Flood Hazard Modelling Sensitivity Pilot Study

Phase II

Environment and Climate Change Canada
Environnement et Changement climatique Canada

Cat. No.: En56-370/2-2026E-PDF
ISBN: 978-0-662-87253-5

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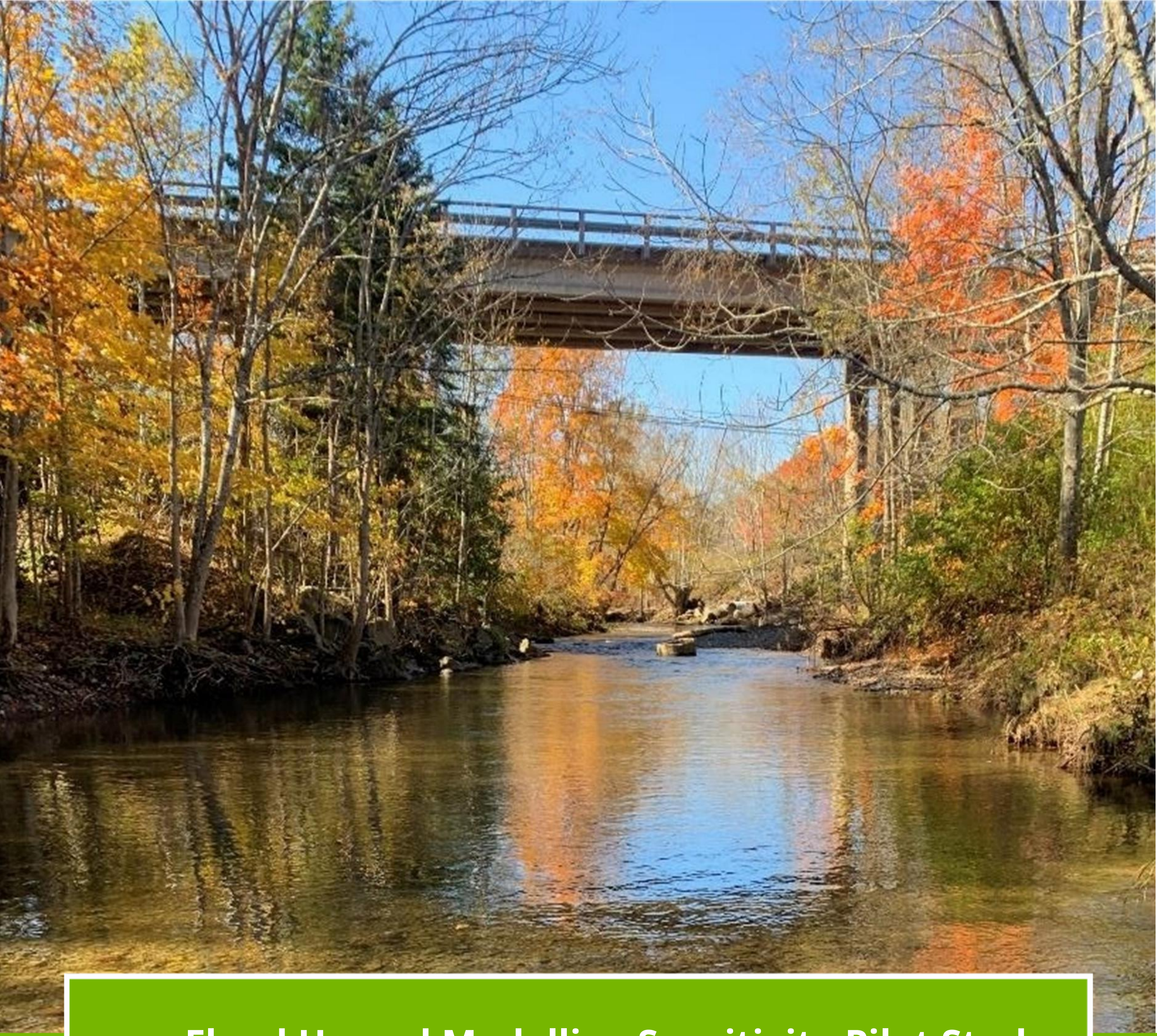

Flood Hazard Modelling Sensitivity Pilot Study

Phase II – Final Report

Environment and Climate Change Canada

CBCL

Associated Engineering

241213.01 • 15 December 2025

01	Final Report	A. Wilson A. MacIsaac	15-Dec-2025	A. Oliver P. Buskas
00	Draft Report	A. Wilson A. MacIsaac	15-Oct-2025	A. Oliver P. Buskas
Rev.	Issue	Reviewed By:	Date	Issued By:

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December 15, 2025

Joel Trubilowicz PhD, P.Eng
National Hydrological Service
ECCC

Dear Mr. Trubilowicz:

RE: Flood Hazard Modelling Sensitivity Pilot Study Phase II - Final Report

CBCL is very pleased to submit this Flood Hazard Modelling Sensitivity Pilot Study Phase II final report. The report includes testing, as well as conclusions and recommendations providing high level interpretation and guidance regarding the uncertainty associated with software selection, geometric and survey data availability. Guidance is also included on how to minimize uncertainty in flood mapping given limitations with data availability, or limited resources.

Please do not hesitate to contact the undersigned if you have any questions or comments regarding this final report.

Yours very truly,

CBCL Limited

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Project No.: 241213.01

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Executive Summary

Following the completion of the Phase I hydrologic, hydraulic and GIS model sensitivity testing, the CBCL Limited – Associated Engineering team was selected by Environment and Climate Change Canada (ECCC) to conduct further sensitivity analysis on two study areas involving varying flood mapping methods given changes in the model used, as well as changes in the availability of supporting data. This Phase II study builds on work done in Phase I of the Sensitivity Analysis Pilot project, where both teams analysed previously completed hydrologic-hydraulic modeling for parameter sensitivity and uncertainty. Focus was placed on the assessment of parameter sensitivity in hydrologic analysis and processes, hydraulic model parameters, and GIS processing to examine the impact of uncertainty and practitioner decisions on flows, water levels, and the extents of the flood hazard maps. This was carried out for two different study areas representing very different hydrologic and hydraulic contexts, with one in Nova Scotia and one in British Columbia.

In Phase II, within the same two study areas, focus was placed on investigating the impacts of selecting an alternative modelling software, modifying the underlying DEM resolution, and addressing lack of, or limited availability of, bridge and culvert geometry data, and bathymetry data. Notably, in both study areas, an approach to using a back-calculated bathymetry to compensate for lack of bathymetric survey data was tested and compared with results from various levels of bathymetric data collection, unmodified 1m-resolution Lidar data, or unmodified 30-m resolution MRDEM data.

Guidance was provided on the selection of modelling software, and adapting the modelling approach given limited topographic, bridge / culvert or bathymetric data availability. The guidance is tailored to either maximize the flood mapping quality potential when working with limited data availability, or optimize levels of effort for the production of flood mapping products.

The findings of the testing generally pointed to the fact that while general trends are evident (e.g. less data generally results in more uncertainty), an understanding of river hydrodynamics, combined with an investigation of the river characteristics, can offer potential opportunities for savings in level of effort. This is true for example where missing river bathymetry may be suitably inferred with available flow gauging data, which would eliminate the need for river cross-section surveys.

In a broad sense, to maximize the quality of the results, it is always valuable to use the highest resolution DEM available, and if only a coarse resolution DEM exists, to give consideration to obtaining lidar data in the floodplain. A review of the watercourse characteristics, as well as the hydraulic structures that may pose restrictions to the flow of water, will be very helpful in identifying potential opportunities for data collection optimization. Given uncertainties in methods for inferring river bathymetry, it is still recommended that river bathymetry be obtained using field surveying methods, while those can also be optimized

If no field data collection is feasible, however, the inference of river bathymetry was found to greatly reduce the uncertainty associated with using only the DEM (whether lidar or MRDEM) for bathymetric data. It will be important to first, however, confirm if opportunities for reducing data collection will be limited by jurisdictional requirements, which will need to be carefully reviewed to ensure compliance.

It is therefore fundamental to exercise dutiful engineering judgement based on experience and expertise to inform decisions on whether to expend the additional effort associated with the gathering of additional field data, even when this data may necessitate a very high amount of effort to collect. In a client / consultant relationship, both parties should be involved in discussions and in the decision-making process. If the choice is made to reduce or forego the collection of supporting data, clear discussions should be included in the associated reports to explain such decisions and the accepted amount of uncertainty resulting from those decisions. Discussions about the additional efforts to reduce the resulting uncertainties should also be included in the reporting, should they be needed in the future.

1 Introduction

In Phase II of the Flood Hazard Modelling Sensitivity Pilot Study, the project team investigated impacts of selecting an alternative modelling software, modifying the underlying DEM resolution, and addressing lack of, or limited availability of bathymetry data. This is further detailed in the following list:

- New hydraulic models were constructed for each selected study area using a different hydraulic modelling software or method than what was completed in the original flood studies. Existing hydraulic models for the proposed study areas included both 1D and 2D HEC-RAS models for Study Area 1 and Study Area 2, respectively. The alternative software used in Phase II were 1D PCSWMM (Study Area 1) and MIKE+ 2D (Study Area 2).
- A reduced DEM resolution available Canada-wide, with the original study area models, was tested for each study area. These models were also used to test impacts of various channel bathymetry choices for the projects assessed, using no bathymetric data, limited data, or capacity-inferred data.
- Combinations of the reduced DEM resolution and the various bathymetric choices were assessed.

Flood line extents, water depth, flow and velocity were exported from each scenario to visualize results. Results were discussed individually for each study area and also compared and contrasted between the physiographic regions tested (both due to the respective watershed characteristics and different flood types).

2 Selected Flood Studies

2.1 Study Area 1: Antigonish County, NS

This study area is located in Antigonish County of northern Nova Scotia. In 2022-2023, CBCL completed a flood mapping study for the area as part of the provincial Municipal Flood Line Mapping program funding by the Nova Scotia Department of Municipal Affairs and Housing and the Flood Hazard Identification and Mapping Program (FHIMP). This project supported the local Eastern District Planning Commission in developing new flood hazard zoning for their jurisdiction.

This study area is an ideal site for a sensitivity analysis due to its physiographic characteristics which are representative of Nova Scotian rivers as well as fact that it has abundant available data and thorough previous studies. The following key attributes contributed to the selection of this river for this analysis.

1. The study has been completed following current best practices including the Nova Scotia Flood Line Mapping Technical Specifications. The project was reviewed by NRCan Staff and a third-party engineering consulting firm.
2. The study area represents typical physiographic conditions for a mid-sized eastern Canadian watershed. Its headwaters consist of partially forested, rolling hill terrain with well-defined watershed boundaries, and some lakes.
3. The climate and flood regime are common to those experienced across eastern Canada, with flood events caused by a variety of different mechanisms, including:
    a. Sudden convective rainstorms in summer months
    b. Hurricanes and tropical storms through the fall months
    c. Rain on frozen ground events in early winter
    d. Mid-winter rainfall with snowmelt
    e. Ice jamming
    f. Spring season freshet caused by snowmelt
4. The river channel and floodplain have a natural alluvial morphology, with a well-defined valley floor, and meandering channel. The floodplain has mixed land cover including forest, agriculture, and residential land use.
5. The study area has excellent hydrometric data coverage. The ECCC Climate Station located in the watershed has over 100 years of rainfall data while the Water Survey of Canada's hydrometric station has over 74 years of data. These have been used to calibrate the hydrological and hydraulic models.

6. Detailed hydrologic and hydraulic models have been developed for the study area. A PCSWMM hydrological-hydraulic model was constructed for the 200 km^2 watershed that is delineated into 35 subcatchments. A range of parameters are available for sensitivity analysis in PCSWMM, including: subcatchment width, slope, roughness, depression storage, soil moisture deficit, soil infiltration rate and methodology. The model uses National Resources Canada (NRCAN) Land Cover Mapping and Agricultural and Agrifood Canada Soil Mapping. A HEC-RAS hydraulic model (version 6.3) was used for the 31 km river length with 197 cross section and 9 hydraulics structures (bridges). Channel bathymetry and structures have been topographically surveyed.
7. All models and mapping have been developed using recent GeoNova Lidar Digital Elevation Model at 1 m grid size in Canadian Vertical Geodetic Datum (CGVD) 2013.

Comparison of the water level and velocity results for each scenario are presented in the following report at 17 nodes throughout the watershed, which represent approximately 1 node for every 10 nodes in the model (total of 174) (Figure 2-1). This will ensure that the effects of changing model parameters throughout the entire watershed is shown for both the water level and velocity in a more readable manner. Flood extents are presented at two specific locations in the watershed, one near a downstream bridge and the other representing a typical length of the river.

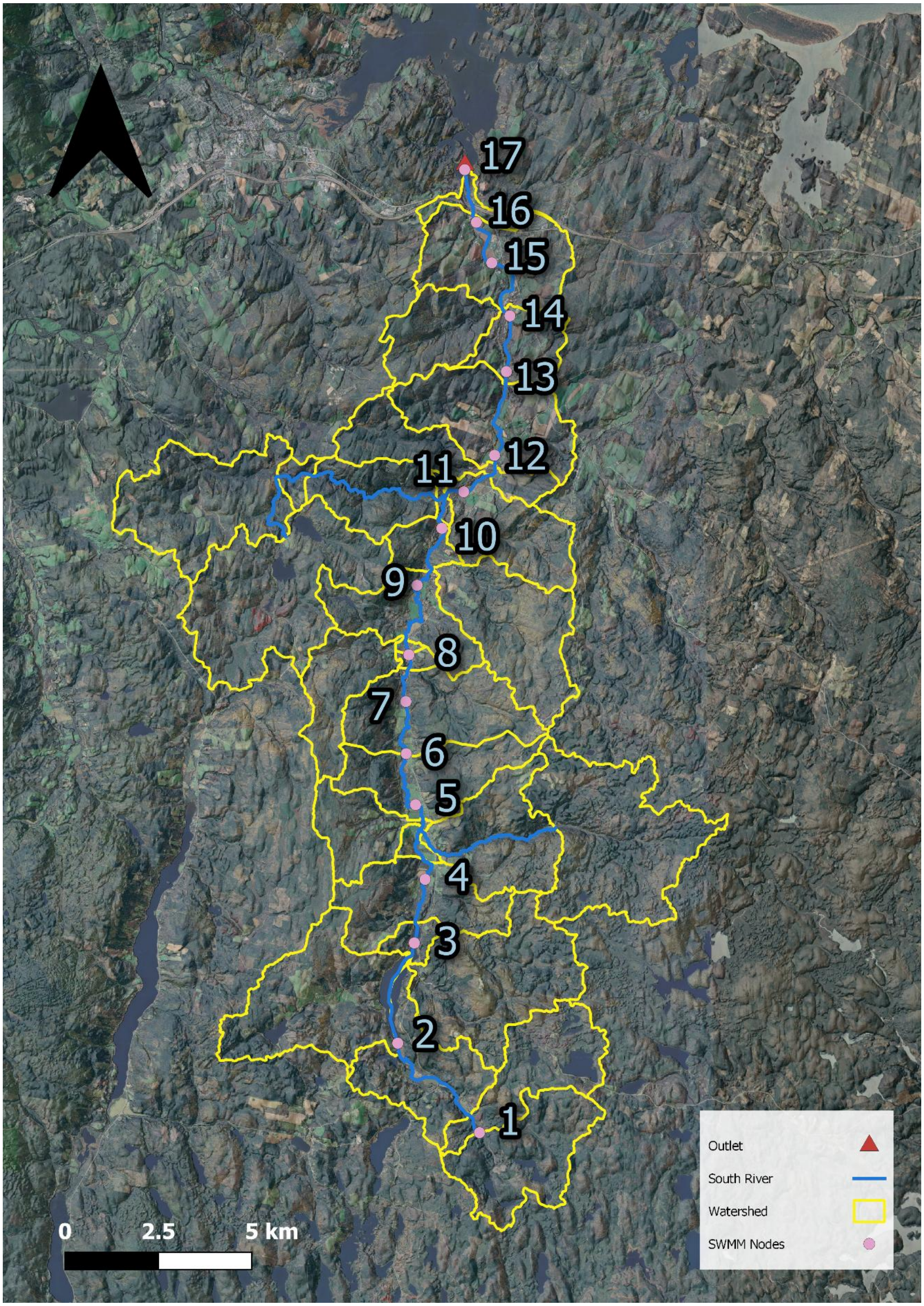

Figure 2-1: Study area showing the seventeen (17) selected nodes for reporting.

2.2 Study Area 2: Salmon River near Prince George, BC

The second study area includes the Salmon River near Prince George, British Columbia (Study Area 2). Associated was contracted in 2022 to complete a flood mapping study of Salmon River for the British Columbia Flood Hazard Identification and Mapping Program (FHIMP) initiative; the project was completed in May 2025. The main objective of this project was to develop high quality, standardized, consistent floodplain mapping for higher-risk communities in B.C. that lack recent flood maps.

The Salmon River reach is 14 km in length between the Community of Salmon River Valley at Highway 97 and the Salmon River confluence with the Fraser River in British Columbia. This reach is highly sinuous and experiences rapid geomorphologic change, including frequent river avulsions and large woody debris (LWD) transport. It includes a large, unrestricted floodplain with hundreds of relic channels that engage during high flow events. The river has a contributing watershed of approximately 4,230 km^2 and also typically experiences peak flood events during freshet. The following key attributes contributed to the selection of Salmon River for this analysis.

1. The original flood study was completed following British Columbia current best practices, including the preliminary updated Flood Hazard Mapping Guidelines for British Columbia and the Flood Hazard Identification and Mapping Program (FHIMP) initiative specifications. The project methodology and results were reviewed by Fraser Basin Council and an official over-sight committee that included ECCC staff.
2. The study area represents typical physiographic conditions for mid-to-large-sized western Canadian watersheds. This includes freshet, snowmelt-driven systems with mountainous, forested headwaters and well-defined watershed boundaries.
3. Climate and flood regimes within the watershed are consistent with those experienced throughout mountainous British Columbia and other Canadian topographic regions with extensive snowpack. Spring freshet is the primary flood mechanism.
4. The river reach demonstrates a typical alluvial morphology, with a well-defined valley floor, and meandering channel. The floodplain has mixed land cover including forest, agriculture, and residential land use.
5. The river reach has excellent hydrometric data coverage. The Water Survey of Canada hydrometric station is located very near the upper end of the reach of interest and provides both annual daily maxima and peak instantaneous flow data. The station has been used for flood frequency analysis and derivation of the flood mapping design flows.
6. The river reach demonstrates a common downstream boundary condition: a confluence with another river.
7. A detailed HEC-RAS 2D (version 6.3) hydraulic model was created for the reach. Channel bathymetry and all bridge structures have been topographically surveyed.

8. All models and mapping have been developed using recent Lidar Digital Elevation Models at a 1 m grid size in Canadian Vertical Geodetic Datum (CGVD) 2013.

For Study Area 2, the peak water levels and average velocities are compared at seven sample cross-sections as shown in Figure 2-2. The locations of the cross-sections were chosen to highlight key features along the Salmon River, such as bridges (Cross-Sections 1 and 6). The selected figures illustrating flood extents were chosen for similar reasons, highlighting bridges and areas where notable differences in extent were observed.

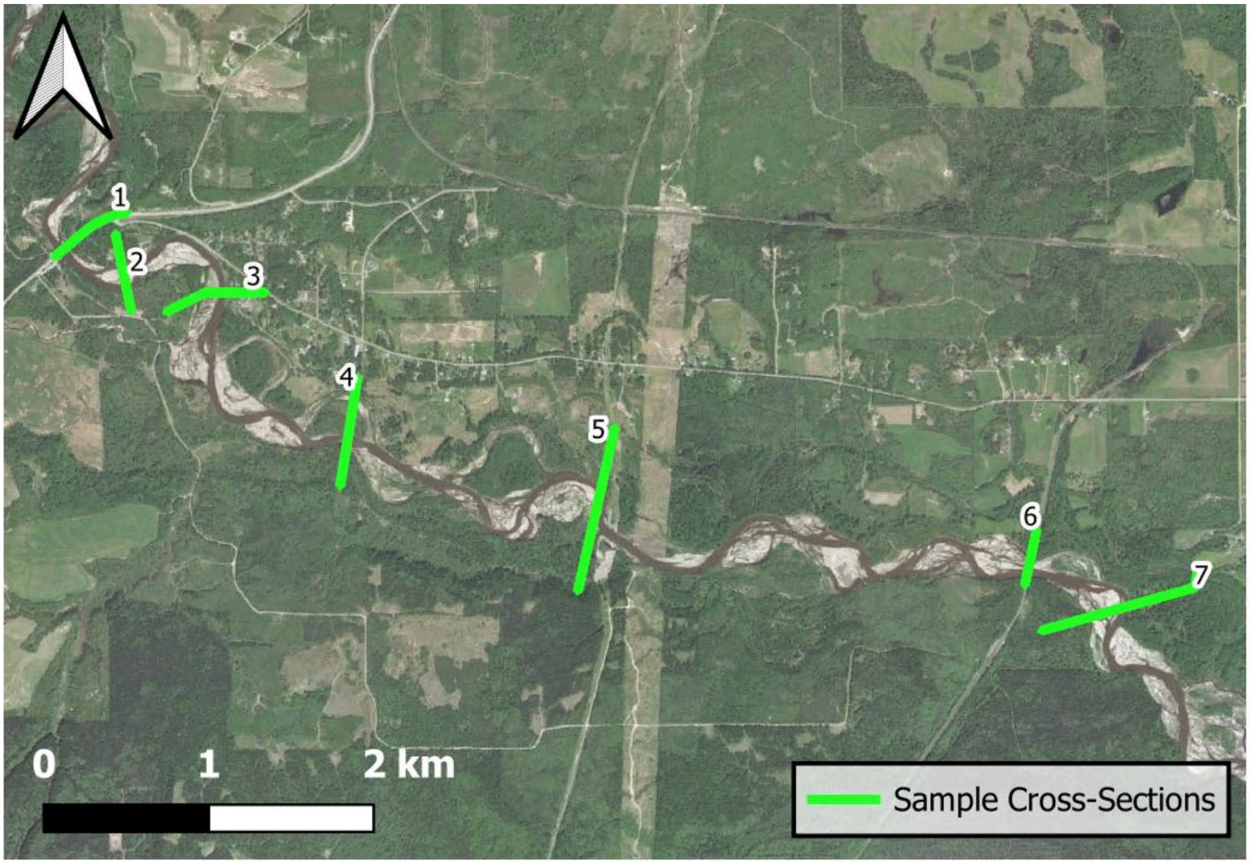

Figure 2-2: Study Area 2 - Salmon River Model Extents and Sample Cross-Sections

3 Exploring Alternative Hydraulic Modelling Methods

This section describes the results of testing the impacts of the hydraulic modelling software selection for each study area, on flood modelling results and flood mapping extents. Both Study Area 1 and Study Area 2 were originally modelled using HEC-RAS, with Study Area 1 modelled in HEC-RAS 1D and Study Area 2 modelled in HEC-RAS 2D. As an alternative, Study Area 1 explored using an alternative 1D hydraulic modelling method (PCSWMM) and Study Area 2 explored a different 2D hydraulic modelling method (MIKE+ 2D).

3.1 Study Area 1: South River, Antigonish, NS

Since the existing hydraulic model for South River is a 1D HEC-RAS model, Phase II involved utilizing a non-HEC model, PCSWMM, to compare results with previously generated flood lines. The previously completed 1D PCSWMM model was originally used to model the hydrology of the site, and inform total maximum cumulative flows input into the HEC-RAS 1D model. The PCSWMM software is built on the industry standard US EPA SWMM5 model that includes a hydraulic modelling capability of unsteady, full-momentum analysis of flow in channels and structures.

In HEC-RAS 1D, cross-sectional data is interpolated from one section to the next, creating dynamic conduits that are gradually changing averages of both specified cross-sections. Whereas PCSWMM uses a fixed specified cross-section throughout a length of conduit, simulating a pipe-like conduit. To account for this difference in approach, and since output water level data from PCSWMM will be directly plotted in GIS, consistent with the current spacing of the nodes, the results may show excessive or insufficient flooding as the topography goes up and down between the nodes. Therefore, the PCSWMM model was altered to include nodes every 10m, such that the results are consistent with the scale of the landforms (Figure 3-1). These nodes contain the maximum hydraulic grade line (HGL) resulting from the PCSWMM model. This information was applied to a cross-section close to the node and a surface was created by interpolating the water levels between two node cross-sections. This water surface is directly mapped in GIS by subtracting the DEM from these elevations. The baseline scenario was used to compare all changes to the models tested, and represents a 1-in-100 year (1% AEP), 24-hour Chicago storm with surveyed bathymetry. The differences in water level and velocity are presented in Figure 3-2 and Figure 3-3. Figure 3-4 shows the difference in flood extents between the baseline HEC-RAS model and the PCSWMM results. Overall, the flood line extents created using GIS and

PCSWMM spanned a slightly larger extent than the baseline 1D HEC-RAS model in the upper extents of the model. This could be due to variations in the routing method, how the surface roughness is included in the calculations, or the GIS surface interpolation method. Changes to water level and velocity at the reported nodes showed both increases and decreases throughout the river reach. Water level changes ranged from -0.55 m to 0.57 m, with most levels decreasing, and velocity changes ranged from -2.45 m/s to 0.85 m/s, with most decreasing.

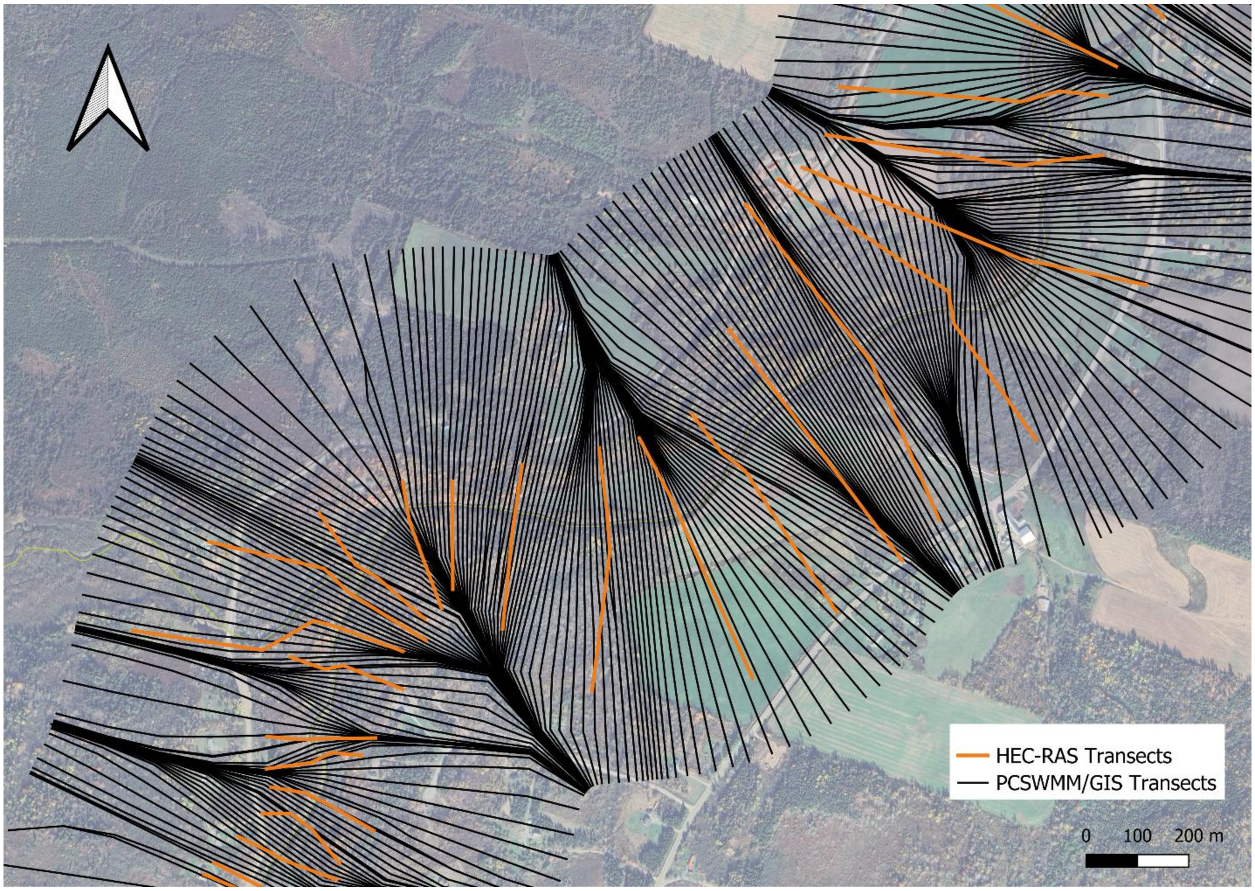

Figure 3-1: Baseline HEC-RAS transects compared to PCSWMM/ GIS transects every 10m.

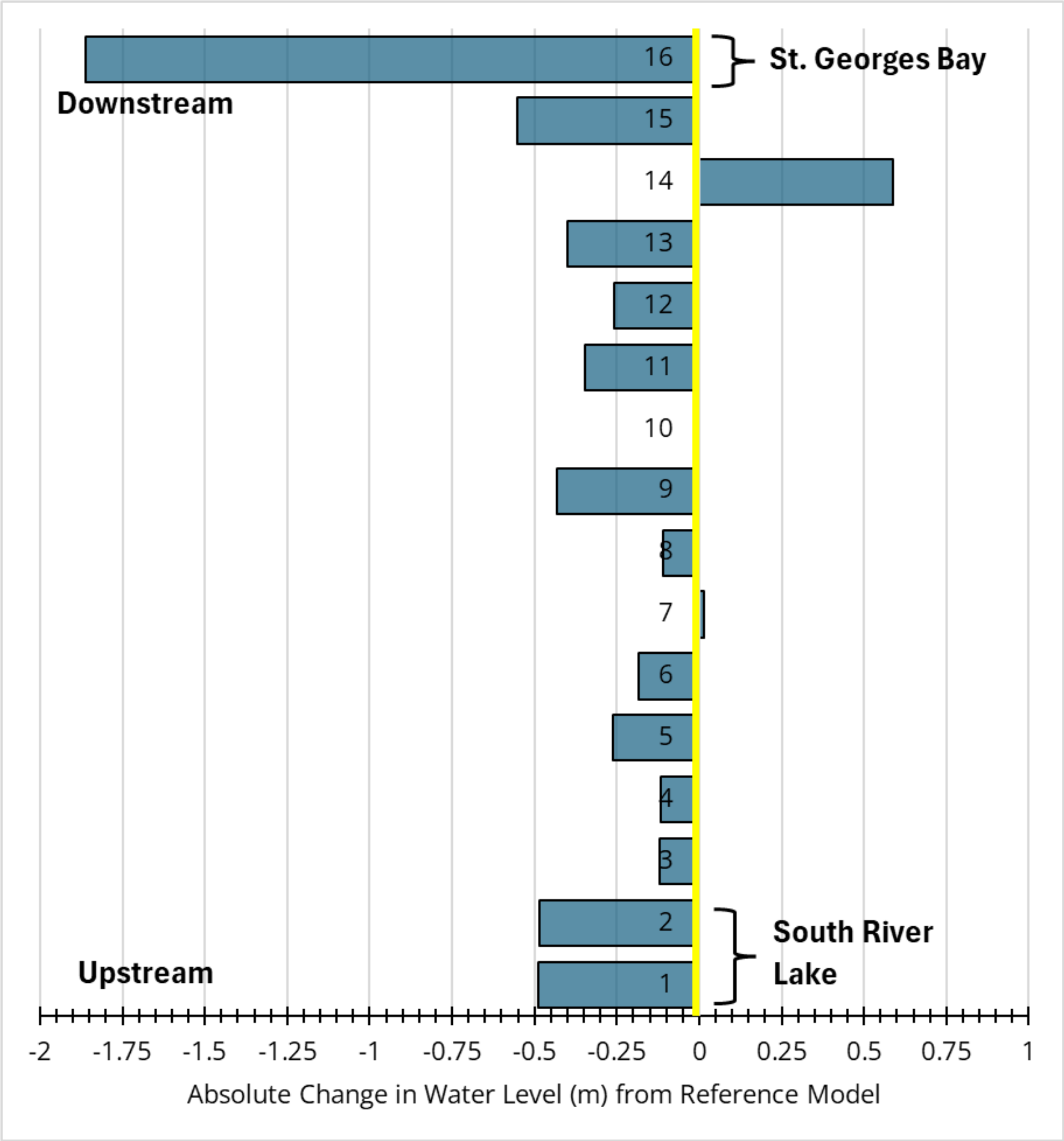

Figure 3-2: Testing Model Change from HEC-RAS 1D to PCSWMM 1D - Results showing change in WSEL

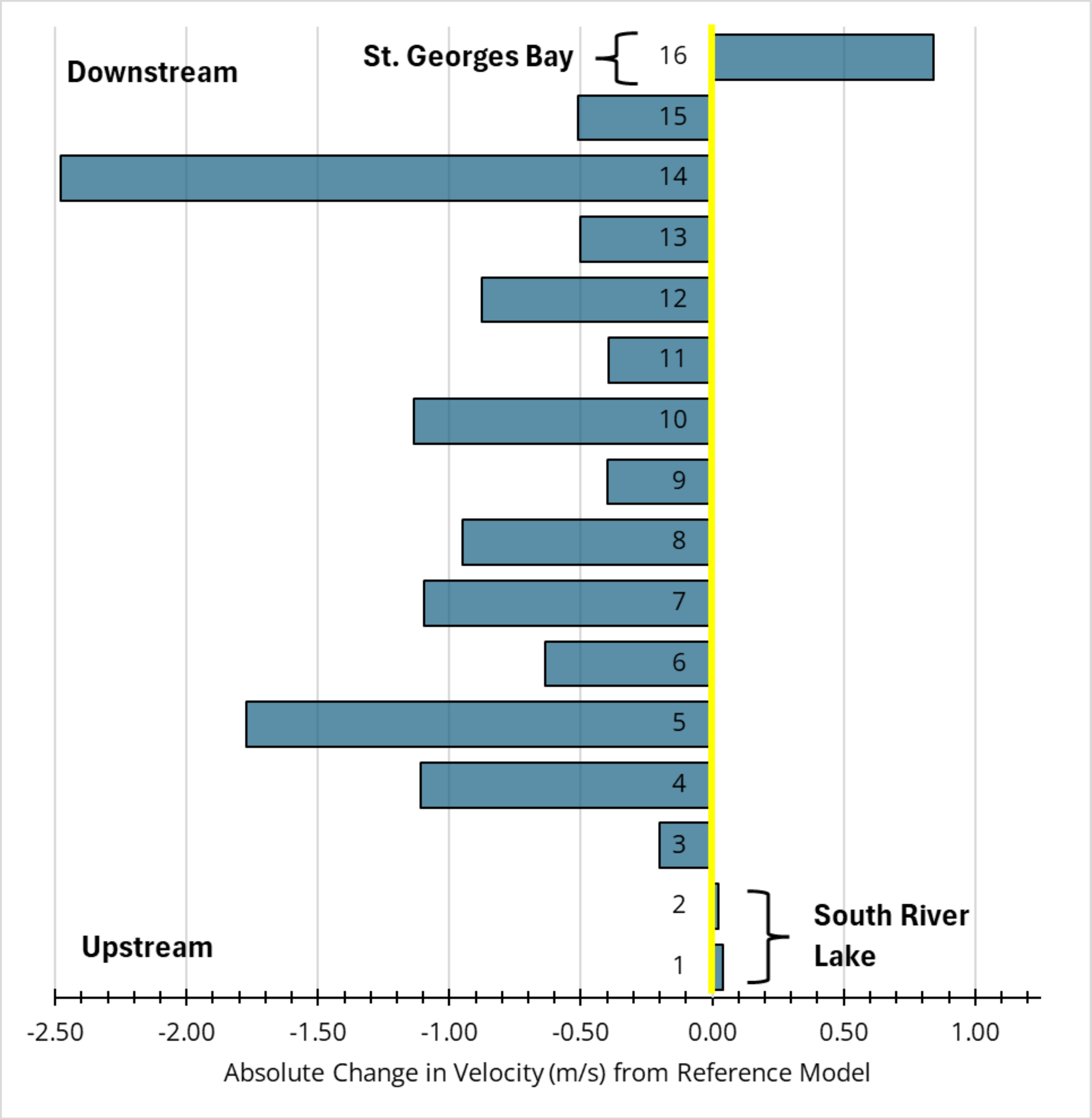

Figure 3-3: Testing Model Change from HEC-RAS 1D to PCSWMM 1D - Results showing change in Velocity

