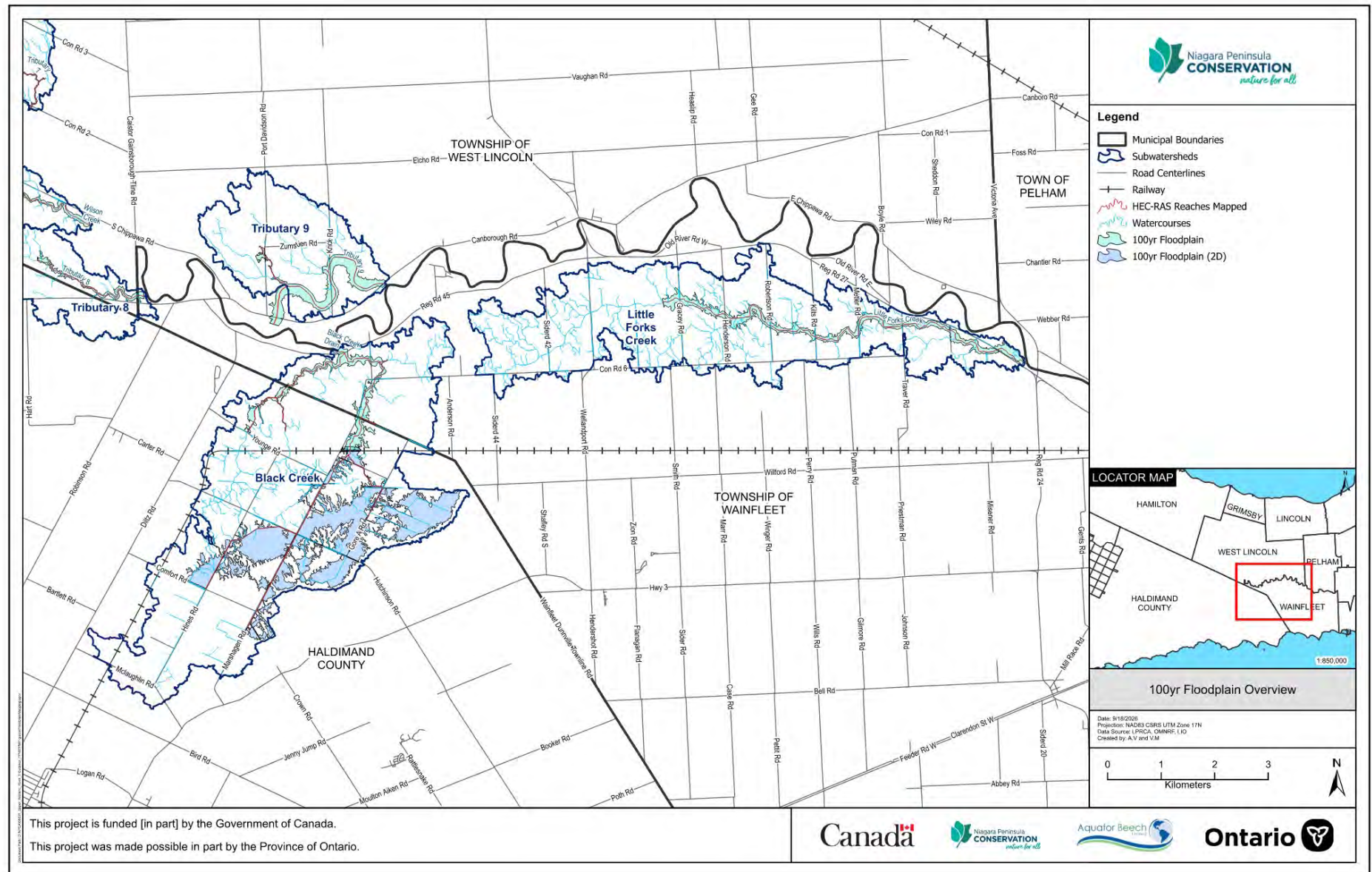


Figure 5-1. Overview of the Upper Welland River Tributaries Regulatory Floodplain Mapping - Eastern Subwatersheds

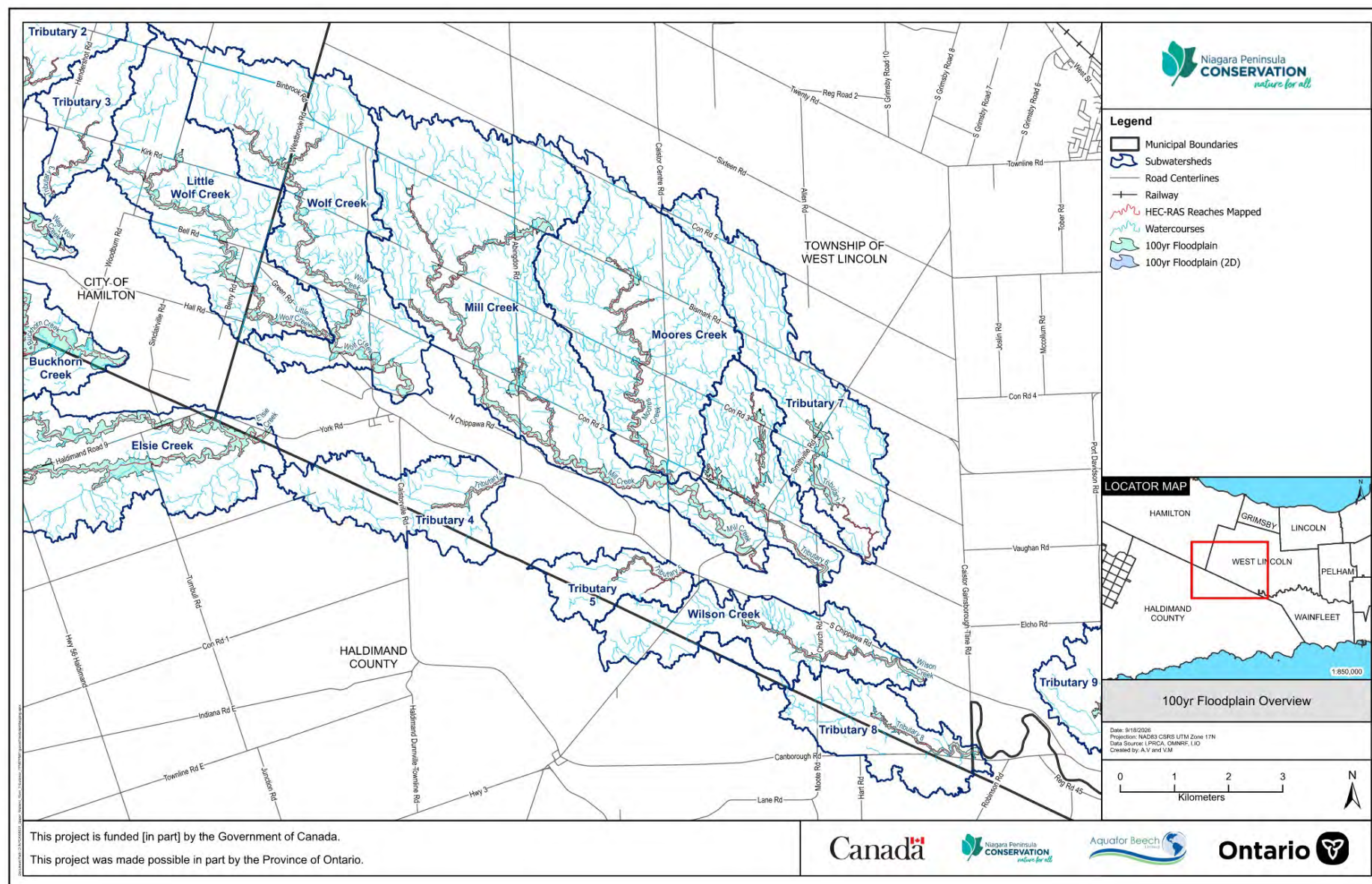


Figure 5-2. Overview of the Upper Welland River Tributaries Regulatory Floodplain Mapping - Central Subwatersheds

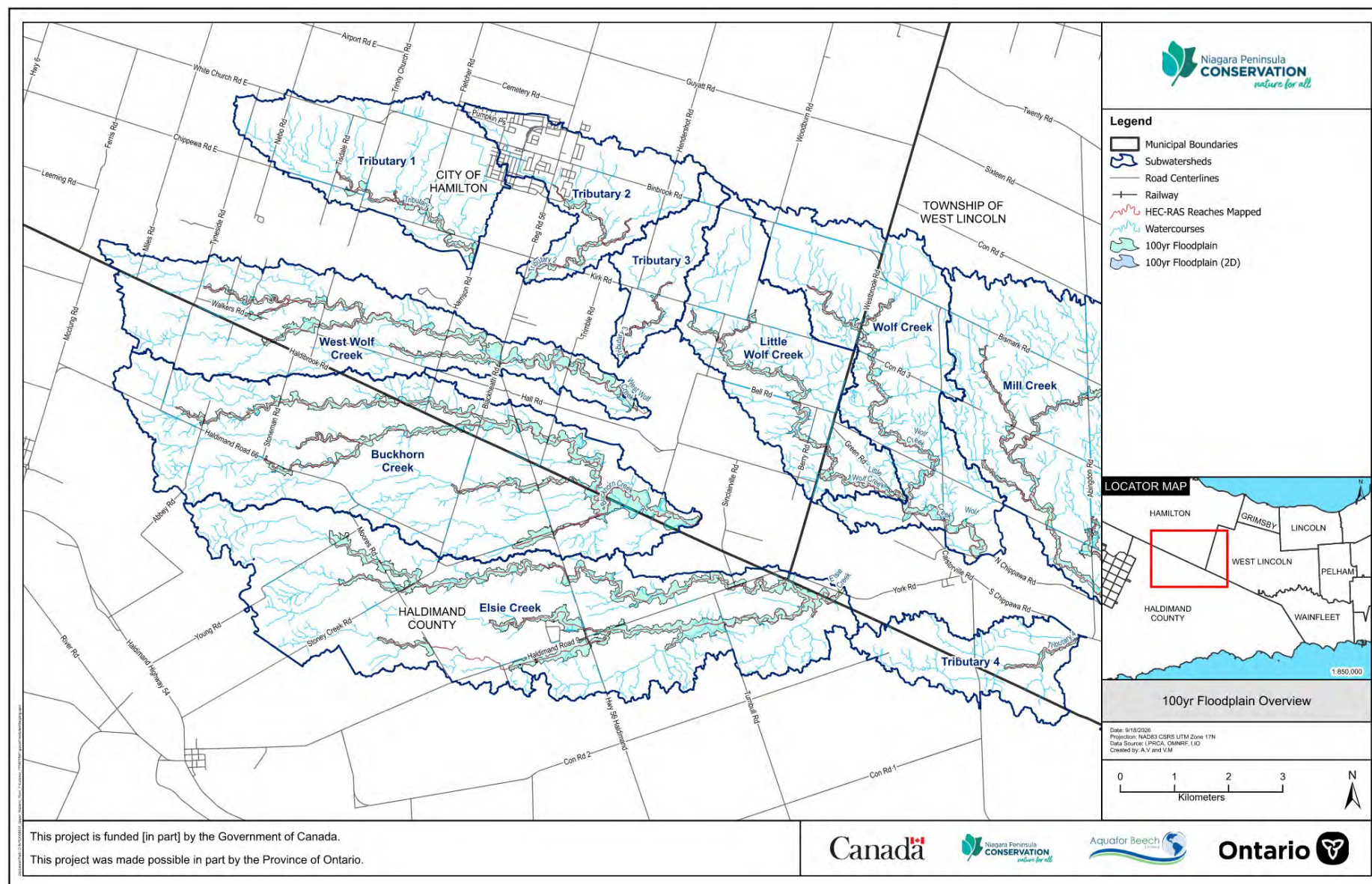


Figure 5-3. Overview of the Upper Welland River Tributaries Regulatory Floodplain Mapping - Western Subwatersheds

5.2 Flooded Building Assessment

The impact of the flood extents on private and public facilities was assessed using the building feature layer shapefile provided by the NPCA and aerial imagery. Upon examination, the Building Footprints shapefile provided by the NPCA was found to be incomplete, missing several residential buildings in the Elsie Creek area.

In total, 113 buildings within the study area are impacted by the Regulatory flooding, as they are either fully or partially located within the flooding extents under the 100-year (Regulatory) flood event. An additional 19 buildings are impacted by the larger flood events, but not the Regulatory event. The flood mapping figures in **Appendix E** show the locations of these impacted buildings for the Regulatory event. A summary of flooded buildings is shown in **Table 5-1**. An overview of the flooded building locations is shown in **Figure 5-4**. Overview of Flooded Building Locations – Eastern Subwatersheds

, **Figure 5-5**, and **Figure 5-6**.

Table 5-1. Summary of Buildings Located within the 100-Year (Regulatory) Flood Extents

Mapping ID	Building Type	HEC-RAS River	Minimum Event Flooded	Mapping ID	Building Type	HEC-RAS River	Minimum Event Flooded
1	Residential	Black Creek	100-Year	27	Residential	Elsie Creek	100-Year
2	Residential	Black Creek	100-Year	28	Residential	Elsie Creek	100-Year
3	Residential	Black Creek	100-Year	29	Residential	Elsie Creek	100-Year
4	Residential	Black Creek	100-Year	30	Residential	Elsie Creek	100-Year
5	Agricultural	Buckhorn Creek	100-Year	31	Residential	Elsie Creek	100-Year
6	Accessory	Buckhorn Creek	100-Year	32	Residential	Elsie Creek	100-Year
7	Commercial	Buckhorn Creek	100-Year	33	Residential	Elsie Creek	100-Year
8	Commercial	Buckhorn Creek	100-Year	34	Residential	Little Forks	100-Year
9	Commercial	Buckhorn Creek	100-Year	35	Agricultural	Little Forks	100-Year
10	Residential	Buckhorn Creek	100-Year	36	Agricultural	Little Forks	100-Year
11	Residential	Elsie Creek	100-Year	37	Residential	Little Forks	100-Year
12	Residential	Elsie Creek	100-Year	38	Agricultural	Little Forks	100-Year
13	Residential	Elsie Creek	100-Year	39	Residential	Little Forks	100-Year
14	Residential	Elsie Creek	100-Year	40	Residential	Little Forks	100-Year
15	Residential	Elsie Creek	100-Year	41	Residential	Little Forks	100-Year
16	Residential	Elsie Creek	100-Year	42	Agricultural	Little Forks	100-Year
17	Residential	Elsie Creek	100-Year	43	Accessory	Little Forks	100-Year
18	Residential	Elsie Creek	100-Year	44	Residential	Mill Creek	100-Year
19	Residential	Elsie Creek	100-Year	45	Agricultural	Mill Creek	100-Year
20	Residential	Elsie Creek	100-Year	46	Agricultural	Mill Creek	100-Year
21	Residential	Elsie Creek	100-Year	47	Agricultural	Mill Creek	100-Year
22	Residential	Elsie Creek	100-Year	48	Agricultural	Mill Creek	100-Year
23	Residential	Elsie Creek	100-Year	49	Residential	Mill Creek	100-Year
24	Residential	Elsie Creek	100-Year	50	Accessory	Mill Creek	100-Year
25	Residential	Elsie Creek	100-Year	51	Commercial	Mill Creek	100-Year
26	Residential	Elsie Creek	100-Year	52	Residential	Mill Creek	100-Year

Mapping ID	Building Type	HEC-RAS River	Minimum Event Flooded
53	Residential	Mill Creek	100-Year
54	Residential	Mill Creek	100-Year
55	Residential	Trib_1	100-Year
56	Accessory	Trib_1	100-Year
57	Residential	Trib_1	100-Year
58	Residential	Trib_1	100-Year
59	Residential	Trib_1	100-Year
60	Residential	Trib_1	100-Year
61	Residential	Trib_1	100-Year
62	Residential	Trib_1	100-Year
63	Residential	Trib_1	100-Year
64	Agricultural	Trib_1	100-Year
65	Accessory	Trib_1	100-Year
66	Accessory	Trib_1	100-Year
67	Accessory	Trib_1	100-Year
68	Accessory	Trib_1	100-Year
69	Residential	Trib_1	100-Year
70	Residential	Trib_1	100-Year
71	Accessory	Trib_1	100-Year
72	Residential	Trib_1	100-Year
73	Residential	Trib_6	100-Year
74	Residential	Trib_6	100-Year
75	Residential	Trib_7	100-Year
76	Accessory	Trib_9	100-Year
77	Agricultural	Trib_9	100-Year
78	Residential	Trib_9	100-Year
79	Agricultural	Trib_9	100-Year
80	Agricultural	Trib_9	100-Year
81	Agricultural	Trib_9	100-Year
82	Agricultural	Trib_9	100-Year
83	Agricultural	West Wolf Creek	100-Year
84	Residential	West Wolf Creek	100-Year
85	Agricultural	West Wolf Creek	100-Year
86	Residential	Wolf Creek	100-Year
87	Accessory	Wolf Creek	100-Year
88	Residential	Wolf Creek	100-Year
89	Residential	Wolf Creek	100-Year
90	Residential	Wolf Creek	100-Year
91	Residential	Wolf Creek	100-Year
92	Residential	Wolf Creek	100-Year

Mapping ID	Building Type	HEC-RAS River	Minimum Event Flooded
93	Residential	Elsie Creek	200-Year
94	Residential	Elsie Creek	200-Year
95	Accessory	Elsie Creek	200-Year
96	Agricultural	Elsie Creek	350-Year
97	Residential	Elsie Creek	100-Year
98	Agricultural	Elsie Creek	100-Year
99	Agricultural	Elsie Creek	100-Year
100	Agricultural	Elsie Creek	100-Year
101	Agricultural	Buckhorn Creek	200-Year
102	Residential	Buckhorn Creek	100-Year
103	Residential	Buckhorn Creek	100-Year
104	Accessory	Buckhorn Creek	100-Year
105	Residential	Buckhorn Creek	100-Year
106	Residential	Buckhorn Creek	100-Year
107	Residential	Buckhorn Creek	200-Year
108	Residential	Trib_1	350-Year
109	Accessory	Wolf Creek	200-Year
110	Residential	Black Creek	200-Year
111	Accessory	Black Creek	350-Year
112	Agricultural	Little Forks	350-Year
113	Agricultural	Little Forks	200-Year
114	Agricultural	Little Forks	200-Year
115	Agricultural	Little Forks	200-Year
116	Agricultural	Little Forks	200-Year
117	Agricultural	Little Forks	200-Year
118	Agricultural	Little Forks	200-Year
119	Accessory	Little Forks	200-Year
120	Accessory	Black Creek 2-D	100-Year
121	Residential	Black Creek 2-D	100-Year
122	Agricultural	Black Creek 2-D	200-Year
123	Agricultural	Black Creek 2-D	100-Year
124	Accessory	Black Creek 2-D	100-Year
125	Accessory	Black Creek 2-D	100-Year
126	Residential	Black Creek 2-D	100-Year
127	Agricultural	Black Creek 2-D	100-Year
128	Accessory	Black Creek 2-D	100-Year
129	Residential	Black Creek 2-D	100-Year
130	Agricultural	Black Creek 2-D	100-Year
131	Agricultural	Black Creek 2-D	100-Year
132	Accessory	Black Creek 2-D	100-Year

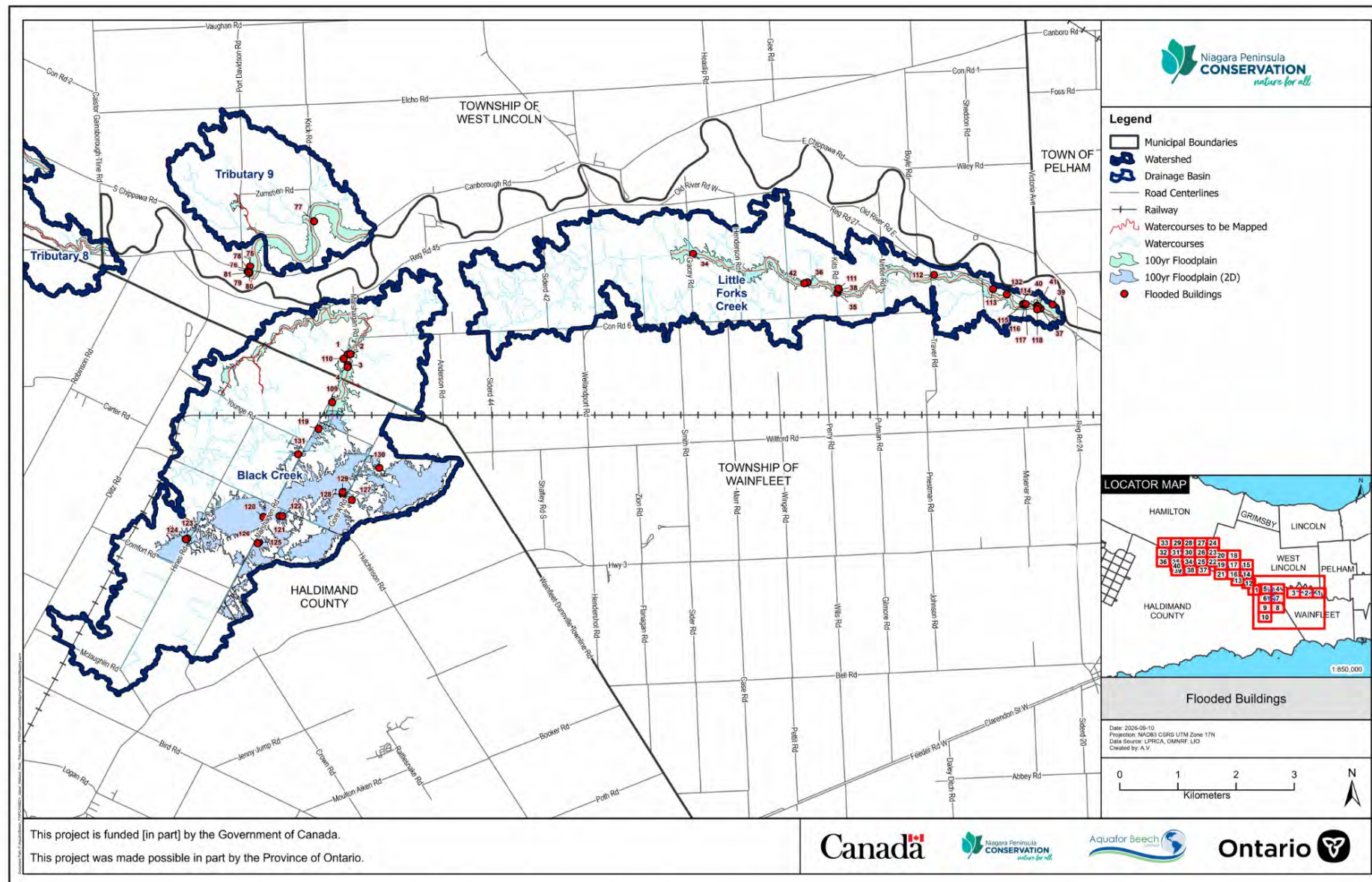


Figure 5-4. Overview of Flooded Building Locations – Eastern Subwatersheds

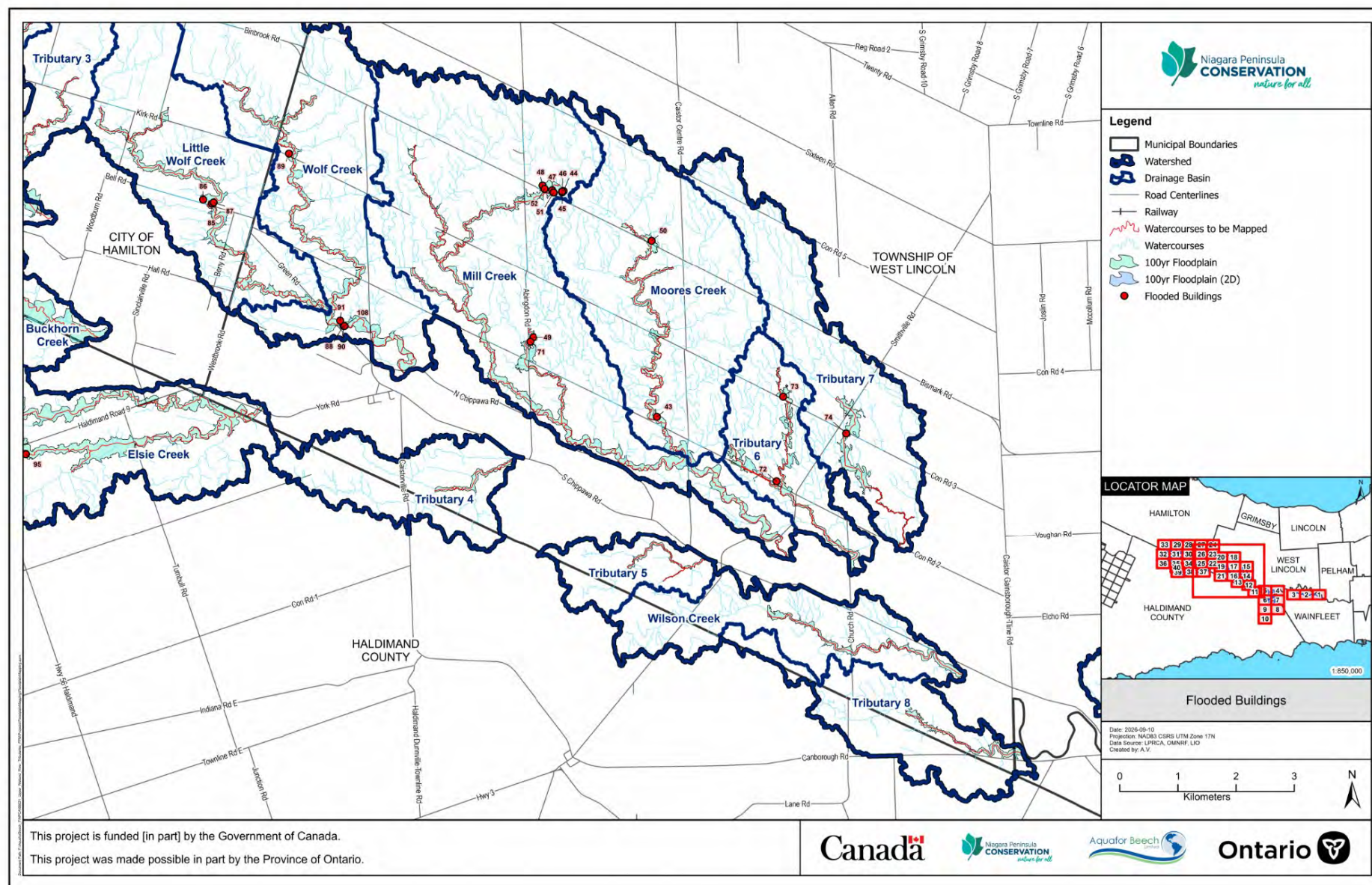


Figure 5-5. Overview of Flooded Building Locations – Central Subwatersheds

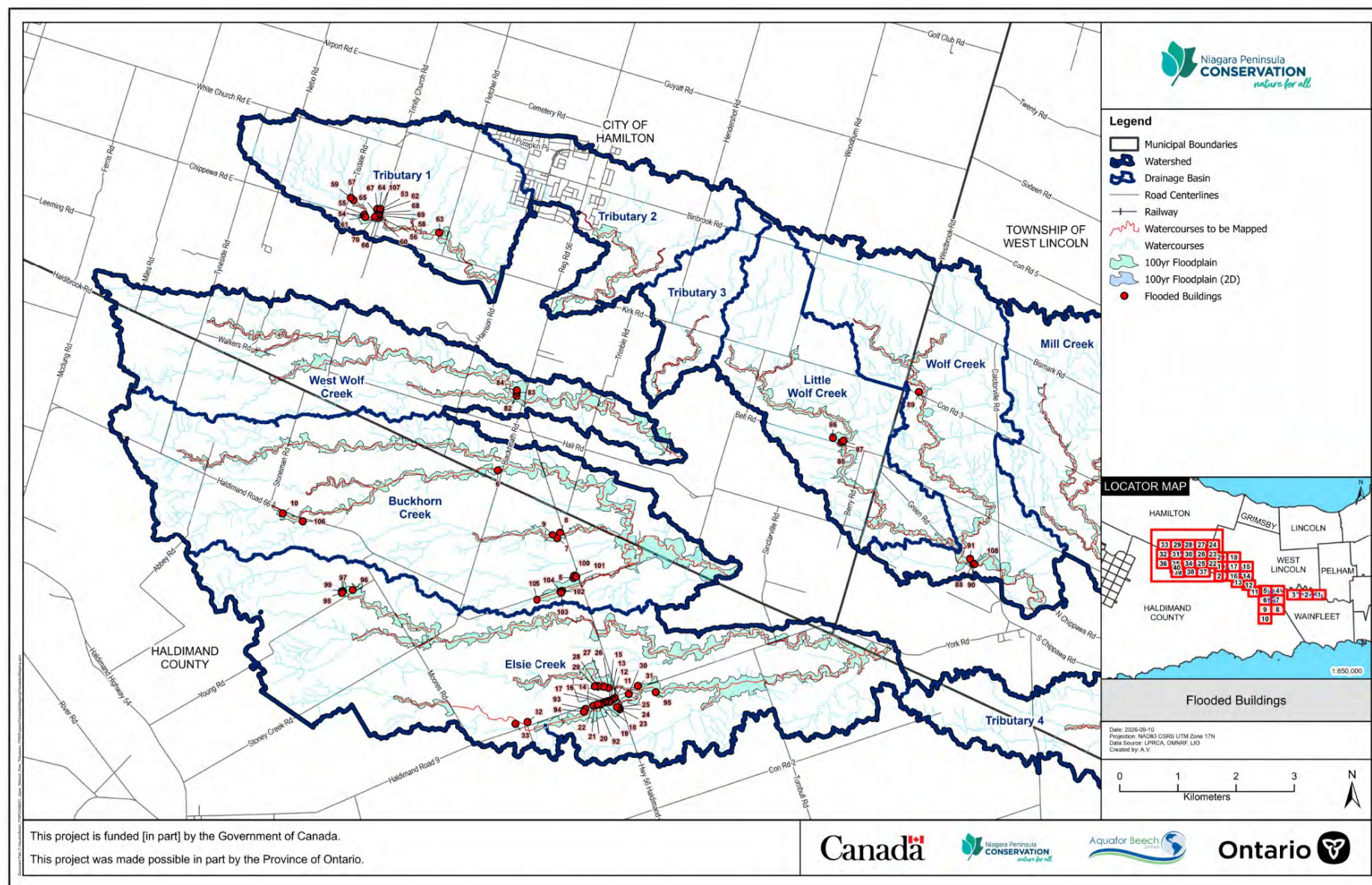


Figure 5-6. Overview of Flooded Building Locations – Western Subwatersheds

5.3 Road Crossing Performance

Pedestrian and vehicle access can be limited when a road crossing is overtopped and inundated. As per the Technical Guide – River and Stream System: Flooding Hazard Limit (OMNR, 2002), a road is impassible if the overtopping water depth is equal or greater than 0.30 m. A road can be overtopped but only becomes impassable if this threshold is reached or exceeded. In order to perform this analysis, the output results from the final HEC-RAS model have been used, taking the lowest elevation point of the roadway (minimum weir flow) and the final estimated water surface elevation at the upstream face of the culvert or bridge. The following section of this report has been completed based on the 1-D hydraulic results associated with this report. No roadway crossings were observed to overtop within the 2-D hydraulic analysis.

Under the Regulatory flood (100-year storm event), flows are expected to exceed the capacity of an estimated 86 roadway structure crossings, causing the road profile to be overtopped, as summarized in **Table 5-2**.

Table 5-2. Total of Road Crossing Structures Overtopped and Impassible for the 50-year, 100-year, 200-year and 350-year Flood Events

		Total Structures Overtopped				Total Structures Impassable			
HEC-RAS River	Total Roadway Crossings	50-Year	100-Year	200-Year	350-Year	50-Year	100-Year	200-Year	350-Year
Little Forks Drain	9	7	8	8	8	2	4	7	7
Trib_9	4	1	3	3	3	0	2	2	2
Black Creek Drain	4	4	4	4	4	1	2	3	4
Trib_8	2	2	2	2	2	0	2	2	2
Wilson Creek	1	1	1	1	1	0	0	0	0
Trib_7	4	3	3	3	3	1	1	1	1
Trib_6	7	4	4	5	5	0	0	0	0
Mill Creek	14	12	12	13	13	2	4	5	6
Trib_5	1	0	0	0	0	0	0	0	0
Trib_4	1	0	0	1	1	0	0	0	0
Wolf Creek	12	9	10	10	10	3	4	7	8
Elsie Creek	15	12	12	13	14	3	4	4	5
Buckhorn Creek	21	14	15	18	19	5	5	7	11
West Wolf Creek	10	8	8	8	8	3	5	5	5
Trib_3	1	0	0	0	0	0	0	0	0
Trib_2	3	1	1	1	1	0	0	0	0
Trib_1	3	3	3	3	3	1	2	2	3
Total	112	81	86	93	95	21	35	45	54

Of these 86 overtopped structures, 35 would be considered impassable (water depth $\geq 0.3\text{m}$) under the Regulatory event. In order to provide additional insight into the road overtopping conditions, each road crossing structure included in the hydraulic model was classified for each storm event using the colour code described below. **Table 5-3** provides details on the hydraulic performance of each roadway crossing modelled in the 1-D HEC

-RAS model, including water depth over the roadway, ABL crossing reference ID corresponding to the structure inventory sheets, and minimum flood event where roadway overtopping was observed. Private crossings were not included in the analysis.

The colour coding of roadway flow depths is based on 3 categories:

- Road not overtopped – highlighted in green
- Road overtopped but passable (water depth < 0.30 m) – highlighted in orange
- Road impassable (water depth ≥ 0.30 m) – highlighted in red

Table 5-3. Roadway Overtopping Depth Conditions for all Roadway Crossings Modelled in 1-D

River	Reach	River Station	ABL Crossing ID	Roadway	Min. Road Elev. (m)	Roadway Flow Depth (m)				Min. Flood Event where Overtopping Occurs
						50-Year	100-Year	200-Year	350-Year	
Little Forks Cr	Little Forks_1	1616	ABL_15	County Road 27	175.25	0.00	0.00	0.00	0.00	None
Little Forks Cr	Little Forks_1	1815	ABL_111	Farr Road	173.06	0.26	1.49	2.08	2.19	25-Year
Little Forks Cr	Little Forks_1	2766	ABL_14	Elsie Road	174.44	0.00	0.14	0.73	0.84	100-Year
Little Forks Cr	Little Forks_1	3801	ABL_13	Traver Road	174.66	0.09	0.28	0.58	0.68	50-Year
Little Forks Cr	Little Forks_1	4857	ABL_20	Metler Road	174.47	0.47	0.63	0.89	0.98	5-Year
Little Forks Cr	Little Forks_1	6065	ABL_19	Kilts Road	175.57	0.23	0.27	0.33	0.36	10-Year
Little Forks Cr	Little Forks_1	7021	ABL_18	Robertson Road	175.79	0.36	0.41	0.45	0.49	5-Year
Little Forks Cr	Little Forks_1	8306	ABL_17	Henderson Road	176.17	0.28	0.34	0.40	0.44	5-Year
Little Forks Cr	Little Forks_1	9269	ABL_16	Gracey Road	176.67	0.17	0.20	0.21	0.23	5-Year
Trib_9	9_1-1	74	ABL_96	Canborough Road	175.22	0.00	0.00	0.00	0.00	None
Trib_9	9_1-1	1633	ABL_95	Krick Road	174.26	0.00	0.68	0.69	0.69	100-Year
Trib_9	9_1-1-West	307	ABL_307	Canborough Road	174.60	0.00	0.39	0.39	0.40	100-Year
Trib_9	9_1-3	4355	ABL_98	Port Davidson Road	179.12	0.06	0.07	0.07	0.09	2-Year
Black Creek Dr	Black Creek_0	1203	ABL_61	Haldimand Road 45	173.72	0.31	1.25	1.26	1.27	25-Year
Black Creek Dr	Black Creek_1	1912	ABL_41	Marshagan Road	174.72	0.08	0.25	0.38	0.4	50-Year
Black Creek Dr	Black Creek_2	2499	ABL_37	Concession Road 6	175.50	0.24	0.31	0.38	0.42	25-Year
Black Creek Dr	Black Creek_3	3355	ABL_142	Wainfleet-Dunville Townline	176.52	0.30	0.30	0.30	0.33	10-Year
Trib_8	8_1	202	ABL_97	Castor-Gainsboro Townline	174.83	0.12	0.33	0.34	0.35	25-Year
Trib_8	8_1	202	ABL_97	Castor-Gainsboro Townline	174.83	0.12	0.33	0.34	0.35	25-Year
Wilson Creek	Wilson_1	3884	ABL_53	Church Road	179.00	0.20	0.22	0.25	0.28	5-Year
Trib_7	7_1-1	1017	ABL_90	Concession Road 2	179.85	0.00	0.00	0.00	0.00	None
Trib_7	7_1-2	4481	ABL_88	Concession Road 3	185.47	0.19	0.22	0.25	0.27	10-Year
Trib_7	7_1-2	4969	ABL_89	Smithville Road	186.56	0.19	0.21	0.23	0.24	2-Year
Trib_7	7_1-2	5103	ABL_308	Allen Road	186.32	0.45	0.47	0.49	0.51	2-Year
Trib_6	6_1-1	1543	ABL_93	Church Road	177.61	0.00	0.00	0.11	0.18	200-Year
Trib_6	6_1-1	3171	ABL_94	Smithville Road	180.94	0.06	0.13	0.18	0.20	50-Year
Trib_6	6_1-1	3749	ABL_92	Concession Road 2	182.60	0.27	0.26	0.26	0.26	100-Year