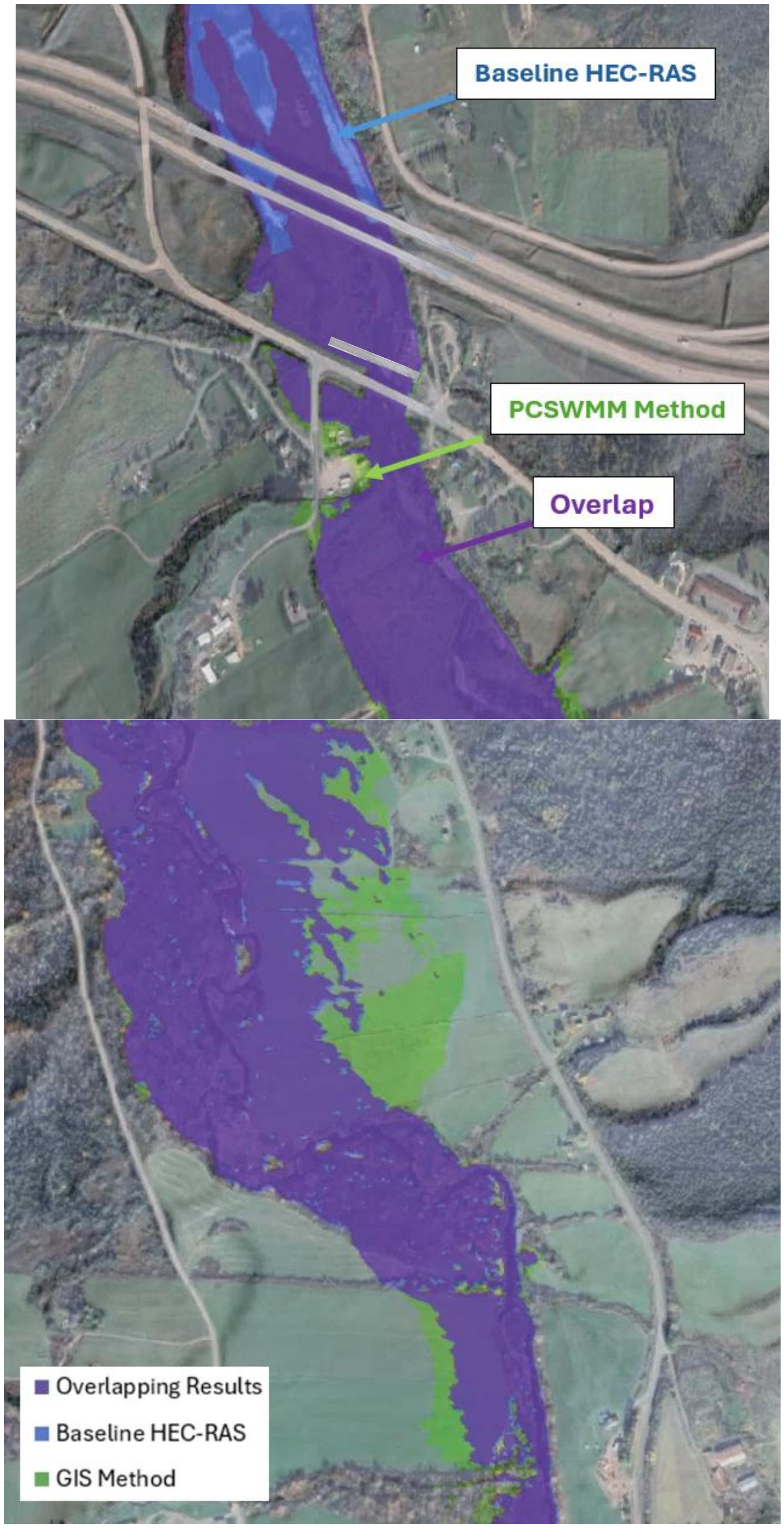

Figure 3-4: Flood extents from PCSWMM/GIS method (Green) vs Baseline HEC-RAS method (Blue)

3.2 Study Area 2: Salmon River near Prince George, BC

The existing hydraulic model for Salmon River was created using HEC-RAS 2D, and Phase II involved modelling the Salmon River with MIKE+ 2D. HEC-RAS 2D is developed by the U.S. Army Corps of Engineers and is an industry standard software used for flood studies and river analysis. HEC-RAS 2D models utilize an implicit mesh design to determine horizontally varying water surface characteristics such as elevation and velocity based on underlying terrain at a sub-mesh level of detail. MIKE+ 2D is developed by DHI and is another industry standard software commonly used for river analysis. Unlike HEC-RAS 2D, MIKE+ 2D utilizes an explicit mesh system and does not capture detail at a sub-mesh scale. The absence of detailed topography within individual cells in MIKE+ 2D can have a material impact on the results. As these models are both industry standard but use different 2D mesh approaches, they are good candidates for comparison.

The boundary condition and terrain inputs were consistent between the HEC-RAS 2D and MIKE+ 2D models. Both models involved the same 1-in-200 year (0.5% AEP) design flow event and included terrain based on the surveyed bathymetry combined with the lidar DEM. The main difference in MIKE+ 2D was the development of the triangular flexible mesh. Arcs were incorporated into the MIKE+ 2D mesh to ensure that the edges of the triangular mesh generated along important features, such as roads and relic channels. Polygons were also used to classify different sizes of mesh in different areas, such as a larger mesh in the floodplain with a finer mesh in the low-flow channel. A sample area of the implicit (HEC-RAS 2D) and explicit mesh (MIKE+ 2D) is shown in Figure 3-5.

Both the MIKE+ 2D model and the original HEC-RAS 2D model were calibrated using the same 2022 calibration event and utilized each software's higher order numerical solution. Results of the MIKE+ 2D calibration yielded channel roughness values 10% lower than in the original HEC-RAS 2D model.

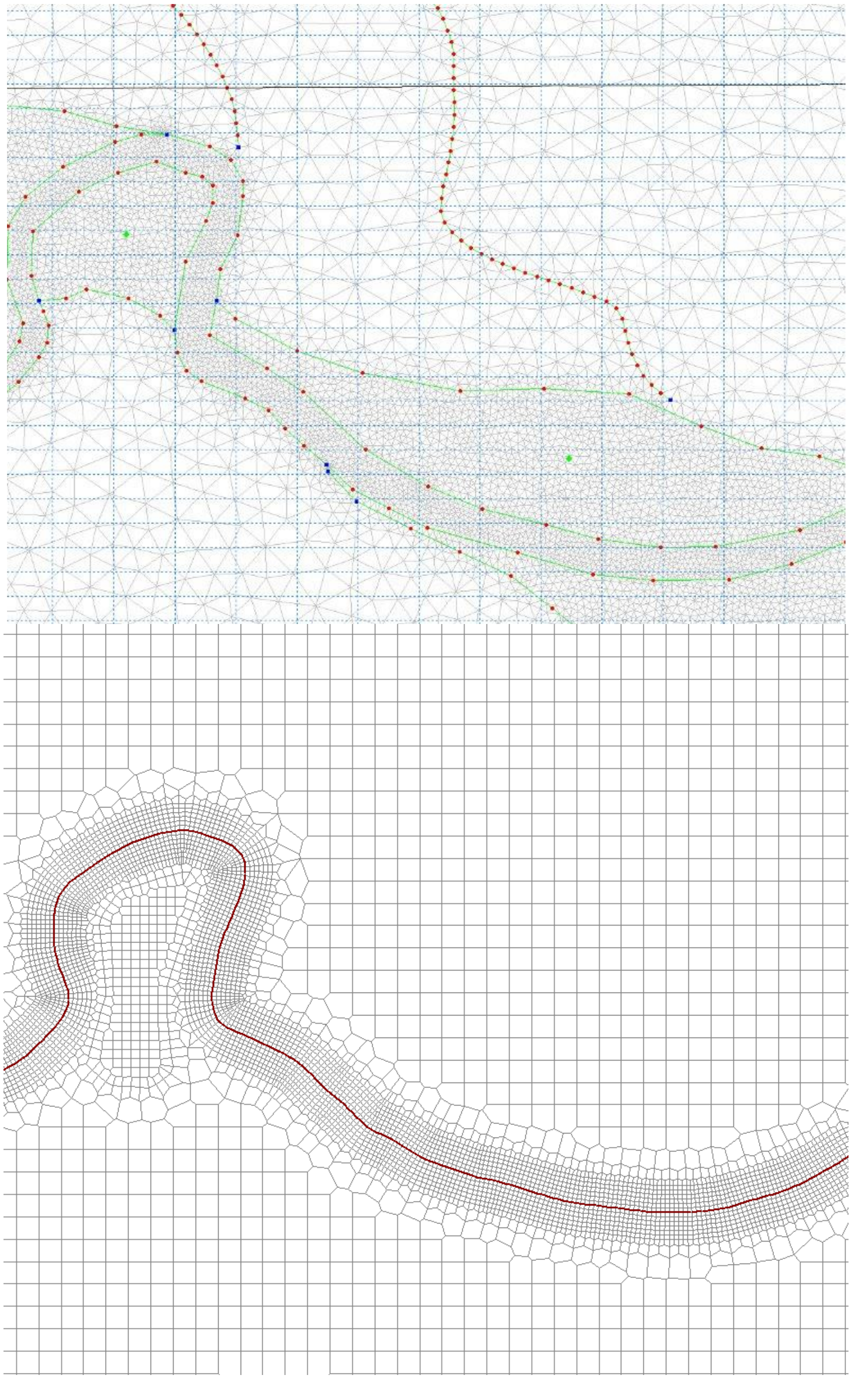

Figure 3-5: Sample of explicit mesh in MIKE+ 2D (top) and implicit mesh in HEC-RAS 2D (bottom)

Figure 3-6 shows the water surface elevations at corresponding sample cross-section locations for the MIKE+ 2D model run relative to the HEC-RAS 2D model. Additionally, Figure 3-7 and Figure 3-8 show the water surface extents at areas of interest along the Salmon River.

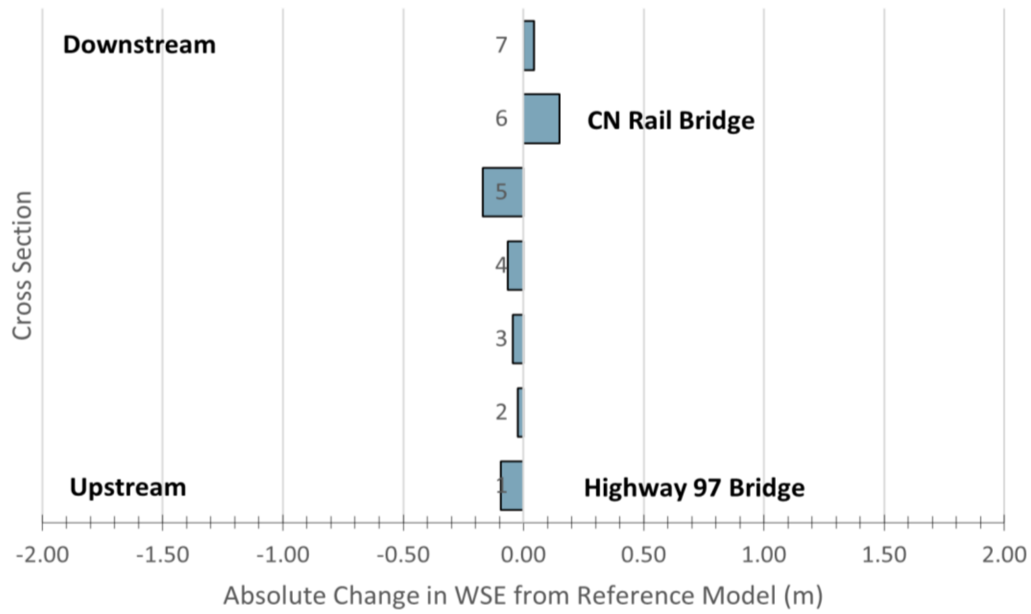

Figure 3-6: Impact of Variation in Modelling Software on Water Surface Elevation at Sample Cross-Sections along the Salmon River

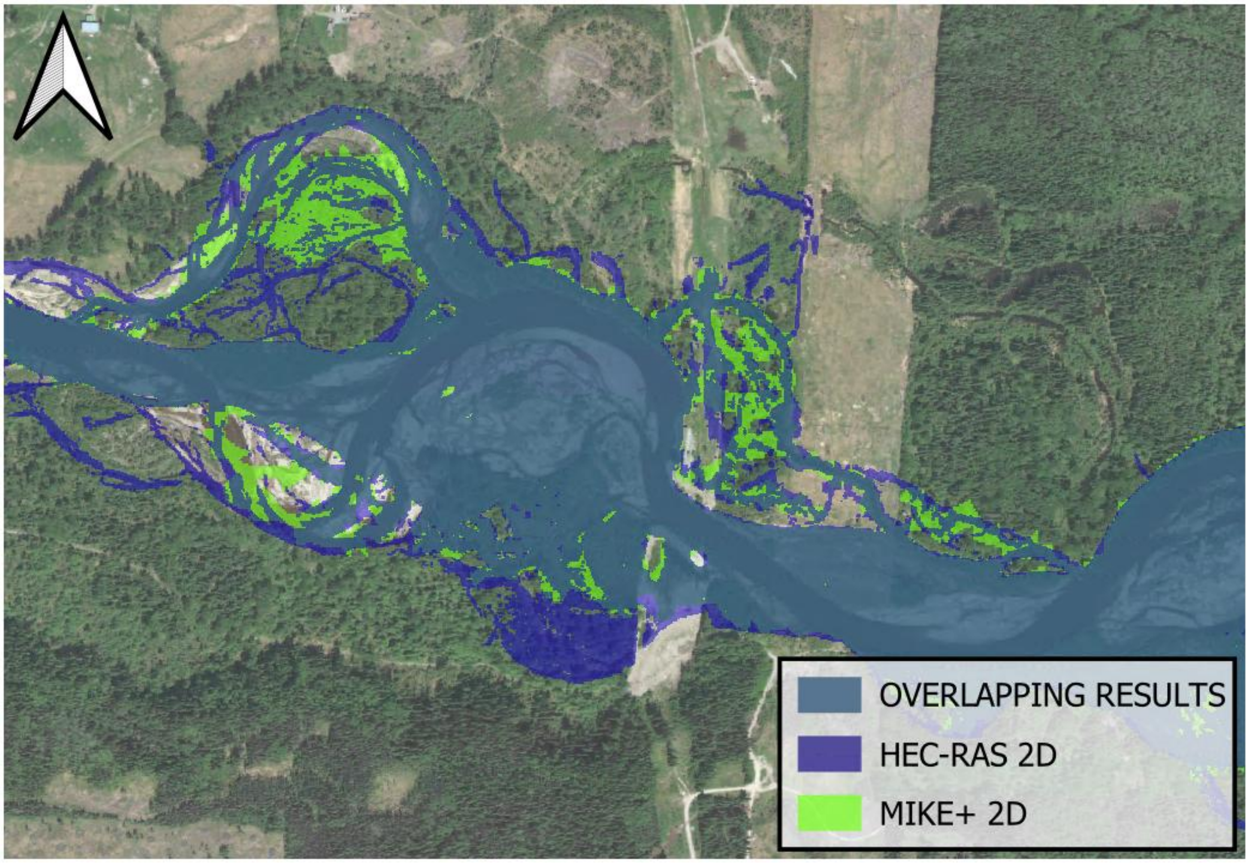

Figure 3-7: Area of interest along the Salmon River with Variation in Modeling Software

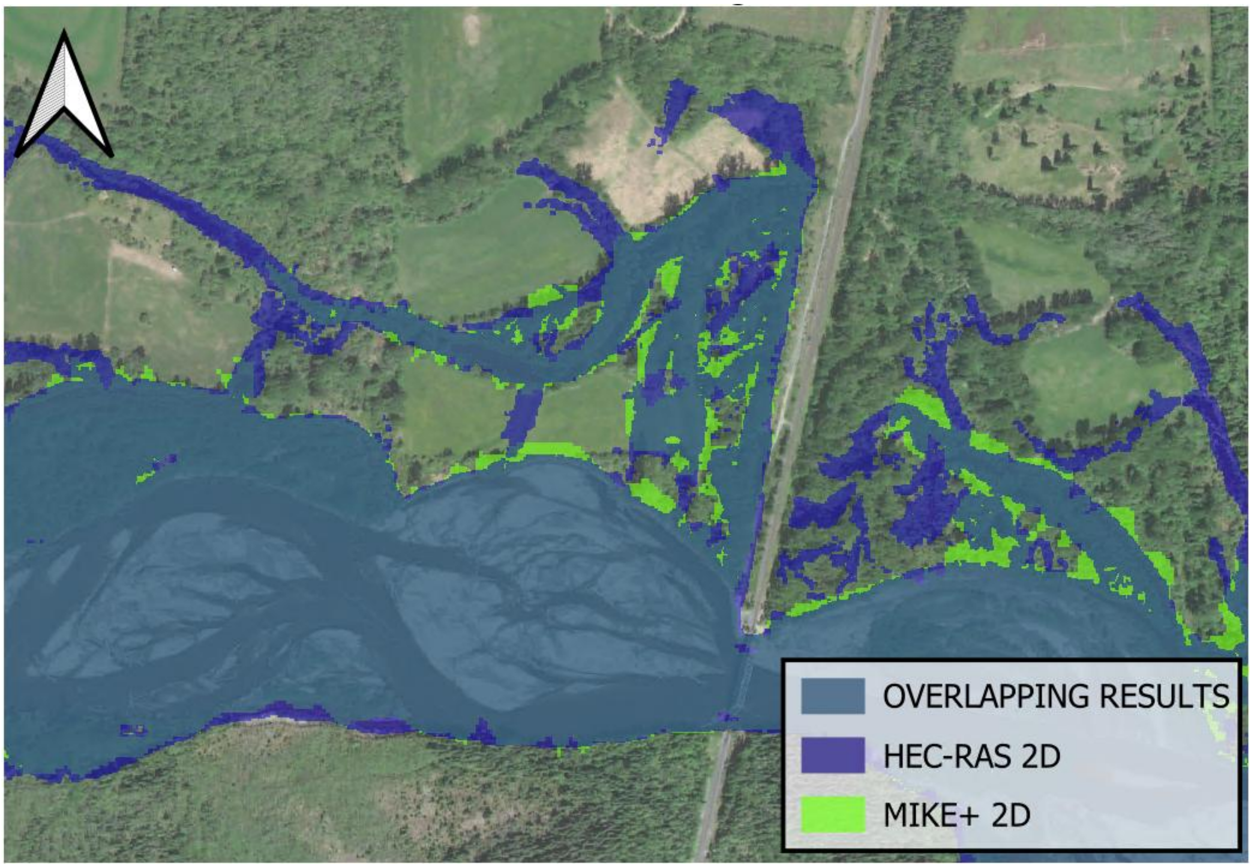

Figure 3-8: Area of interest along the Salmon River with Variation in Modeling Software

The results from the MIKE+ 2D model provided overall similar flood levels to the HEC-RAS 2D model. The observed difference in flood extent in MIKE+ 2D appears to be the result of using an explicit mesh instead of an implicit mesh, leading to loss of fine detail in terrain (i.e. smaller side channels and relic channels). This supports the idea that greater channel complexity favours the implicit mesh, such as that used in HEC-RAS 2D, in representing more variable hydraulic features. In particular, the braided channels and relic channels within the Salmon River flood plain are better captured in the HEC-RAS 2D implicit mesh.

To ensure the MIKE+ 2D mesh is properly describing these important points in the terrain, the use of explicit mesh requires more intentional engineer-led review of surface terrain with informed mesh adjustments, and engineering expertise-led identification of secondary channels with significant hydraulic conveyance. This iterative process was implemented for the MIKE+ 2D mesh developed for this study.

4 Exploring the Impact of Alternative Digital Elevation Models

This section describes the results of the sensitivity testing for each study area, which consisted of using different Digital Elevation Models (DEM) to the original modelling. Specifically, it includes comparing the results using the nationally available MRDEM with the originally used high resolution DEMs.

4.1 Study Area 1: South River, Antigonish, NS

The impact of using a low resolution (30m) DEM (denoted as MRDEM) to create cross-sections in HEC-RAS instead of high resolution (1m) lidar in the baseline scenario was tested. The intent with this test is to maintain the original surveyed bathymetry in the model. However, when the channel bathymetry from surveyed cross-sections was inserted into the MRDEM, it was apparent that the low-resolution DEM did not accurately depict the riverbanks or positioning of the channel, as the MRDEM was found to significantly dampen topographic features. This sometimes resulted in deep channels alongside the MRDEM delineated channel (Figure 4-2 and Figure 4-3), producing flood extents that are shifted compared to the lidar-based flood extents (Figure 4-7). In some cases, the entire flow of water was contained within the channel, with no water in the floodplain. This is explained by the fact that the MRDM floodplain is on average at a higher elevation (than the actual ground level) around the river channel, since it averages the topography with higher elevation features in the floodplain. The channel bottom is already missing in the original data used to assemble the MRDEM, which uses a combination of lidar and radar satellite data to extract elevations, and therefore does not include any underwater elevations. The combination of those two aspects results in a surface that is higher than the channel bottom and in most cases higher than the actual ground in low areas, especially around the channel. The example below in Figure 4-1 shows a cross-section extracted from the lidar data, and from the MRDEM data along the same transect, which shows how the channel elevation in the MRDEM section is not only higher, but also seems to be displaced to the left compared to the lidar section.

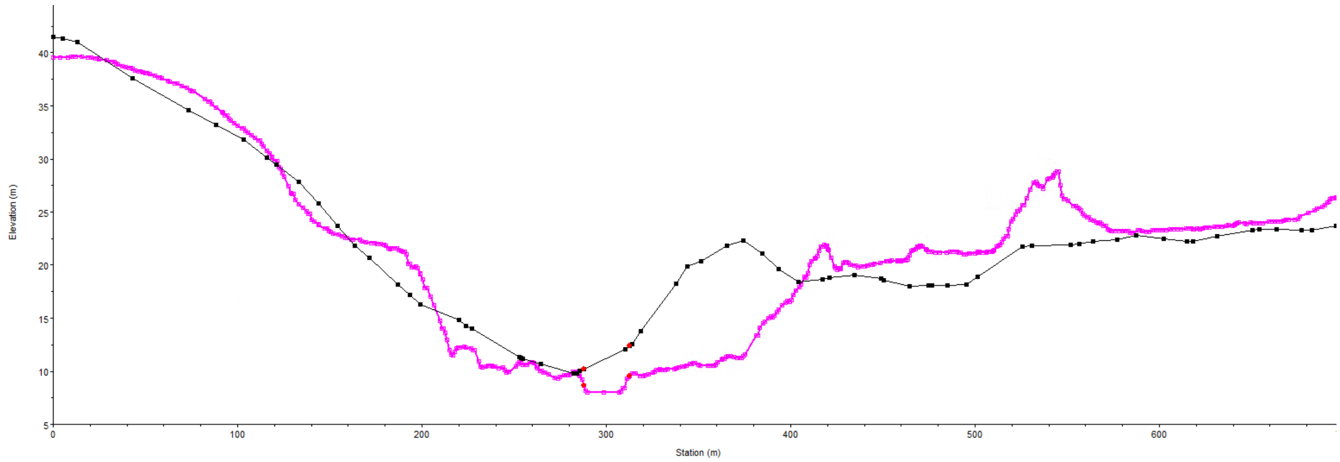

Figure 4-1: Comparison of 1m resolution lidar cross-section (pink) and 30m resolution MRDEM cross-sections

Since the river banks are at a generally higher elevation in the MRDEM section, this can result in artificially high, steep river banks, as seen on Figure 4-2, meaning the flood extents are not only decreased, but in some cases also eliminated, as in the example shown in Figure 4-3. This occurs when the water level in the channel is below the MRDEM low point elevation. Unless the DEM itself is modified to include the surveyed channel bathymetry (i.e. not just in the cross-sections), the floodlines will disappear in some locations. For example, stations 17944 through 17638 did not show any inundation (Figure 4-3 and Figure 4-4).

Figure 4-5 and Figure 4-6 show the distribution of absolute change in water level and velocity over the reported 17 nodes. Due to changing the DEM from lidar to the MRDEM, water levels throughout the watershed show an increase ranging from 0.1m to 0.85m (Figure 4-5). Changes in velocity due to this change are less consistent throughout the watershed, with both increases and decreases in velocity reported at the nodes, with differences in velocity generally becoming greater in magnitude from upstream to downstream (Figure 4-6).

Flood extents for the MRDEM scenario are not necessarily larger but are shifted from baseline floodlines (Figure 4-7). This illustrates the fact that the MRDEM defines different channels from the higher resolution lidar DEM and thus could misrepresent flooded areas if directly applied without any correction or attention to missing topographic detail.

These results show that there is a mismatch in location of thalweg between the high-resolution survey and the low resolution MRDEM, leading to unrealistic river cross-sections. It is recommended that in this case, the survey be used to correct the MRDEM such that the MRDEM thalweg matches the location of the survey, and that any additional hydraulically necessary detail that is filtered out by the MRDEM be surveyed in addition to the river bathymetry (e.g., edge of river banks, floodplain, berms, railway crossings and roads, etc).

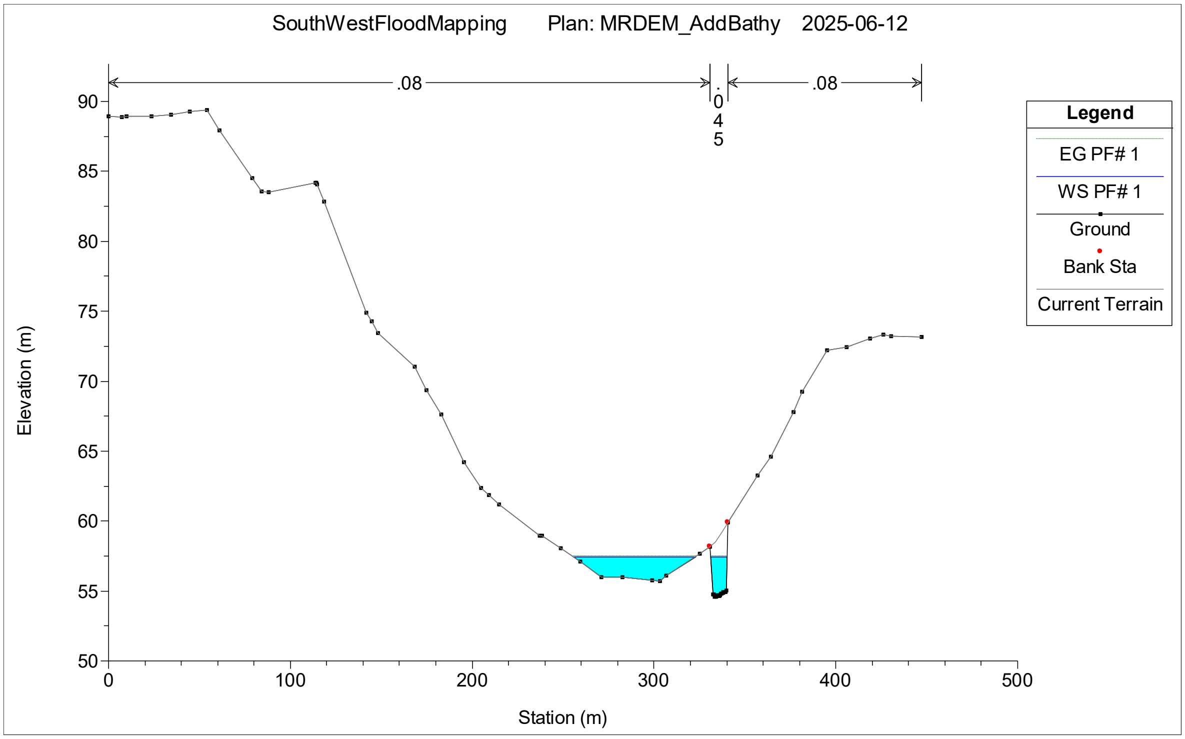

Figure 4-2: Cross-Section 26939 cut from MRDEM, Channel cut into slope using bathymetry survey data

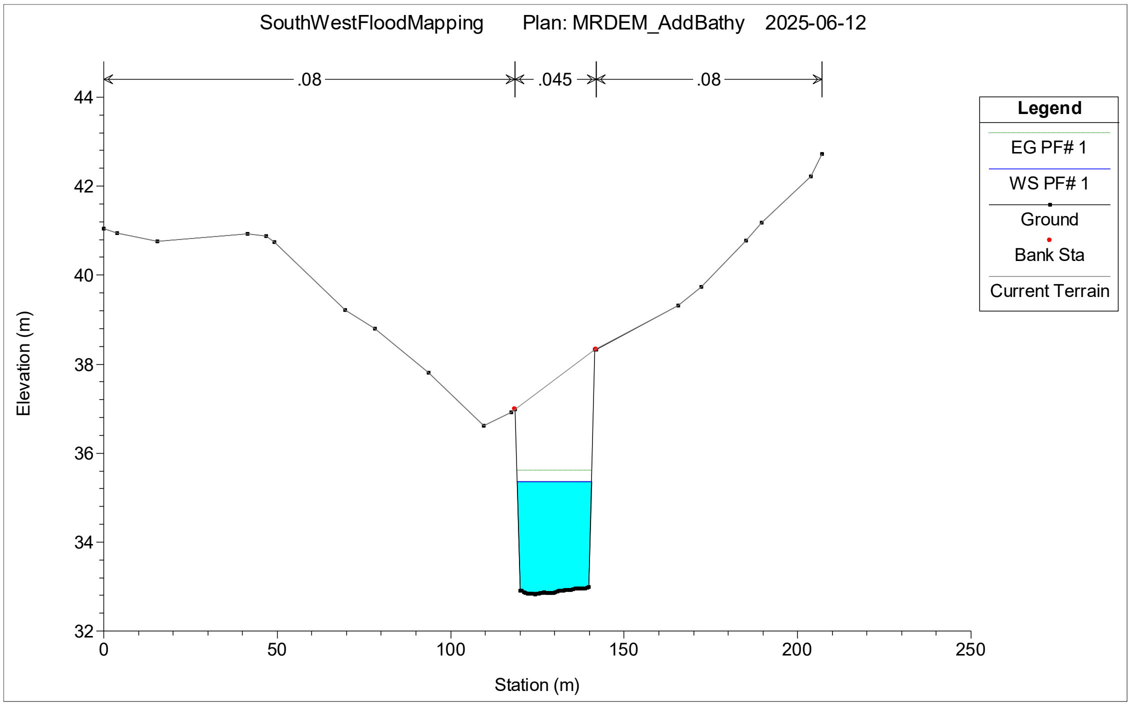

Figure 4-3: Cross-Section 17899 cut from MRDEM, Deep channel cut into slope using bathymetry survey data, showing water depth below MRDEM low point.

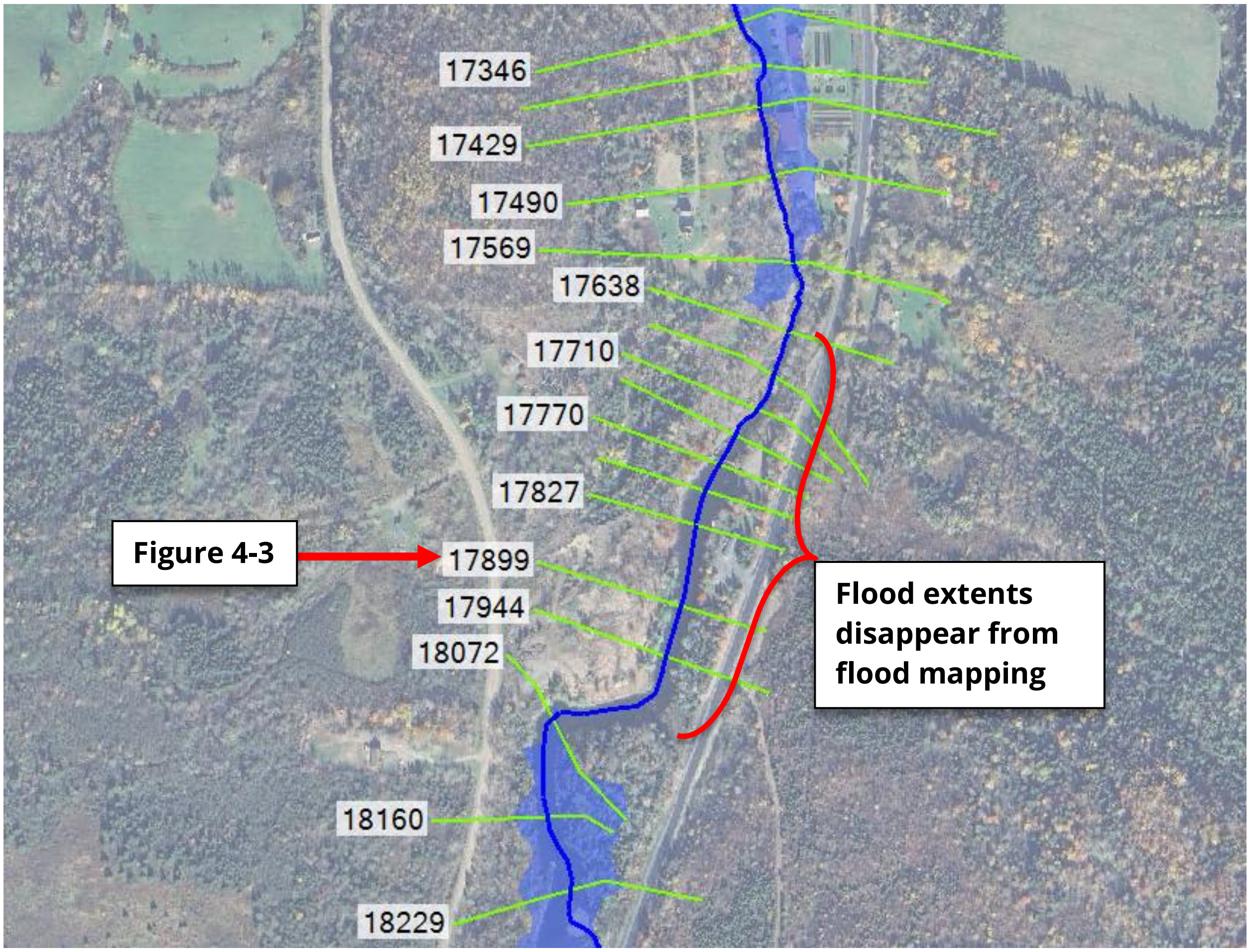

Figure 4-4: Peak Flood Extents for MRDEM and Surveyed Bathymetry Model between Section 18229 (Bottom of Map, Upstream) to 17346 (Top of Map, Downstream).