River	Reach	River Station	ABL Crossing ID	Roadway	Min. Road Elev. (m)	Roadway Flow Depth (m)				Min. Flood Event where Overtopping Occurs
						50-Year	100-Year	200-Year	350-Year	
Trib_6	6_1-2	5683	ABL_85	Concession Road 3	188.88	0.06	0.06	0.07	0.08	10-Year
Trib_6	6_1-2	5683	ABL_301	Concession Road 3	188.88	0.06	0.06	0.07	0.08	10-Year
Trib_6	6_2-1	113	ABL_86	Concession Road 2	183.34	0.00	0.00	0.00	0.00	None
Trib_6	6_2-2	353	ABL_302	Concession Road 2	183.88	0.00	0.00	0.00	0.00	None
Mill Creek	Mill_1	1700	ABL_12	Smithville Road	178.96	0.00	0.00	0.08	0.47	200-Year
Mill Creek	Mill_1	5552	ABL_3	Calstor Centre Road	179.78	0.43	0.54	0.71	0.86	5-Year
Mill Creek	Mill_3	10661	ABL_33	Abingdon Road	184.19	0.29	0.34	0.38	0.41	10-Year
Mill Creek	Mill_3	12837	ABL_32	Concession Road 2	186.79	0.25	0.32	0.38	0.41	25-Year
Mill Creek	Mill_5	16620	ABL_76	Concession Road 3	193.03	0.13	0.18	0.22	0.25	50-Year
Mill Creek	MillTrib_2	1995	ABL_36	Abingdon Road	187.43	0.23	0.24	0.25	0.26	2-Year
Mill Creek	MillTrib_2	2161	ABL_34	Concession Road 2	187.61	0.27	0.29	0.31	0.33	2-Year
Mill Creek	MillTrib_2	2531	ABL_35	Abingdon Road	188.28	0.00	0.00	0.00	0.00	2-Year
Mill Creek	MillTrib_4	1022	ABL_6	Concession Road 3	193.03	0.20	0.24	0.26	0.27	10-Year
Mill Creek	MillTrib_4	2968	ABL_7	Abingdon Road	197.79	0.14	0.16	0.18	0.19	5-Year
Mill Creek	MillTrib_4	3467	ABL_8	Silver Street/Bismark Road	199.19	0.10	0.11	0.12	0.13	5-Year
Mill Creek	Moore's_1	1374	ABL_2	Concession Road 2	181.85	0.36	0.42	0.47	0.51	10-Year
Mill Creek	Moore's_1	5342	ABL_1	Concession Road 3	186.90	0.23	0.26	0.29	0.30	10-Year
Mill Creek	Moore's_2	9217	ABL_68	Silver Street	194.70	0.15	0.16	0.17	0.18	2-Year
Trib_5	5_1-1	1009	ABL_91	South Chippawa Road	179.89	0.00	0.00	0.00	0.00	None
Trib_4	4_1	1014	ABL_87	South Chippawa Road	183.18	0.00	0.00	0.06	0.11	200-Year
Wolf Creek	LittleWolf_1	501	ABL_75	Green Road	185.66	0.42	0.50	0.55	0.60	5-Year
Wolf Creek	LittleWolf_1	3965	ABL_74	Westbrook Road	190.19	0.00	0.00	0.00	0.00	None
Wolf Creek	LittleWolf_1	4463	ABL_73	Berry Road	190.62	0.16	0.24	0.32	0.37	50-Year
Wolf Creek	LittleWolf_1	5807	ABL_72	Bell Road	192.14	0.14	0.23	0.33	0.38	50-Year
Wolf Creek	LittleWolf_2	8811	ABL_60	Woodburn Road	197.14	0.00	0.00	0.00	0.00	None
Wolf Creek	LittleWolfTrib_1	900	ABL_69	Kirk Road	199.47	0.09	0.10	0.10	0.11	5-Year
Wolf Creek	Wolf_1	1016	ABL_55	North Chippawa Road	181.49	0.49	0.71	0.77	0.70	5-Year
Wolf Creek	Wolf_1	3315	ABL_54	Caistorville Road	185.05	0.00	0.27	0.42	0.52	100-Year

River	Reach	River Station	ABL Crossing ID	Roadway	Min. Road Elev. (m)	Roadway Flow Depth (m)				Min. Flood Event where Overtopping Occurs
						50-Year	100-Year	200-Year	350-Year	
Wolf Creek	Wolf_2	6016	ABL_45	Concession Road 2	187.25	0.09	0.18	0.25	0.29	50-Year
Wolf Creek	Wolf_2	10990	ABL_46	Concession Road 3	194.00	0.31	0.34	0.38	0.41	10-Year
Wolf Creek	Wolf_2	12169	ABL_47	Westbrook Road	196.22	0.28	0.31	0.30	0.32	5-Year
Wolf Creek	WolfTrib_2	138	ABL_21	Concession Road 3	196.57	0.23	0.25	0.27	0.30	5-Year
Elsie Creek	Elsie_1	1112	ABL_77	York Street	183.28	0.50	0.58	0.65	0.70	5-Year
Elsie Creek	Elsie_3	4766	ABL_43	Haldimand Road 9	185.75	0.17	0.18	0.22	0.25	25-Year
Elsie Creek	Elsie_3	9828	ABL_43	Highway 56	193.12	0.19	0.31	0.37	0.41	50-Year
Elsie Creek	Elsie_4	13828	ABL_40	Stoney Creek Road	198.04	0.49	0.53	0.56	0.57	25-Year
Elsie Creek	Elsie_4	14873	ABL_39	Moore's Road	199.55	0.17	0.18	0.19	0.20	2-Year
Elsie Creek	Elsie_4	15978	ABL_38	Young Road	201.69	0.17	0.19	0.18	0.21	5-Year
Elsie Creek	ElsieTrib_2-1	2733	ABL_78	Turnbull Road	187.54	0.31	0.38	0.44	0.47	10-Year
Elsie Creek	ElsieTrib_2-3	5297	ABL_80	Haldimand Road 9	189.16	0.00	0.00	0.00	0.01	350-Year
Elsie Creek	ElsieTrib_2-3	5669	ABL_79	Highway 56	192.95	0.00	0.00	0.00	0.00	None
Elsie Creek	ElsieTrib_2-5	490	ABL_84	Highway 56	191.52	0.00	0.00	0.10	0.15	200-Year
Elsie Creek	ElsieTrib_2-5	2200	ABL_83	Singer Road	192.53	0.19	0.23	0.25	0.28	5-Year
Elsie Creek	ElsieTrib_2-5	2321	ABL_82	Haldimand Road 9	193.00	0.24	0.27	0.29	0.30	5-Year
Elsie Creek	ElsieTrib_2-5	4010	ABL_81	Moore's Road	196.33	0.19	0.20	0.21	0.22	10-Year
Elsie Creek	ElsieTrib_3	363	ABL_10	Stoney Creek Road	198.59	0.02	0.03	0.06	0.07	50-Year
Elsie Creek	ElsieTrib_3	495	ABL_9	Moore's Road	198.84	0.15	0.17	0.18	0.19	2-Year
Buckhorn Creek	Buckhorn_2	5227	ABL_67	Haldibrook Road	186.34	0.39	0.42	0.47	0.49	5-Year
Buckhorn Creek	Buckhorn_3	8141	ABL_70	Trimble Road	189.35	0.00	0.00	0.18	0.23	200-Year
Buckhorn Creek	Buckhorn_3	9120	ABL_181	Highway 56	190.63	0.38	0.47	0.54	0.59	5-Year
Buckhorn Creek	Buckhorn_4	9976	ABL_66	Blackheath Road	190.98	0.57	0.68	0.77	0.82	10-Year
Buckhorn Creek	Buckhorn_4	11230	ABL_65	Harrison Road	193.14	0.26	0.28	0.31	0.32	5-Year
Buckhorn Creek	Buckhorn_4	11782	ABL_64	Haldibrook Road	193.98	0.26	0.29	0.31	0.33	2-Year
Buckhorn Creek	Buckhorn_4	12893	ABL_186	Moore's Road	195.57	0.39	0.42	0.45	0.47	2-Year
Buckhorn Creek	Buckhorn_4	14345	ABL_63	Stoneman Road	199.68	0.24	0.26	0.29	0.31	5-Year
Buckhorn Creek	Buckhorn_4	16169	ABL_62	Abbey Road	204.59	0.22	0.23	0.25	0.28	2-Year

River	Reach	River Station	ABL Crossing ID	Roadway	Min. Road Elev. (m)	Roadway Flow Depth (m)				Min. Flood Event where Overtopping Occurs
						50-Year	100-Year	200-Year	350-Year	
Buckhorn Creek	BuckTrib_1	315	ABL_58 E	Concession 4	188.23	0.17	0.22	0.25	0.29	25-Year
Buckhorn Creek	BuckTrib_1	690	ABL_58 E	Concession 4	192.84	0.00	0.00	0.03	0.08	200-Year
Buckhorn Creek	BuckTrib_1	1046	ABL_58	Concession 4	193.41	0.10	0.12	0.16	0.18	25-Year
Buckhorn Creek	BuckTrib_1	1164	ABL_59	Highway 56	195.59	0.00	0.00	0.00	0.34	350-Year
Buckhorn Creek	BuckTrib_2	715	ABL_25	Haldibrook Road	188.99	0.00	0.00	0.00	0.00	None
Buckhorn Creek	BuckTrib_2	1440	ABL_23	Highway 56	192.16	0.00	0.10	0.22	0.26	100-Year
Buckhorn Creek	BuckTrib_2	3181	ABL_24	Stoney Creek Road	195.44	0.00	0.00	0.00	0.00	None
Buckhorn Creek	BuckTrib_3-1	159	ABL_29	Blackheath Road	191.08	0.33	0.40	0.46	0.51	10-Year
Buckhorn Creek	BuckTrib_3-1	645	ABL_28	Haldibrook Road	191.73	0.23	0.26	0.29	0.31	5-Year
Buckhorn Creek	BuckTrib_3-2	3716	ABL_182	Moore's Road	197.05	0.26	0.28	0.30	0.31	2-Year
Buckhorn Creek	BuckTrib_3-2	4584	ABL_52	Highway 66	202.72	0.00	0.00	0.05	0.08	200-Year
Buckhorn Creek	BuckTrib_3-3	494	ABL_300	Moore's Road	196.54	0.20	0.21	0.22	0.23	2-Year
West Wolf Creek	WestWolf_1	3412	ABL_50	Trimble Road	188.28	0.78	0.82	0.86	0.88	2-Year
West Wolf Creek	WestWolf_1	5936	ABL_51	Highway 56	192.61	0.25	0.31	0.36	0.39	25-Year
West Wolf Creek	WestWolf_1	5965	ABL_51.1	Blackheath Road	191.00	1.86	1.92	1.97	2.00	5-Year
West Wolf Creek	WestWolf_2	7534	ABL_0	Harrison Road	192.92	0.29	0.36	0.40	0.44	25-Year
West Wolf Creek	WestWolf_3	10523	ABL_22	Trinity Church Road	196.97	0.35	0.38	0.41	0.44	2-Year
West Wolf Creek	WestWolfTrib_1	1046	ABL_11	Harrison Road	194.42	0.00	0.00	0.00	0.00	None
West Wolf Creek	WestWolfTrib_2	1034	ABL_57	Trinity Church Road	199.98	0.15	0.19	0.23	0.24	50-Year
West Wolf Creek	WestWolfTrib_2	2170	ABL_56	Haldibrook Road	201.64	0.00	0.00	0.00	0.00	None
West Wolf Creek	WestWolfTrib_3	926	ABL_192	Walkers Road	202.04	0.24	0.25	0.27	0.29	2-Year
West Wolf Creek	WestWolfTrib_3	926	ABL_193	Walkers Road	202.04	0.24	0.25	0.27	0.29	2-Year
Trib_3	3_1	3305	ABL_107	Kirk Road	198.09	0.00	0.00	0.00	0.00	None
Trib_2	2_1-1	2119	ABL_106	Kirk Road	193.24	0.20	0.23	0.25	0.27	2-Year
Trib_2	2_1-2	5620	ABL_103	Southbrook Drive	206.00	0.00	0.00	0.00	0.00	None
Trib_1	1_1-1	2106	ABL_105	Kirk Road	194.50	0.22	0.26	0.29	0.31	10-Year
Trib_1	1_1-1	3087	ABL_104	Fletcher Road	196.12	0.36	0.40	0.42	0.44	5-Year
Trib_1	1_1-2	4626	ABL_100	Trinity Church Road	201.40	0.21	0.37	0.49	0.56	10-Year

5.3.1 Undersized Crossings

From a roadway and crossing design perspective, crossings can also be considered undersized if they do not convey the design peak flow event without roadway overtopping. While many crossings in this study are undersized from the overtopping perspective, low roadway profiles provide conveyance such that the upstream flood conditions are not significantly impacted. Such low-event conveyance crossings can be identified in **Table 5-3**.

For the purposes of this study, an undersized crossing is defined as one that has a significant impact on upstream flood conditions. To identify these crossings, several components of the hydraulic results were reviewed, including water surface elevation change across the roadway, flow width increase across the roadway, and the presence of buildings within the upstream Regulatory flood extents. Based on these factors, a list of crossings considered to significantly impact upstream flooding has been developed, and a priority level of 1 (highest) to 3 (lowest) assigned to each. A summary of the high flood impact crossings is provided in **Table 5-4**.

Table 5-4. Crossings with Significant Upstream Flood Impacts

River	Reach	River Station	ABL Crossing ID	Roadway	Priority Level
Trib_6	6_1-2	5683	ABL_85	Concession Road 3	1
Trib_6	6_1-2	5683	ABL_301	Concession Road 3	1
West Wolf Creek	WestWolf_1	5936	ABL_51	Highway 56	1
Trib_6	6_1-1	3749	ABL_92	Concession Road 2	1
Mill Creek	MillTrib_4	3467	ABL_8	Silver Street/Bismark Road	1
Buckhorn Creek	BuckTrib_1	1164	ABL_59	Highway 56	1
Buckhorn Creek	BuckTrib_3-2	4584	ABL_52	Highway 66	1
Trib_1	1_1-2	4626	ABL_100	Trinity Church Road	1
Buckhorn Creek	BuckTrib_2	1440	ABL_23	Highway 56	1
Black Creek Dr	Black Creek_3	3355	ABL_142	Wainfleet-Dunville Townline	1
Mill Creek	MillTrib_4	2968	ABL_7	Abingdon Road	1
Elsie Creek	ElsieTrib_2-3	5669	ABL_79	Highway 56	1
Elsie Creek	ElsieTrib_2-5	2321	ABL_82	Haldimand Road 9	1
West Wolf Creek	WestWolf_1	5965	ABL_51.1	Blackheath Road	1
Elsie Creek	Elsie_3	9828	ABL_43	Highway 56	2
Elsie Creek	Elsie_4	13828	ABL_40	Stoney Creek Road	2
Elsie Creek	ElsieTrib_2-5	4010	ABL_81	Moore's Road	2
Trib_1	1_1-1	2106	ABL_105	Kirk Road	2
Mill Creek	MillTrib_2	1995	ABL_36	Abingdon Road	3
Mill Creek	Moore's_1	5342	ABL_1	Concession Road 3	3
Elsie Creek	ElsieTrib_2-1	2733	ABL_78	Turnbull Road	3
Buckhorn Creek	Buckhorn_4	14345	ABL_63	Stoneman Road	3
Buckhorn Creek	Buckhorn_4	16169	ABL_62	Abbey Road	3

5.4 Climate Change Assessment

The hydrologic study for Upper Welland River Tributaries derived flows for the 200-year flood event and the 350-year flood events. As per FHIMP guidelines, these events represent proxy scenarios for climate change. As previously discussed, the tailwater condition for the climate change proxy events was the 100-Year Welland River water surface elevation with the respective 200/350-Year peak flows. Unlike the 100-Year simulation, no reduction in peak flow was used in the larger events. The extent of the flooding hazard limit for both of these events has been mapped, and results are included in **Appendix E**.

5.5 Spill Areas

Spill areas were noted across the model, where 1-D flows were not contained within the channel banks, and likely overtop into adjacent reaches. Spills are noted on the Regulatory mapping provided in **Appendix D**. Areas addressed by the flow balancing exercise described in section 3.11 of this report are considered contained within the model and have not been marked as spills. Flood extents in these areas reflect this accounting. However, in reaches where flows spill to unmapped adjacent reaches, the spill has not been quantified, and flood mapping was completed with the full peak flow accounted for. A brief summary of the spills out of the model is provided below.

5.5.1 Trib 4: 4_1

Flows upstream of South Chippawa Road just upstream of the Welland River confluence overtop a private laneway into an adjacent reach. This adjacent reach outlets to the Welland River a short distance downstream of the Trib_4 confluence. See **Figure 5-7** for a schematic of the spill area.

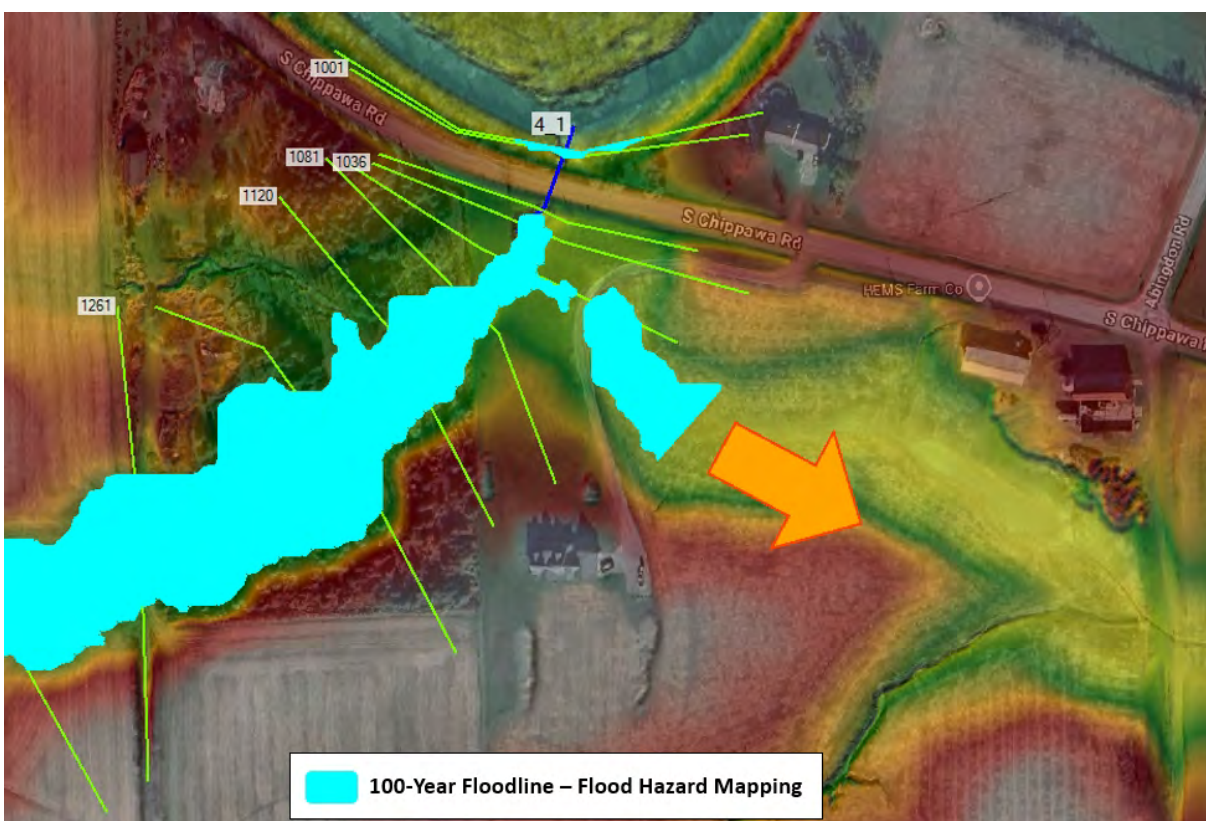


Figure 5-7. Reach 4_1 Spill to Adjacent Welland River Tributary

5.5.2 Trib 6: 6_1-2

Flows in Trib_6, Reach 6_1-2 between Concession Roads 2 and 3 spill out of the natural watercourse into an adjacent reach to the west. This reach returns to Trib_6, Reach 6_1-2 farther downstream. See **Figure 5-8** for a schematic of the spill area.