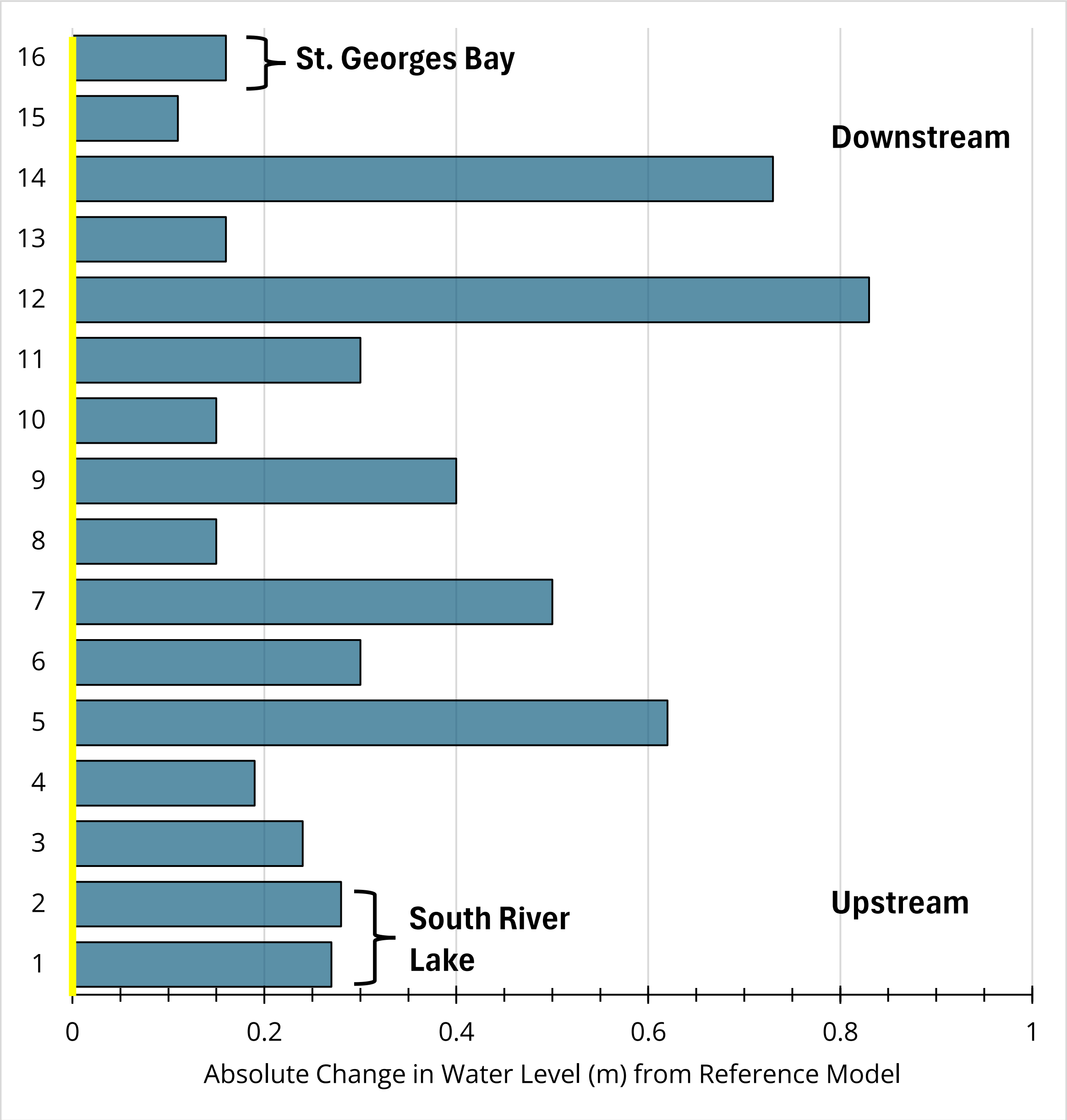

Figure 4-5: DEM Resolution Change Testing (from 1m resolution to 30m resolution) Results showing change in WSEL

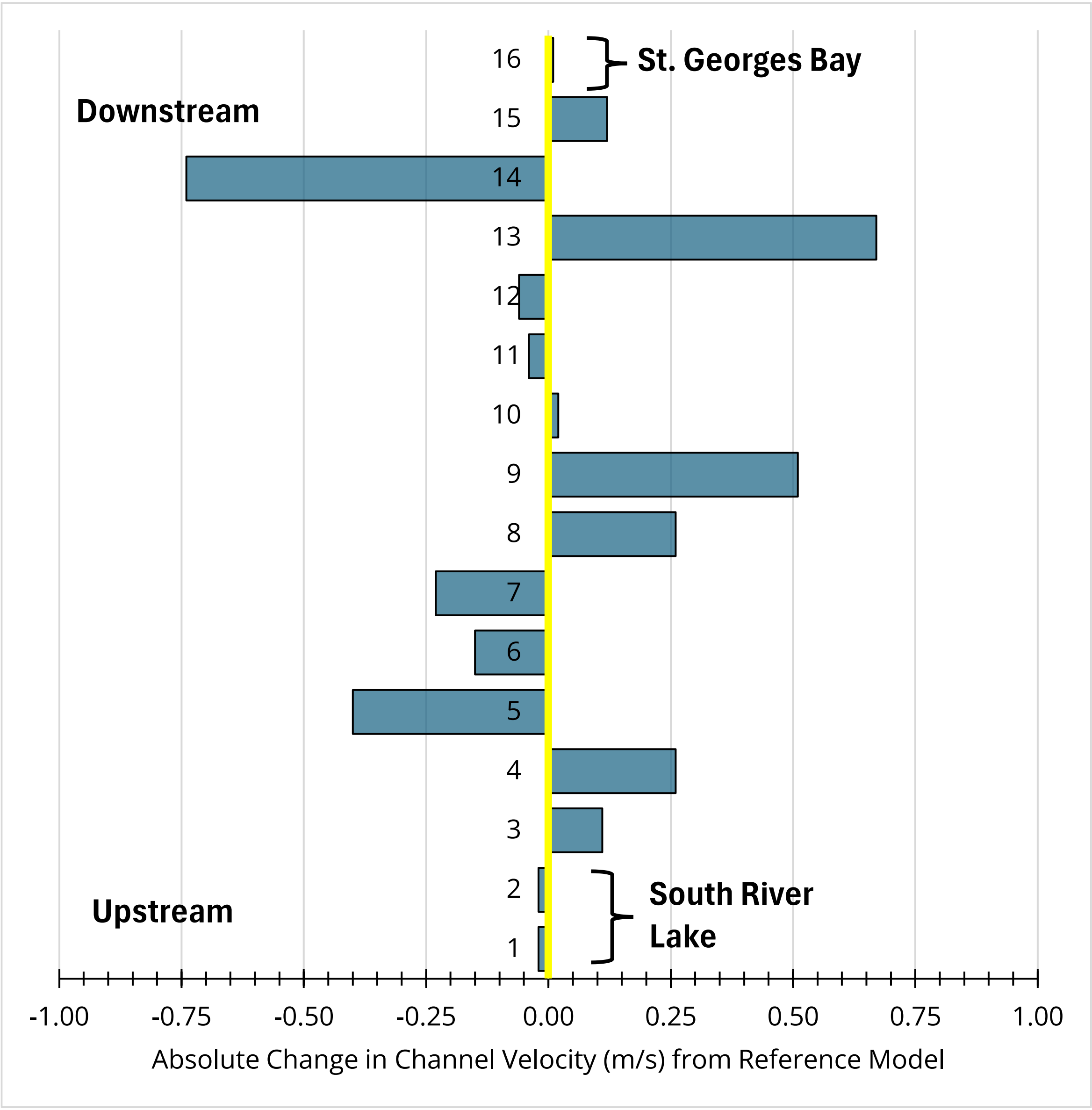

Figure 4-6: DEM Resolution Change Testing (from 1m resolution to 30m resolution) Results showing change in Channel Velocity

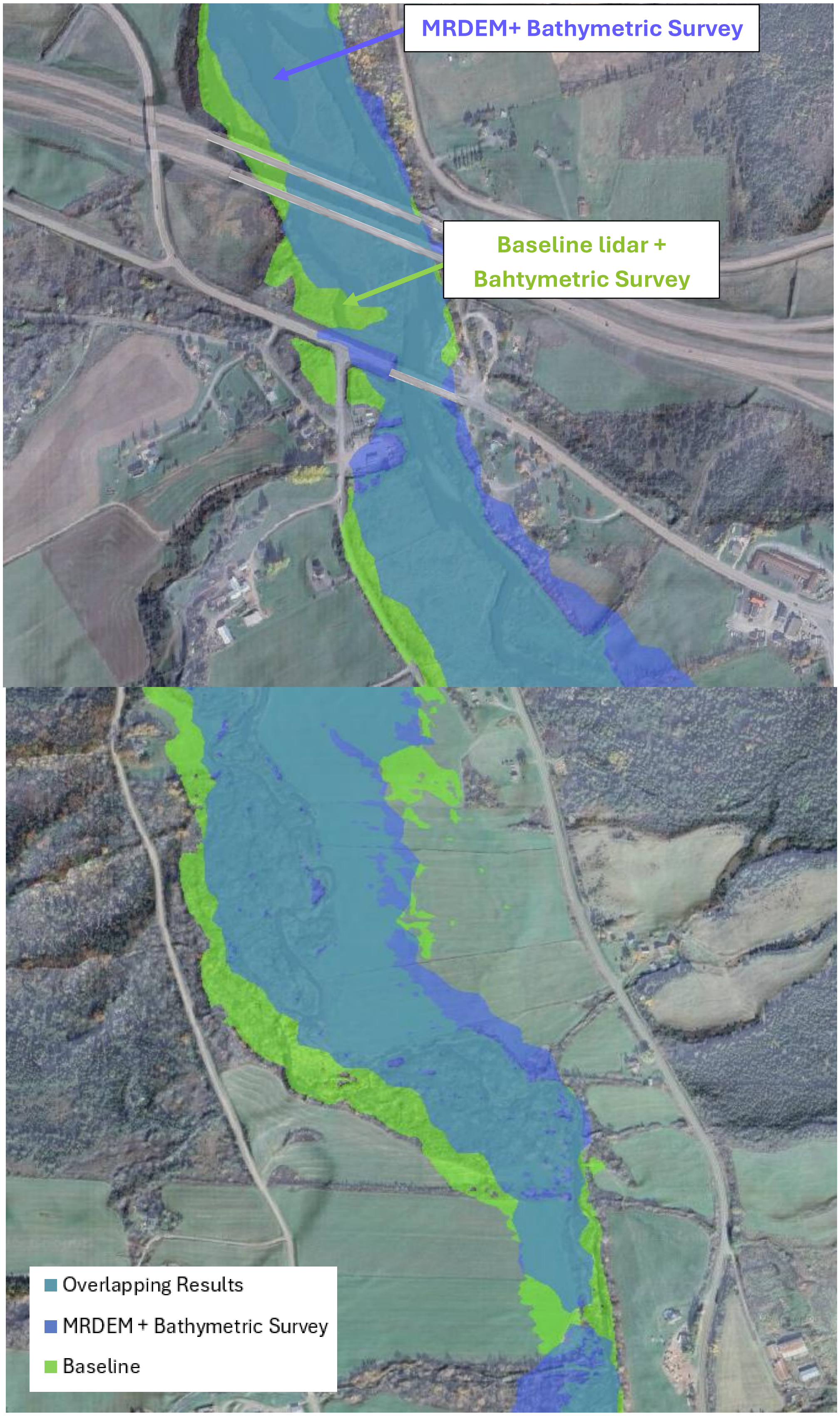

Figure 4-7: Flood extents from MRDEM with survey (Blue) vs Baseline HEC-RAS method (Green)

4.2 Study Area 2: Salmon River near Prince George, BC

The existing HEC-RAS 2D model was developed using a recent lidar DEM at a 1 m grid size merged with surveyed bathymetric data. These baseline results were compared to the following DEM alternatives:

a) Replacement of the recent high-resolution lidar DEM (1 m) with the Canadian MRDEM (30 m) while retaining the full bathymetry collected in the original study.
b) Use of the MRDEM with different combinations of available bathymetric data and bathymetric assumptions (see Section 5 and Section 6, below).

The MRDEM was merged with the bathymetry in HEC-RAS, and large interpolated zones were created to transition between the coarse and fine datasets. Subsequently, we attempted to smooth this transition with the polygon terrain modification in HEC-RAS, but the large modification area caused issues with the tool. The merged surface with the interpolation issue (Figure 4-8) was kept in the model and used to produce results, highlighting the challenges of integrating coarse and fine datasets.

In Study Area 2, the MRDEM was off by approximately 50 m in both the X and Y directions when compared to the high resolution LIDAR DEM. The MRDEM is in a projection intended for national-scale coverage and can introduce distortion at local scales. To address this discrepancy, we shifted the MRDEM horizontally and vertically to better match the the lidar surface and local features.

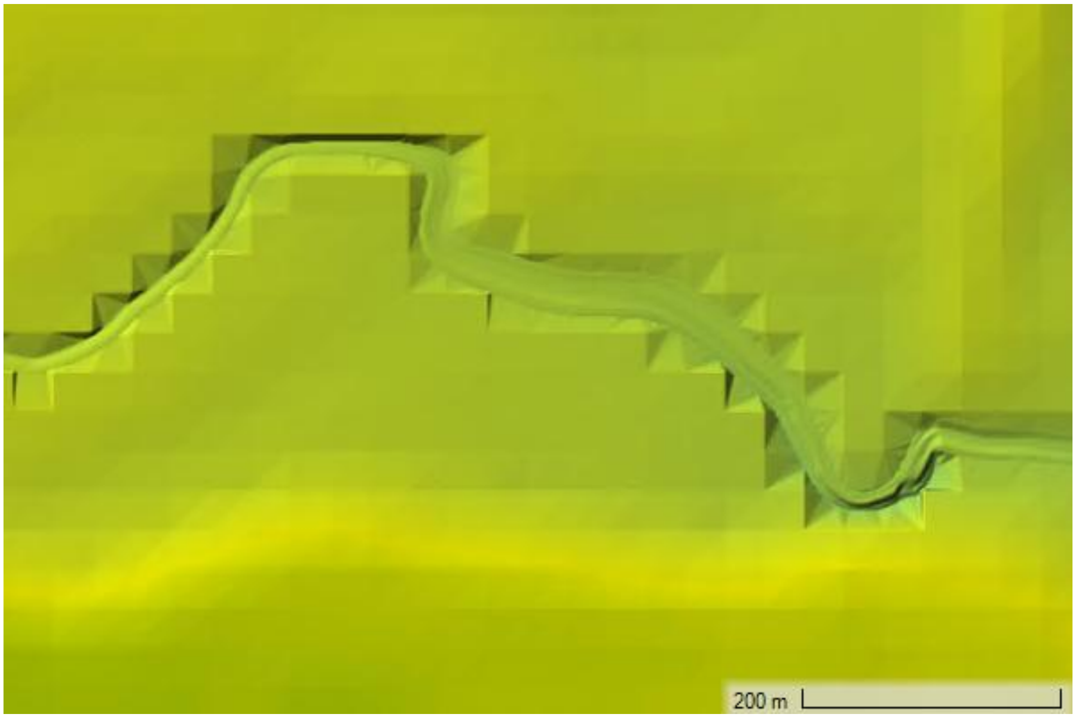

Figure 4-8: Example Section of Merge Between MRDEM and Bathymetry

A sample cross-section of the MRDEM merged with the bathymetry is shown in Figure 4-9 below. Although the merge appeared blocky in plan view, the cross-sections generally looked adequate, as the bathymetry transitioned well into the MRDEM.

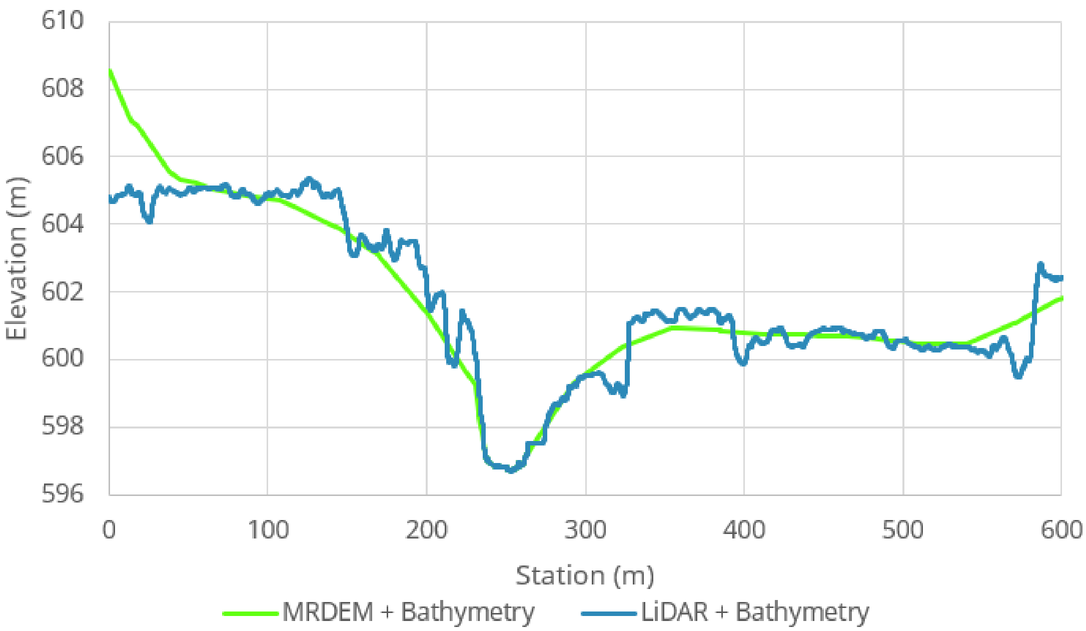

Figure 4-9: Sample Cross-Section along the Salmon River with MRDEM and Bathymetry

Figure 4-10 and Figure 4-11 show the difference from the reference model in water surface elevations and velocities at corresponding sample cross-section locations for the adjusted DEM resolution model runs. Additionally, Figure 4-12 shows the water surface extents at areas of interest along the Salmon River.

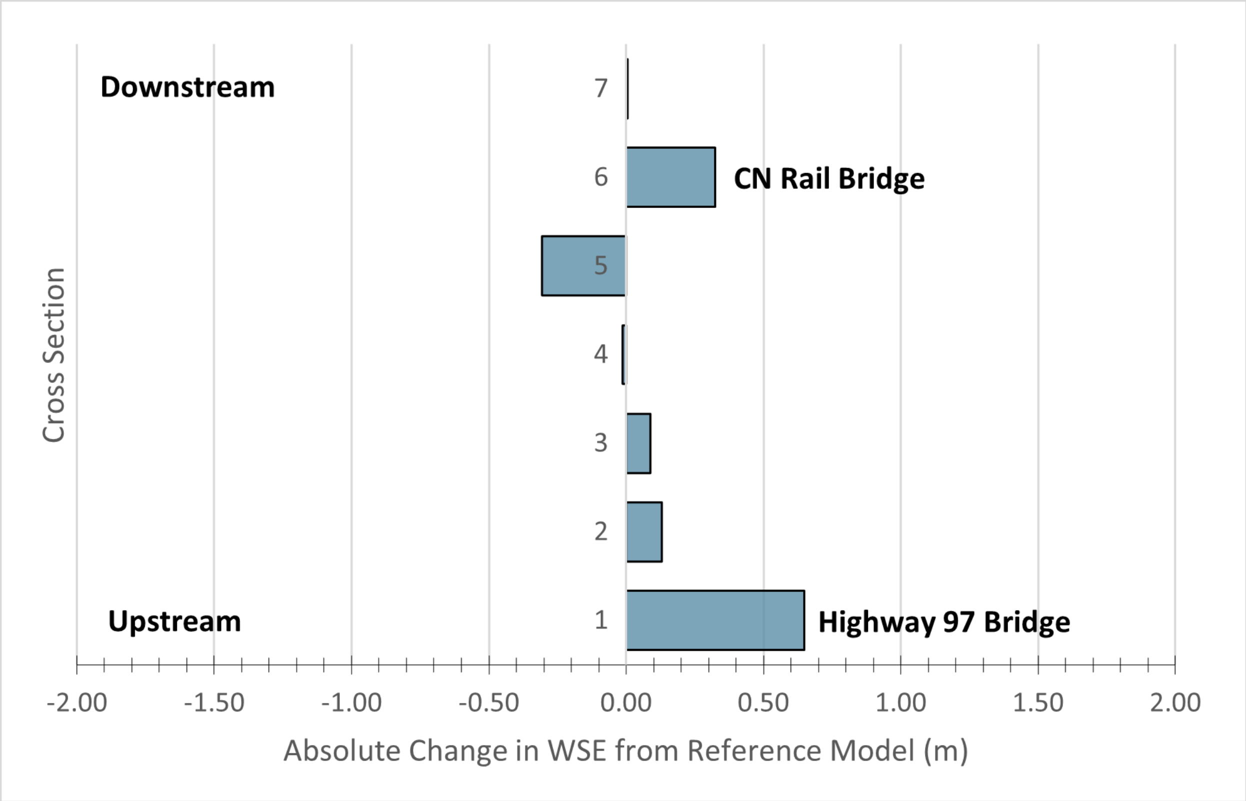

Figure 4-10: Impact of Variation in DEM Resolution on Water Surface Elevation at Sample Cross-Sections along the Salmon River

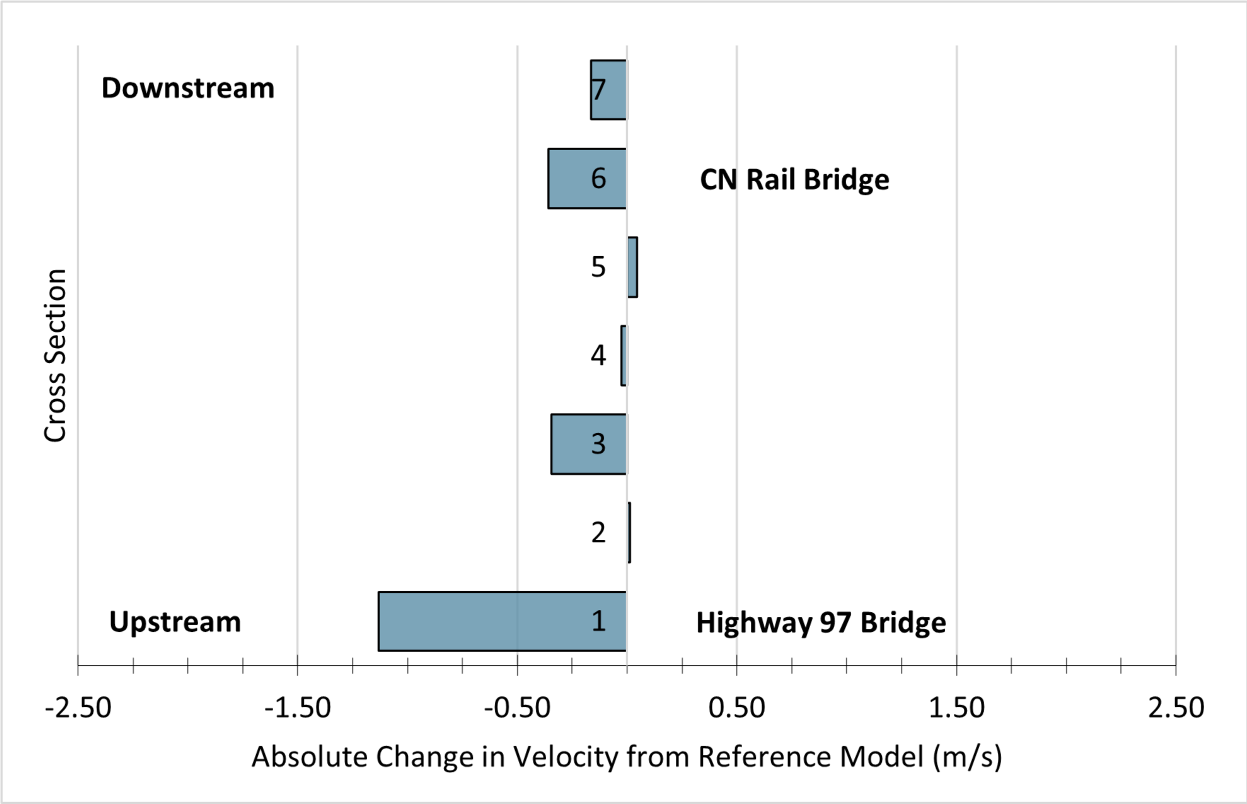

Figure 4-11: Impact of Variation in DEM Resolution on Velocity at Sample Cross-Sections along the Salmon River

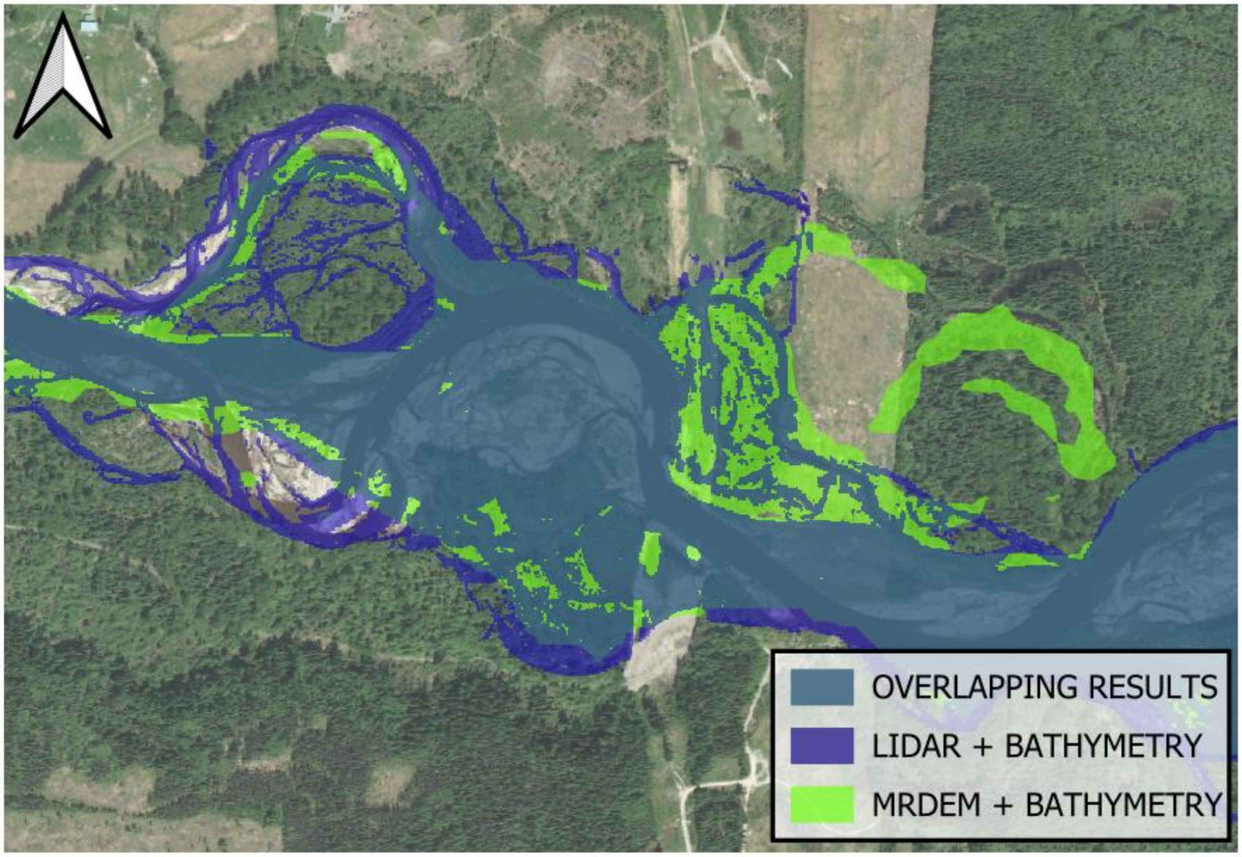

Figure 4-12: Area of interest along the Salmon River with Variation in DEM Resolution

The results of the MRDEM merged with the full bathymetry vary dependent on location, with the possibility of both increased (+0.65 m) and decreased water levels (-0.31 m) when compared to the baseline model. With regards to velocity, the MRDEM merged with the full bathymetry is on average 0.3 m/s lower than the baseline model.

When using the MRDEM, the coarse resolution fails to capture key terrain features, which can lead to both overestimation and underestimation in water levels and extents. The addition of the bathymetry to the MRDEM had more similar results to the baseline model when compared to the pure MRDEM model, highlighting the importance of available survey data in the channel.

5 Exploring the Impact of Varying Levels of Field Survey Data

This section describes the results of the sensitivity testing for each study area, which consists of using differing amounts of field survey data. The effects of the following changes to the culvert/bridge and bathymetric survey data were investigated:

- Removing bridge deck and abutment structure data
- Using no bathymetric data (Lidar DEM Only)
- Reducing the number of survey points by half
- Using calculated bathymetric data

5.1 No Data on Bridge Deck and Abutment Structures

5.1.1 Study Area 1: South River, Antigonish, NS

This test involved removing the nine bridge structures in the existing HEC-RAS 1D model (no culverts are present in the study area), as shown on Figure 5-1. Typically, bridges in hydraulic models constrict flow and back up upstream water levels, increasing flood extents upstream and decreasing flood extents downstream of the structure. However, the effects may be area specific, and testing conducted will shed light on the processes. The flows tested included a design flow event (1-in-100 year event or 1% AEP) as well as an event of magnitude greater than the design flow event (1-in-500 year event or 0.2% AEP event). In this scenario, the cross-section data from the baseline model was retained (1 m lidar with surveyed bathymetry), but all the bridge structures in the model and their ineffective flow areas were removed. Since the bridge abutments are within the DEM, these were retained in the modelled scenario. It should be noted that under the baseline condition (100-year event), at two of the nine bridges, the water surface elevation surpasses the low chord bridge elevation by 15 cm and 33 cm respectively at river stations 24838 and 7123 (Figure 5-1).

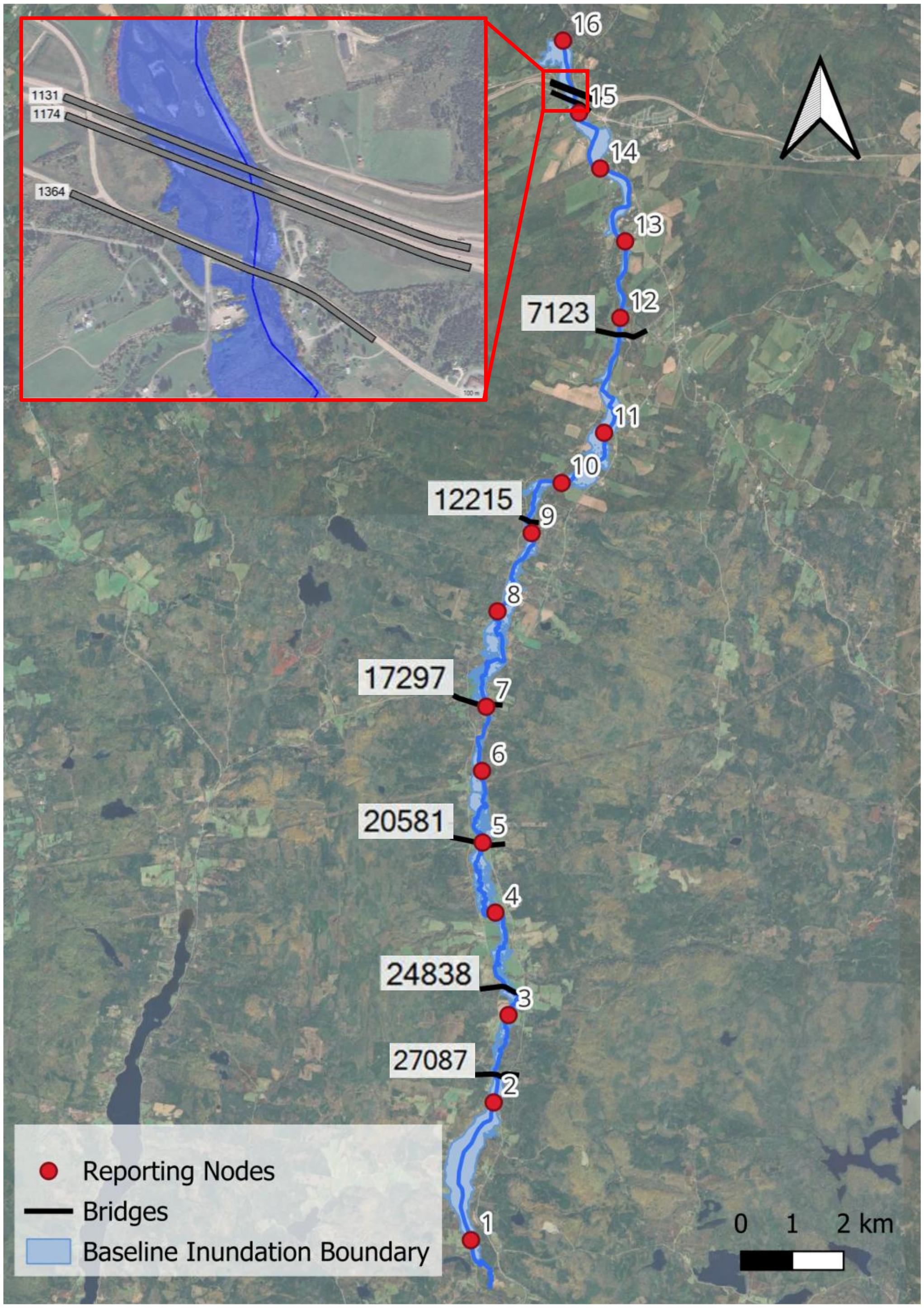

Figure 5-1: HEC-RAS river stations showing locations of nine structures that were removed from the model. Baseline flood line extents are shown. Structure stations presented on the left, and reported stations presented on the right

5.1.1.1 1-in-100 Year (1% AEP) Flow Event

This model was first run using the same flow scenario as the baseline model, the 1-in-100 Year (1% AEP) flow event modelled in PCSWMM and inserted into HEC-RAS at 17 stations. Figure 5-2 shows the differences in water levels due to this change. There is little change in water level, however, a few nodes have slight decreases in water level due to their proximity to bridge structures. Figure 5-3 shows that generally there was little difference to velocity in most nodes, however there are some significant differences in nodes 5 and 7, corresponding to nodes near the location of bridges in the watershed (node 7 is the closest to). Figure 5-4 shows the difference between baseline and the tested scenario flood line extents, revealing negligible change at the reporting location. These results indicate that this change mainly resulted in localized effects to water level and velocity near the bridge locations.