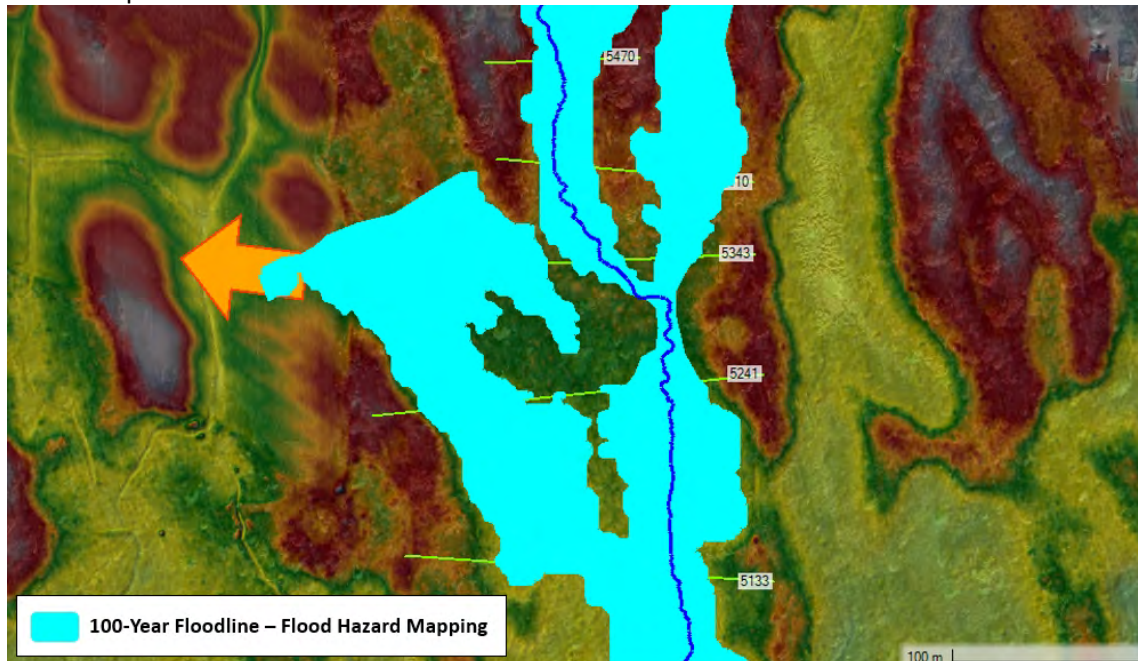


Figure 5-8. Reach 6_1-2 Spill from Channel

5.5.3 Trib 6: 6_2-2

Flows in Trib_6, Reach 6_2-2 upstream of Concession Road 2 overtop a private laneway into an adjacent reach to the west. This adjacent reach outlets to the Mill Creek river system. See **Figure 5-9** for a schematic of the spill area.

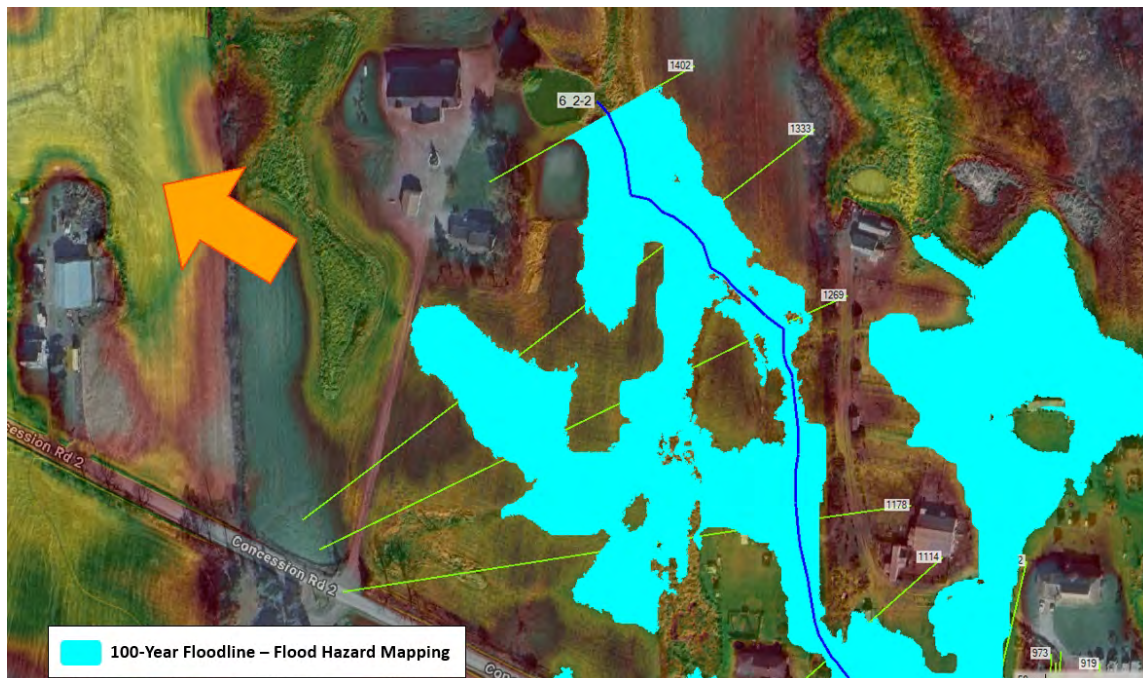


Figure 5-9. Reach 6_2-2 Spill to Mill Creek

5.5.4 Elsie Creek: Elsie_3

Flows in Elsie Creek, Reach Elsie_3 upstream of Sinclairville Road exceed the channel limits and overflow into an unmapped channel to the north. This adjacent reach outlets to the Welland River east of Sinclairville Road. See **Figure 5-10** for a schematic of the spill area.

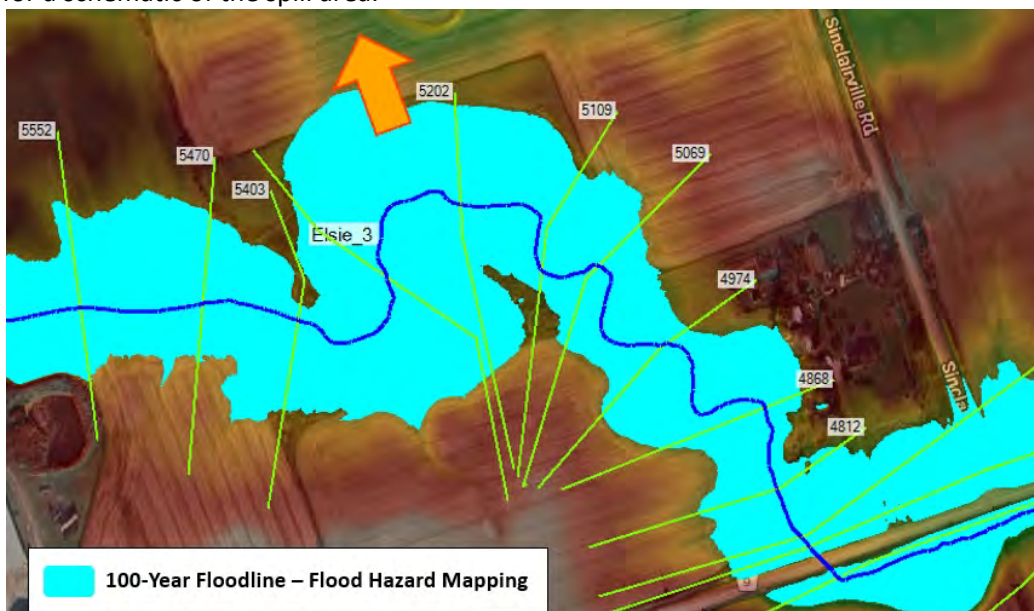


Figure 5-10. Reach Elsie_3 Spill to Adjacent Welland River Tributary

5.5.5 Buckhorn Creek: Buckhorn_1

Flows in Buckhorn Creek, Reach Buckhorn_1 exceed the upstream channel limits and overflow through a constructed channel the Welland River. See **Figure 5-11** for a schematic of the spill area.

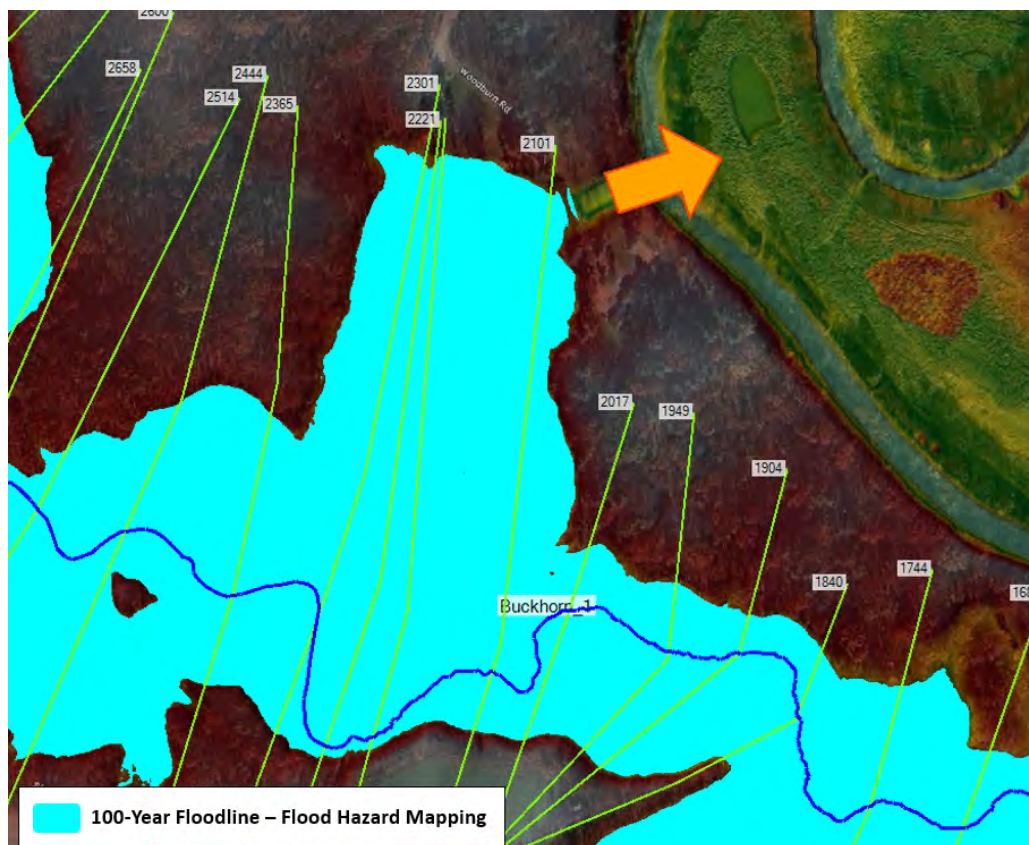


Figure 5-11. Reach Buckhorn_1 Spill to Welland River

5.5.6 Buckhorn Creek: BuckTrib_1

Flows in Buckhorn Creek, Reach BuckTrib_1 upstream of Highway 56 overtop to an unmapped watercourse to the north. High flood elevations in this area are the result of backwater from the Highway 56 crossing. See **Figure 5-12** for a schematic of the spill area.



Figure 5-12. Reach BuckTrib_1 Spill to Adjacent Watercourse

5.5.7 Buckhorn Creek: BuckTrib_3-2

Flows in Buckhorn Creek, Reach BuckTrib_3-2 upstream of Highway 66 overtop to an unmapped watercourse to the southeast. This watercourse eventually conflues with BuckTrib_3-2 downstream of the Highway and Moores Road crossings. High flood elevations in this area are the result of backwater from the Highway 66 crossing.. See **Figure 5-13** for a schematic of the spill area.

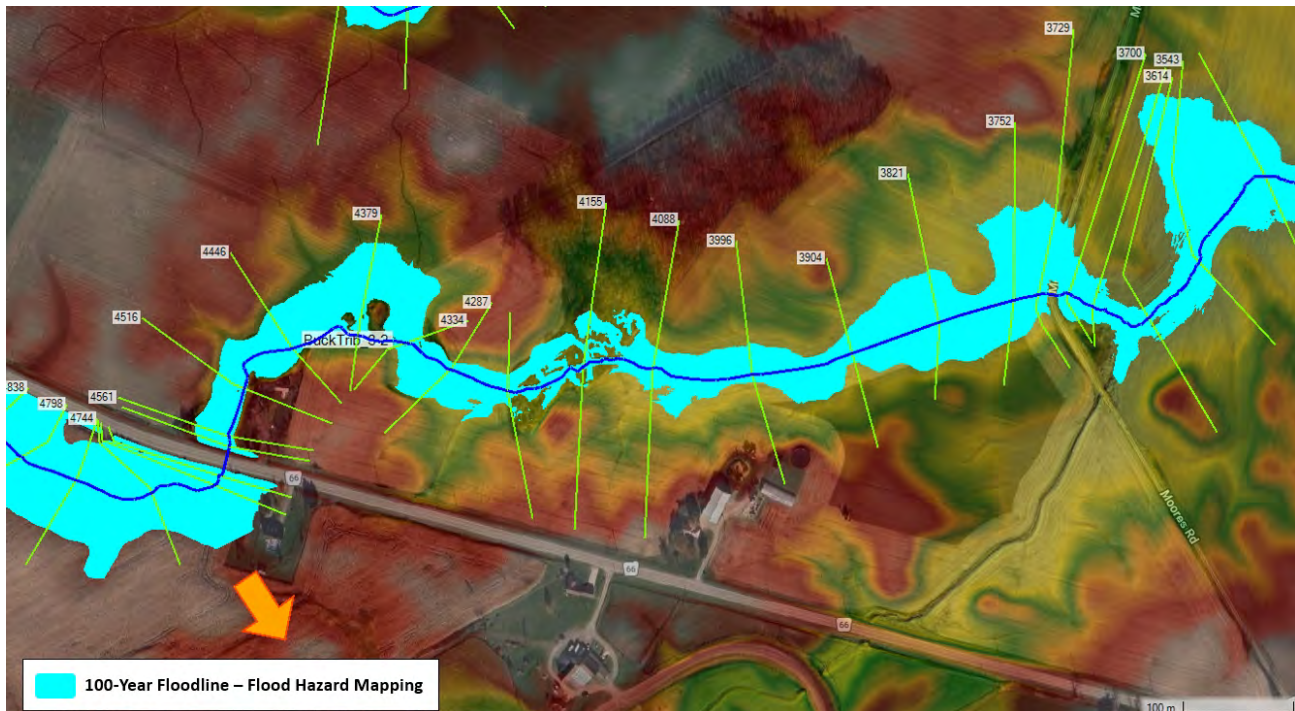


Figure 5-13. Reach BuckTrib_3-2 Spill to Adjacent Watercourse

5.5.8 West Wolf Creek: WestWolf_1

Flows in West Wolf Creek, Reach WestWolf_1 exceed the upstream channel limits and overflow to the Welland River. See **Figure 5-14** for a schematic of the spill area.

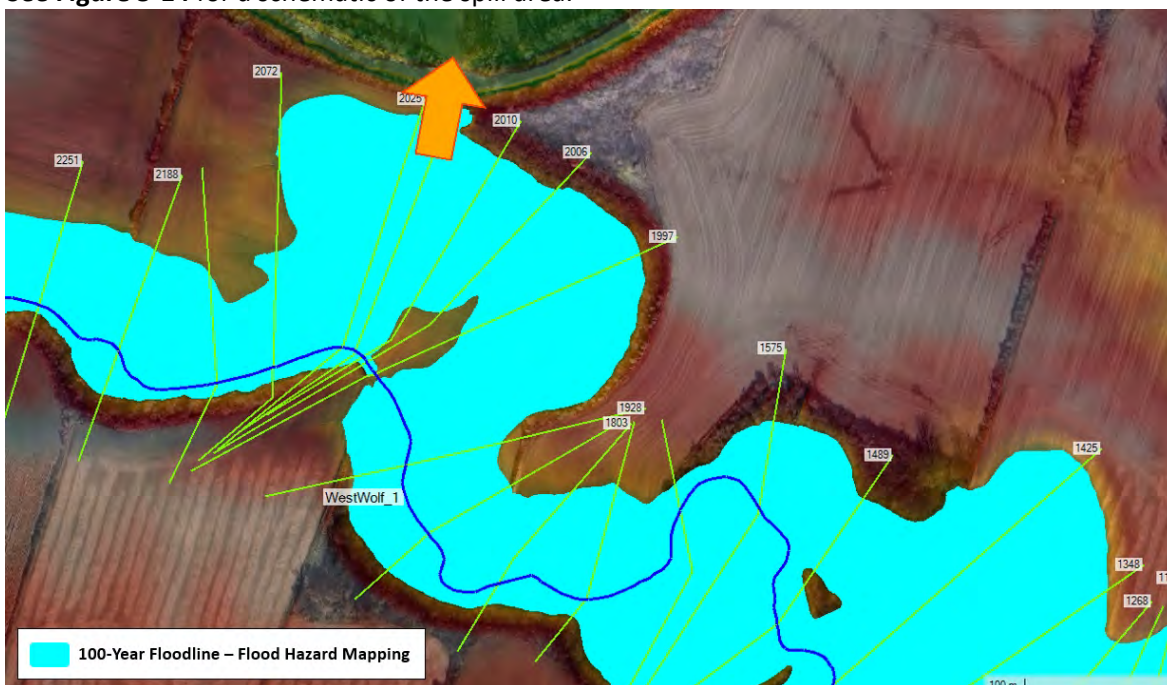


Figure 5-14. Reach WestWolf_1 Spill to Adjacent Watercourse

5.5.9 Trib_9: 9_1-3

Flows in Trib_9, Reach 9_1-3 exceed the upstream channel limits upstream of Port Davidson Road and overflow to the south, eventually returning to Reach 9_1-3. See **Figure 5-15** for a schematic of the spill area.

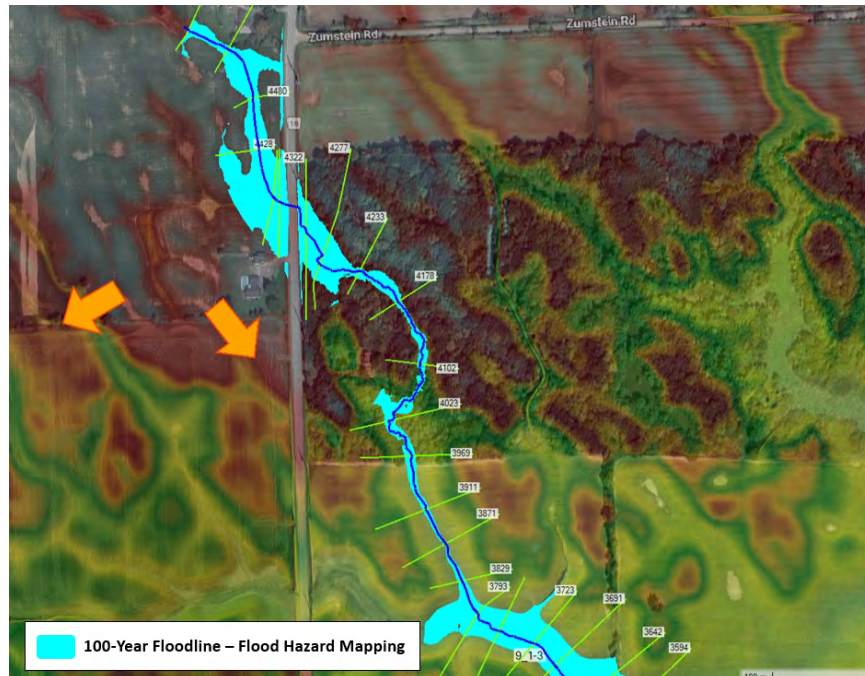


Figure 5-15. Reach 9_1-3 Spill to Adjacent Watercourse

5.6 Floodline Validation & Calibration

Historical flow and depth data was unavailable for model calibration and validation at the time of this study. While three stream gauges are present on the Welland River within the extents of this study, no gauges exist along the specific tributaries mapped. Similarly, the NPCA was unable to provide historical flood evidence such as high water marks or flood records to complete model validation.