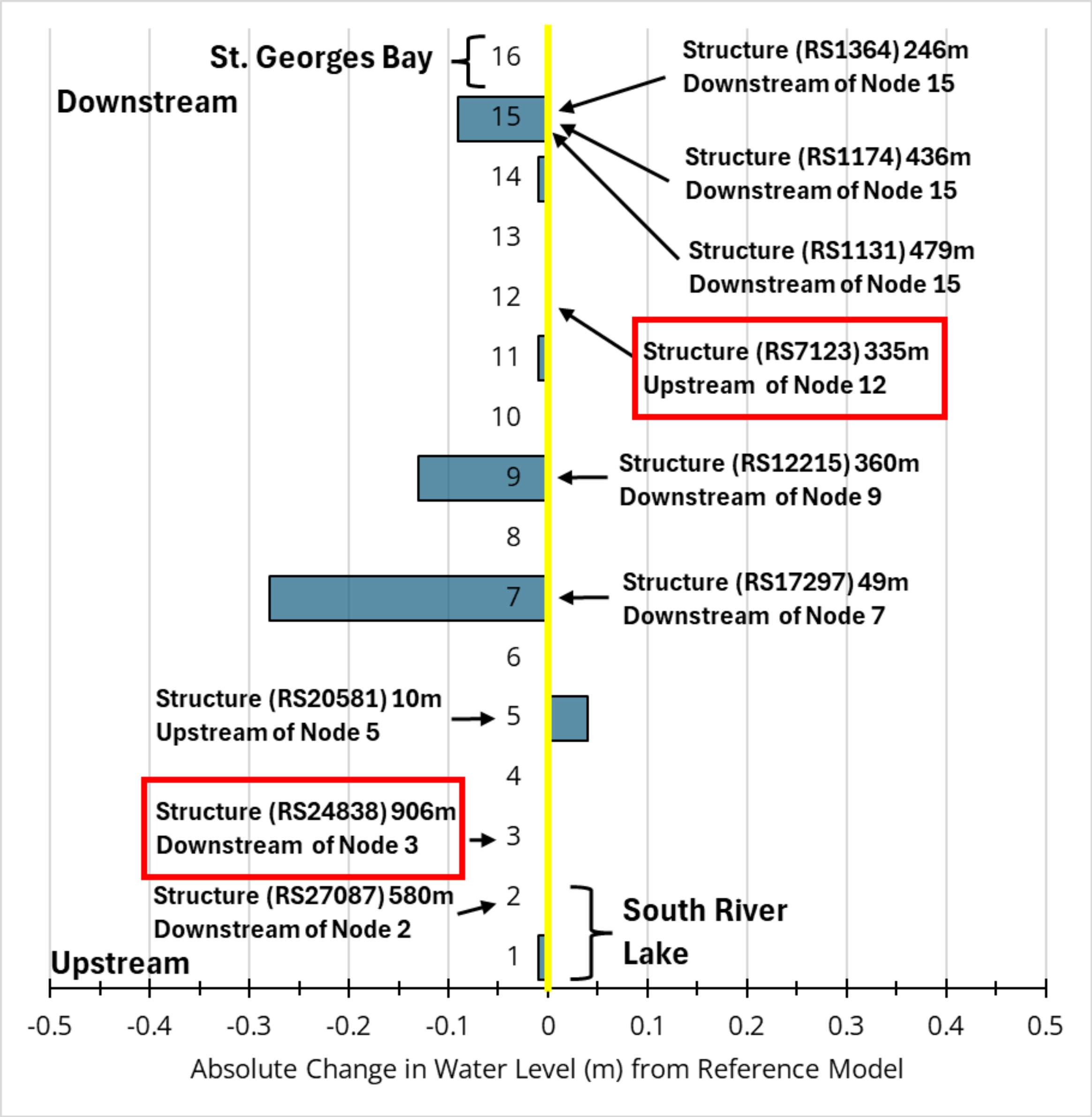

Figure 5-2: Removal of Structures Testing Results showing change in WSEL. Distance of structure to closest upstream node is noted. Red boxes denote structures that are under capacity under the baseline (1 in 100-yr) scenario.

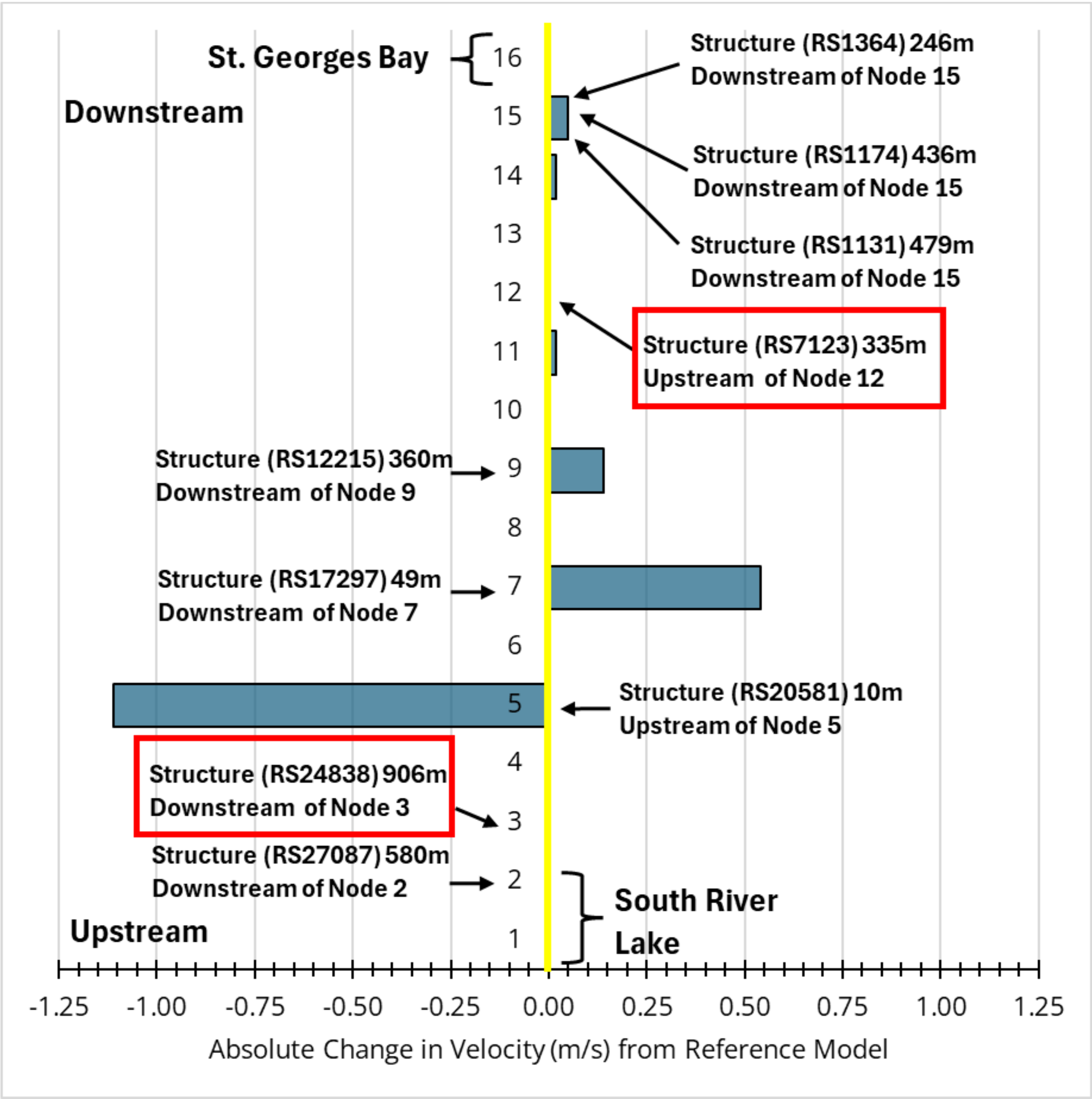

Figure 5-3: Removal of Structures Testing Results showing change in Channel Velocity Distance of structure to closest upstream node is noted. Red boxes denote structures that are under capacity under the baseline (1 in 100-yr) scenario.

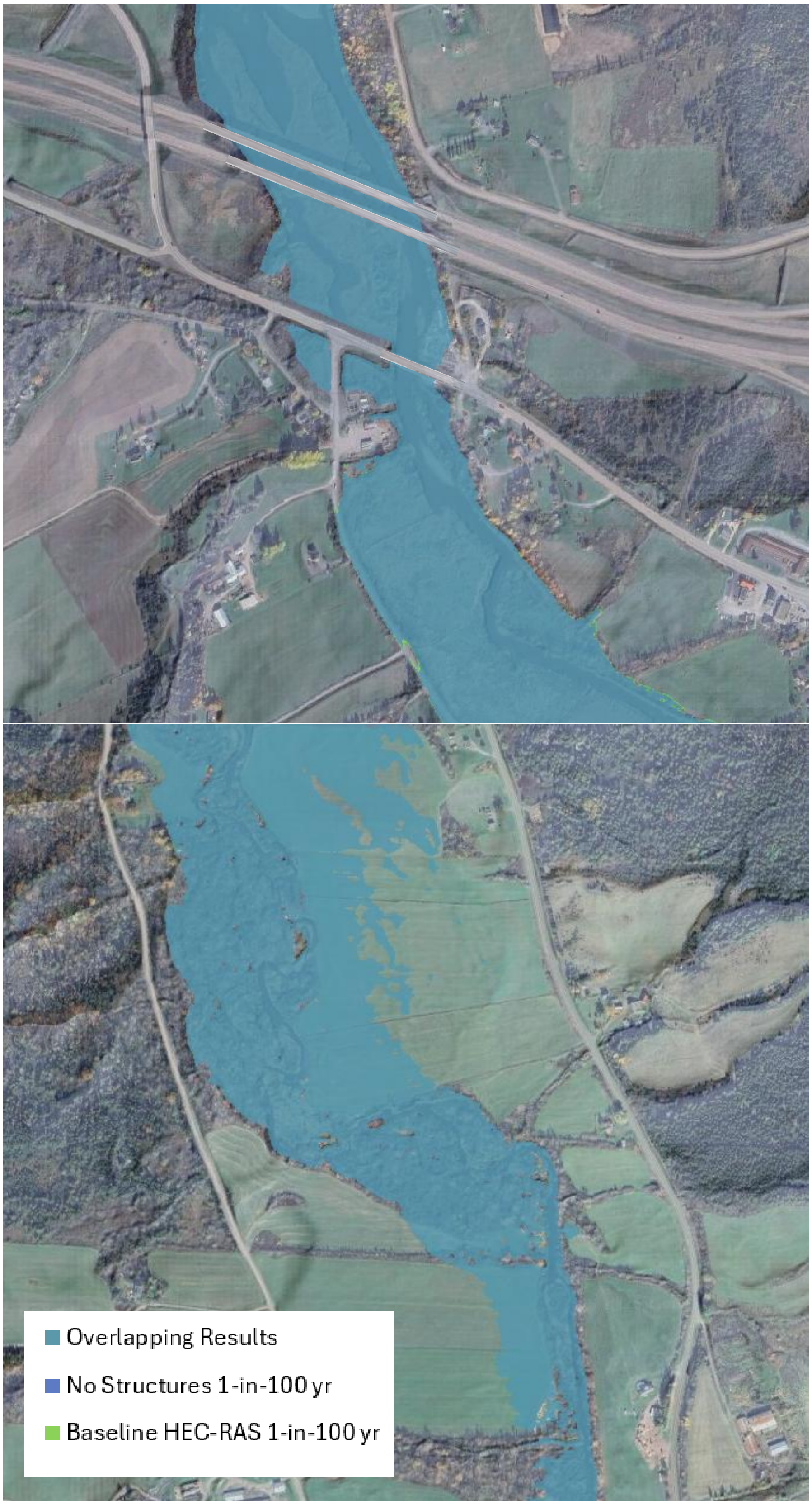

Figure 5-4: Flood extents from removing structures for a 1-in-100 year storm vs baseline (extents directly overlap, causing blue color)

5.1.1.2 1-in-500 Year (0.2% AEP) Flow Event

An additional scenario was run where baseline flow inputs in HEC-RAS were changed from a 1-in-100 year (1% AEP) flow to a greater, 1-in-500 year (0.2% AEP) flow event and structures were removed. It should be noted that under the baseline condition (500-year event), at four of the nine bridges, the water surface elevation surpasses the low chord bridge elevation by 0.09 m, 0.9 m, 1.33 m, and 1.95 m respectively at river stations 27087, 24838, 20581, and 7123 (Figure 5-1).

To calculate this 1-in-500 year (0.2% AEP) flow, two methods were used and compared. First, a flood frequency analysis (FFA) was completed on peak flow data at the WSC gauge station (South River at St. Andrews [01DR001]) located on the river in the modeled area, at HEC-RAS river station 6989. Then, this flow was prorated by subcatchment area to the other 16 points (17 in total), chosen for flow input to the 1D HEC-RAS model (Appendix A). Using RMC-BestFit software, three distributions were shortlisted using Root Mean Squared Error (RMSE) as a measure of fit: Generalized Logistic (RMSE 4.99 m^3/s), Generalized Extreme Value (RMSE 6.29 m^3/s), and Log-Pearson Type III (RMSE 6.32 m^3/s) (Figure 5-5). Corresponding flow values are shown in Table 5-1. Since flows from the Generalized Logistic distribution are significantly higher than the other distributions, it was ruled out, and the next most conservative Generalized Extreme Value flow value 496 m^3/s was chosen as representative at the WSC gauge location for a 1-in-500 year (0.2% AEP) storm.

This FFA value was compared to the resultant flow at the WSC gauge location in PCSWWM when a 1-in-500 year (0.2% AEP) rainfall event was created and input as a rain gauge in the model. Annual maximum rainfall amounts from the Tracadie [Climate ID 8205895] ECCC climate station were used in a Gumbel Extreme value analysis using the method of least squares to extrapolate a 1-in-500 year (0.2% AEP) 24 hr rainfall amount (Appendix A). This amount was then used to scale the existing 1-in-100 year (1% AEP) rainfall distribution in PCSWMM, which resulted in a 1-in-500 year (0.2% AEP) modelled flow of 309.9 m^3/s. To be conservative, and considering the FFA results to be more accurate, since the gauge is directly on the modelled river, the FFA result of 496 m^3/s was chosen as representative and was used to prorate flow values for the other flow input locations in HEC-RAS (Table 5-2).

Table 5-1: FFA Flow Results for Three Shortlisted Distributions

Return Period (yr)	Generalized Extreme Value Flow (m^3/s)	Generalized Logistic (m^3/s)	Log-Pearson Type III (m^3/s)
500	496	730	456
200	377	497	359
100	305	374	297
50	247	283	244
20	184	197	185
10	146	151	148
5	114	115	115

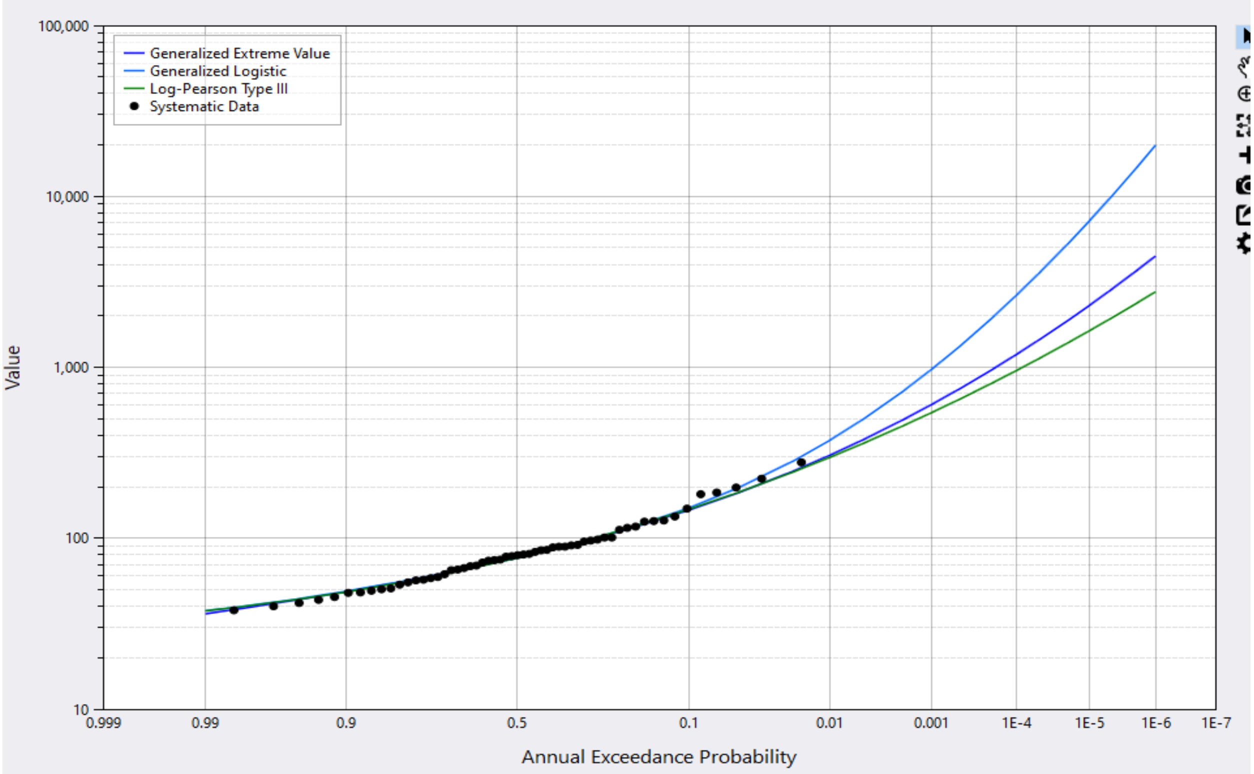

Figure 5-5: Shortlisted Distributions for FFA on South River St. Andrews [01DR001] WSC Station

Table 5-2: Input Flows to HEC-RAS for a 1-in-500 yr Storm

HEC-RAS River Station	Specified Flow (m^3/s)
31079	52.0144
30639	61.28754
27667	122.6634
25744	151.991
22791	236.003
20571	253.4149
18784	265.6615
17346	279.4418
14699	307.9316
12575	340.3667
10963	436.0217
9425	470.8982
6788	496.9522
5179	501.6261
3073	522.3092
1610	540.8193

It should be noted that under the baseline condition (500-year event), at four of the nine bridges, the water surface elevation surpasses the low chord bridge elevation by 0.09 m, 0.9 m, 1.33 m and 1.95 m respectively at river stations 27087, 24838, 20581 and 7123 (Figure 5-6).

Changes in velocity due to the removal of the structures exhibited a similar pattern to the 1-in-100 year (1% AEP) flow, however the changes were of a higher magnitude (Figure 5-7). Changes in velocity for the 1-in-100 year event range from -1.1 m/s to 0.55 m/s (Figure 5-3), while changes in velocity for the 1-in-500 year event range from -2.1 m/s to 1.55 m/s (Figure 5-7).

Overall the largest changes to velocity were localized to just upstream or just downstream of bridges which constricted the river width (i.e., under 30 m spans) at Node 5 and 7. Node 5, the location of the greatest decrease in velocity for both design events (Figure 5-3 and Figure 5-7), is only 10 m downstream of a 16 m span bridge, and Node 7 is 49 m upstream of bridge with 30m span; these nodes are the closest reporting nodes to bridge locations.

Figure 5-6 shows the distribution of changes in water level due to removing the structures during a 1-in-500 year (0.2% AEP) design event. Changes to water level due to this change during the 1-in-100 year event ranged from -0.28 m to 0.05 m (Figure 5-2), while changes in water level for the 1-in-500 year event ranged from -0.75 m to 0 m (Figure 5-6). In general, water level is further reduced as a result of removing the structures for the 1-in-500 year event than for the 1-in-100 year event.

Node 7 experiences the highest change in water level as a result of the change, likely due to the straight nature of the river through the downstream bridge in this section of the river, which means the bridge is the only constriction to width in this area. Node 9 is 360 m upstream of a bridge, and between the Node and the bridge are several river meanders. This meandering could contribute to the lessened change to water level at this Node compared to Node 7. There were no other changes to channel cross-section, other than the bridge constriction, found to be affecting water levels or velocities.

Flood line extents at the reported locations are not significantly changed, however, over the entire watershed, there are differences observed near the structures with the baseline having more flooding just upstream and the new model having more flooding just downstream of the structures (Figure 5-8), and the impact is relatively proportional to the distance to the structures (and is naturally impacted by other factors such as the amount of constriction, land slope, available storage in the topography upstream of the constriction, the relative amount of flow, the surface roughness, etc.)

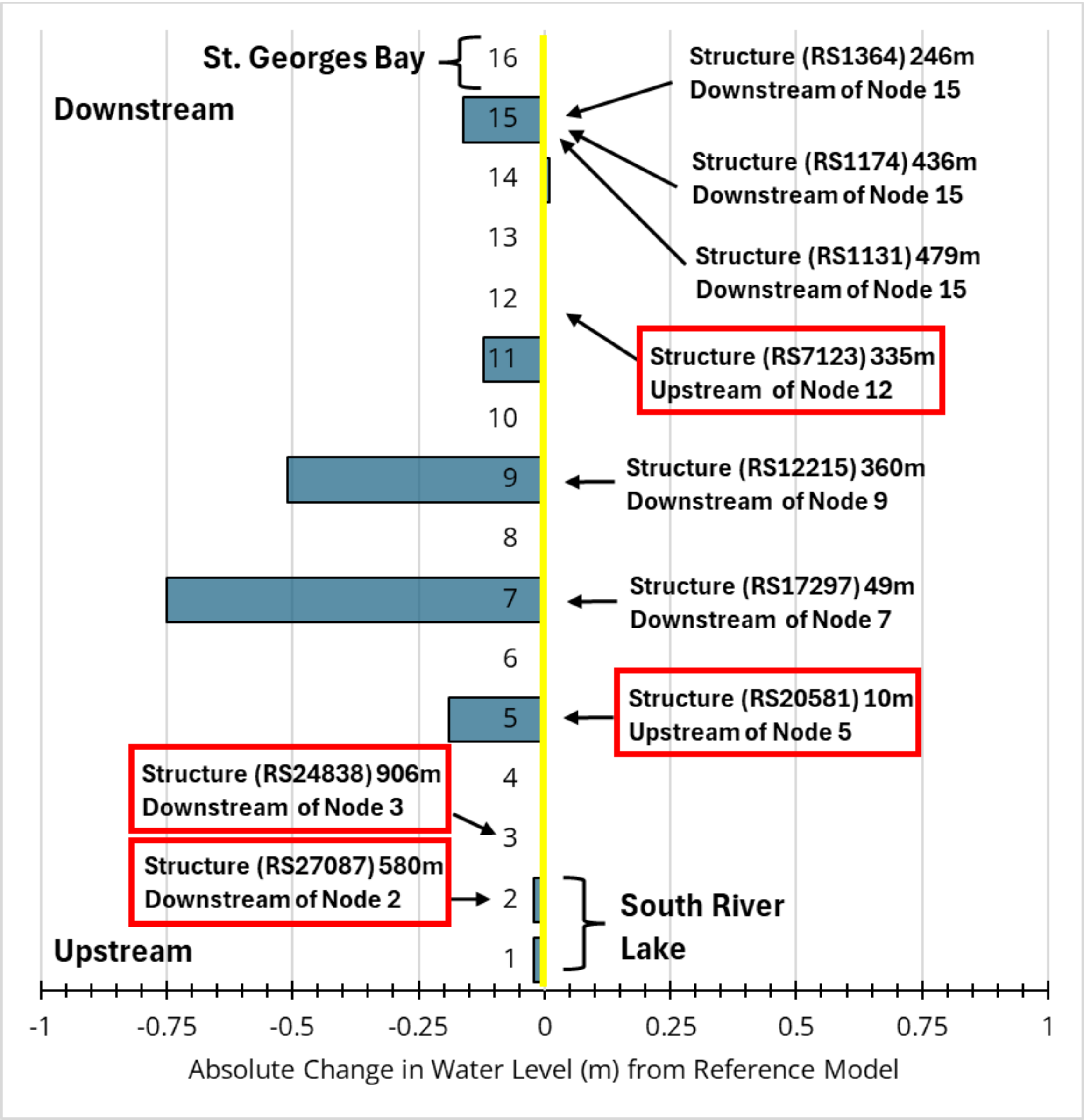

Figure 5-6: Removal of Structures Testing Results showing change in WSEL. Distance of structure to closest upstream node is noted. Red boxes denote structures that are under capacity under the baseline (1 in 500-yr) scenario.

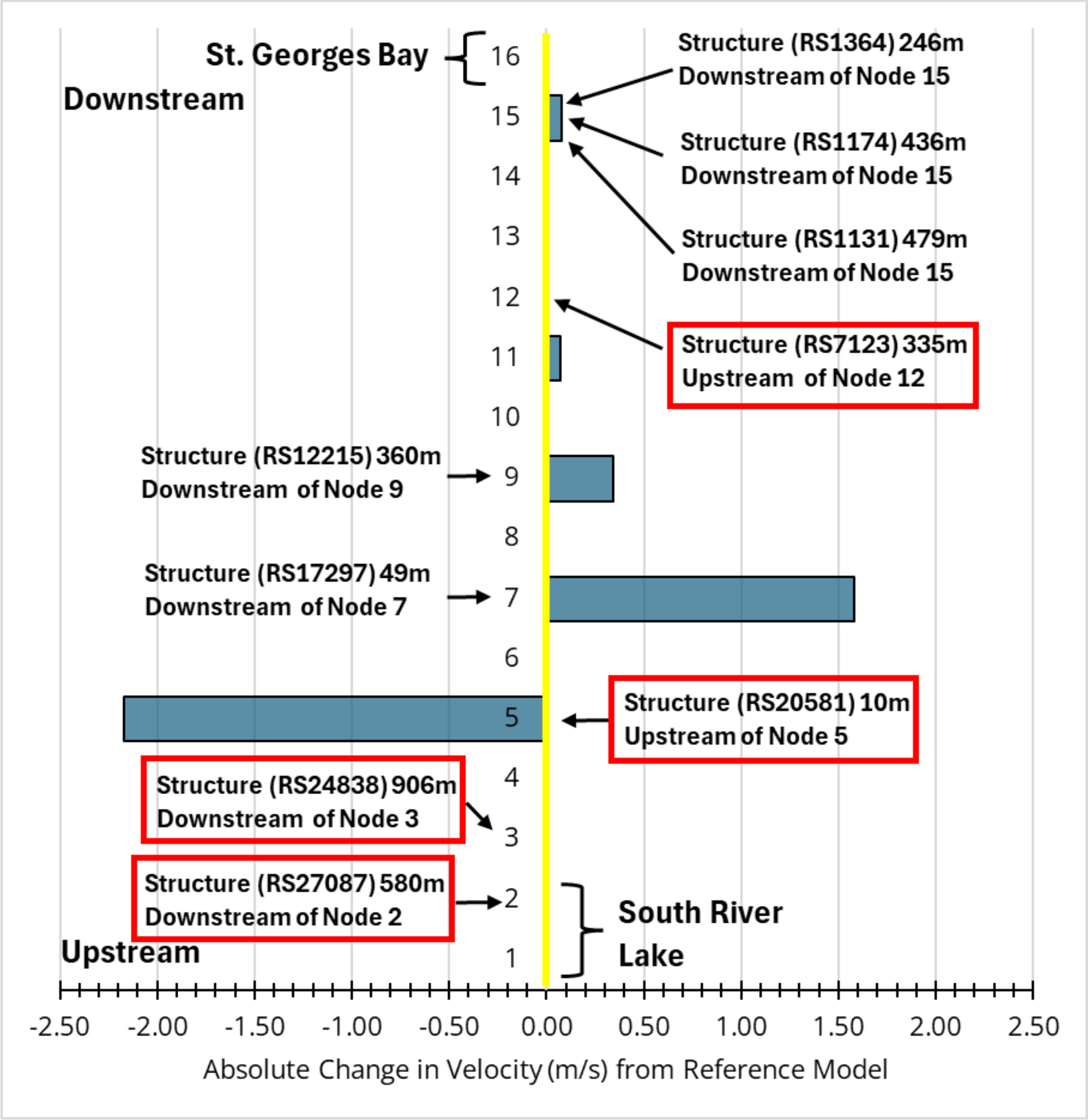

Figure 5-7: Removal of Structures Testing Results showing change in Channel Velocity. Distance of structure to closest upstream node is noted. Red boxes denote structures that are under capacity under the baseline (1 in 500-yr) scenario.

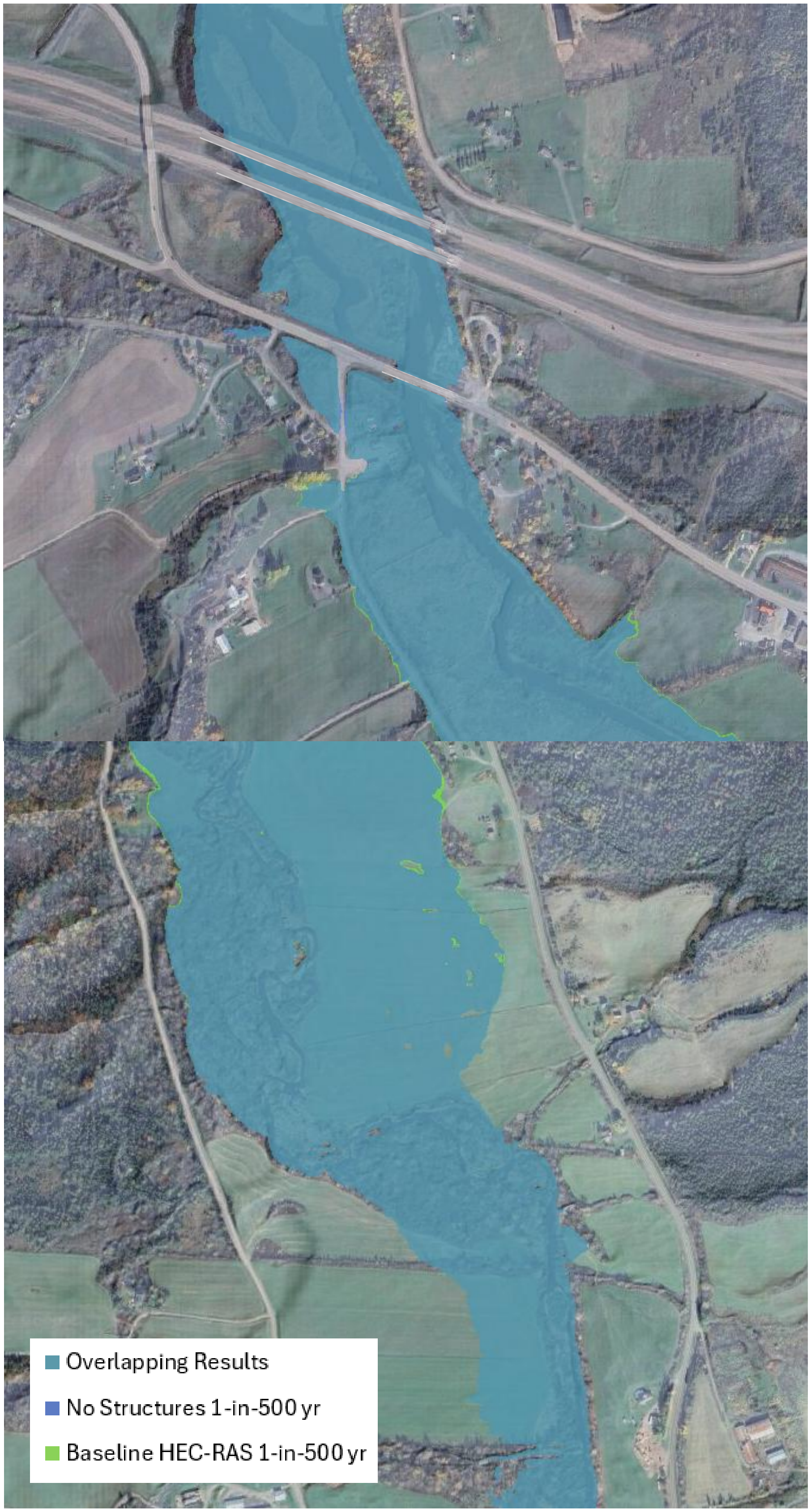

Figure 5-8: Flood extents from removing structures for a 1-in-500 yr storm vs baseline (extents directly overlap, causing blue color)

5.1.2 Study Area 2: Salmon River near Prince George, BC

The existing HEC-RAS 2D model of Salmon River includes two bridge structures. The upstream bridge is a highway bridge with no piers, and the downstream bridge is a rail bridge with two piers. Bridges in HEC-RAS 2D are modelled as SA/2D Area Connections where HEC-RAS uses the input data to develop rating curves for the bridge. For the purposes of this test, the bridge structures were removed including all bridge decks and piers by completely removing the SA/2D Area Connections. Abutments were not included in the original model. The flows tested included a design flow event (1-in-200 year event or 0.5% AEP) as well as an event of magnitude greater than the design flow event (1-in-500 year event or 0.2% AEP). Profile lines for each bridge (Figure 5-9) show that the existing bridges have ample freeboard for both the 1-in-200 and 1-in-500 year events.

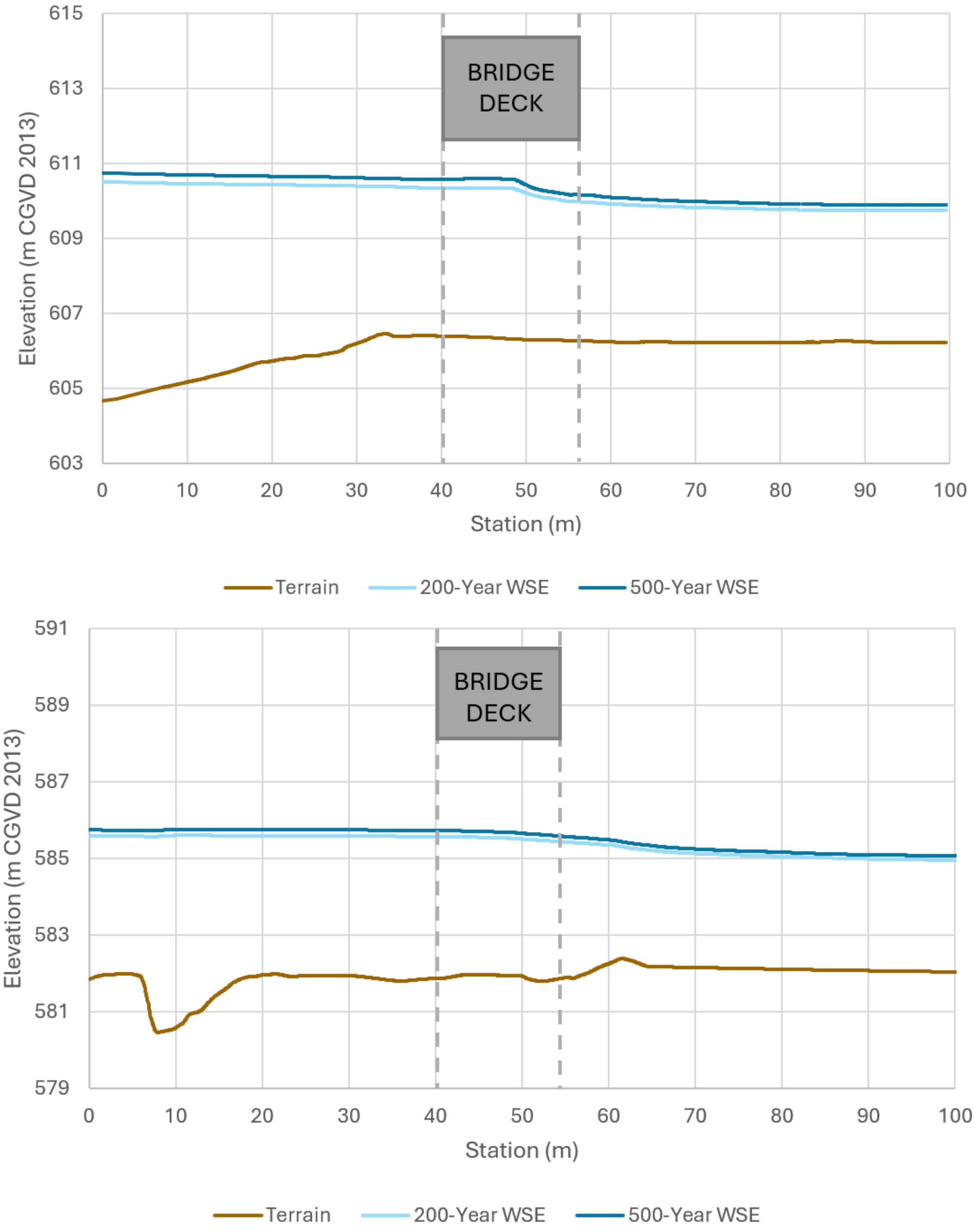

Figure 5-9: Profile Line at Highway 97 Bridge (top) and CN Rail Bridge (bottom)

5.1.2.2 1-in-200 Year (0.5% AEP) Flow Event

The bridges were removed from the baseline model, which was then run using the 1-in-200 Year (0.5% AEP) flow event.