5.7 1-D Model Sensitivity

Given the lack of historical flood data to verify the 1-D HEC-RAS hydraulic model, a sensitivity analysis has been completed for various model input parameters. This is the recommended approach by the current MNR guidelines, which specifically suggest sensitivity to roughness coefficients be used in-lieu of calibration. In addition to roughness coefficients, the model's sensitivity to peak flow inputs can be observed through the variation in mapped flood events shown in **Appendix D**.

To complete the sensitivity analysis of roughness coefficients within the 1-D hydraulic model, two additional geometry files were created. These input files were modified to first increase, then decrease, the Manning's roughness coefficients by 20% across the entire geometry. The resulting input coefficients are shown in **Table 5-5**.

Table 5-5. Manning's Roughness Coefficient Variation for Sensitivity Analysis

Land Cover	Manning's Roughness Coefficient		
	Mapping Scenario	+ 20%	- 20%
Forest	0.07	0.084	0.056
Coniferous Forest	0.07	0.084	0.056
Mixed Forest	0.07	0.084	0.056
Deciduous Forest	0.07	0.084	0.056
Treed Swamp	0.08	0.096	0.064
Thicket Swamp	0.08	0.096	0.064
Marsh	0.08	0.096	0.064
Open Water	0.03	0.036	0.024
Plantations - Tree Cultivated	0.055	0.066	0.044
Hedge Rows	0.08	0.096	0.064
Tilled	0.07	0.084	0.056
Transportation	0.025	0.03	0.02
Built-Up Area - Pervious	0.05	0.06	0.04
Built-Up Area - Impervious	0.025	0.03	0.02
Extraction - Aggregate	0.05	0.06	0.04
Undifferentiated	0.05	0.06	0.04

Each updated geometry file was run with a new scenario, and the resulting water surface elevations and channel velocities were compared to the Flood Hazard Mapping scenario. For the purposes of this analysis, any flood elevation change greater than 0.10 m in the 100-Year (Regulatory) flood event was noted. A summary of the water surface elevation and total velocity changes throughout the entire model (3066 cross sections) is shown in Table 5-6.

Table 5-6. Manning's Sensitivity Analysis Results Summary – 100-Year Event - Entire Model

HEC-RAS River	Cross Section Count	Manning's +20%		Manning's -20%	
		Average WSE Change (m)	Average Velocity Change (m/s)	Average WSE Change (m)	Average Velocity Change (m/s)
Black Creek Dr	121	0.03	-0.04	-0.04	0.05
Buckhorn Creek	444	0.05	-0.04	-0.05	0.05
Elsie Creek	458	0.05	-0.04	-0.05	0.06
Little Forks Cr	159	0.04	-0.02	-0.03	0.02
Mill Creek	489	0.08	-0.06	-0.08	0.08
Trib_1	89	0.05	-0.08	-0.04	0.06
Trib_2	99	0.03	-0.06	-0.04	0.11
Trib_3	49	0.04	-0.09	-0.05	0.13
Trib_4	32	0.05	-0.09	-0.05	0.11
Trib_5	47	0.03	-0.07	-0.03	0.10
Trib_6	141	0.02	-0.03	-0.02	0.05

HEC-RAS River	Cross Section Count	Manning's +20%		Manning's -20%	
		Average WSE Change (m)	Average Velocity Change (m/s)	Average WSE Change (m)	Average Velocity Change (m/s)
Trib_7	94	0.07	-0.11	-0.07	0.11
Trib_8	43	0.02	-0.03	-0.02	0.04
Trib_9	84	0.00	-0.01	0.00	0.01
West Wolf Creek	305	0.04	-0.03	-0.05	0.06
Wilson Creek	68	0.04	-0.05	-0.04	0.08
Wolf Creek	343	0.07	-0.05	-0.07	0.07

Throughout the model, 310 cross sections were identified as showing a 100-Year water surface elevation increase greater than 0.10 m with the increased roughness coefficients. The largest individual increase was 0.24 m, and the average noted (> 0.10 m) increase was 0.13 m. These results, including the percentage of total cross sections with higher WSE changes, and max and average WSE increases are summarized by River in **Table 5-7**. The most sensitive river systems appear to be Mill Creek and Trib_7, as both rivers have over one third (33%) of the cross sections showing higher sensitivity to the Manning's roughness coefficient increases under the Regulatory event in the +20% scenario. The potential impacts of Manning's sensitivity to the flood hazard of these systems are detailed below.

It is noted that several Rivers in the model had no cross sections showing WSE increases greater than 0.10 m, including Trib_2, Trib_3, Trib_4, Trib_5, Trib_6, Trib_8, Trib_9, and Wilson Creek. These reaches are therefore considered less sensitive to roughness changes within the model.

Table 5-7. Manning's Sensitivity Analysis Results – Cross Sections with >0.10 m WSE Increase (+20% Scenario) 100-Year Event

HEC-RAS River	Cross Section Count	Percentage of Total Cross Sections	Max WSE Change (m)	Average WSE Change (m)
Black Creek Dr	1	1%	0.11	0.11
Buckhorn Creek	9	2%	0.17	0.12
Elsie Creek	16	3%	0.13	0.11
Little Forks Cr	4	3%	0.11	0.11
Mill Creek	159	33%	0.20	0.14
Trib_1	3	3%	0.24	0.16
Trib_7	36	38%	0.19	0.13
West Wolf Creek	8	3%	0.11	0.11
Wolf Creek	74	22%	0.20	0.12

5.7.1 Mill Creek

The area of the Mill Creek river system that shows the greatest water surface elevation increases in the Manning's roughness sensitivity analysis is located between Reach Mill_1, XS 2400, and Reach Mill_3, XS 12826 and is highlighted in **Figure 5-16**. Flood extent comparisons for the 100-Year event through this area are shown in **Figure 5-17**, **Figure 5-18**, and **Figure 5-19**. Generally these figures show very minor increases in the 100-Year flood extent with the increase in Manning's roughness coefficients.

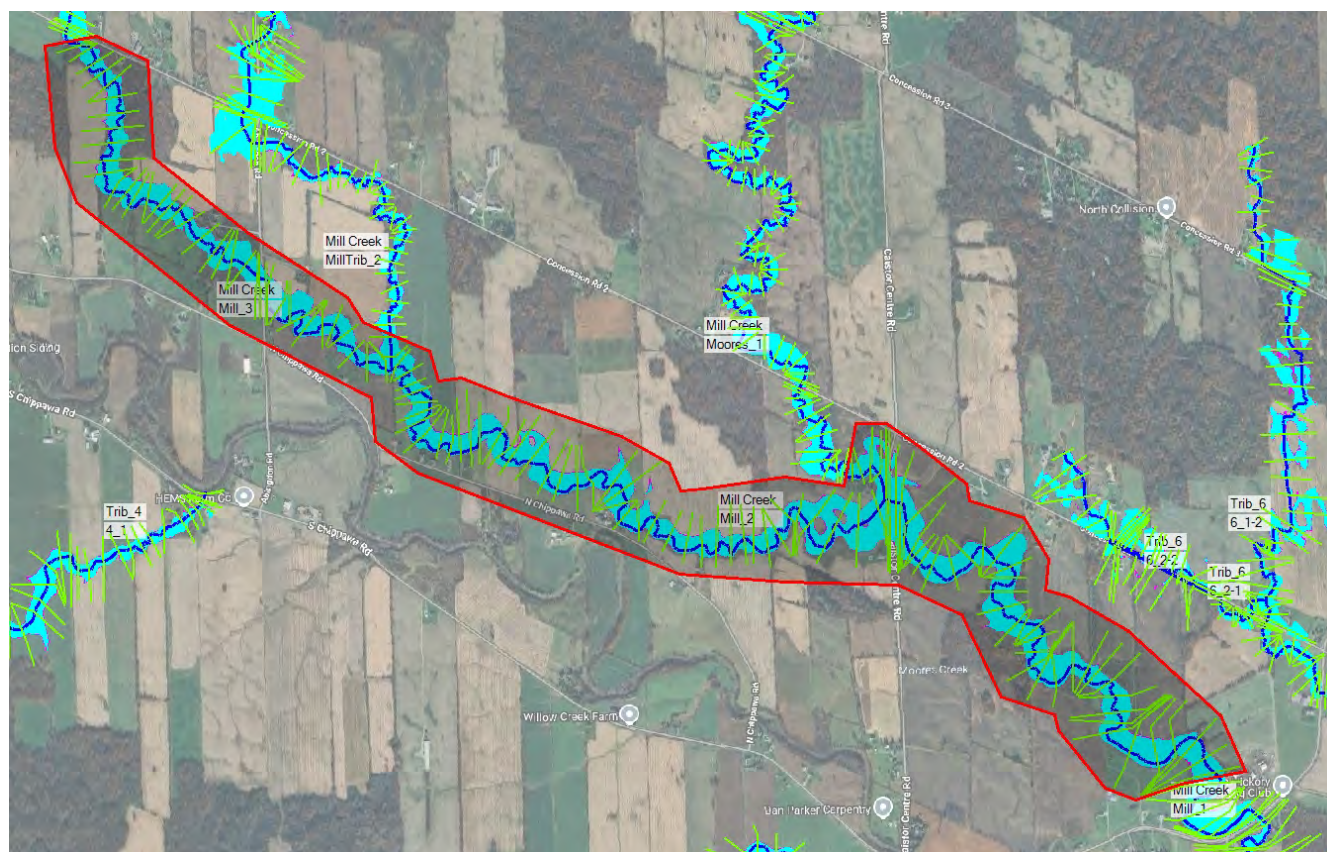


Figure 5-16. Area of Highest Manning's Sensitivity in the 100-Year Event – Mill Creek (red outline)

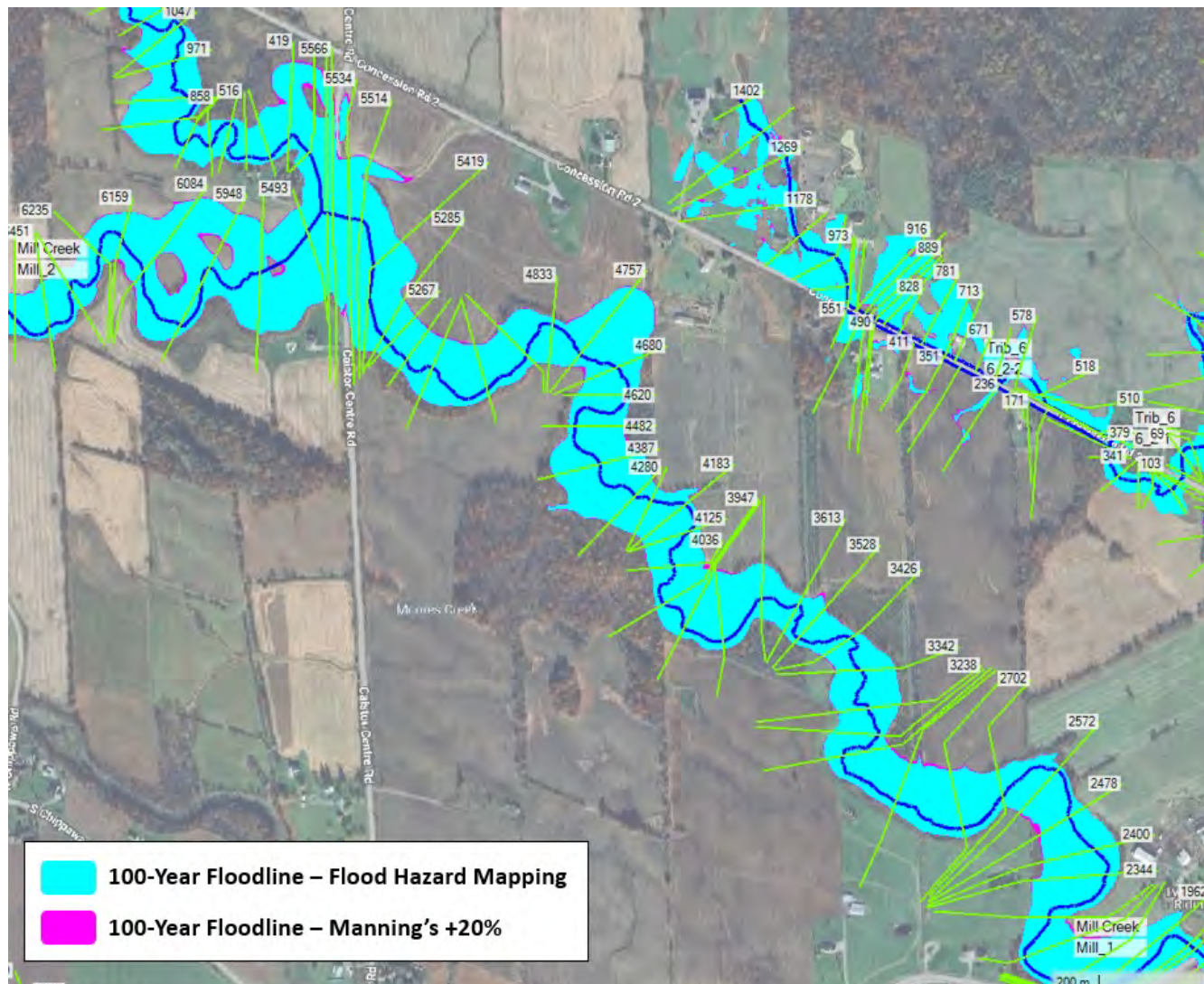


Figure 5-17. 100-Year Manning's Sensitivity Flood Extent Comparison for River: Mill Creek, Reach: Mill_1

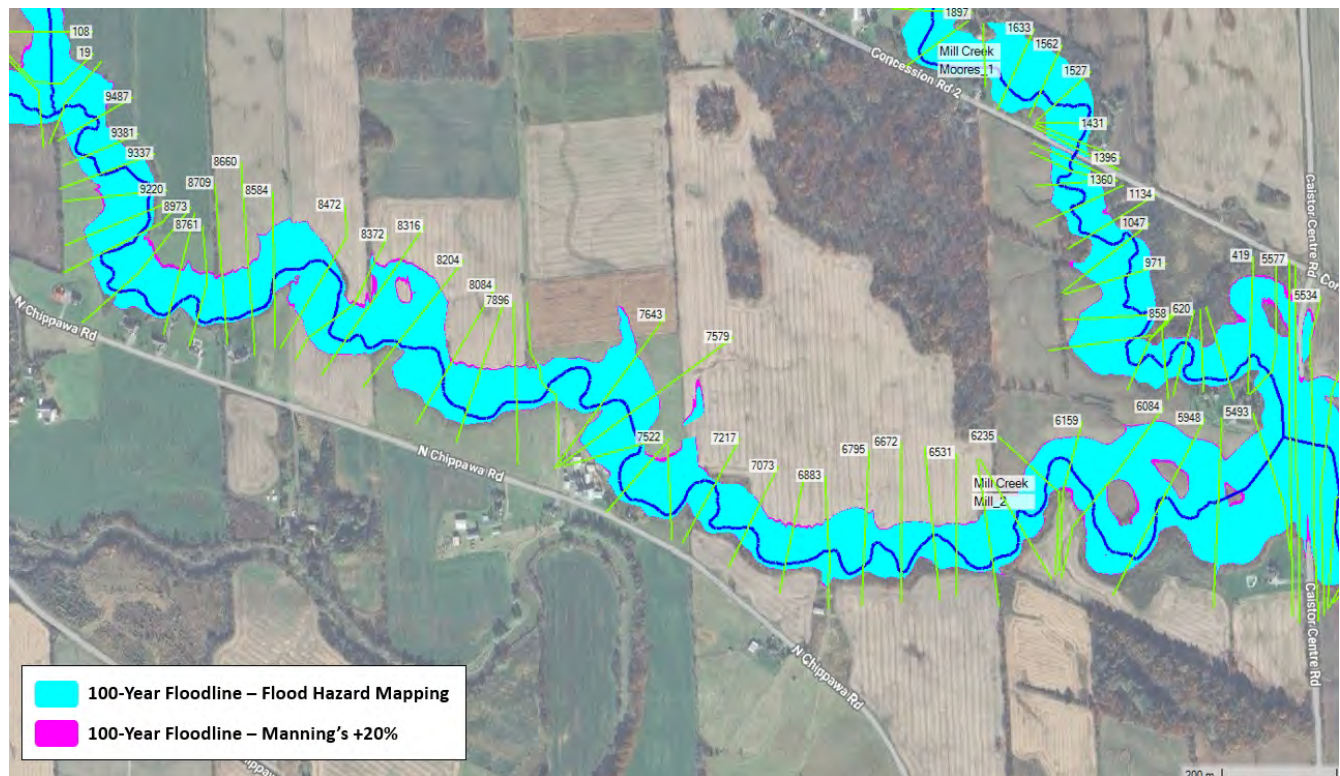


Figure 5-18. 100-Year Manning's Sensitivity Flood Extent Comparison for River: Mill Creek, Reach: Mill_2

A summary of the water surface elevation increases through the Mill Creek high-sensitivity area is provided in **Table 5-8**. A comparison of cross section flow top widths in the baseline and +20% Manning's scenarios is shown, along with the calculated percent increase in top width. Similar to the flood extent figures above, the results show that the water surface elevation increases largely do not affect the overall flooded area.

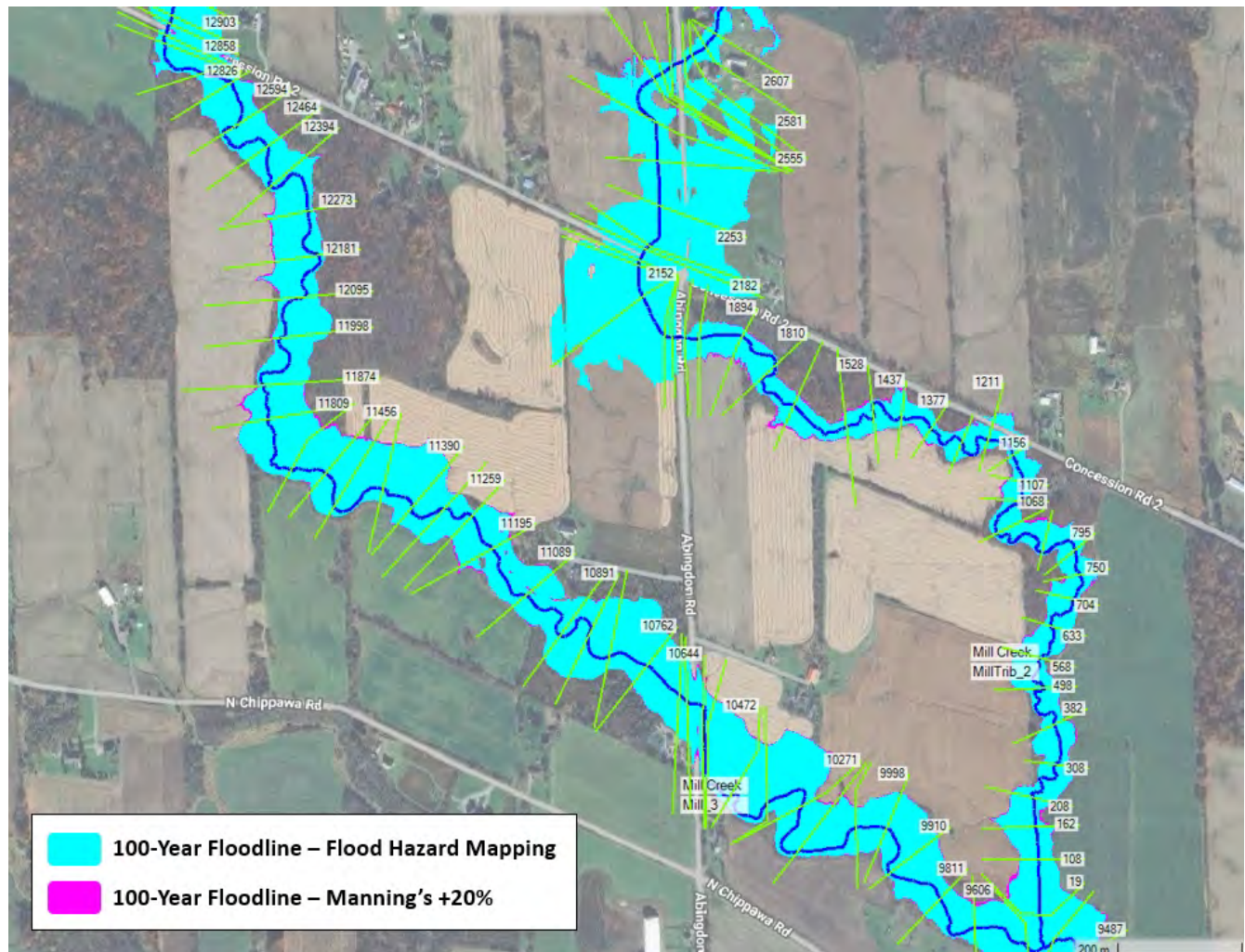


Figure 5-19. 100-Year Manning's Sensitivity Flood Extent Comparison for River: Mill Creek, Reach: Mill_3

Table 5-8. Mill Creek Manning's Sensitivity Analysis Results for High-Sensitivity Area (100-Year Event)

Reach	River Sta	Flood Hazard Mapping Scenario		Manning's +20% Scenario		WSE Change (m)	Flow Top Width Change (m)	Flow Top Width Change (%)
		WSE (m)	Top Width (m)	WSE (m)	Top Width (m)			
Mill_1	2400	178.64	141.54	178.74	143.1	0.10	1.56	1%
Mill_1	2478	178.65	97.37	178.76	100.73	0.11	3.36	3%
Mill_1	2572	178.69	114.62	178.81	116.56	0.12	1.94	2%
Mill_1	2702	178.74	68.51	178.87	69.92	0.13	1.41	2%
Mill_1	2803	178.79	128.31	178.93	130.92	0.14	2.61	2%
Mill_1	2945	178.84	93.75	178.98	97.38	0.14	3.63	4%
Mill_1	3091	178.94	118.92	179.09	122.61	0.15	3.69	3%
Mill_1	3183	178.97	99.69	179.12	101.13	0.15	1.44	1%
Mill_1	3238	178.99	116.3	179.14	119.21	0.15	2.91	3%
Mill_1	3342	179.02	108.57	179.18	111.29	0.16	2.72	3%
Mill_1	3426	179.04	77.45	179.21	78.94	0.17	1.49	2%
Mill_1	3528	179.12	85.85	179.29	89.89	0.17	4.04	5%
Mill_1	3613	179.16	75.53	179.33	76.57	0.17	1.04	1%
Mill_1	3686	179.21	105.46	179.38	109.15	0.17	3.69	3%
Mill_1	3797	179.27	144.94	179.45	152.04	0.18	7.1	5%
Mill_1	3876	179.3	138.25	179.47	144.66	0.17	6.41	5%

Reach	River Sta	Flood Hazard Mapping Scenario		Manning's +20% Scenario		WSE Change (m)	Flow Top Width Change (m)	Flow Top Width Change (%)
		WSE (m)	Top Width (m)	WSE (m)	Top Width (m)			
Mill_1	3947	179.31	126.15	179.49	133.29	0.18	7.14	6%
Mill_1	4036	179.34	100.3	179.52	108.81	0.18	8.51	8%
Mill_1	4125	179.4	109.06	179.58	111.41	0.18	2.35	2%
Mill_1	4183	179.46	119	179.64	122.71	0.18	3.71	3%
Mill_1	4247	179.51	95.38	179.69	97.23	0.18	1.85	2%
Mill_1	4280	179.55	112.5	179.72	114.41	0.17	1.91	2%
Mill_1	4387	179.6	168.93	179.77	170.23	0.17	1.3	1%
Mill_1	4482	179.63	104.05	179.81	105.91	0.18	1.86	2%
Mill_1	4620	179.74	107.08	179.91	108.36	0.17	1.28	1%
Mill_1	4680	179.77	120.19	179.95	122.2	0.18	2.01	2%
Mill_1	4757	179.82	188.28	179.99	189.86	0.17	1.58	1%
Mill_1	4833	179.84	82.93	180.02	84.19	0.18	1.26	2%
Mill_1	4920	179.92	99.47	180.1	104.17	0.18	4.7	5%
Mill_1	5021	179.99	98.73	180.17	101.35	0.18	2.62	3%
Mill_1	5154	180.06	117.93	180.24	122.04	0.18	4.11	3%
Mill_1	5219	180.1	91.06	180.28	93.52	0.18	2.46	3%
Mill_1	5267	180.14	98.72	180.33	101.2	0.19	2.48	3%
Mill_1	5285	180.16	108.33	180.35	110.27	0.19	1.94	2%
Mill_1	5419	180.21	229.98	180.39	232.1	0.18	2.12	1%
Mill_1	5514	180.22	343.21	180.4	347.42	0.18	4.21	1%
Mill_1	5534	180.22	380.67	180.4	398.6	0.18	17.93	5%
Mill_1	5566	180.26	382.45	180.42	406.5	0.16	24.05	6%
Mill_1	5577	180.26	377.15	180.42	398.22	0.16	21.07	6%
Mill_2	5493	180.26	178.76	180.42	179.78	0.16	1.02	1%
Mill_2	5690	180.26	196.58	180.43	200.97	0.17	4.39	2%
Mill_2	5948	180.29	224.43	180.45	230.92	0.16	6.49	3%
Mill_2	6084	180.3	197.27	180.47	204.75	0.17	7.48	4%
Mill_2	6159	180.33	89.59	180.49	94.11	0.16	4.52	5%
Mill_2	6235	180.39	67.2	180.56	69.76	0.17	2.56	4%
Mill_2	6350	180.58	82.69	180.73	84.13	0.15	1.44	2%
Mill_2	6451	180.68	107.28	180.82	109.52	0.14	2.24	2%
Mill_2	6531	180.73	74.79	180.88	76.87	0.15	2.08	3%
Mill_2	6584	180.81	72.85	180.96	74.88	0.15	2.03	3%
Mill_2	6672	180.92	94.9	181.06	97	0.14	2.1	2%
Mill_2	6795	181.02	105.96	181.16	107.52	0.14	1.56	1%
Mill_2	6883	181.08	118.94	181.22	125.24	0.14	6.3	5%
Mill_2	6964	181.13	75.72	181.27	79.65	0.14	3.93	5%
Mill_2	7073	181.31	75.1	181.44	76.77	0.13	1.67	2%
Mill_2	7217	181.44	73.04	181.57	74.55	0.13	1.51	2%
Mill_2	7324	181.5	104.01	181.64	111.81	0.14	7.8	7%
Mill_2	7419	181.56	92.72	181.69	96.18	0.13	3.46	4%
Mill_2	7522	181.6	95.1	181.73	96.19	0.13	1.09	1%
Mill_2	7579	181.61	154.87	181.74	156.1	0.13	1.23	1%
Mill_2	7643	181.63	119.02	181.76	120	0.13	0.98	1%
Mill_2	7829	181.7	95.55	181.84	99.55	0.14	4	4%
Mill_2	7896	181.75	74.31	181.89	76.97	0.14	2.66	4%
Mill_2	7997	181.89	99.93	182.01	103.61	0.12	3.68	4%
Mill_2	8084	181.95	86.66	182.07	89.95	0.12	3.29	4%
Mill_2	8204	182.02	127.15	182.14	128.55	0.12	1.4	1%
Mill_2	8316	182.08	193.09	182.21	203	0.13	9.91	5%
Mill_2	8372	182.15	111.97	182.26	121.77	0.11	9.8	9%
Mill_2	8472	182.25	112.67	182.36	114.15	0.11	1.48	1%
Mill_2	8584	182.33	118.25	182.44	119.62	0.11	1.37	1%

Reach	River Sta	Flood Hazard Mapping Scenario		Manning's +20% Scenario		WSE Change (m)	Flow Top Width Change (m)	Flow Top Width Change (%)
		WSE (m)	Top Width (m)	WSE (m)	Top Width (m)			
Mill_2	8660	182.39	87.64	182.51	90.48	0.12	2.84	3%
Mill_2	8709	182.48	81.46	182.6	86.02	0.12	4.56	6%
Mill_2	8761	182.58	89.22	182.69	93.05	0.11	3.83	4%
Mill_2	8861	182.67	81.47	182.78	86.49	0.11	5.02	6%
Mill_2	8973	182.76	99.05	182.88	106.36	0.12	7.31	7%
Mill_2	9136	182.87	110.27	182.99	111.62	0.12	1.35	1%
Mill_2	9187	182.89	127.84	183.02	128.87	0.13	1.03	1%
Mill_2	9220	182.91	89.33	183.04	93.08	0.13	3.75	4%
Mill_2	9337	183.1	98.28	183.21	99.09	0.11	0.81	1%
Mill_2	9381	183.13	78.44	183.25	79.95	0.12	1.51	2%
Mill_2	9487	183.3	79.21	183.42	80.38	0.12	1.17	1%
Mill_2	9557	183.38	102.32	183.5	104.66	0.12	2.34	2%
Mill_3	9606	183.38	103.2	183.5	112.38	0.12	9.18	9%
Mill_3	9706	183.48	66.76	183.6	74.22	0.12	7.46	11%
Mill_3	9811	183.64	61.52	183.77	63.6	0.13	2.08	3%
Mill_3	9910	183.76	104.29	183.89	105.91	0.13	1.62	2%
Mill_3	9998	183.81	96.31	183.94	99.27	0.13	2.96	3%
Mill_3	10048	183.85	74.3	183.98	77.47	0.13	3.17	4%
Mill_3	10161	183.96	106.71	184.08	115.24	0.12	8.53	8%
Mill_3	10271	184.05	71.72	184.17	73.61	0.12	1.89	3%
Mill_3	10361	184.13	110.14	184.25	113.16	0.12	3.02	3%
Mill_3	10472	184.17	116.96	184.29	119.14	0.12	2.18	2%
Mill_3	10520	184.19	143.21	184.31	144.57	0.12	1.36	1%
Mill_3	10644	184.2	165.64	184.32	175.47	0.12	9.83	6%
Mill_3	10675	184.53	147.19	184.56	147.3	0.03	0.11	0%
Mill_3	10691	184.53	135.49	184.56	135.62	0.03	0.13	0%
Mill_3	10762	184.55	97.55	184.58	98.24	0.03	0.69	1%
Mill_3	10829	184.59	119.1	184.63	119.56	0.04	0.46	0%
Mill_3	10891	184.62	143.63	184.67	145.14	0.05	1.51	1%
Mill_3	10978	184.68	119.66	184.74	120.18	0.06	0.52	0%
Mill_3	11089	184.78	82.45	184.86	85.73	0.08	3.28	4%
Mill_3	11195	184.98	86.66	185.08	91.5	0.10	4.84	6%
Mill_3	11259	185.17	74.08	185.26	75.9	0.09	1.82	2%
Mill_3	11316	185.26	96.93	185.35	98.15	0.09	1.22	1%
Mill_3	11390	185.31	126.94	185.4	129.47	0.09	2.53	2%
Mill_3	11456	185.37	94.95	185.46	101.78	0.09	6.83	7%
Mill_3	11553	185.49	139.25	185.58	142.74	0.09	3.49	3%
Mill_3	11615	185.54	110.95	185.64	115.32	0.10	4.37	4%
Mill_3	11680	185.63	101.18	185.73	108.82	0.10	7.64	8%
Mill_3	11809	185.76	110.11	185.86	113.14	0.10	3.03	3%
Mill_3	11874	185.81	75.63	185.91	77.44	0.10	1.81	2%
Mill_3	11998	185.93	92	186.04	94.72	0.11	2.72	3%
Mill_3	12095	186.01	63.11	186.13	64.01	0.12	0.9	1%
Mill_3	12181	186.11	78.42	186.23	81.31	0.12	2.89	4%
Mill_3	12273	186.25	72.16	186.36	76.05	0.11	3.89	5%
Mill_3	12394	186.4	82.45	186.51	83.46	0.11	1.01	1%
Mill_3	12464	186.46	65.95	186.58	67.21	0.12	1.26	2%
Mill_3	12594	186.63	75.51	186.75	76.7	0.12	1.19	2%
Mill_3	12667	186.71	68.54	186.84	70.28	0.13	1.74	3%
Mill_3	12714	186.77	69.15	186.89	70.24	0.12	1.09	2%
Mill_3	12812	186.83	138.76	186.95	140.5	0.12	1.74	1%
Mill_3	12826	186.83	135.01	186.95	136.55	0.12	1.54	1%

5.7.2 Trib_7

The area of the Trib_7 river system that shows the greatest water surface elevation increases in the Manning's roughness sensitivity analysis is located between Reach 7_1-1, XS 1427, and Reach 7_1-2, XS 4089 and is highlighted in **Figure 5-20**. Flood extent comparisons for the 100-Year event through this area are shown in **Figure 5-21**, and **Figure 5-22**. Generally the lower portion of the area (**Figure 5-21**) shows very minor increases in the 100-Year flooded area with the increase in Manning's roughness coefficients. The upper portion of the area (**Figure 5-22**) experiences more increases in the flooded area.

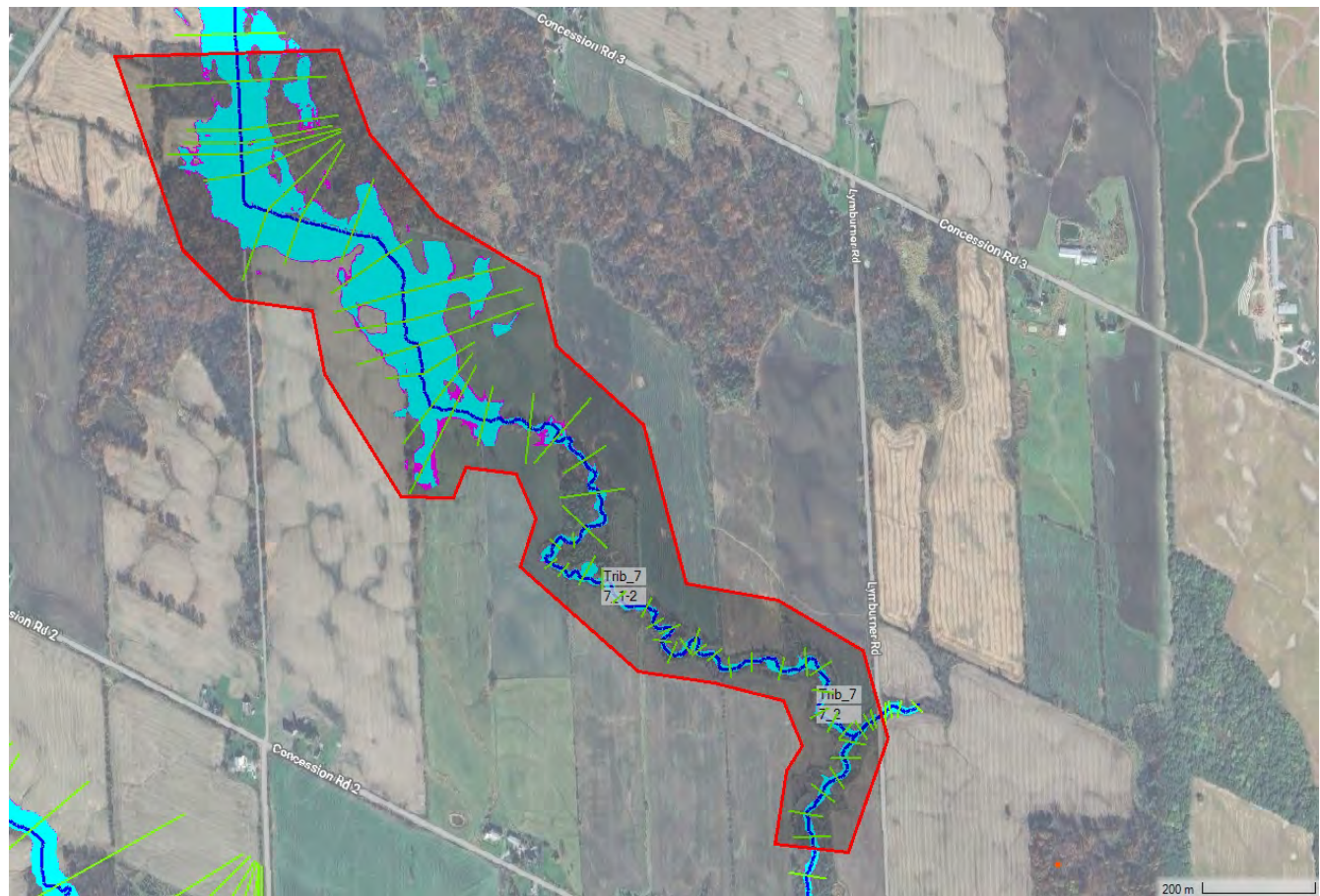


Figure 5-20. Area of Highest Manning's Sensitivity in the 100-Year Event – Trib_7 (red outline)