Figure 5-10 and Figure 5-11 show the difference from the reference model in water surface elevations and velocities at corresponding sample cross-section locations for the model runs with removed bridges with the 1-in-200 year (0.5% AEP) flow event. Additionally, Figure 5-12 shows the water surface extents at areas of interest along the Salmon River.

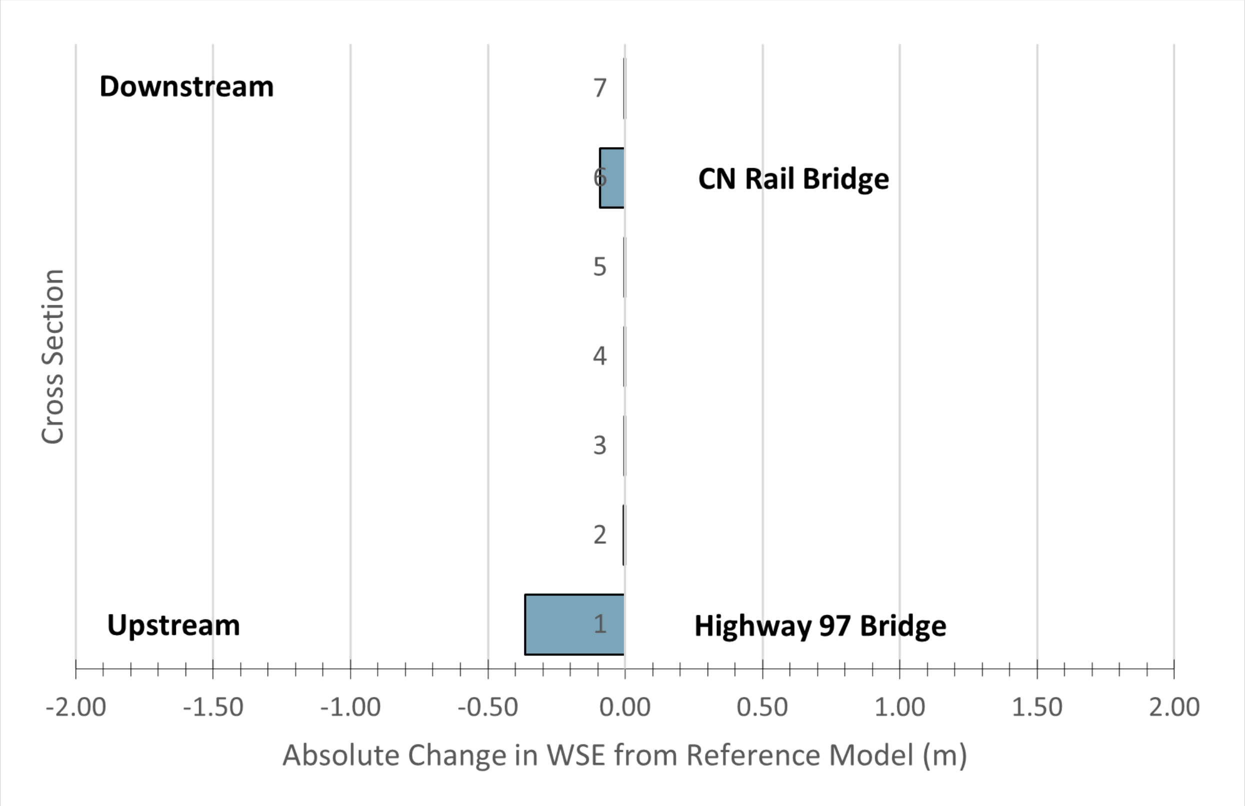

Figure 5-10: Impact of Removal of Bridge Decks and Abutment Structures during the 1-in-200 Year (0.5% AEP) Flow Event on Water Surface Elevation at Sample Cross Sections along the Salmon River

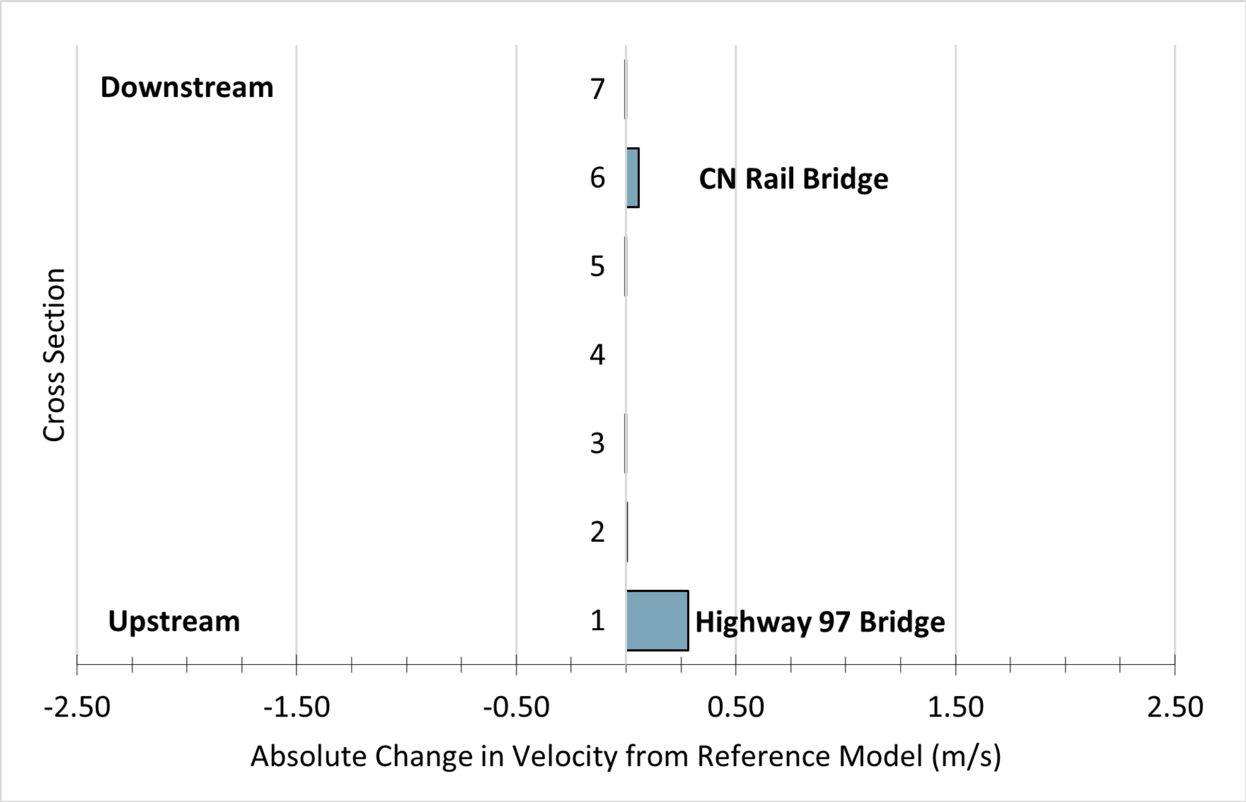

Figure 5-11: Impact of Removal of Bridge Decks and Abutment Structures during the 1-in-200 Year (0.5% AEP) Flow Event on Velocity at Sample Cross Sections along the Salmon River

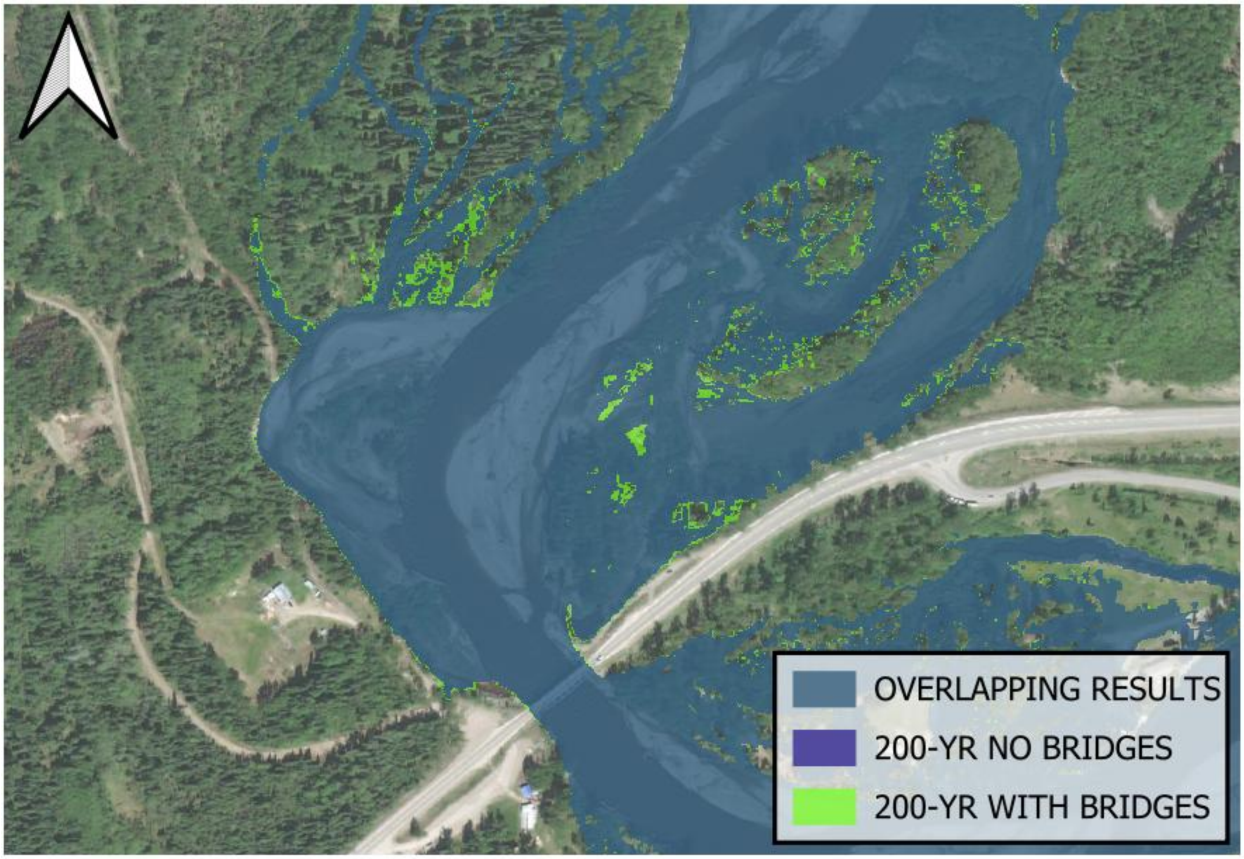

Figure 5-12: Area of interest along the Salmon River at Highway 97 with Removal of Bridge Decks and Abutment Structures during the 1-in-200 Year (0.5% AEP) Flow Event

Overall, there was minimal change in extents, water levels, and velocities between the baseline model and the model with the bridges removed. The largest difference occurred upstream of bridges, which showed lower water levels at these locations when the bridges were removed. This effect was most pronounced at the Highway 97 bridge, where the absence of piers and the ample freeboard in the baseline model suggest that the presence of a SA/2D Area Connection has an impact on the hydraulic calculation. This is reasonable as SA/2D Area Connections and standard HEC-RAS 2D use different equations to produce results (i.e. 1D vs. 2D). To address these discrepancies, it may require adjusting Manning's coefficients within the SA/2D Area Connections to account for additional bed roughness. These adjustments were not examined in this study but could be considered in future work.

5.1.2.3 1-in-500 Year (0.2% AEP) Flow Event

An additional scenario was run where baseline flow inputs in HEC-RAS were increased from a 1-in-200 year (0.5% AEP) flow to a 1-in-500 year (0.2% AEP) flow event and structures were removed. The 1-in-500 year (0.2% AEP) flow was previously calculated in the original floodplain mapping project.

Figure 5-13 and Figure 5-14 show the difference from the reference model in water surface elevations and velocities at corresponding sample cross-section locations for the model runs with removed bridges with the 1-in-500 year (0.2% AEP) flow event. Additionally, Figure 5-15 shows the water surface extents at areas of interest along the Salmon River.

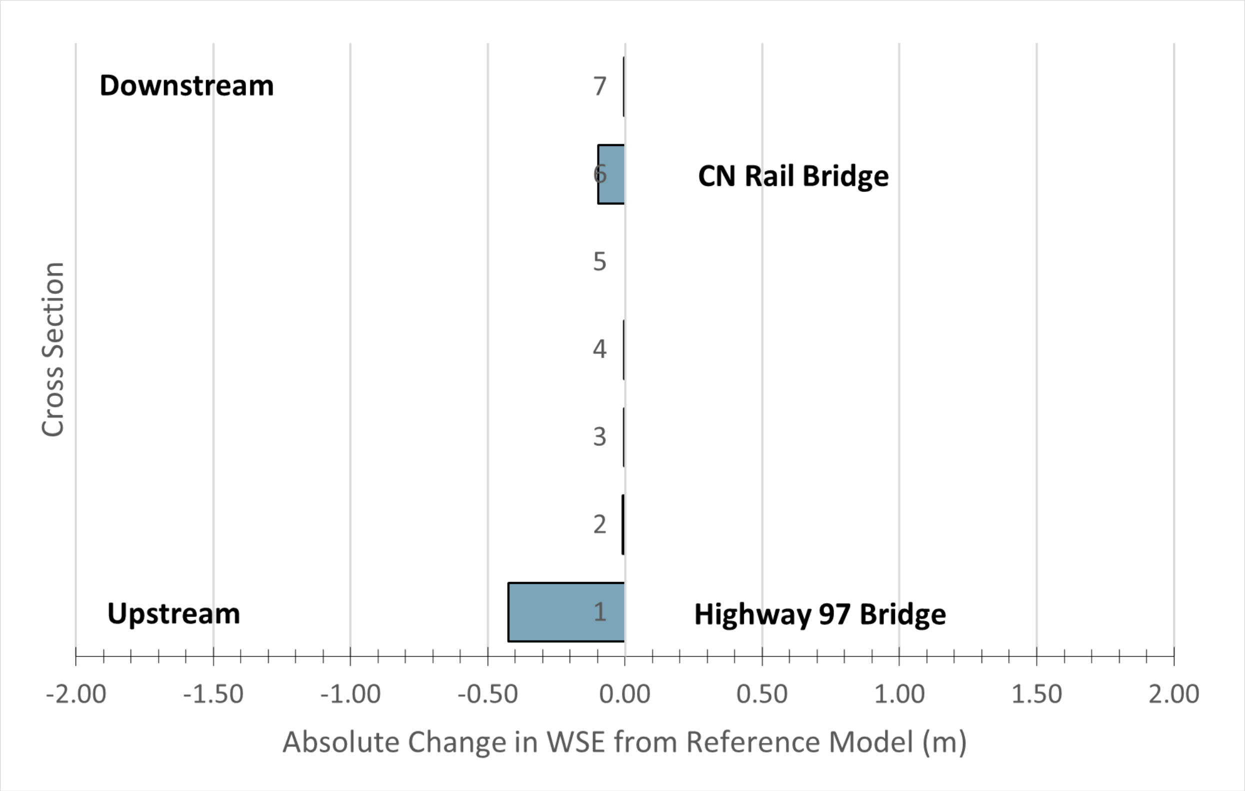

Figure 5-13: Impact of Removal of Bridge Decks and Abutment Structures during the 1-in-500 Year (0.2% AEP) Flow Event on Water Surface Elevation at Sample Cross Sections along the Salmon River

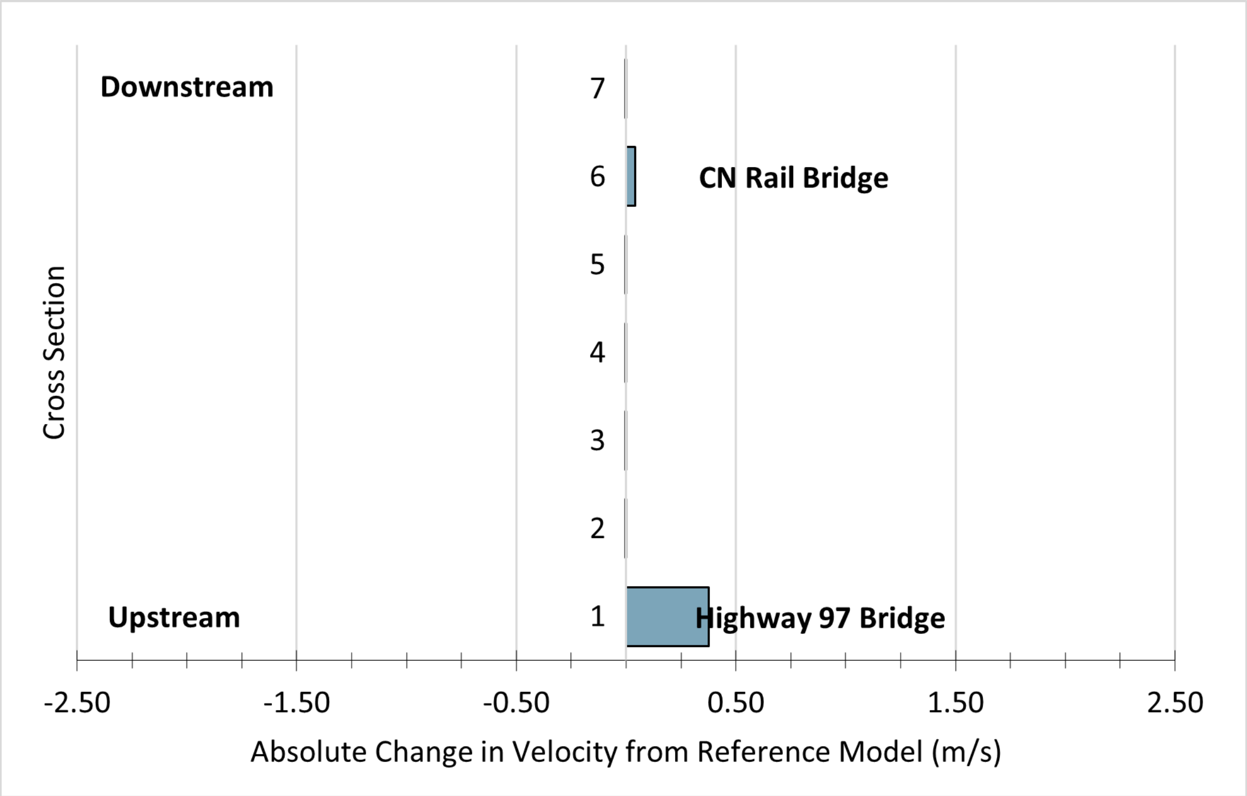

Figure 5-14: Impact of Removal of Bridge Decks and Abutment Structures during the 1-in-500 Year (0.2% AEP) Flow Event on Velocity at Sample Cross Sections along the Salmon River

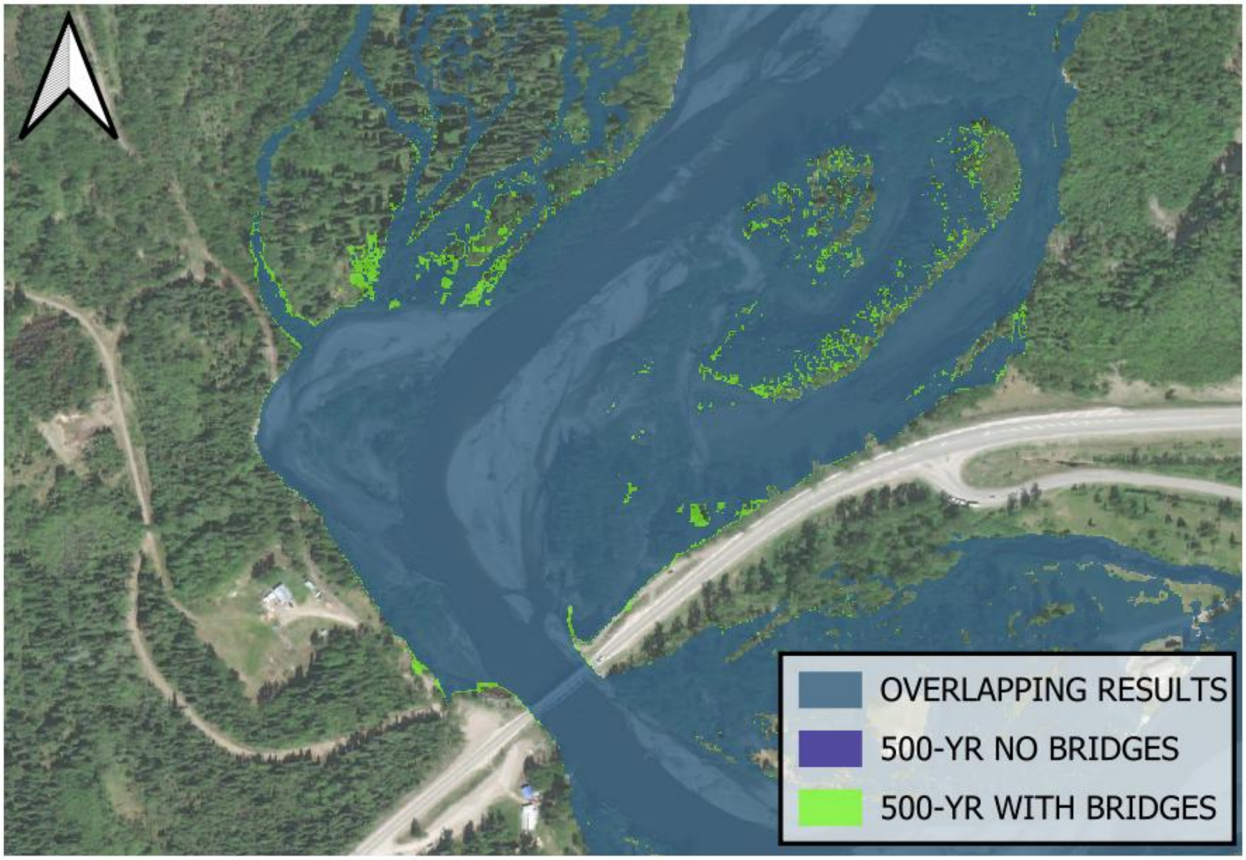

Figure 5-15: Area of interest along the Salmon River at Highway 97 with Removal of Bridge Decks and Abutment Structures during the 1-in-500 Year (0.2% AEP) Flow Event

The 1-in-500 year (0.2% AEP) model run with bridges removed overall had very similar results to the 1-in-200 year (0.5% AEP) model run with bridges removed. The largest difference in water levels and extents continued to be upstream of bridges, with the 1-in-500 year (0.2% AEP) model run having a slightly larger change than the 1-in-200 year (0.5% AEP). Overall, changes in extents, water levels, and velocities were minimal compared to the baseline 1-in-500 year (0.2% AEP) model.

5.2 No Bathymetric Data: Lidar DEM Only

5.2.1 Study Area 1: South River, Antigonish, NS

This scenario represents a situation where high resolution 1m lidar is available (e.g., 1m lidar is available across the Province of NS), but bathymetry is not available. Baseline bathymetry was removed from the modelled scenario and cross-sections were extracted directly from the lidar Terrain Model. The surveyed bathymetry that was removed from the model generally represents a minor portion of the channel's conveyance capacity, as illustrated in Figure 5-16.

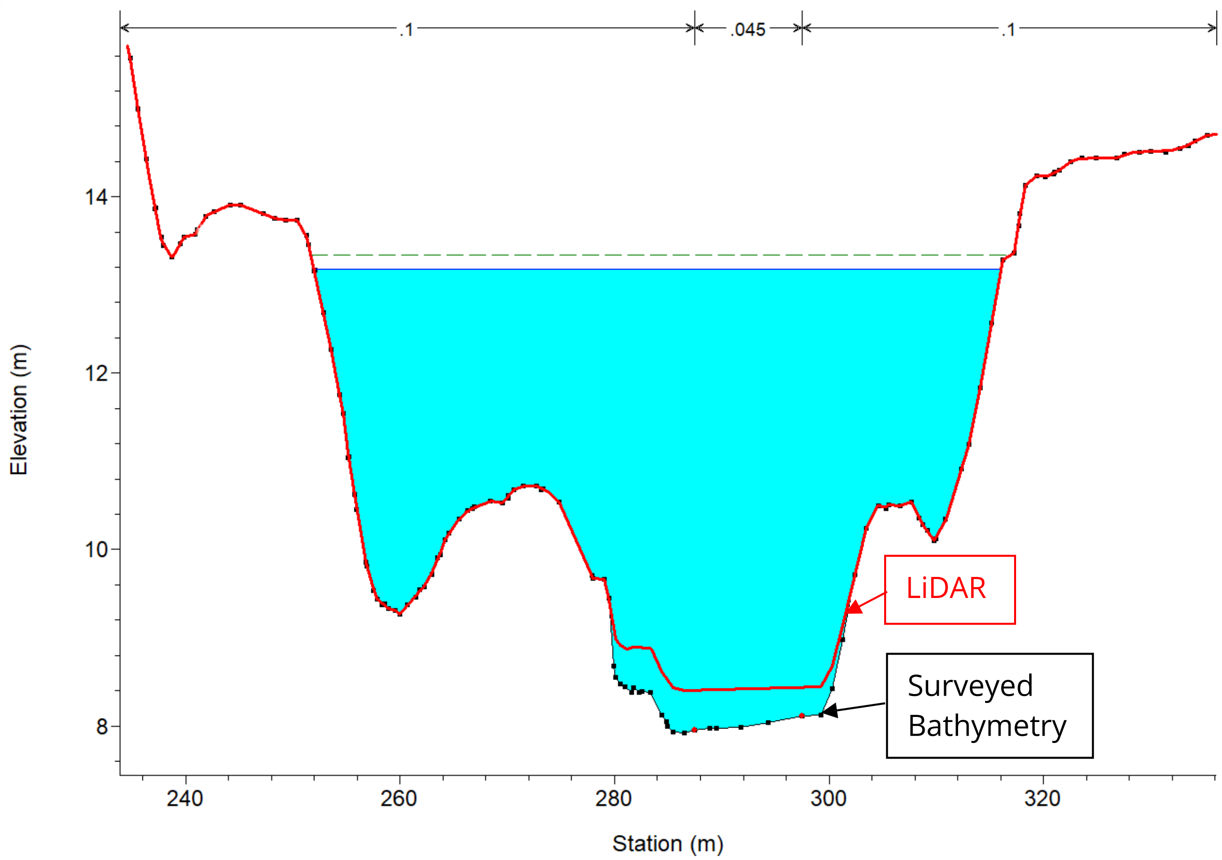

Figure 5-16: Example cross-section showing lidar vs surveyed bathymetry

Figure 5-17 shows that in general, water levels are increased slightly from the baseline scenario due to this change, and Figure 5-18 shows that velocities were both increased and decreased by a minor amount as result of this change. It is noted that the model was not re-calibrated following the change in bathymetry definition. It is therefore to be expected that if the cross-sectional area available for flow is slightly decreased, the water levels would slightly increase.

The peak flood extents from the lidar only model lined up generally with the baseline model, differing by 1-3 m (Figure 5-19). This difference is accounted for by the difference in cross sectional area from the removal of the bathymetry data. It is therefore likely that if the model was re-calibrated after the removal of the data, the results would show even less difference. Velocity was found to be more variable, changing upwards or downwards, likely depending on whether the slight shift upwards in the bottom elevation reduced the flow area in a smoother section of the channel (increase in velocity) or allowed water to overflow into rougher floodplain areas, reducing the average velocity.

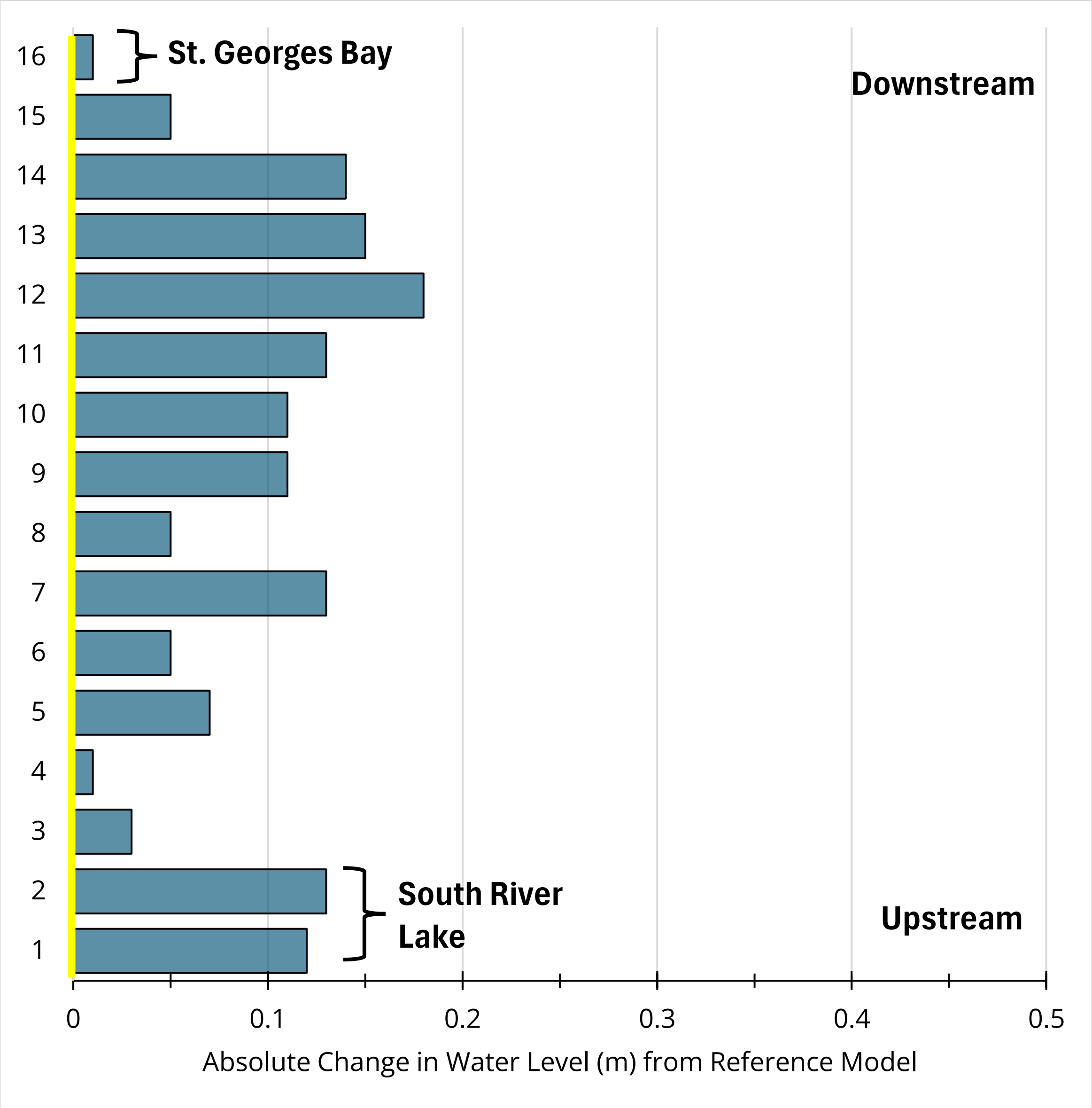

Figure 5-17: Removal of Channel Bathymetry Testing Results showing change in WSEL

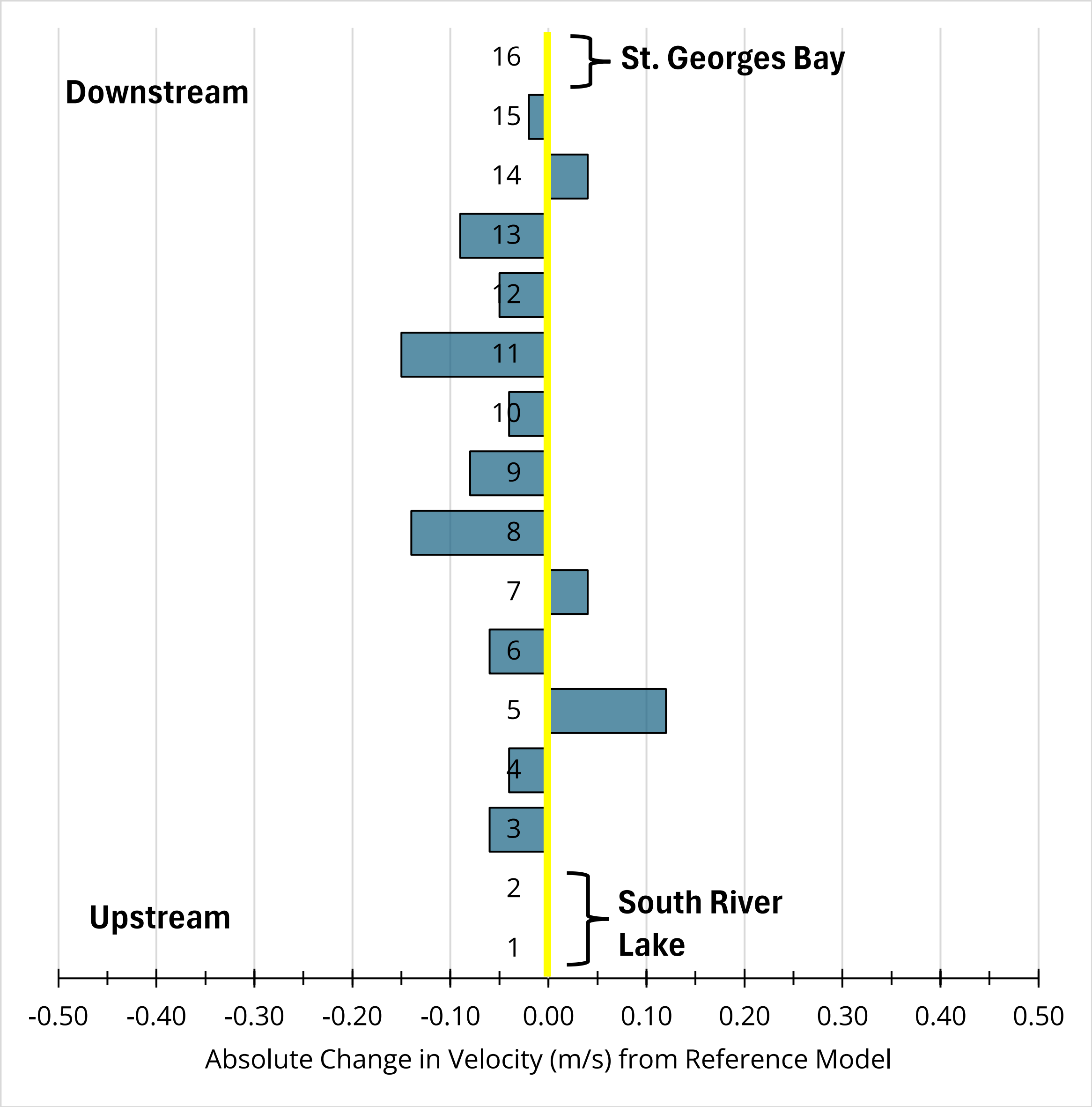

Figure 5-18: Removal of Channel Bathymetry Testing Results showing change in Channel Velocity

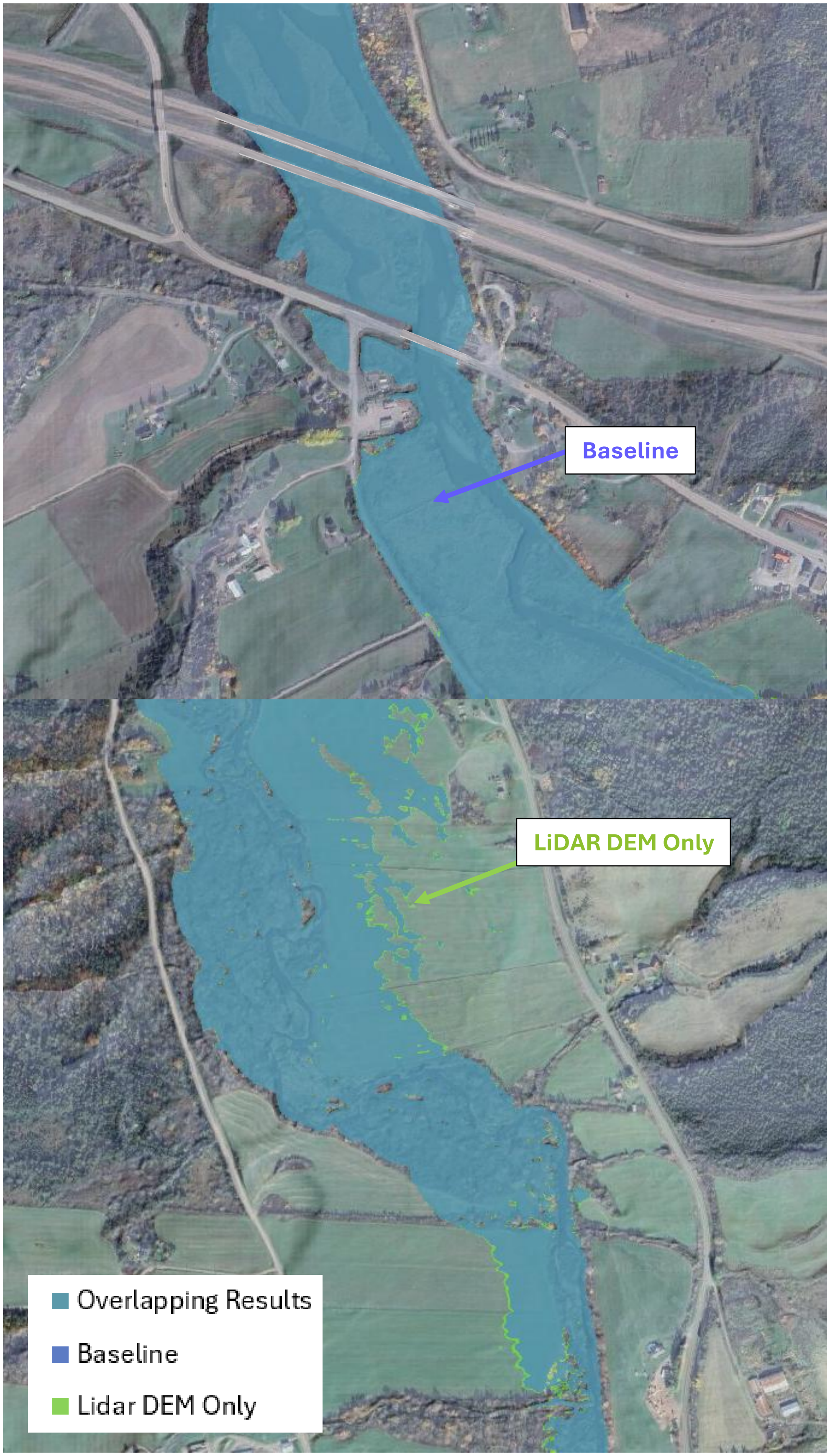

Figure 5-19: Flood extents for lidar DEM only vs Baseline

5.2.2 Study Area 2: Salmon River near Prince George, BC

This scenario reflects conditions where high-resolution lidar data is available, but bathymetric data is lacking. For the purposes of the test, the bathymetric data surface was removed from the model, and elevations were replaced with those from the existing high-resolution lidar. This illustrates the impact of using only the existing high-resolution LiDAR surface as channel geometry, which does not penetrate the water surface and hence does not include channel bathymetry below the water surface at the time of lidar data capture. Figure 5-20 shows a sample cross-section with the channel bathymetry removed and reduced channel conveyance.

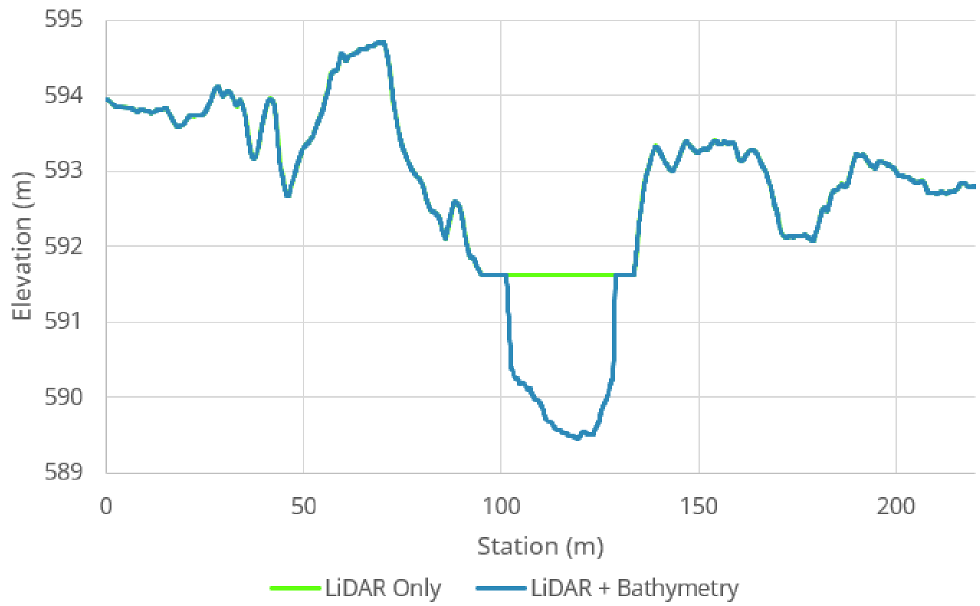

Figure 5-20: Sample Cross-Section along the Salmon River with Bathymetry Removed

Figure 5-21 and Figure 5-22 show the difference from the reference model in water surface elevations and velocities at corresponding sample cross-section locations for the lidar DEM Only model runs. Additionally, Figure 5-23 shows the water surface extents at areas of interest along the Salmon River.

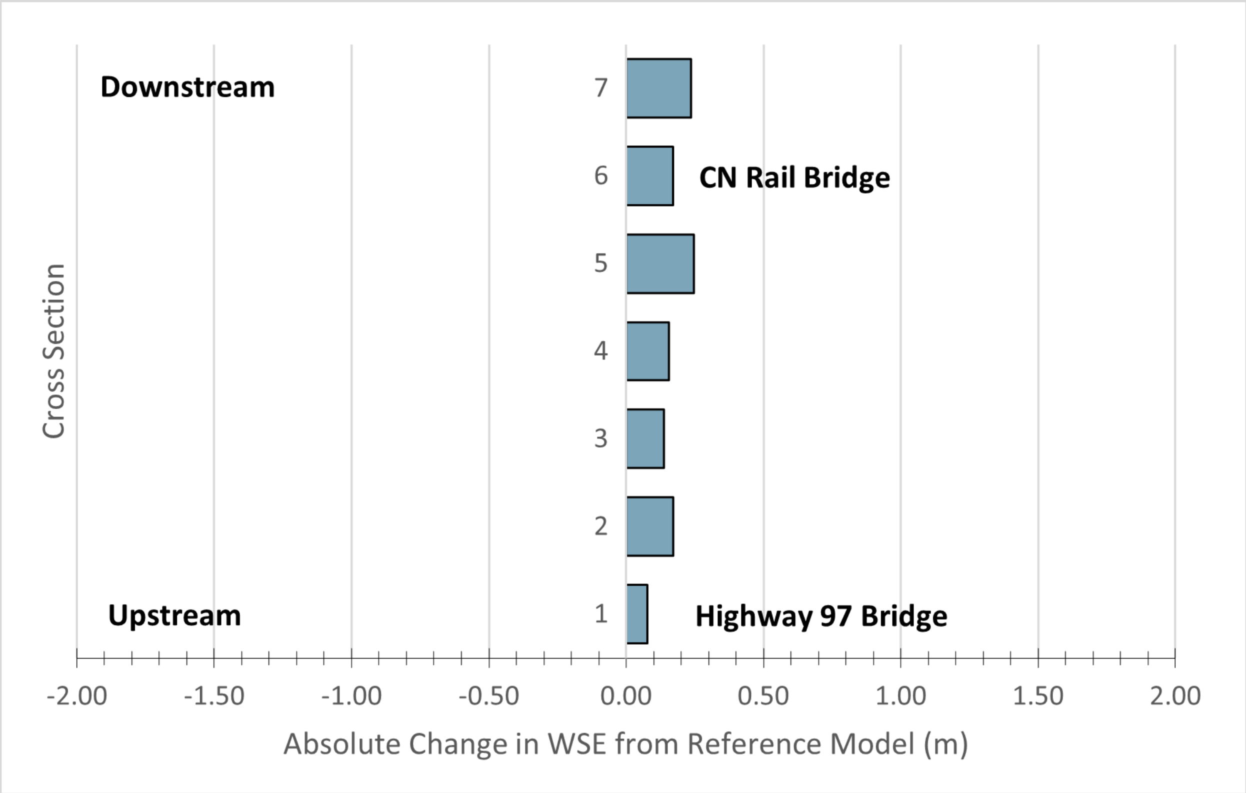

Figure 5-21: Impact of Excluding Bathymetry on Water Surface Elevations at Sample Cross Sections along the Salmon River

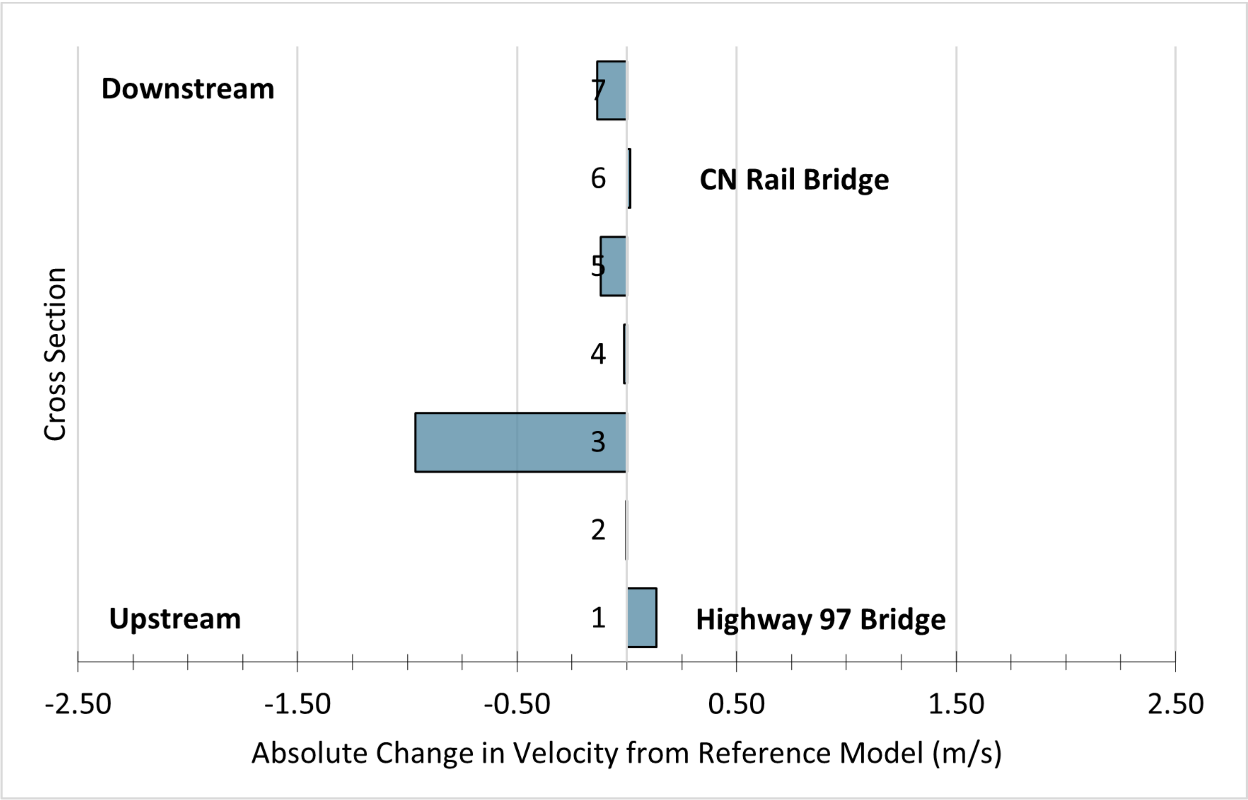

Figure 5-22: Impact of Excluding Bathymetry on Velocity at Sample Cross Sections along the Salmon River

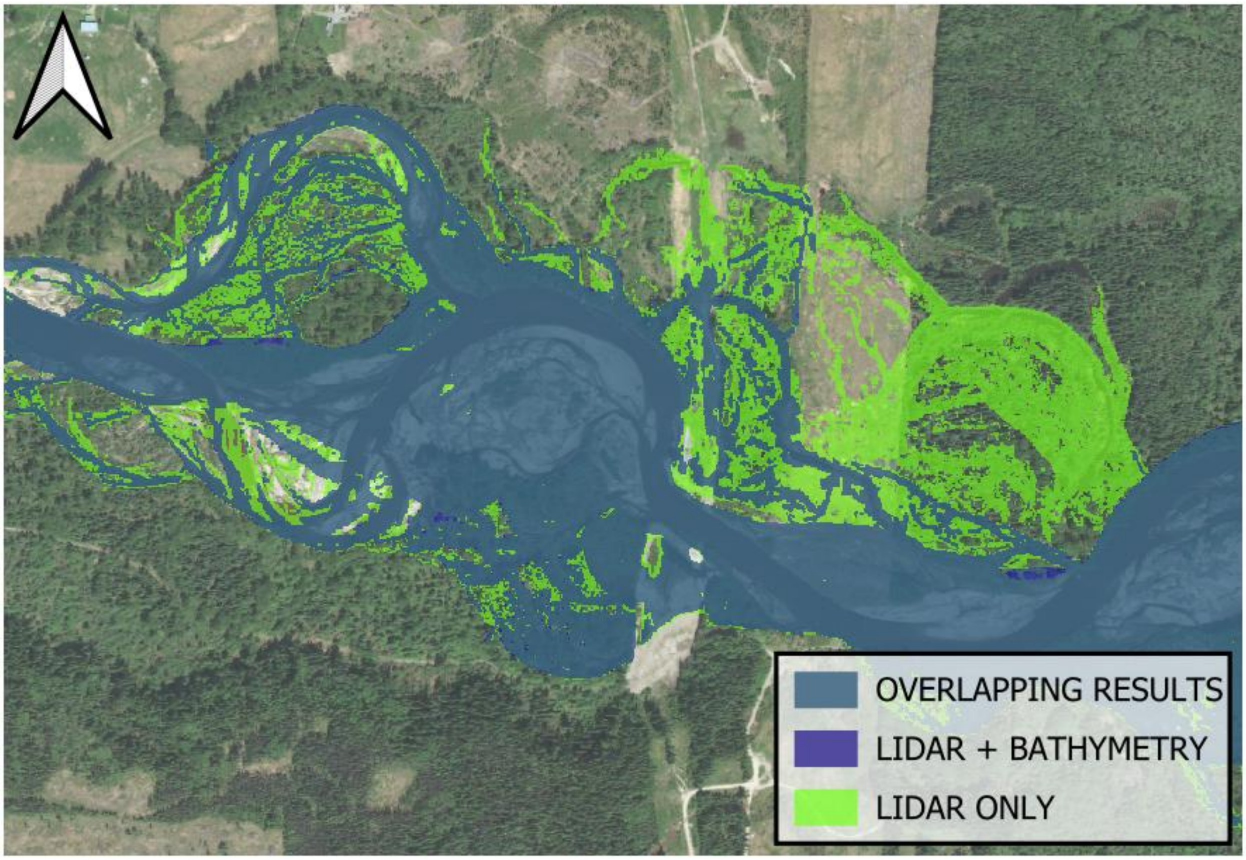

Figure 5-23: Area of interest along the Salmon River with Removal of Bathymetry

With the removal of bathymetry, there was an average increase in water level of approximately 17 cm across our sampled cross-sections. Along with the increase in water level, there was a substantial increase in flooding extents. The Salmon River contains several secondary and relic channels that became active once bathymetry data was removed. Since the lidar was collected during low flow conditions, it effectively captured these side channels. Had the lidar been acquired at a different time, these features might not have been visible, and the absence of bathymetry would have resulted in a more pronounced deviation in water levels from the baseline model. On average, the lidar DEM Only model produced velocities that were 0.2 m/s lower than those in the baseline model.

5.3 Reducing the Number of Survey Points by Half

5.3.1 Study Area 1: South River, Antigonish, NS

This scenario represents the situation where high quality lidar data is available, and surveyed bathymetry is completed, but the number of points are taken at each transect are reduced by half from the baseline scenario. In this scenario, the cross-section data from the baseline model was retained, then every other point of the channel bathymetry was deleted from the model. This caused very little change in cross section shape, only reducing the resolution of the surveyed bathymetry but not altering the overall shape (Figure 5-24).

Figure 5-25 shows that there was very little difference in water level observed after the change at the reported nodes (<0.03m). Figure 5-26 shows that there were also only small differences in velocity due to the change, with the largest difference at node 12 (-0.18 m/s) and node 7 (+0.14 m/s). The largest changes at these two nodes correspond to cross-sections with few surveyed points, due to the depth of the channel (i.e., not wadable), which when removed, greatly affect the shape of the cross-section. Figure 5-27 shows no observable change in resulting flood extents from the change.

These results show that the relative cross-sectional area of the river affects the sensitivity of the cross-section to resolution of surveyed bathymetry points. For example, when a river is wider, it may take more points to achieve similar resolution to a less-wide cross-section. Our results show that if the river section has too few points to define it, the cross-section may misrepresent water levels and velocities, although this example only showed minimal change.

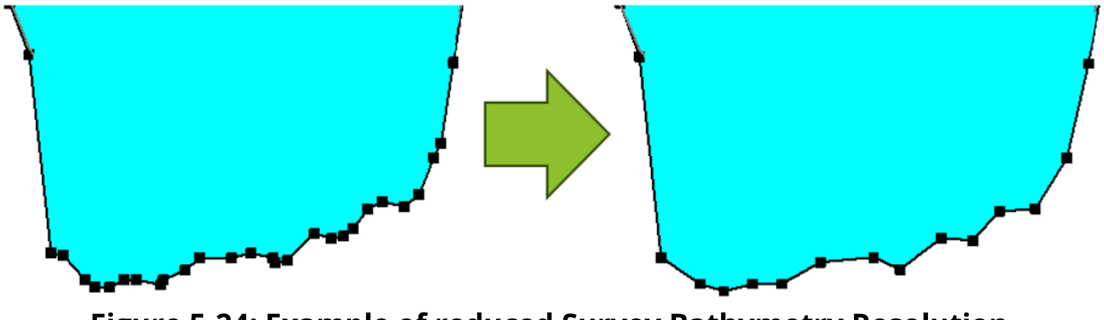

Figure 5-24: Example of reduced Survey Bathymetry Resolution

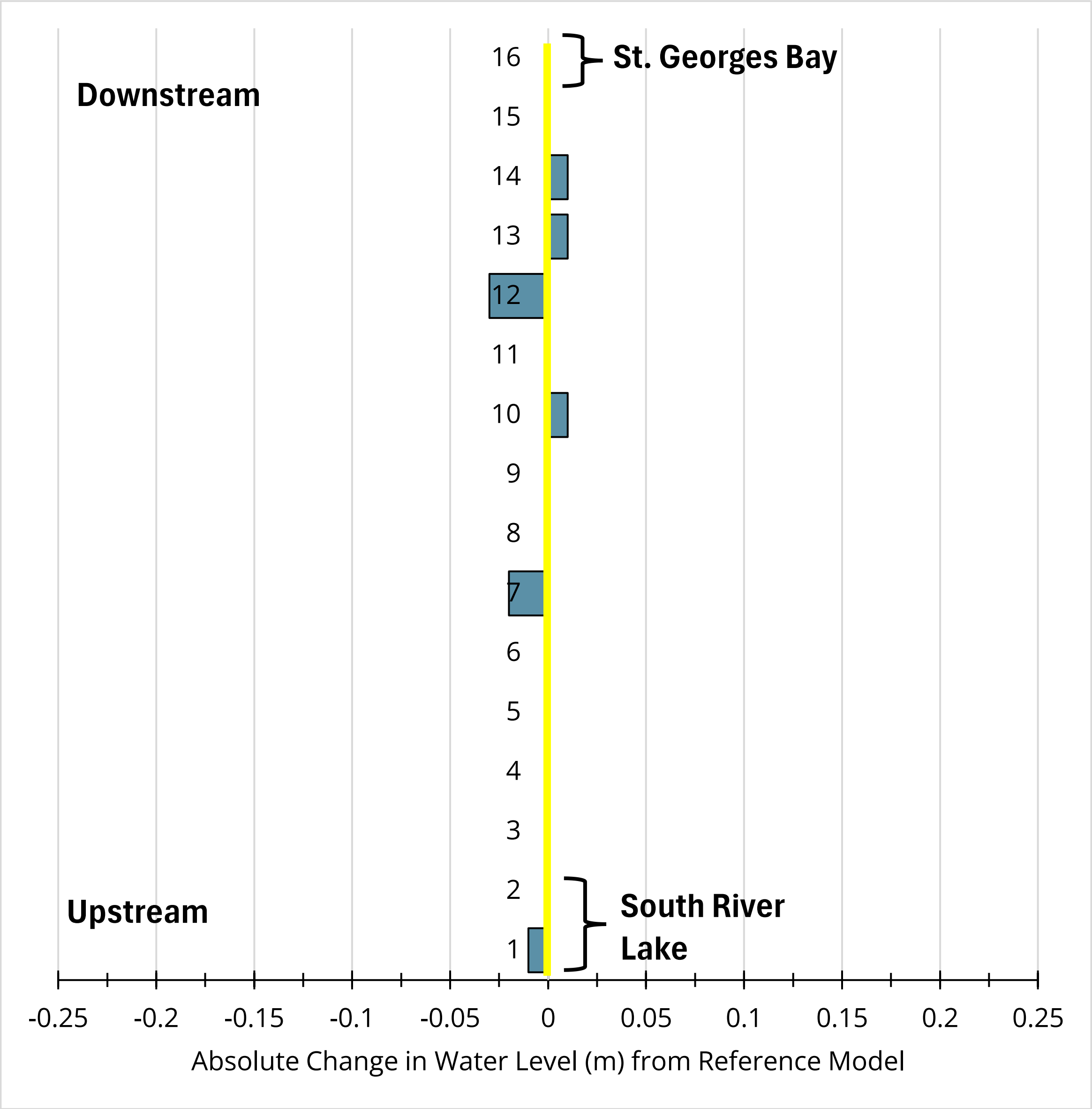

Figure 5-25: Removal of Half the Survey Points Testing Results showing change in WSEL

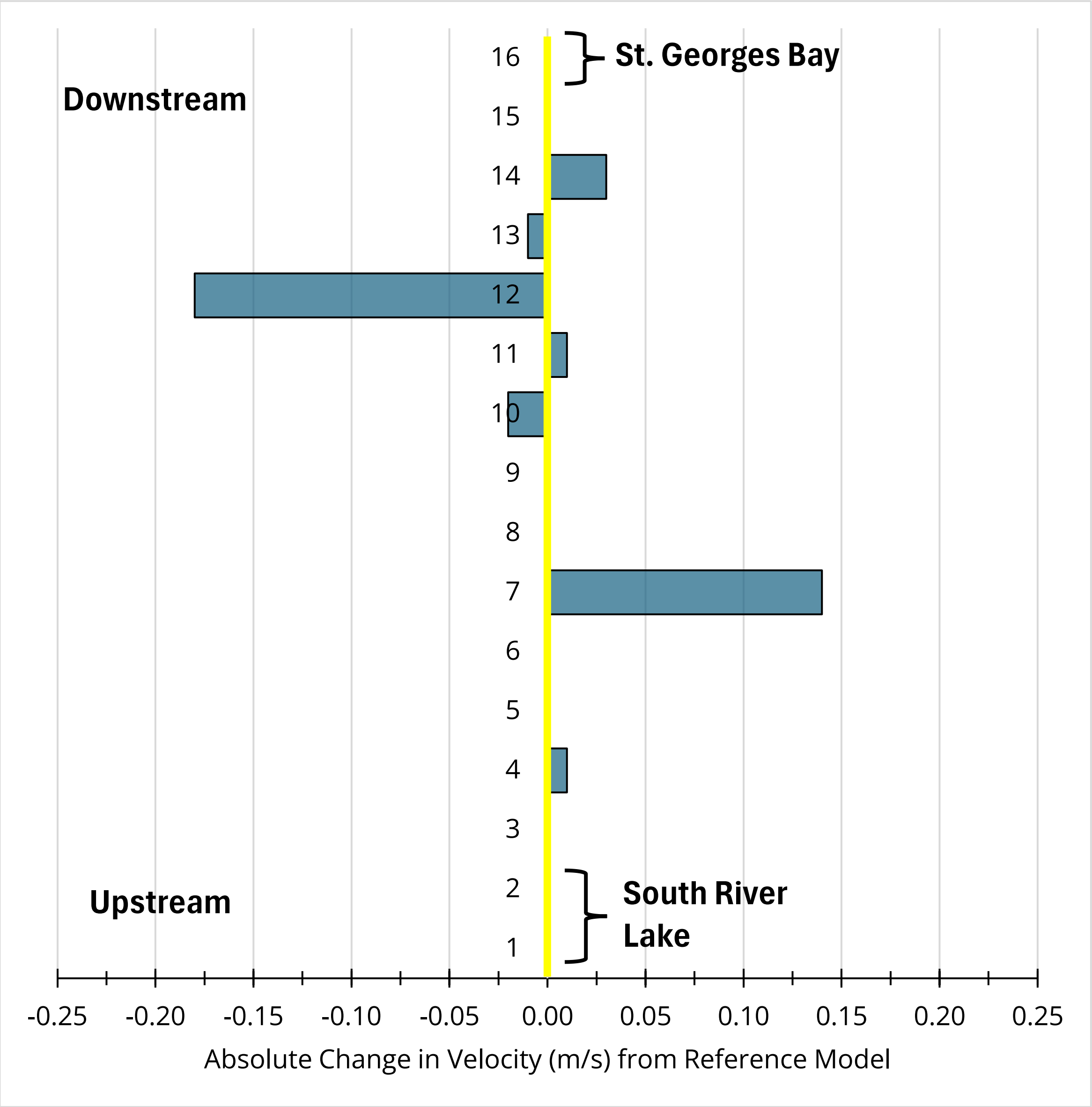

Figure 5-26: Removal of Half the Survey Points Testing Results showing change in Channel Velocity

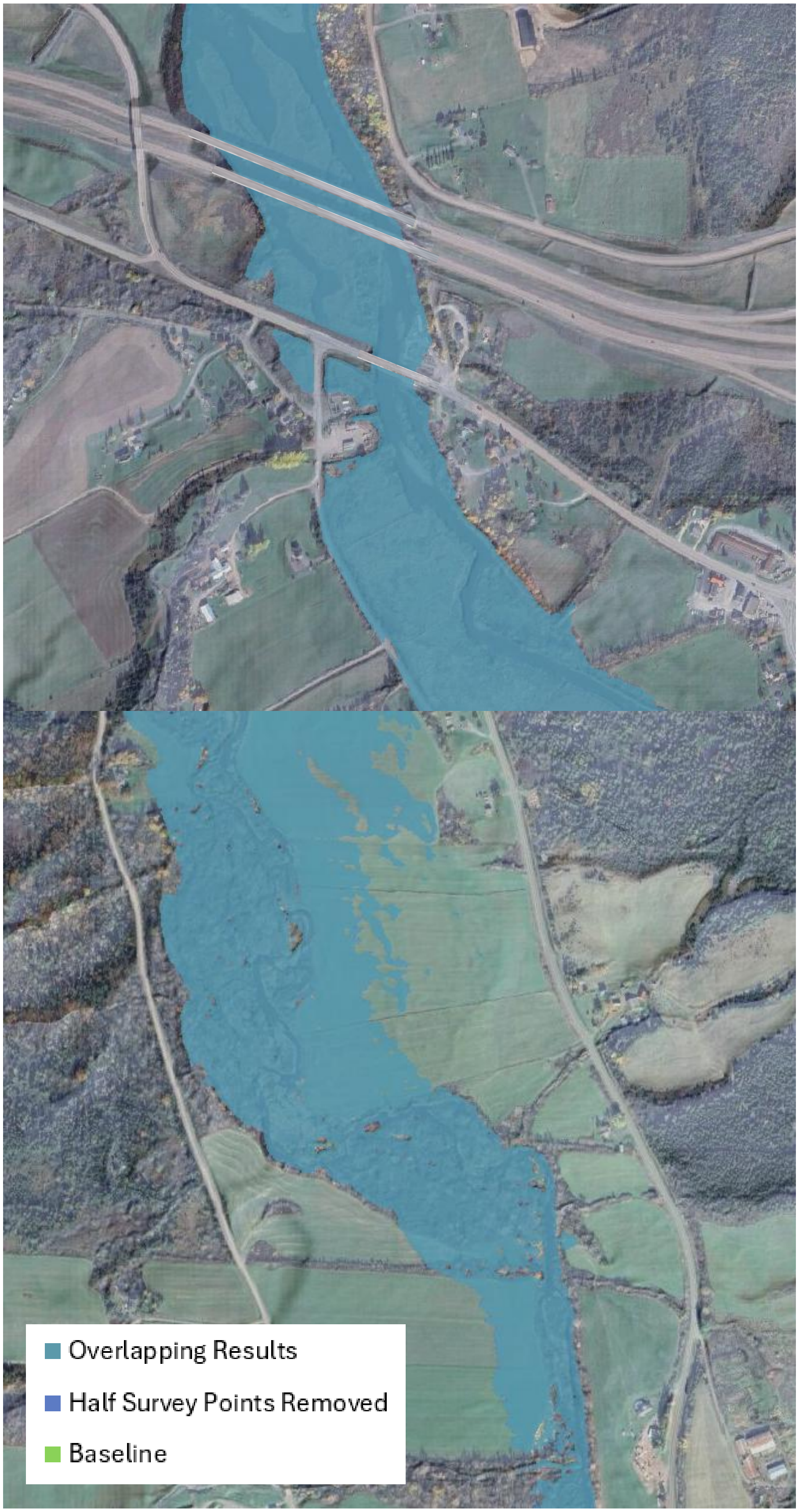

Figure 5-27: Flood Extents from removing Half of Surveyed Points vs Baseline.

5.3.2 Study Area 2: Salmon River near Prince George, BC

The impact of using coarser surveyed bathymetry data on flood map results was analyzed by reducing the number of surveyed cross-section points by half in the channel geometry. Once half of the points were deleted from the surveyed cross-sections in GIS, the data was used to interpolate a bathymetric surface in HEC-RAS. In the case of the Salmon River bathymetric survey, this increased spacing in survey data points from approximately every 0.6 m to 1.2 m. Although there is noticeably less detail in the cross-sections with half of the data, the overall shape of the cross-sections was largely maintained (Figure 5-28).

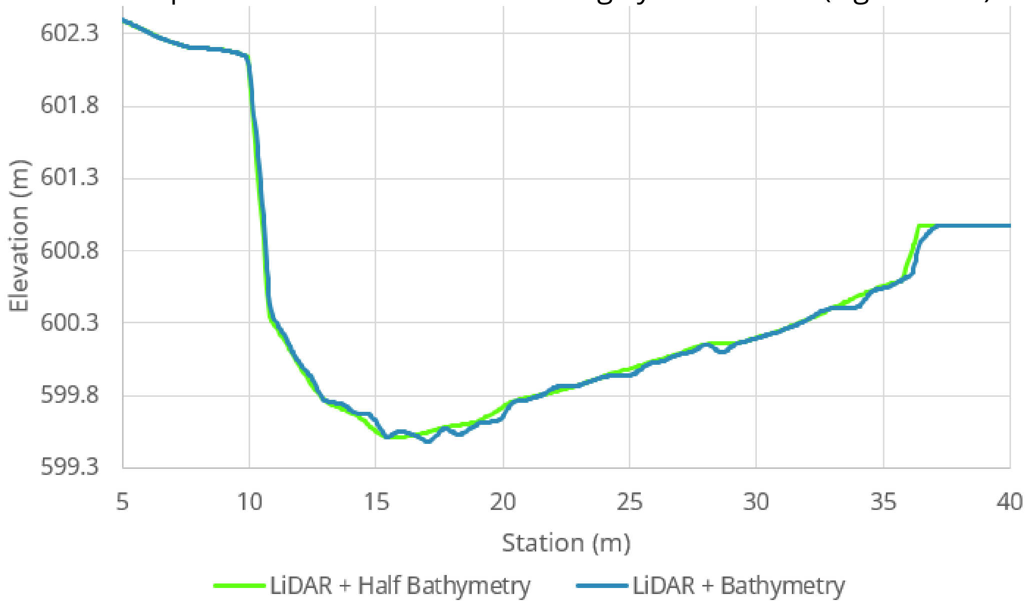

Figure 5-28: Sample Cross-Section along the Salmon River with Reduction of Survey Points by Half

Figure 5-29 and Figure 5-30 show the difference from the reference model in water surface elevations and velocities at corresponding sample cross-section locations for the half bathymetry points removed model runs. Additionally, Figure 5-31 shows the water surface extents at areas of interest along the Salmon River.