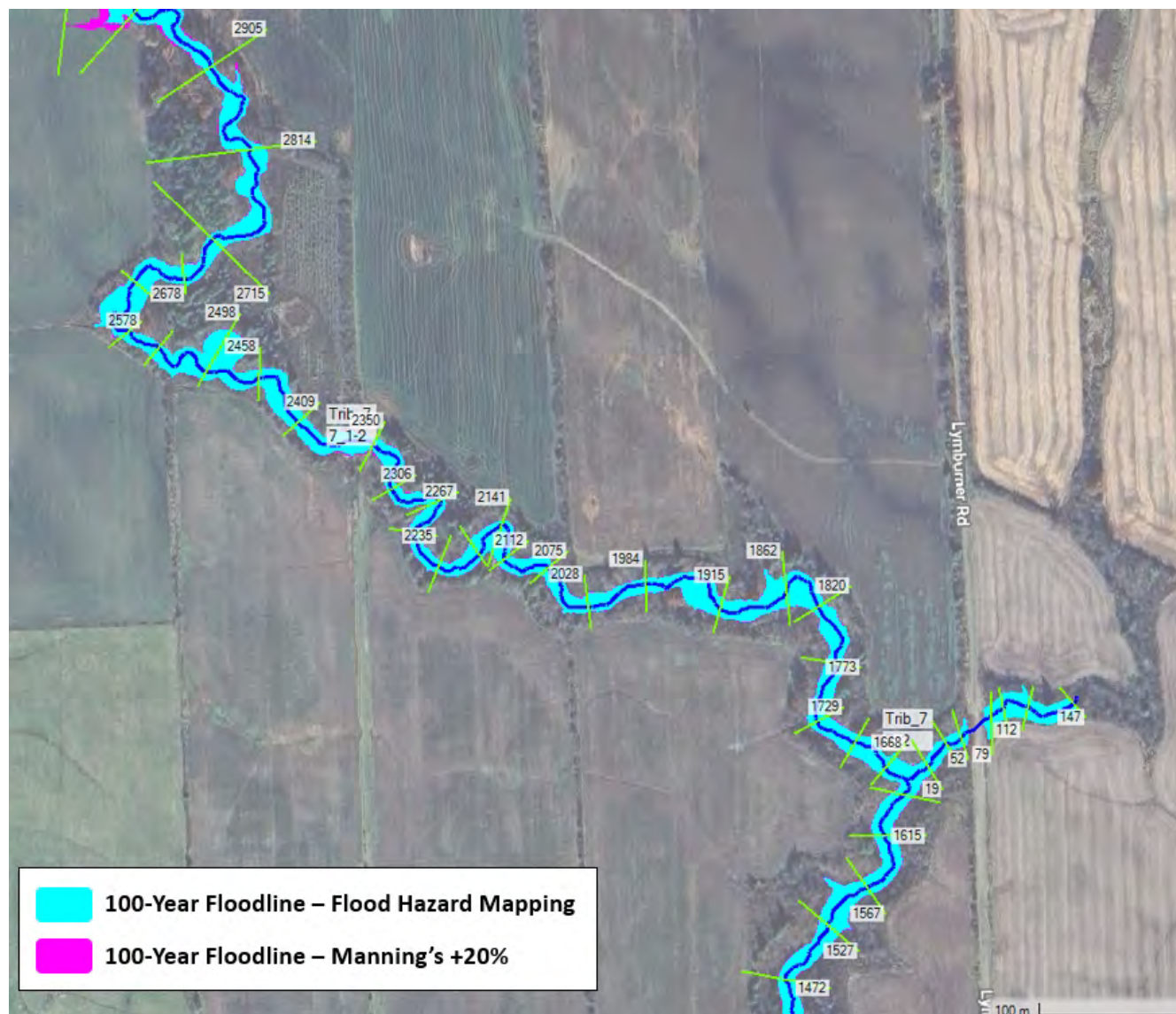


Figure 5-21. 100-Year Manning's Sensitivity Flood Extent Comparison for River: Trib_7, Reaches: 7_1-1 & 7_1.2

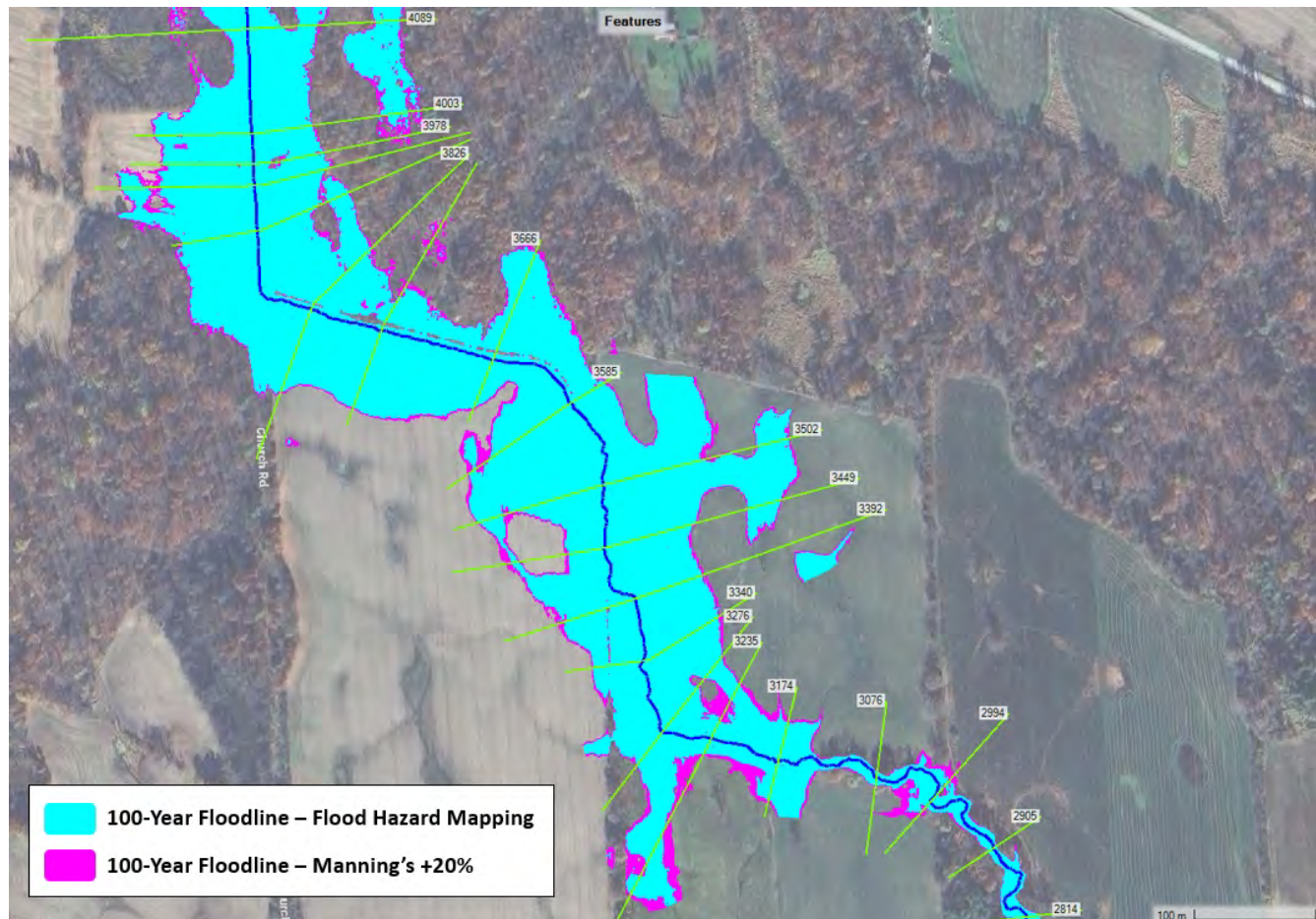


Figure 5-22. 100-Year Manning's Sensitivity Flood Extent Comparison for River: Trib_7, Reach: 7_1-2

A summary of the water surface elevation increases through the Trib_7 high-sensitivity area is provided in **Table 5-9**. A comparison of cross section flow top widths in the baseline and +20% Manning's scenarios is shown, along with the calculated percent increase in top width. Similar to the flood extent figures above, the results show that the water surface elevation increases largely do not affect the overall flooded area downstream of Reach 7_1-2 XS 2905, but upstream there are more significant flood width increases. The most notable width increases occur at Reach 7_1-2, XS 2994 and 3235, with 101% and 75% increases respectively. These cross sections, and the flood line comparisons are shown in greater detail in **Figure 5-23**.

Table 5-9. Trib_7 Manning's Sensitivity Analysis Results for High-Sensitivity Area (100-Year Event)

Reach	River Sta	Flood Hazard Mapping Scenario		Manning's +20% Scenario		WSE Change (m)	Flow Top Width Change (m)	Flow Top Width Change (%)
		WSE (m)	Top Width (m)	WSE (m)	Top Width (m)			
7_1-1	1427	176.06	13.05	176.17	13.56	0.11	0.51	4%
7_1-1	1472	176.24	11.37	176.37	12.02	0.13	0.65	6%
7_1-1	1527	176.57	17.79	176.68	18.33	0.11	0.54	3%
7_1-1	1567	176.62	11.8	176.76	12.57	0.14	0.77	7%
7_1-1	1615	176.91	15.24	177.03	16.04	0.12	0.8	5%
7_1-1	1651	176.99	16.18	177.13	17.04	0.14	0.86	5%
7_1-2	1668	177.1	16.54	177.2	16.95	0.10	0.41	2%
7_1-2	1698	177.12	15.48	177.23	16.17	0.11	0.69	4%
7_1-2	1729	177.16	13.55	177.28	14.05	0.12	0.5	4%

Reach	River Sta	Flood Hazard Mapping Scenario		Manning's +20% Scenario		WSE Change (m)	Flow Top Width Change (m)	Flow Top Width Change (%)
		WSE (m)	Top Width (m)	WSE (m)	Top Width (m)			
7_1-2	1773	177.27	13.39	177.39	14.02	0.12	0.63	5%
7_1-2	1820	177.39	10.52	177.52	11.31	0.13	0.79	8%
7_1-2	1862	177.55	22.33	177.66	22.89	0.11	0.56	3%
7_1-2	1915	177.56	13.74	177.69	14.29	0.13	0.55	4%
7_1-2	1984	177.9	10.29	178.03	10.98	0.13	0.69	7%
7_1-2	2028	178.17	12.46	178.29	13.67	0.12	1.21	10%
7_1-2	2075	178.38	11.12	178.5	11.5	0.12	0.38	3%
7_1-2	2112	178.47	10.29	178.6	11.06	0.13	0.77	7%
7_1-2	2141	178.62	24.07	178.73	24.56	0.11	0.49	2%
7_1-2	2169	178.63	15.2	178.76	15.74	0.13	0.54	4%
7_1-2	2202	178.74	8.97	178.88	9.42	0.14	0.45	5%
7_1-2	2235	178.91	9.79	179.05	10.31	0.14	0.52	5%
7_1-2	2267	179.11	11.85	179.23	12.48	0.12	0.63	5%
7_1-2	2306	179.19	9.15	179.34	9.59	0.15	0.44	5%
7_1-2	2350	179.45	8.42	179.64	10.97	0.19	2.55	30%
7_1-2	2409	180.05	11.76	180.12	12.04	0.07	0.28	2%
7_1-2	2458	180.17	11.7	180.27	12.24	0.10	0.54	5%
7_1-2	2498	180.31	38.67	180.4	39.00	0.09	0.33	1%
7_1-2	2550	180.25	10.86	180.37	11.32	0.12	0.46	4%
7_1-2	2578	180.45	10.2	180.56	10.49	0.11	0.29	3%
7_1-2	2634	180.71	17.26	180.82	17.74	0.11	0.48	3%
7_1-2	2678	180.86	13.49	180.99	13.96	0.13	0.47	3%
7_1-2	2715	181.07	12.37	181.18	12.8	0.11	0.43	3%
7_1-2	2814	181.46	17.56	181.57	18.27	0.11	0.71	4%
7_1-2	2905	181.7	7.57	181.84	8.17	0.14	0.6	8%
7_1-2	2994	182.03	20.01	182.16	40.19	0.13	20.18	101%
7_1-2	3076	182.1	11.45	182.25	13.9	0.15	2.45	21%
7_1-2	3174	182.42	64.35	182.53	71.37	0.11	7.02	11%
7_1-2	3235	182.55	92.85	182.65	162.11	0.10	69.26	75%
7_1-2	3276	182.77	104.79	182.8	112.12	0.03	7.33	7%
7_1-2	3340	182.91	113.35	182.96	115.05	0.05	1.7	1%
7_1-2	3392	183.09	114.34	183.13	125.96	0.04	11.62	10%
7_1-2	3449	183.24	138.66	183.28	153.53	0.04	14.87	11%
7_1-2	3502	183.32	215.22	183.36	244.15	0.04	28.93	13%
7_1-2	3585	183.42	119.86	183.48	137.02	0.06	17.16	14%
7_1-2	3666	183.59	132.17	183.65	137.66	0.06	5.49	4%
7_1-2	3764	183.82	100.48	183.87	122.53	0.05	22.05	22%
7_1-2	3826	183.91	140.76	183.95	144.38	0.04	3.62	3%
7_1-2	3923	184.03	131.59	184.08	136.67	0.05	5.08	4%
7_1-2	3960	184.13	156.85	184.16	173.08	0.03	16.23	10%
7_1-2	3978	184.16	135.4	184.2	145.98	0.04	10.58	8%
7_1-2	4003	184.22	144.47	184.26	161.91	0.04	17.44	12%
7_1-2	4089	184.35	86.32	184.41	100.65	0.06	14.33	17%

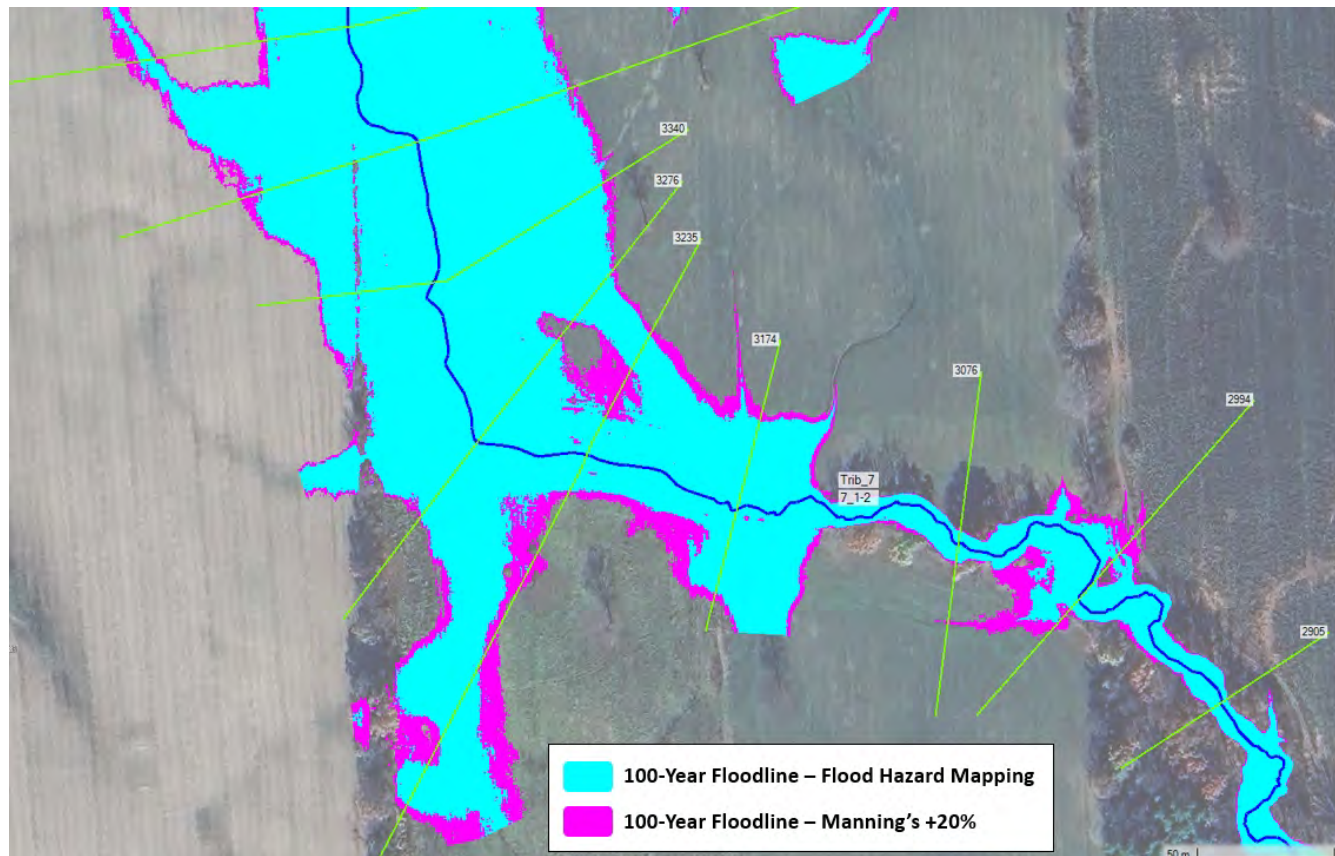


Figure 5-23. 100-Year Manning's Sensitivity Flood Extent Comparison for River: Trib_7, Reach: 7_1-2 – Area of Largest Top Width Increase

The flood extent comparison in **Figure 5-23** shows increases in the flooded area resulting from the 20% increase in Manning's coefficients. The results of the analysis show that there is a wide range of sensitivity to Manning's roughness coefficients throughout the 1-D HEC-RAS model, from negligible impacts to doubling of the flow width in the most affected areas (Trib_7). Full results of the sensitivity analysis are provided in **Appendix C**.

5.8 Evaluation of 2-D Modelling Stability

5.8.1 2-D Un-Steady State Flow Routing

The HEC-RAS 2-D Users Manual provides the following with regards to the Shallow Water Equation Eulerian-Lagrangian Method (SWE-ELM) for flow routing;

"There are some obvious situations that the SWE should always be used. The following is a list of examples of situations in which the user should generally use the SWE based equations:

3.Flat Sloping River Systems: For rivers with very flat slopes (less than 1 ft/mi), gravity and friction may not be the dominant forces acting on a body of water as it travels from one point to another. The forces associated with changes in velocity with respect to time and distance, will play a much more significant role in how a floodwave moves and changes shape in a flat system. Because of this, users should use the Full Momentum equation set instead of then Diffusion Wave equations. As Diffusion wave does not include the acceleration terms with respect to time and space."

Given the wide and flat terrain associated with the Regulatory floodplain of the Black Creek 2-D modelling area, the Shallow Water Equation Eulerian-Lagrangian Method (SWE-ELM) has been selected for routing equations.

5.8.2 Mesh and Time Step Analysis

To assess the consistency capabilities of the 2-D mesh with respect to cell sizing and the selected time step for the Regulatory Event, the Courant (Velocity/Length) Results map has been developed and reviewed. As noted in the HEC-RAS 2-D User's Manual;

*“For the **Courant** number method, the default approach for computing the Courant number is to take the velocity times the time step divided by the length (between 1-D cross sections, or between two 2-D cells). For 2-D, the velocity is taken from each face and the length is the distance between the two cell centers across that face.”*

Based on the above, it is desirable obtain a maximum Courant value of less than 1.0. However, it is possible for the 2-D model to produce a Courant value of greater than 1 and still produce a stable and accurate solution.

Figures 6-3 and 6-4 below illustrates the Courant (Velocity/Length) Map for 100-year Regulatory event followed by additional commentary surrounding the calculated Courant values.