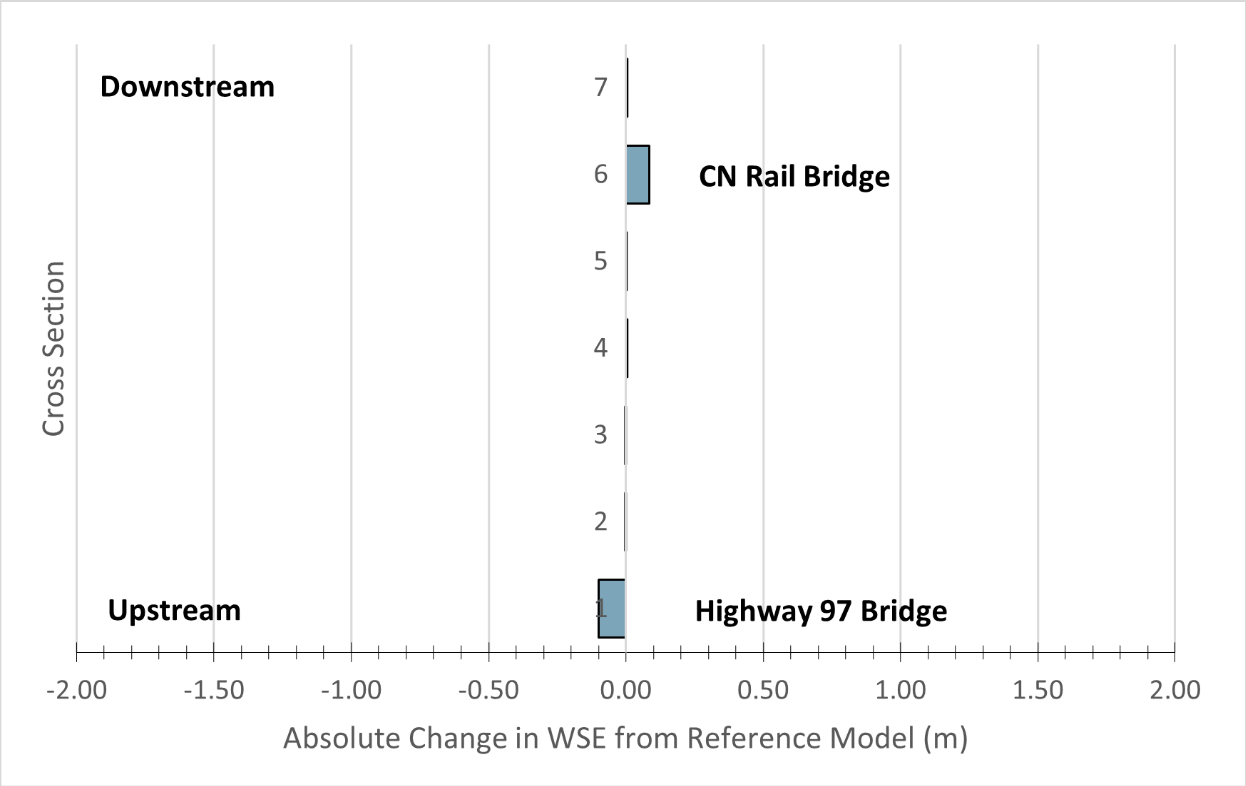

Figure 5-29: Impact of Removing Half of the Bathymetry Points on Water Surface Elevations at Sample Cross Sections along the Salmon River

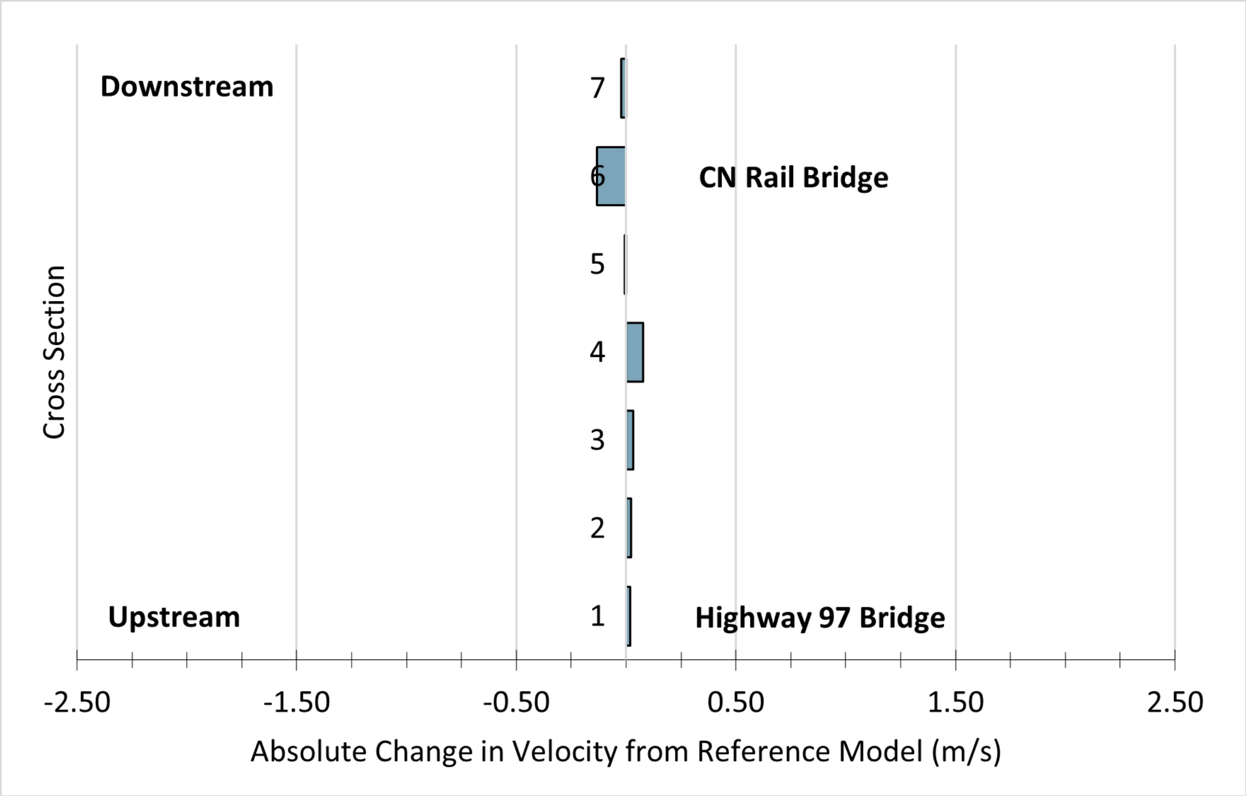

Figure 5-30: Impact of Removing Half of the Bathymetry Points on Velocity at Sample Cross Sections along the Salmon River

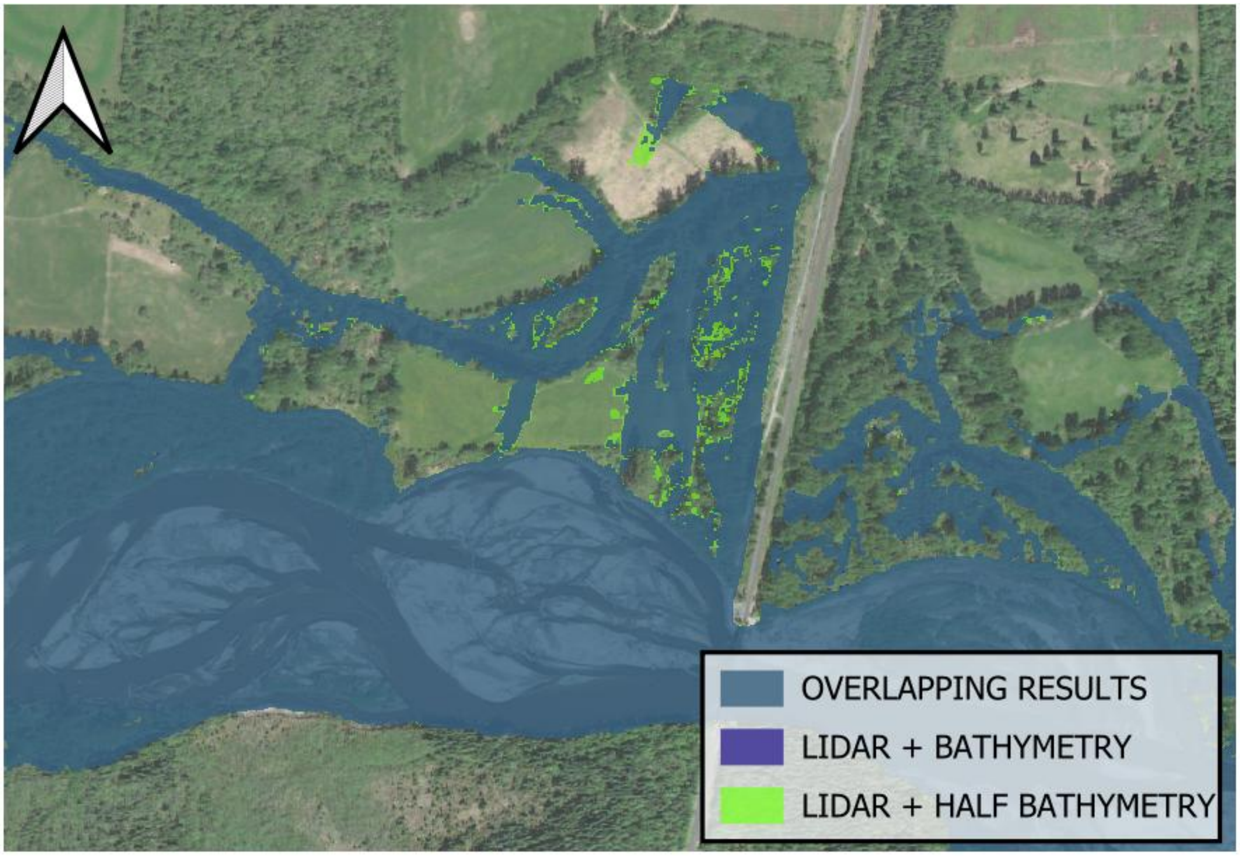

Figure 5-31: Area of interest along the Salmon River with Removal of Bathymetry

The model with half of the surveyed bathymetry data had almost identical results to the model with the full bathymetry data. The only major differences occurred in the flood elevations upstream of bridges where the channel is confined, with differences in the magnitude of approximately +/- 10 cm. The results confirm that higher density data at hydraulic structures is important.

5.4 Lidar DEM with Calculated Trapezoid Bathymetry

This scenario includes the calculation of a trapezoid channel bathymetry, where surveyed bathymetry is not available, paired with a high-resolution lidar DEM. Available flow and water level data is used to derive an estimated channel size to match the measured flow capacity, which is then inserted and tested in the model.

5.4.1 Study Area 1: South River, Antigonish, NS

5.4.1.1 Calculated Bathymetry Methodology

In order to develop bathymetry where no survey data is available, a method was applied using river flow and water level data and the HEC-RAS 1D model to 'back-calculate' a representative trapezoid bathymetry that was applied across the entire river reach, similar to the process used by Choné et al. (2018). The river in the study area contains a WSC flow gauge station, South River at St. Andrews [01DR001], with daily flow and water level data from 1917 to 2023 (Figure 5-32). This flow gauge was utilized for this method, however in the absence of a flow gauge on the study river, prorated flows could be used as an alternative, so long as there is an understanding of the limitations of this data.

Figure 5-33 shows that the lidar collected DEM did not penetrate the water, thus, the bottom of the channel according to the DEM is a flat line corresponding to the surface of the water. A trapezoid channel, following the slopes of the existing channel banks (4.77 H:V on left bank, and 1.47 H:V on right bank) was added beneath the DEM elevation to replace the missing bathymetry.

To identify the target water depth and flow capacity of the modified channel, a flow and corresponding water level were chosen from the WSC record. Using the Manning's Equation to estimate the capacity of the modified channel, the depth of the trapezoid was iteratively altered until the calculated flow matched the total recorded flow for the same water level. This was attempted for a range of flows and water level pairs (low, medium, high), but it was found that the method did not work for low flows, or very high flows. The lower flows did not result in any depth change needed to achieve the target flow (likely due to a small amount of local backwatering that means the Manning's equation is not representative), and the highest flows exceeded the main channel on both sides, making the Manning's calculation less focused on the channel shape (and more on the overbank areas' capacity), and therefore more uncertain. A higher mid-range record, on January 18, 2022 (Figure 5-32), which had most of the flow in the main channel, was chosen for this calculation, and resulted in a trapezoid depth of 0.185m. An additional adjustment was added to this calculation, since at the water level of 9.613m (January 18, 2022), there is flow in the smaller channel to the left of the main channel (see Figure 5-33). HEC-RAS was used to identify that this small channel account for 5% of flow, therefore the trapezoid was matched using 5% less flow than was reported by the flow gauge (which removed the effect of overbank flow). To verify this trapezoid depth, the flow on January 18, 2022, 64.0 m^3/s, was input into the HEC-RAS 1D model at the WSC gauge location, and prorated by area to find the input flow at the other 17 flow input locations (Appendix A). An iterative approach was followed to lower the depth of the trapezoid until the water level matched the recorded level, which resulted in a final trapezoid depth of 0.45m below the DEM. This trapezoid was then applied through the entire modeled river system.

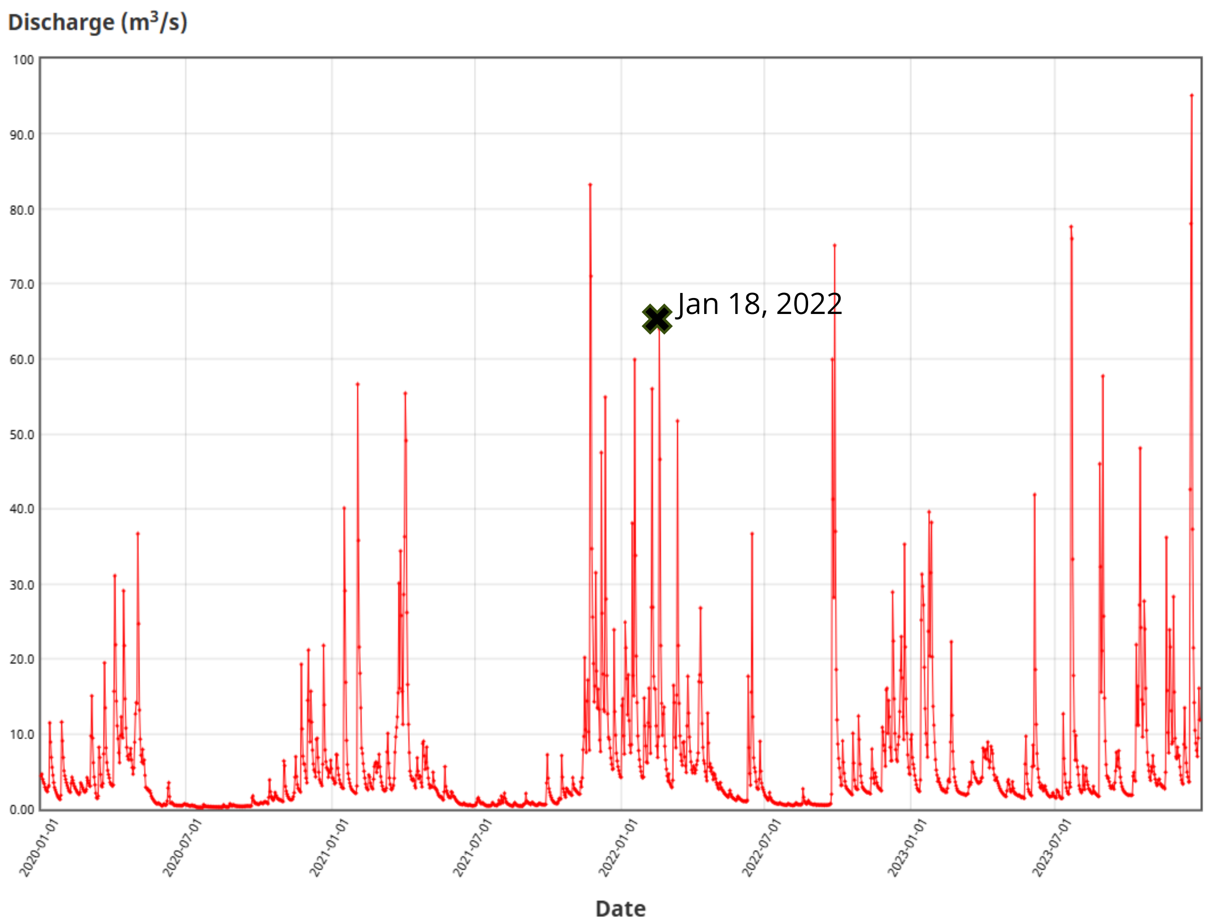

Figure 5-32: Daily Discharge, South River at St. Andrews [01DR001]

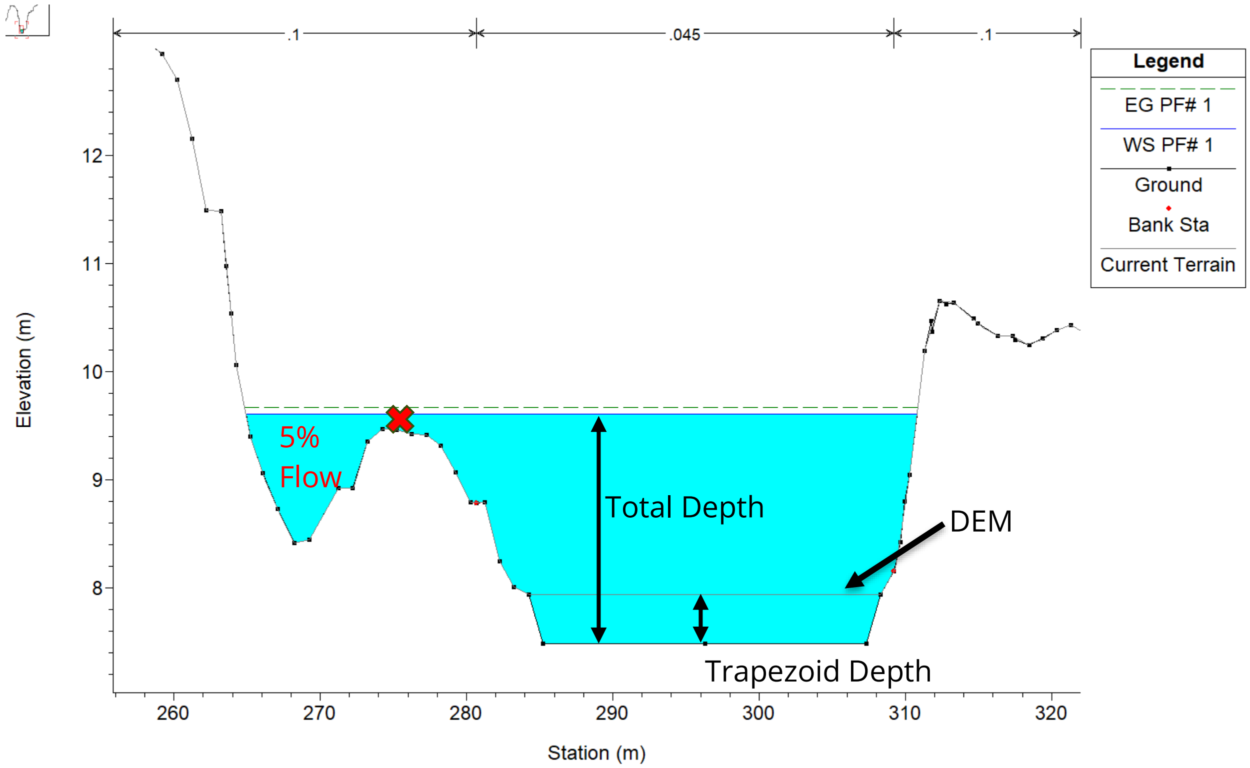

Figure 5-33: Determining Trapezoid Depth

5.4.1.2 Results

Figure 5-34 shows the distribution of change in water level at the reported nodes resulting from the change in bathymetry. Due to the change, there is a general increase in water level across the watershed, with the largest change of 0.18m at node 12. Figure 5-35 shows the distribution of change in velocity at the reported nodes resulting from the change in bathymetry. The velocity is both increased and decreased at the reported nodes as a result of these changes, with the largest change at node 7 of 0.2 m/s.

The calculated trapezoid bathymetry scenario produced similar results to the baseline scenario. Near the mouth of the river, the flooding extents were slightly narrower than the baseline, and upstream, they were slightly greater than the baseline (difference of 1-2 m, Figure 5-36). These results indicate that at this river, surveyed bathymetry performed similarly to calculated bathymetry. Given budget or time restraints, the calculated bathymetry could have been used for flood mapping at this river without significant change to results.

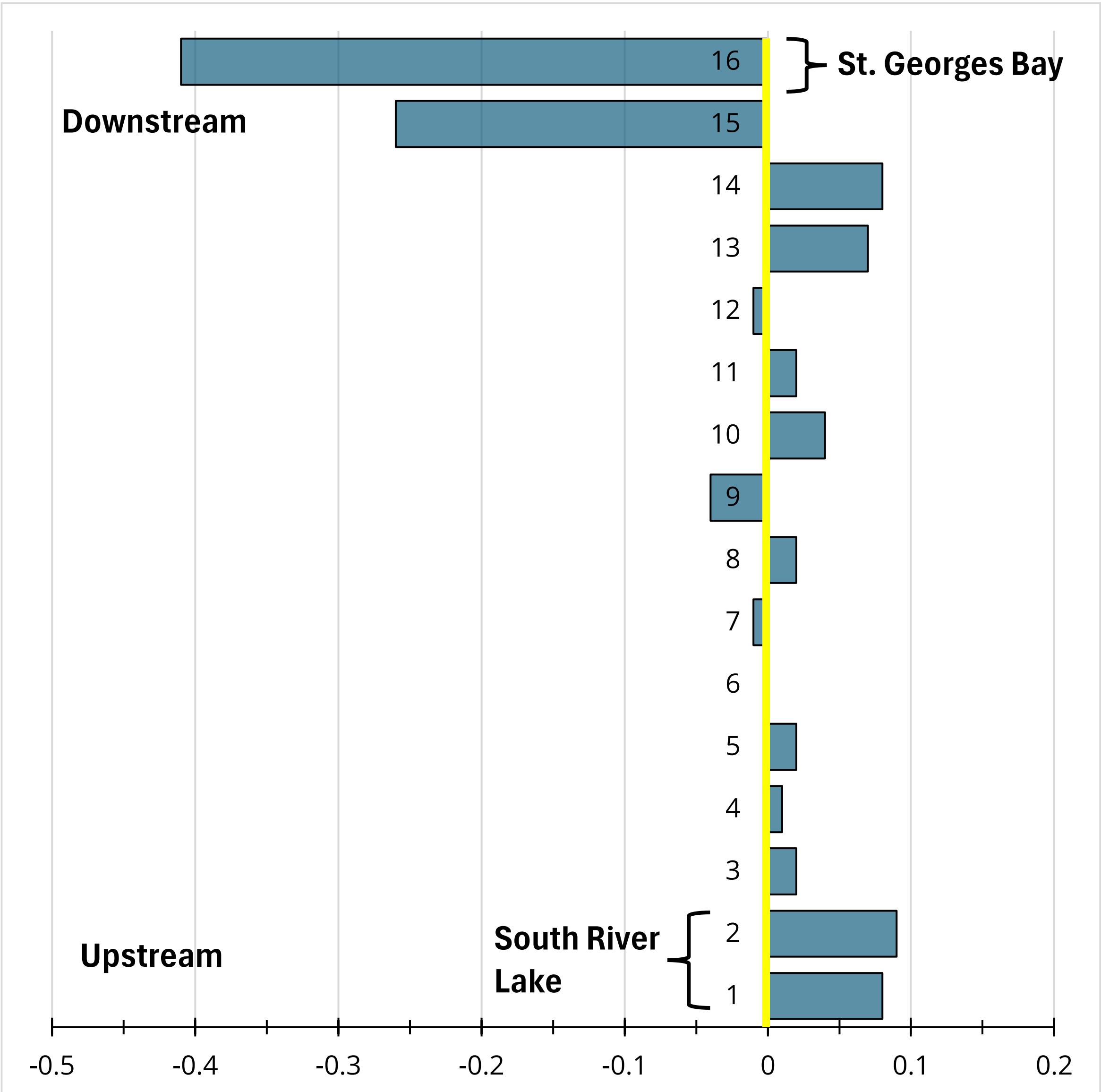

Figure 5-34: Calculated Channel Bathymetry Testing Results showing change in WSEL

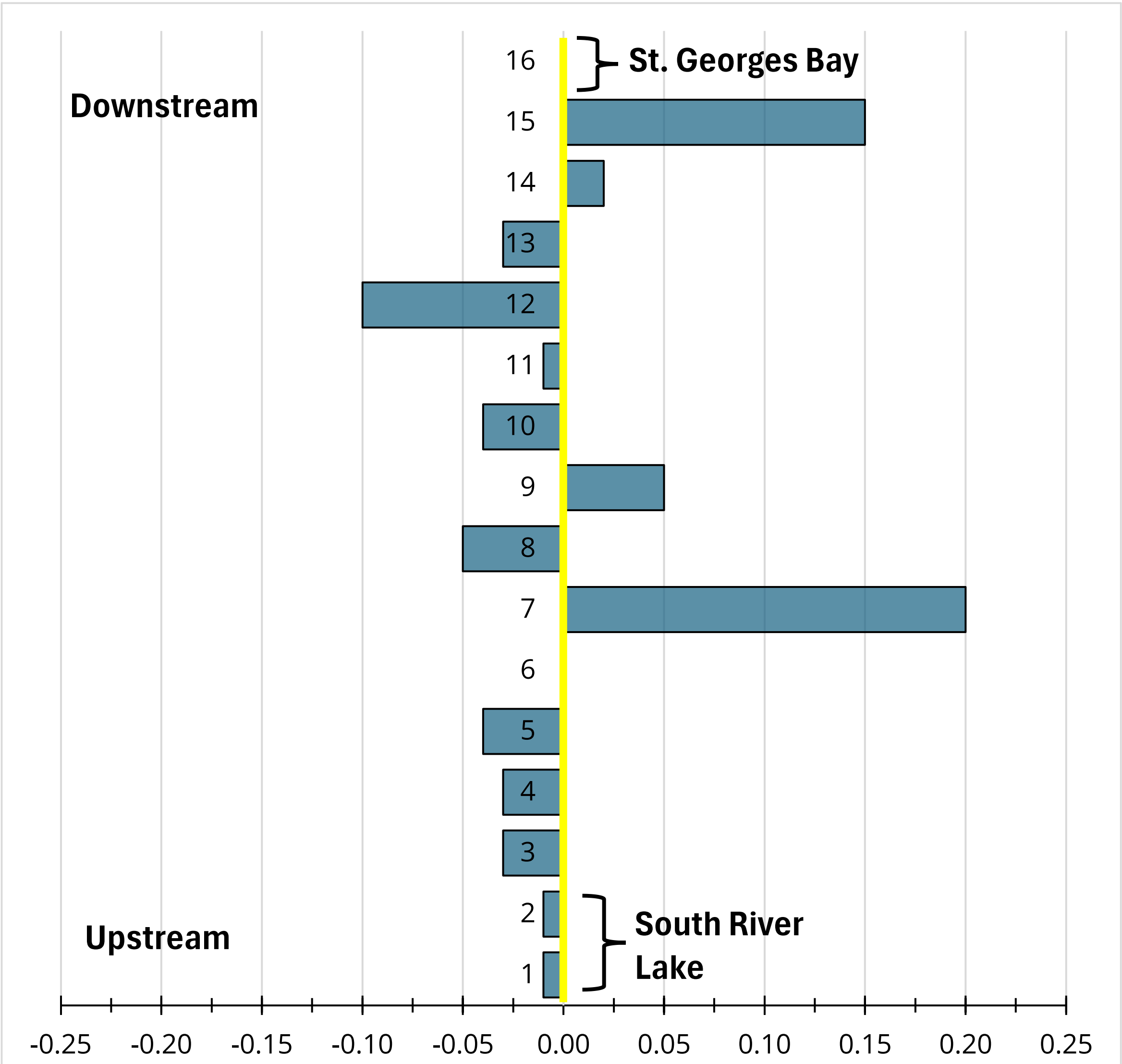

Figure 5-35: Calculating Channel Bathymetry Testing Results showing change in Channel Velocity (m/s)

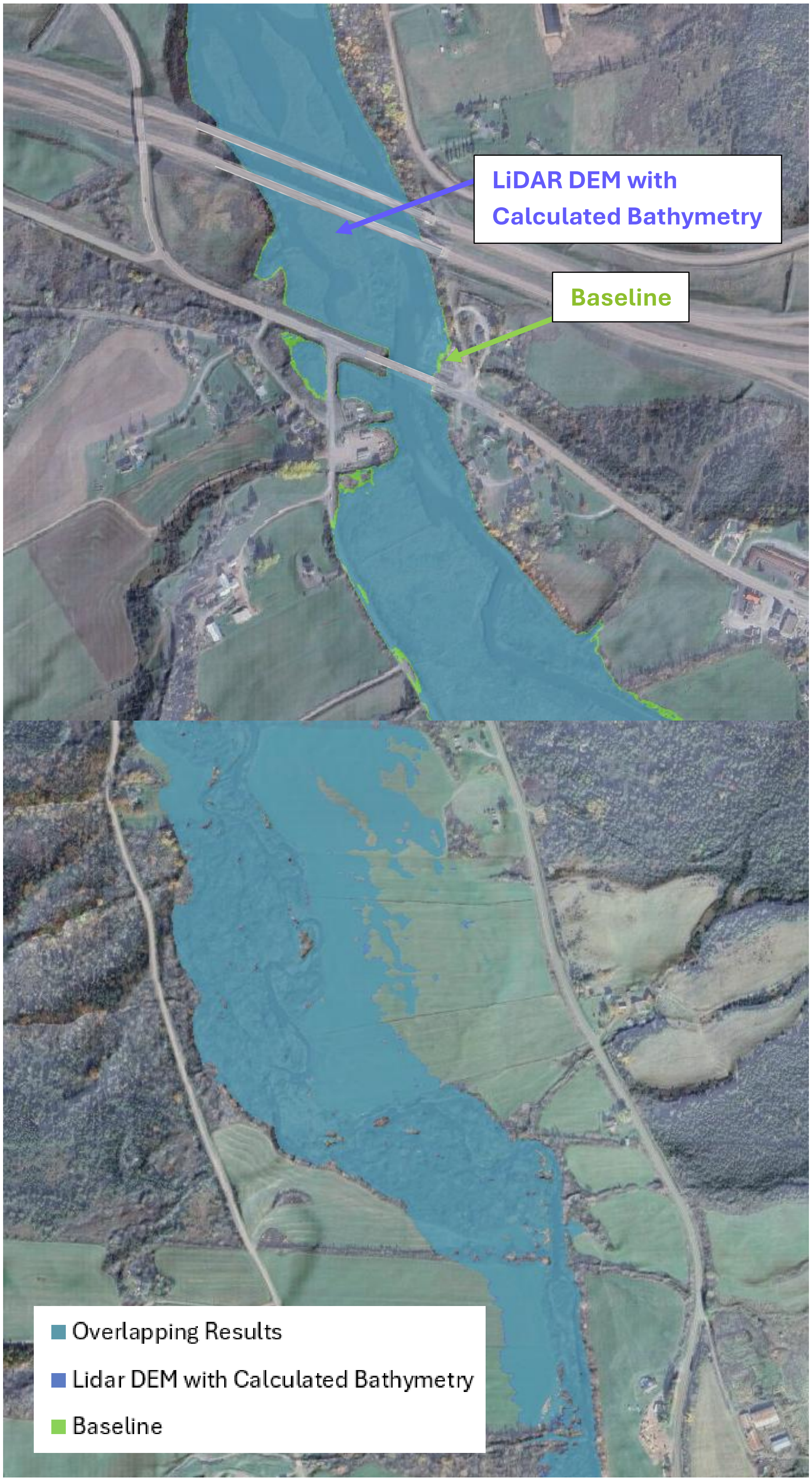

Figure 5-36: Flood extents from lidar DEM with calculated trapezoid bathymetry vs baseline.

5.4.2 Study Area 2: Salmon River near Prince George, BC

To analyze the approach of inferring the bathymetric data where not available, the missing bathymetry data was calculated as follows. Flow and water level data was downloaded from WSC gauge Salmon River Near Prince George (08KC001) located just downstream of the highway bridge in Study Area 2. The flow and water level at the WSC gauge allowed the use of the Manning's equation to estimate a trapezoidal channel that has the required capacity to convey the bank full conditions. This trapezoidal channel and calculated channel depth was burned into the lidar DEM terrain using the HEC-RAS DEM layer modification tool. The trapezoid was extrapolated throughout the river reach, as shown in Figure 5-37.

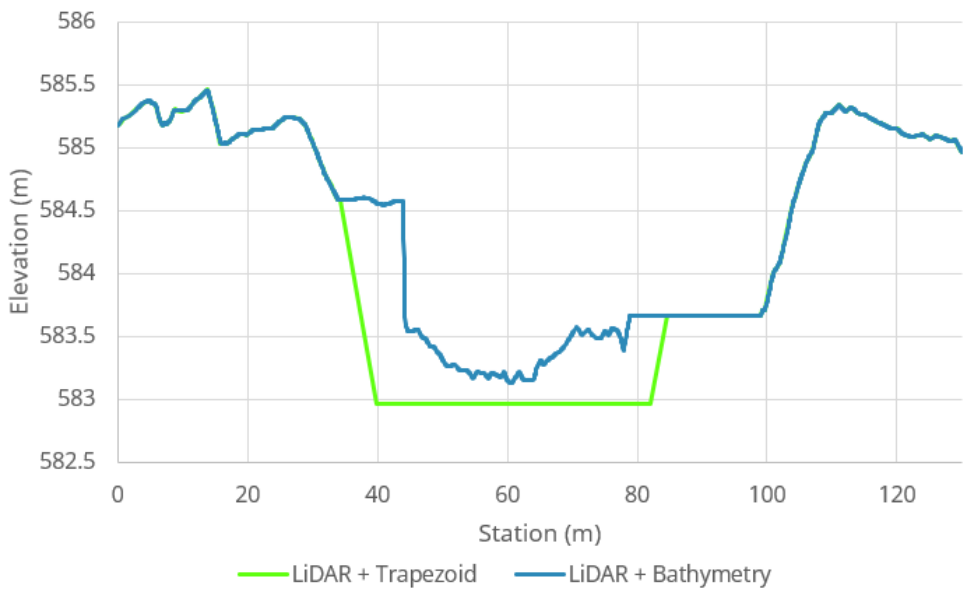

Figure 5-37: Sample Cross-Section along the Salmon River with Lidar DEM and Calculated Trapezoid Bathymetry

Figure 5-38 and Figure 5-39 show the difference from the reference model in water surface elevations and velocities at corresponding sample cross-section locations for the lidar DEM and calculated trapezoid bathymetry model runs. Additionally, Figure 5-40 and Figure 5-41 show the water surface extents at areas of interest along the Salmon River.