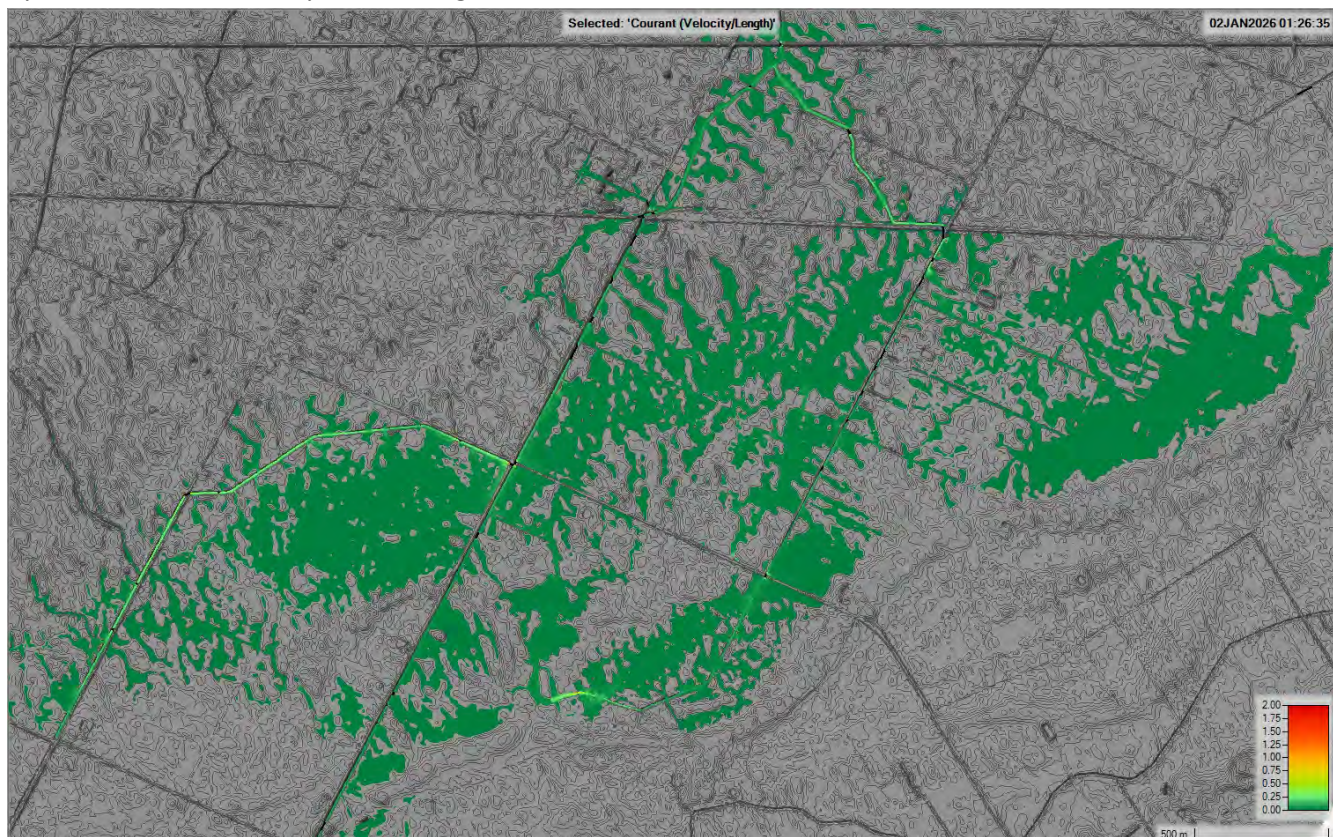


Figure 5-24. Black Creek 2-D - 100-year Regulatory Courant (Velocity/Length) Map

Within the top of bank limits of Black Creek, Courant values have generally been observed to reside less than 1 whereby indicating that that mesh cell sizing defined by the Breakline regime and selected computational time step of 5 seconds, as outlined in **Section 5.10**, provides stable hydraulic results.

5.8.3 Unsteady Flow Volume Accounting Analysis

The Computational Message Window and it's associated Computational Log File were also reviewed with respect to the 2-D models overall volume accounting. Based on our experience with 2-D modelling, we would identify a stable model with having an overall volume accounting error of less than 2% with an optimal result producing a volume accounting error of less than 1%. The above noted thresholds would apply for both the overall simulation as well as each 2-D flow area.

Table 5-10. 2-D Flow Volume Accounting Summary

Plan	Ending Volume (1000 m3)	Percent Error (%)
2-D_NPCA Black Creek 100yr v3 HYD	622.8	0.03095

The overall 100-year Regulatory simulation illustrates that the model gained negligible volumes of water for all modelling scenarios and in turn produce volume accounting errors of up to 0.031%. Therefore, the overall volume accounting error is quite low and within desirable modelling tolerances.

5.8.4 100-year → 1-D vs 2-D Modelling Results

A direct comparison between the 1-D (blue) and 2-D (green) 100-year floodplain modelling results has been provided in Figure 5-25 below. The 2-D model replaces 1-D Reaches BlackCreek_4, BlackCreek_5, BlackTrib_4, and BlackTrib_5 on the Black Creek Drain river system.

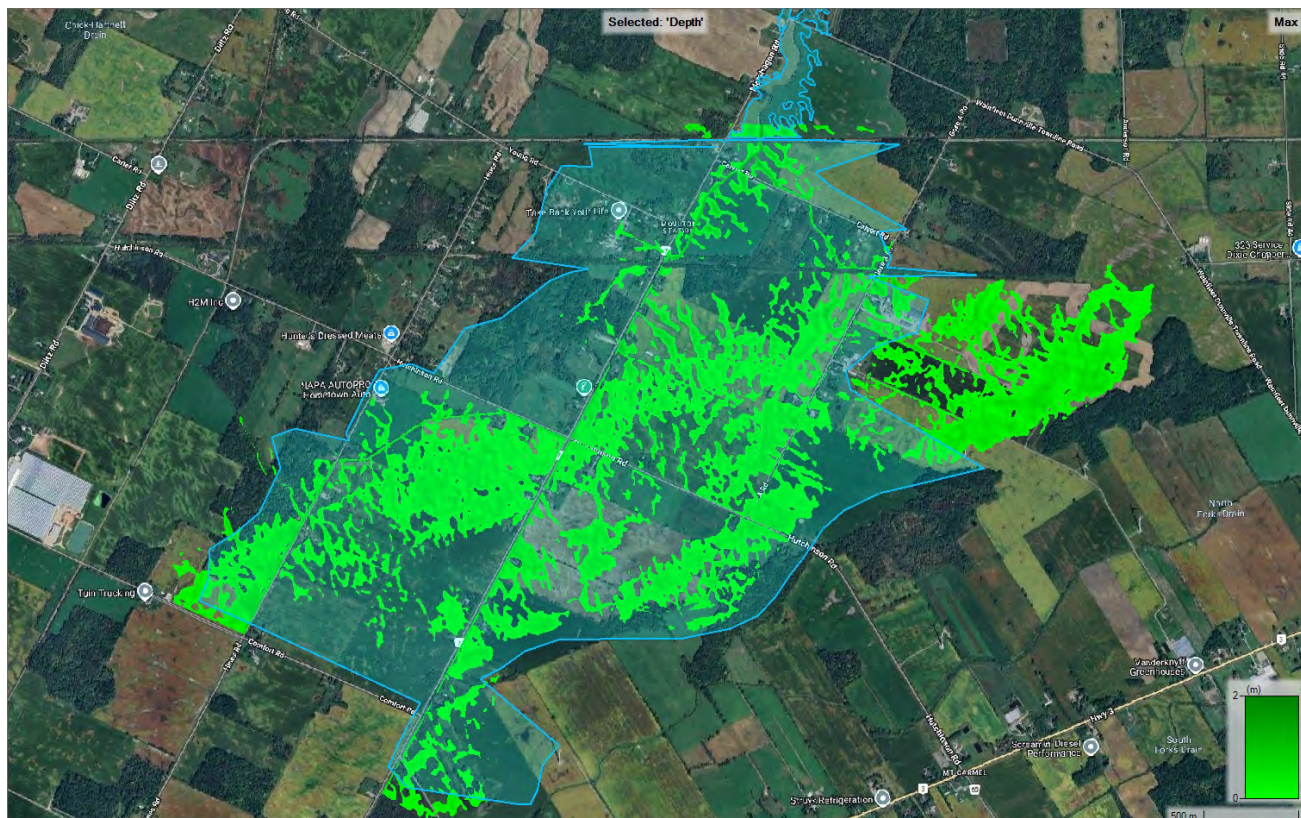


Figure 5-25. Black Creek 1-D vs 2-D - 100-year Floodplain Comparison

As noted previously, the steady state 1-D 100-year modelling results provided very wide (in excess of 2km) floodplain extents have been observed. We further note that 1-D 100-year floodplain depths exceed 2m in many locations. Based on the excessive floodplain width, wide cross sections have not been able to contain the 100-year floodplain extents and has therefore resulted in floodplain depths that would not represent field conditions. While the 2-D 100-year modelling results provide refined modelling results that are more representative of field conditions we note that by solely using the raw 100-year hydrographs (or incremental hydrographs) and by forcing the 100 year 1-D water surface elevations of 177.13m at the downstream limits of the 2-D model, calculated water surface elevations upstream of the downstream railway crossing have been calculated at 176.95m. The water surface elevations upstream of the downstream railway crossing are lower than the conservative 1-D water surface elevations as the overall 100-year flood flow volume has been absorbed within the floodplain whereby resulting in lower flows and therefore flood elevations upstream of the railway. To refine floodplain elevations at the downstream limits of the 2-D model, a series of Quasi-Unsteady State iterations have been completed of 6,12 and 24-hr durations. **Figure 5-26** provides a direct comparison between the 100-year Unsteady State (green) and 100-year 12hr Quasi Unsteady State (blue) modelling runs.

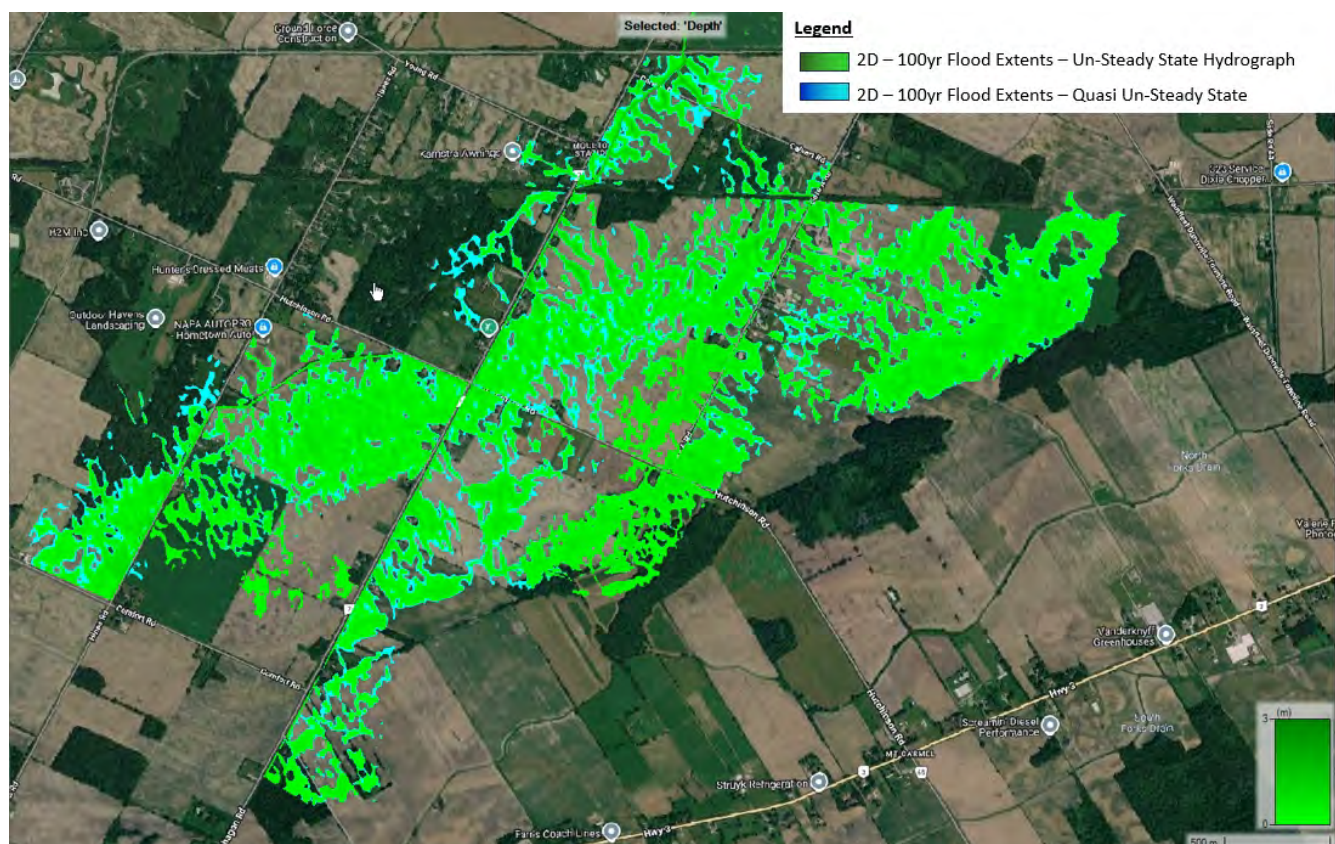


Figure 5-26. Black Creek 2-D - 100-year Un-Steady vs 12hr Quasi Un-Steady State Comparison

Firstly, based on a direct visual comparison of floodplain footprint extents, both results are quite similar. However, due to extended duration of the Quasi-Unsteady State modelling run, the 100-yr water surface elevation has been calculated at 177.19m upstream of the downstream railway crossing. We note that this elevation is slightly above the 1-D 100 year calculated water surface elevation of 177.13m at the downstream

limits of the railway crossing. The elevation drop through the railway crossing itself is anticipated and consistent with standard crossing hydraulics. We note that the 100yr 12hr Quasi-Unsteady State modelling run contains a total 864 (1000m³) of flow volume vs the 598.3 (1000m³) total flow volume 100yr Unsteady State modelling run. This represents roughly a 44% increase in flood flow volume for Quasi-Unsteady State modelling run and therefore provides a conservative floodplain estimate. As the direct visual comparison between the 100 year 12hr Quasi-Unsteady State and Unsteady State modelling runs are similar and given the 12hr Quasi-Unsteady State results mimic the 1-D modelling results at the downstream limits of the 2-D modelling, we have maintained the 12hr Quasi-Unsteady State modelling approach for the 50,100,200 and 350-year modelling runs for the 2D Black Creek Modelling area.

6 UNCERTAINTIES, LIMITS AND RECOMMENDATIONS

Aquafor undertook a variety of measures to reduce uncertainty and increase confidence in the HEC-RAS hydraulic model's ability to predict water surface elevations. These included the use of flow rate estimates from the refined HEC-HMS model completed as part of this study, the use of appropriate hydraulic parameters based on technical guidelines, reviewing errors, warnings and notes in the model, and adjusting regulatory flood lines based on a visual inspection of preliminary model results and flood lines. A sensitivity analysis of Manning's roughness coefficients, and downstream boundary conditions was undertaken, and areas of high sensitivity were investigated in detail to determine the impacts on Regulatory flood extents.

Detailed reach investigations of the low flow channel were not conducted along the entirety of the creek due to the scale of the study area and because of site access and safety conditions. River cross-sections were only surveyed within the channel at certain locations and generally located a few meters upstream and downstream hydraulic structures. Aquafor was able to correct the low flow shape including the bed channel elevation on an as-need basis to accurately represent road crossings but did not correct the channel bed for the entire study area.

It is noted that the hydraulic model has first and foremost been developed for the purposes of flood hazard mapping. The development of the model was focused on assessing the hydraulic regime for the Regulatory flood event (100-year flood event). The hydraulic model results for other return period storm events have higher degrees of uncertainty. The hydraulic model and the results presented within this report for storms other than the Regulatory event are intended to only provide general guidance for infrastructure planning and/or flood estimation purposes. Additional detailed studies (e.g., placement of levees) may be required to ensure adequate accuracy of modelling results for these storm events.

6.1 2-D Hydraulic Modelling

Aquafor undertook different measures to reduce uncertainty and increase confidence in the HEC-RAS hydraulic model's ability to predict water surface elevations. Those included the use of estimated flow rates from the approved HEC-HMS hydrologic model and approved scenario (average past soil moisture conditions under SCS Type II distribution, 24 hours duration), the use of appropriate hydraulic parameters based on technical guidelines, reviewing errors, warnings and notes in the model, and completing a visual verification of the preliminary model results screening the regulatory flood lines delineation.

Detailed reach investigations of the low flow channel were not conducted all along the creek due to the scale of the study area and site access and safety conditions. River cross-section was only surveyed within the channel at certain locations and mostly a few meters upstream and downstream hydraulic structures. Aquafor has corrected the low flow shape including the bed channel elevation in the direct vicinity of roadway crossings but did not correct the channel bed for the entire study area. The absence of low flow geometry between crossings produces conservative flood elevations and floodplain extents within the reach and therefore is a desirable characteristic for Regulatory Floodplain Mapping.

It is noted that the hydraulic model has first and foremost been developed for the purposes of flood hazard mapping. The development of the model was focused on generating water surface elevations for the Regulatory flood event (100-year SCS storm distribution). The hydraulic model results for smaller return period storm events have not been run for this project and are anticipated to have higher degrees of uncertainty. Additional detailed studies (i.e., low flow channel corrections, placement of levees, etc.), may be required to ensure adequate accuracy of modelling results for smaller storm events.

7 CONCLUSIONS

The 1-D and preliminary 2-D HEC-RAS hydraulic models were built using the most recent data in the NPCA's possession. The 1-D HEC-RAS model is compliant with all pertinent technical guidelines (OMNR, 2002; EWRG et al., 2017; NRCan, 2023). This study thus provides detailed insight into the hydraulic behaviour of the Upper Welland River Tributaries systems.

The following points are key conclusions drawn from this study:

- The 1-D hydraulic model includes a total of 3,066 river cross-sections, covering a total creek length of 197 km;
- The 1-D model includes a total of 145 hydraulic structures, consisting of bridges and culverts;
- The 1-D model incorporates HEC-HMS peak flows from a total of 259 flow nodes;
- The preliminary 2-D model assessed an area of approximately 1470 hectares where conditions prevented a reliable 1-D model analysis;
- Survey investigations were conducted by Aquafor Beech Limited throughout 2025 and 2026 to confirm the details of all hydraulic structures within the study area and to more accurately define stream bathymetry;
- Structure inventory sheets were developed for each of the surveyed hydraulic structures;
- A LiDAR-derived DTM referenced to the NAD83 (CSRS) UTM Zone 17N horizontal coordinate system and the CGVD2013 vertical datum was applied to define river cross-sections, stream centreline, and overbank locations, and to generate flood lines;

- Flows for the 2-year to 350-year were input into the hydraulic model based on results from the Aquafor HEC-HMS hydrologic model. These flows were adjusted as-needed to better represent channel containment between reaches;
- A tailwater sensitivity analysis was completed based on MNR technical guidelines to determine the appropriate tailwater condition and to evaluate the tailwater sensitivity of each reach outletting to the Welland River;
- Manning's roughness values for existing land use conditions were assigned in the model according to Design Chart 2.01 of the MTO Drainage Management Manual (MTO, 1997) and Technical Guidelines for Flood Hazard Mapping (EWRG et al., 2017). A sensitivity analysis of these values and the potential impacts on flood hazard extents was completed.
- The model was run under steady state conditions and a mixed flow regime;
- Spill areas where uncontained flows exceeded channel limits and spilled to adjacent reaches were noted;
- Floodplain mapping was produced for the 50-year, 100-year (Regulatory), 200-year and 350-year flood events.

Aquafor has confidence in the hydraulic model to predict water surface elevations with a reasonable degree of accuracy for the Regulatory event (100-year flood event) and therefore, in the Regulatory Floodplain Mapping product.

8 REFERENCES

Canadian Geodetic Survey (2026) *GPS.H Conversion Tool*

EWRG, TRCA, CVC, CLOCA, GRCA, GC, & NVCA. (2017). *Technical guidelines for flood hazard mapping*.

Environment Canada Water Office (2026) *Real-time & Historical Hydrometric Data*

Ministry of Transportation Ontario. (1997). *MTO Drainage Management Manual*.

M.M. Dillon Limited. (1977) *Flood Plain Mapping Project – Haldimand-Norfolk*.

Natural Resources Canada. (2023). *Federal hydrologic and hydraulic procedures for flood hazard delineation*.

OMNRF. (2002). *Technical guidelines - River & stream systems: Flooding hazard limit*.

US Army Corps of Engineers. (2016). *HEC-RAS river analysis system – Hydraulic reference manual, version 5.0*.

US Army Corps of Engineers. (2022). *River analysis system: HEC-RAS user's manual, version 6.3*.