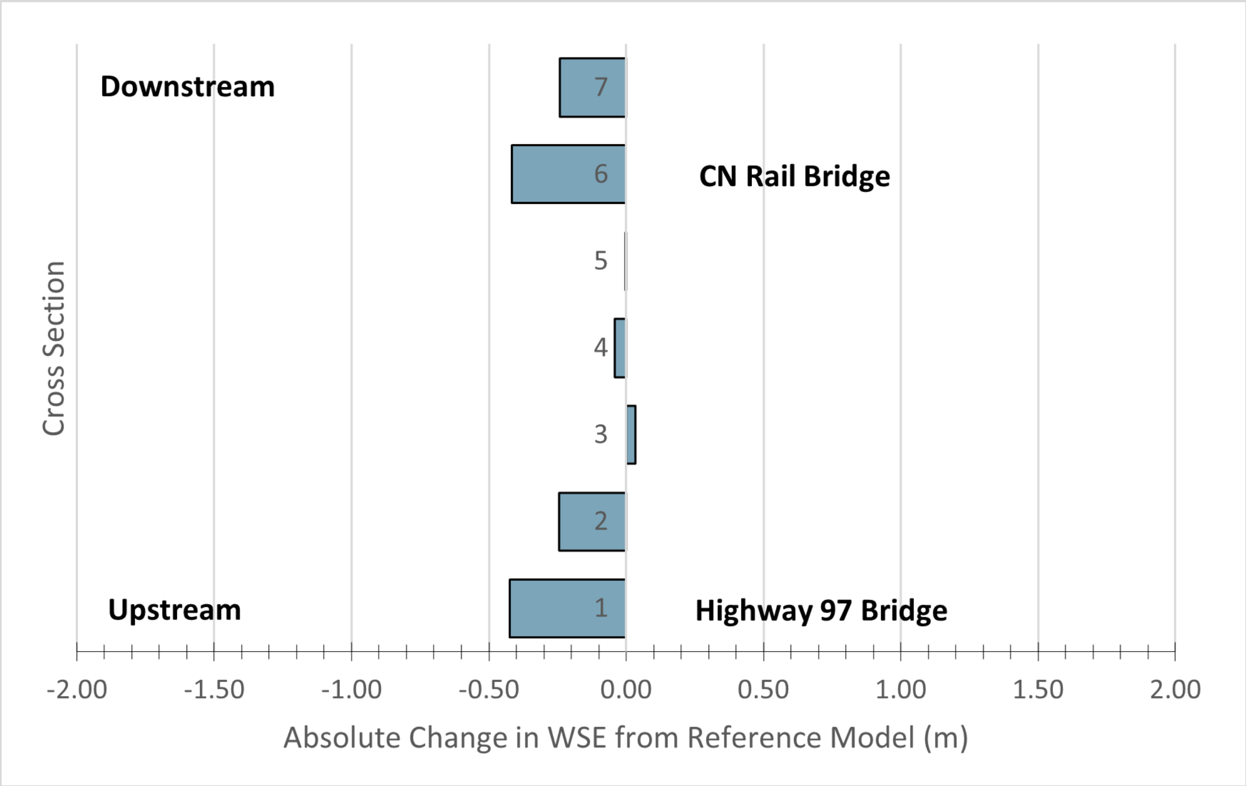

Figure 5-38: Impact of Using Lidar and Calculated Trapezoid Bathymetry on Water Surface Elevations at Sample Cross Sections along the Salmon River

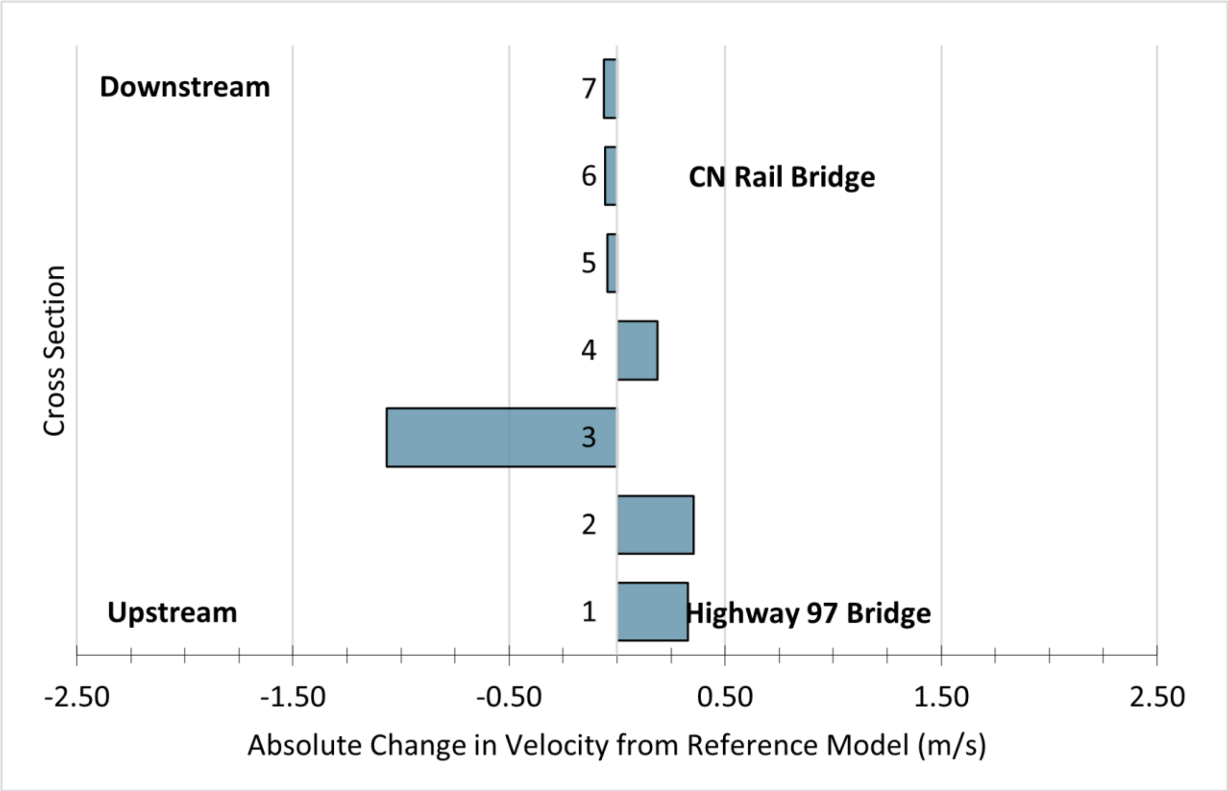

Figure 5-39: Impact of Using Lidar and Calculated Trapezoid Bathymetry on Velocity at Sample Cross Sections along the Salmon River

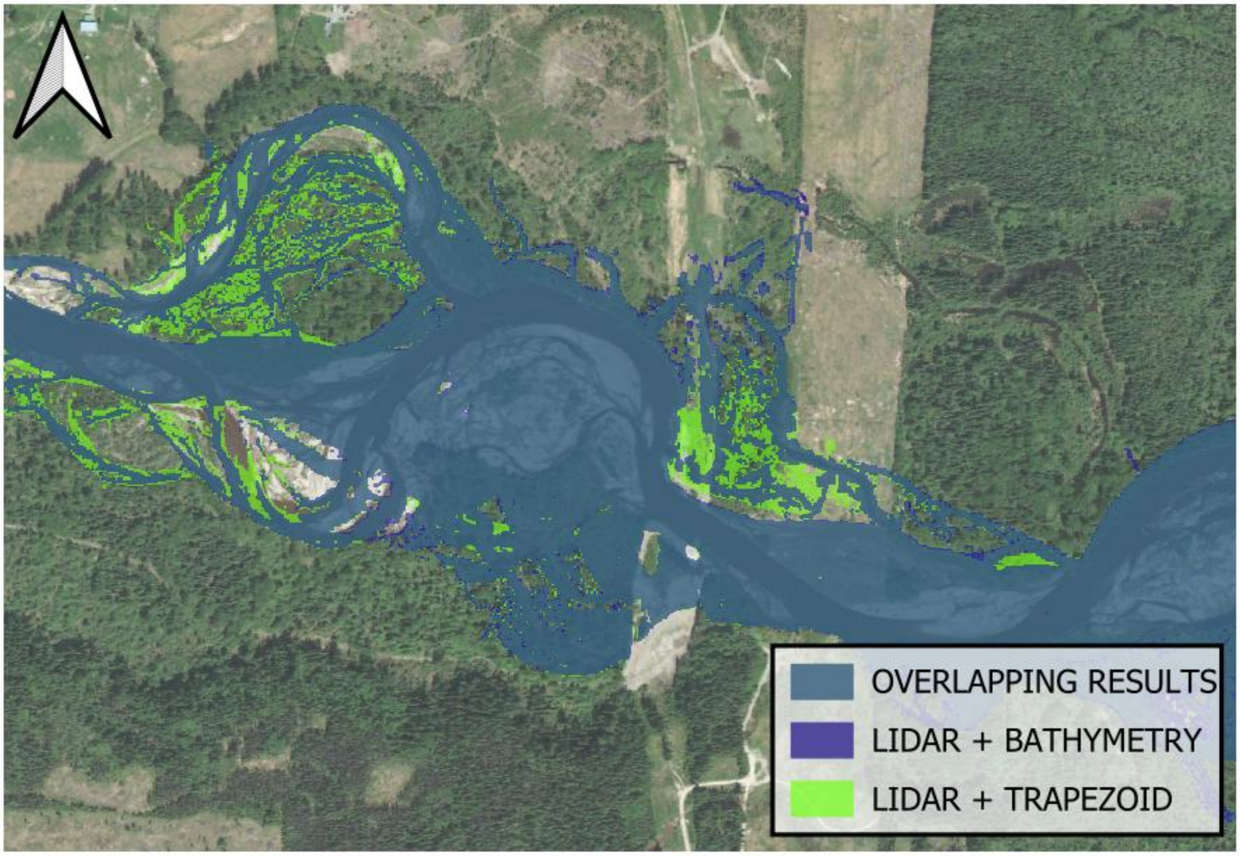

Figure 5-40: Area of interest along the Salmon River with Lidar DEM and Calculated Trapezoid Bathymetry

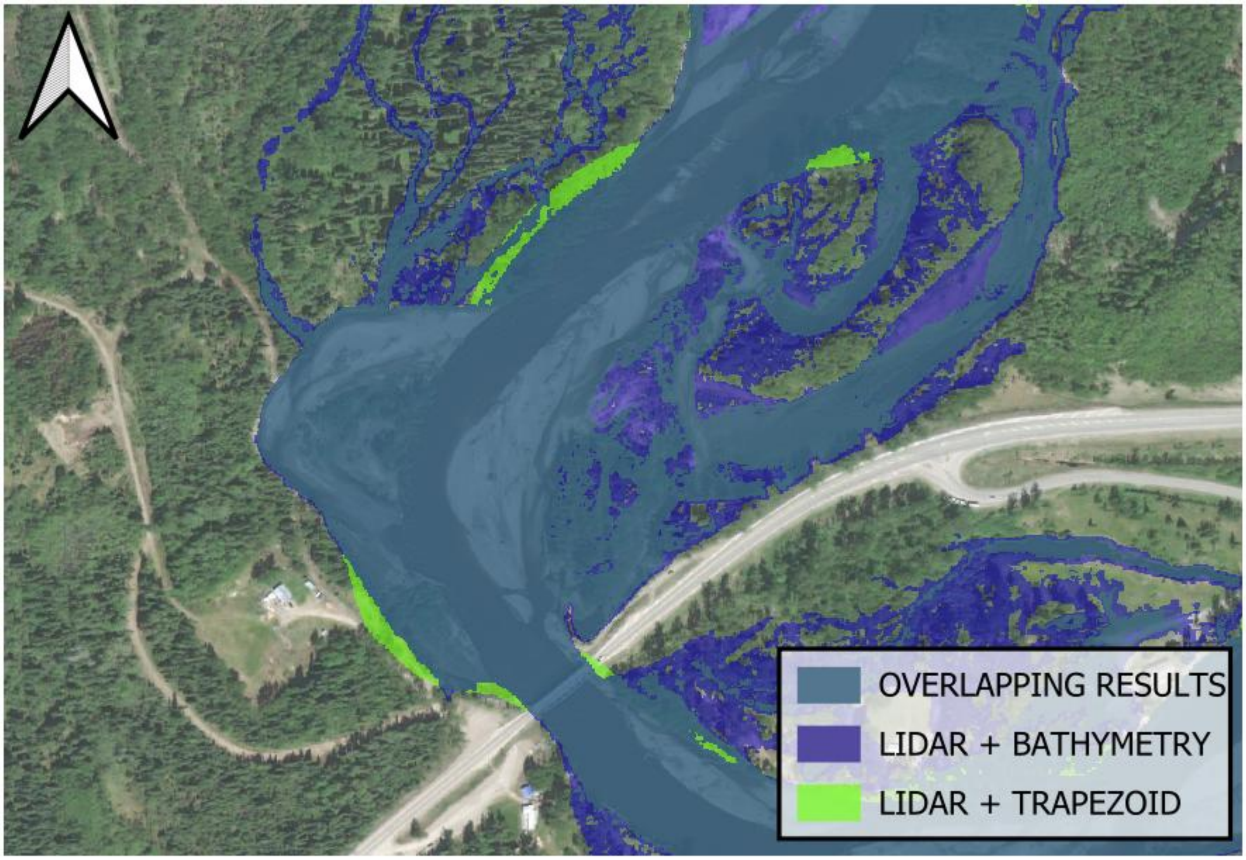

Figure 5-41: Area of interest along the Salmon River with Lidar DEM and Calculated Trapezoid Bathymetry

The greatest change in velocity was observed at Cross-Section 3, where the average velocity was 1.1 m/s lower than in the baseline model. This is likely due to an increase in the channel cross-sectional area when using the calculated trapezoid bathymetry which has overrepresented hydraulic conveyance in the primary channel. This overestimation is due to the high channel complexity at this location, which includes multiple braided channels and multiple directions of flow. In this area, calculation of a single trapezoidal main channel with a single focussed flow is not representative of the natural bedform. Both increases and decreases in velocity were noted throughout, likely due to these changes in channel geometry. The average water level with the calculated trapezoid bathymetry and lidar was on average approximately 19 cm lower than the baseline model.

Due to the nature of the 2D model, it was difficult to implement a consistent trapezoid in HEC-RAS 2D that conveyed the appropriate flow. This was largely due to the trapezoid being calculated at the highway bridge, one of the only constricted sections of channel in the modelled reach and one of the few locations where the river channel is not braided. Overall, there were challenges assigning low flow hydraulic conveyance to a naturally braided channel without over or underestimating hydraulic conveyance.

6 Evaluating Some Combinations of Data and Survey Availability

6.1 MRDEM with Calculated Trapezoid Bathymetry

6.1.1 Study Area 1: South River, Antigonish, NS

This scenario represents a situation where there is no high resolution DEM available, thus the MRDEM is used, and there is no bathymetry available, thus a trapezoid bathymetry is calculated. This scenario follows identical logic to the previous scenario (1m lidar DEM with calculated trapezoid bathymetry) for the calculation of trapezoid bathymetry data.

This scenario used the calculated trapezoid bathymetry directly inserted from the previous scenario. This would assume that a gauged station with a surveyed cross section is available to determine the shape and area of the trapezoid. It also assumes that the width of the channel and the appropriate starting elevations are available to transform the trapezoid for each section.

Figure 6-1 shows the distribution of change in water level at the reported nodes resulting from the change in bathymetry and DEM from baseline. Due to the change, there is a general increase in water level across the watershed, with the largest change of 0.9m at node 14. Figure 6-2 shows the distribution of change in velocity at the reported nodes resulting from the change. The velocity is both increased and decreased at the reported nodes as a result of these changes, increasing in value from upstream to downstream with the largest change at node 14 of -0.8 m/s.

The calculated trapezoid bathymetry with MRDEM scenario produced significantly different flood line extents to the baseline scenario (Figure 6-3). The addition of the MRDEM, similar to the scenario including surveyed cross-sections in the MRDEM, produced unrealistic cross-sections. The MRDEM with the calculated bathymetry varied from the lidar DEM with the calculated bathymetry, since the lidar typically shows a flat plane water level where the calculated bathymetry is inserted. Since the resolution of the MRDEM is 30m, the straight edge representing the water's surface is averaged out, and the location to input the calculated bathymetry is not as evident.

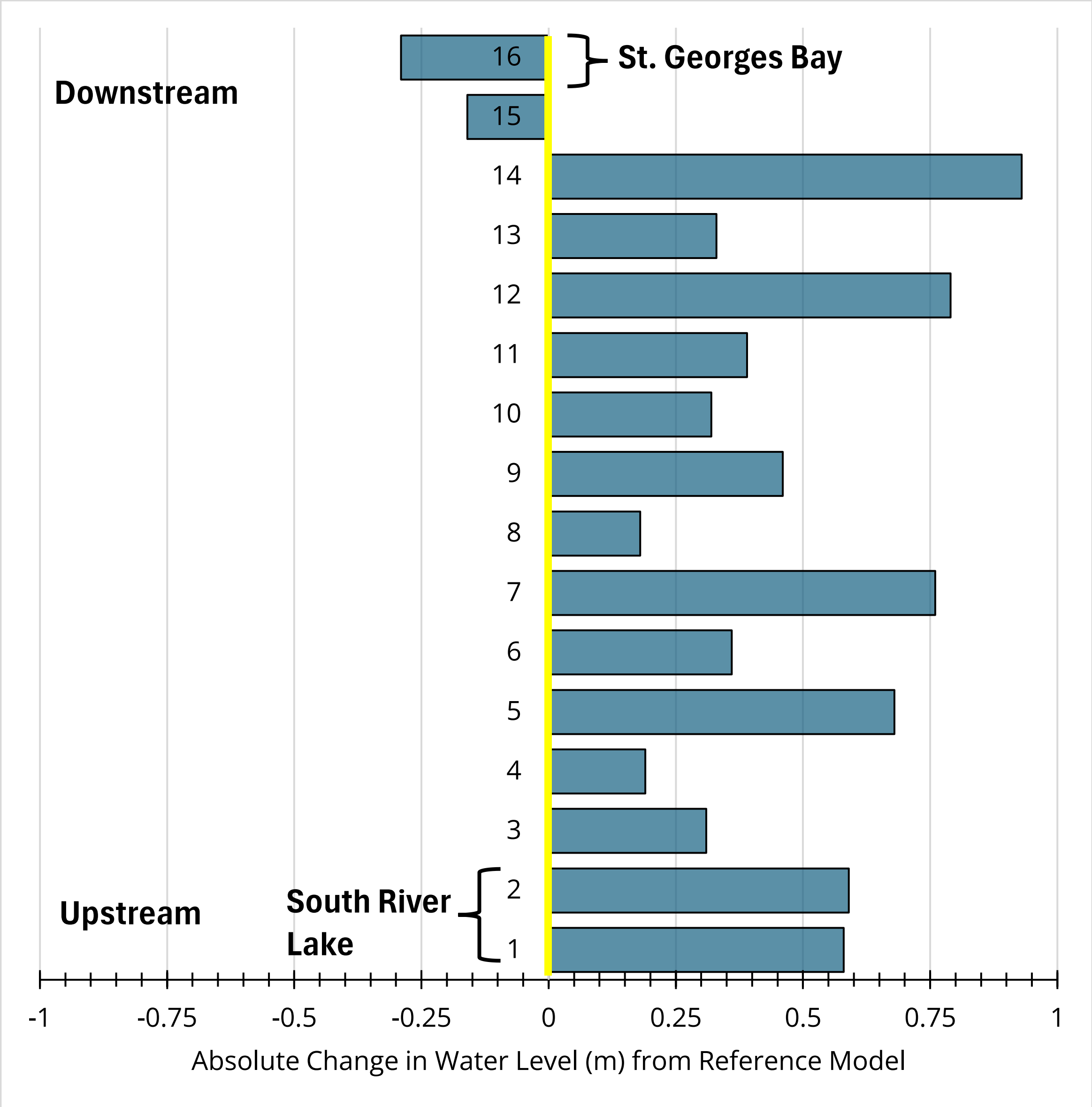

Figure 6-1: Calculating Channel Bathymetry and Adjusting DEM Resolution Testing Results showing change in WSEL

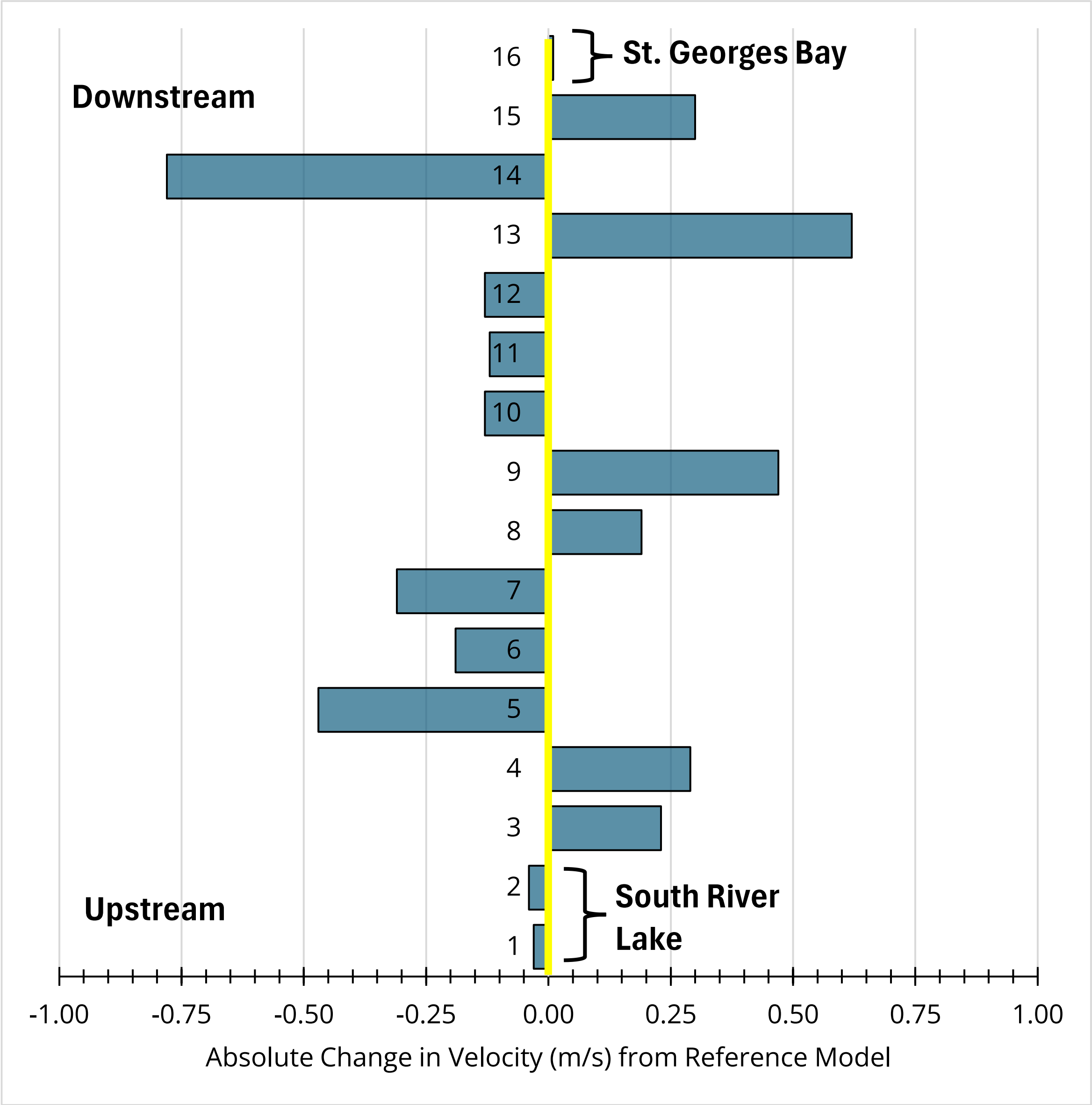

Figure 6-2: Calculating Channel Bathymetry and Adjusting DEM Resolution Testing Results showing change in Channel Velocity

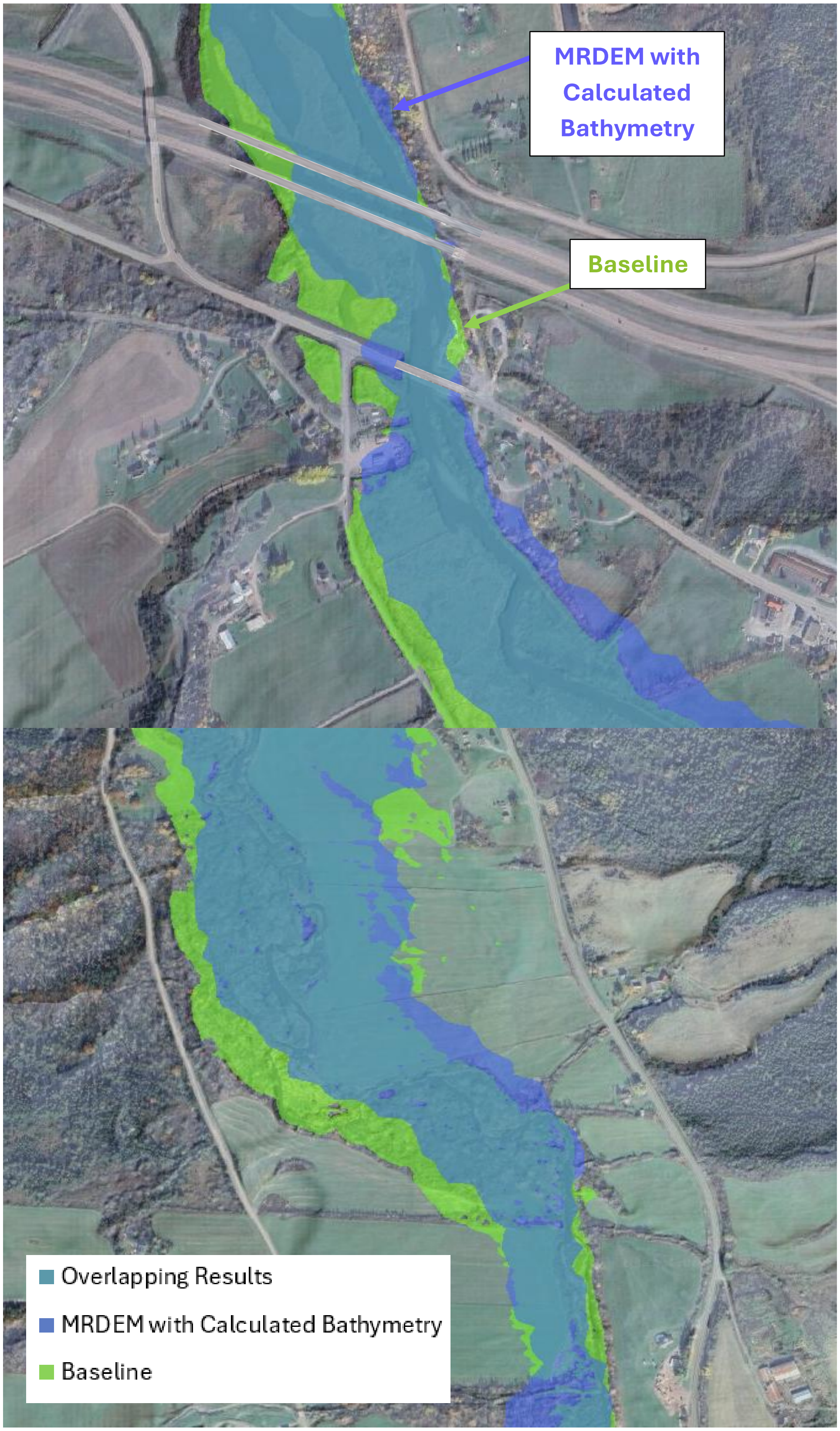

Figure 6-3: Flood extents for MRDEM with calculated trapezoid bathymetry vs baseline.

6.1.2 Study Area 2: Salmon River near Prince George, BC

This scenario assumed that both high resolution lidar data and bathymetry data are not available, and that calculated bathymetry must be used for channel geometry along with the MRDEM. Flow and water level data was downloaded from WSC gauge Salmon River Near Prince George (08KC001) located just downstream of the highway bridge in Study Area 2. The flow and water level at the WSC gauge location allowed the use of the Manning's equation to estimate a trapezoidal channel that has the required capacity to convey the bank full conditions with the MRDEM. This trapezoidal channel was burned into the MRDEM terrain using the HEC-RAS DEM layer modification tool and was extrapolated throughout the river reach, as shown in Figure 6-4.

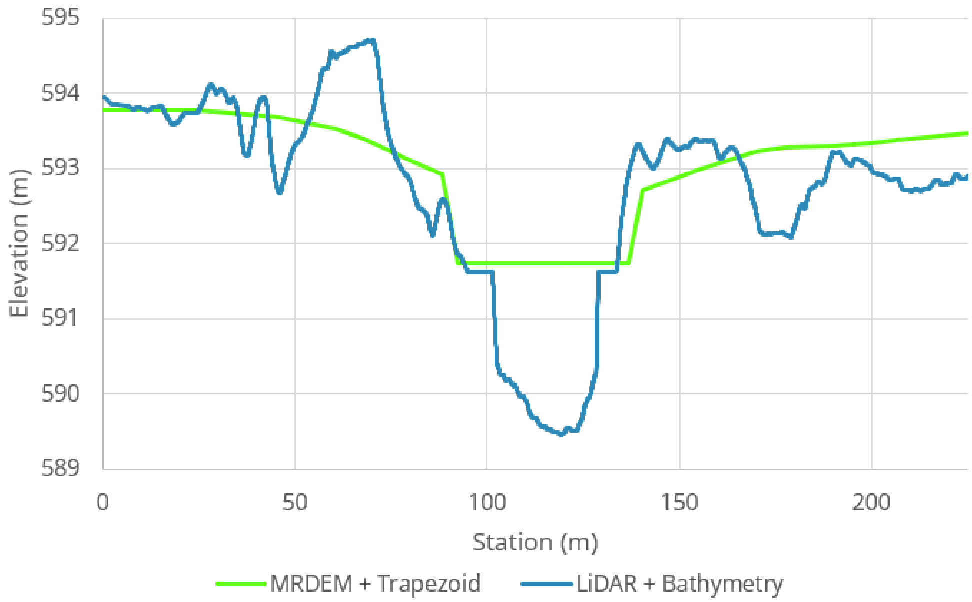

Figure 6-4: Sample Cross-Section along the Salmon River with MRDEM and Calculated Trapezoid Bathymetry

Figure 6-5 and Figure 6-6 show the difference from the reference model in water surface elevations and velocities at corresponding sample cross-section locations for the MRDEM and calculated trapezoid bathymetry model runs. Additionally, Figure 6-7 and Figure 6-8 show the water surface extents at areas of interest along the Salmon River.

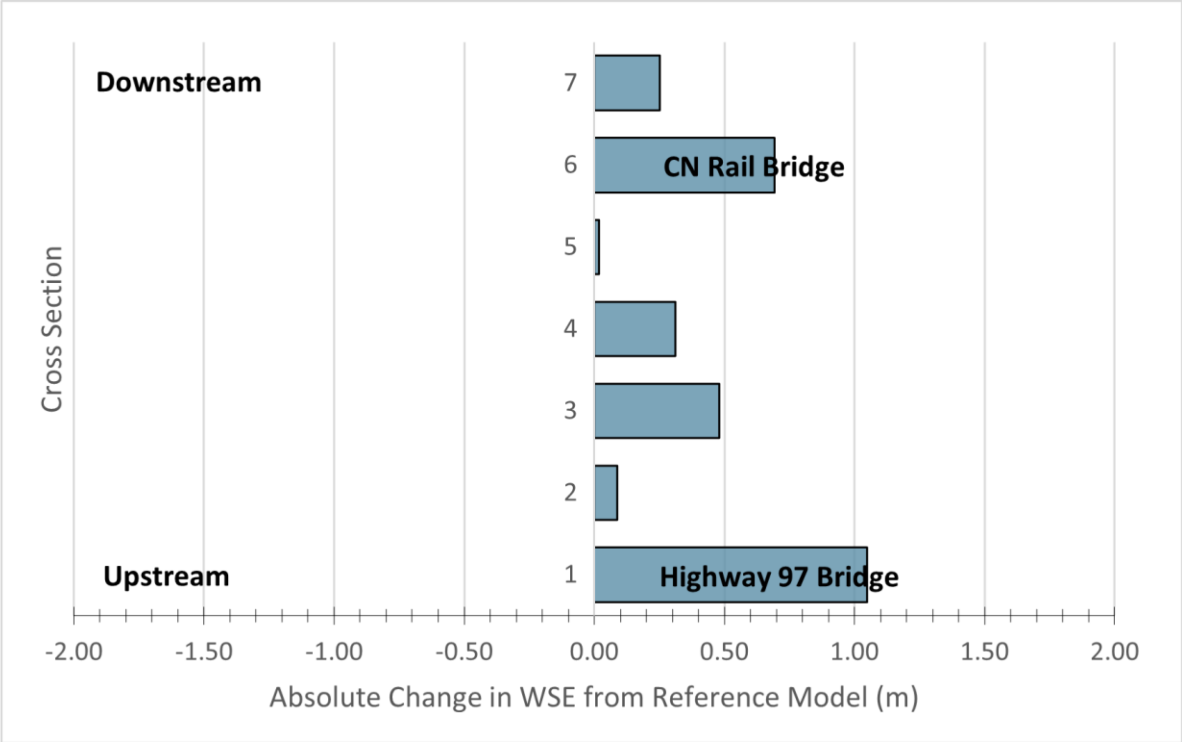

Figure 6-5: Impact of Using MRDEM and Calculated Trapezoid Bathymetry on Water Surface Elevations at Sample Cross Sections along the Salmon River

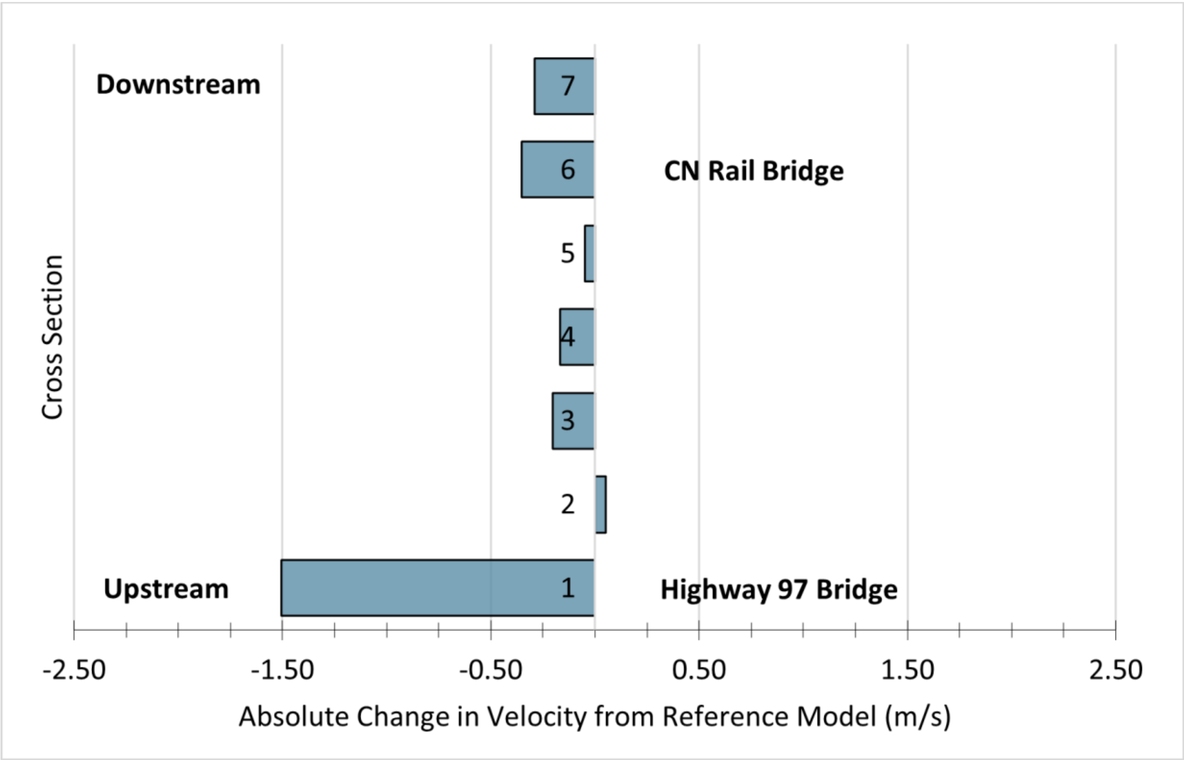

Figure 6-6: Impact of Using MRDEM and Calculated Trapezoid Bathymetry on Velocity at Sample Cross Sections along the Salmon River

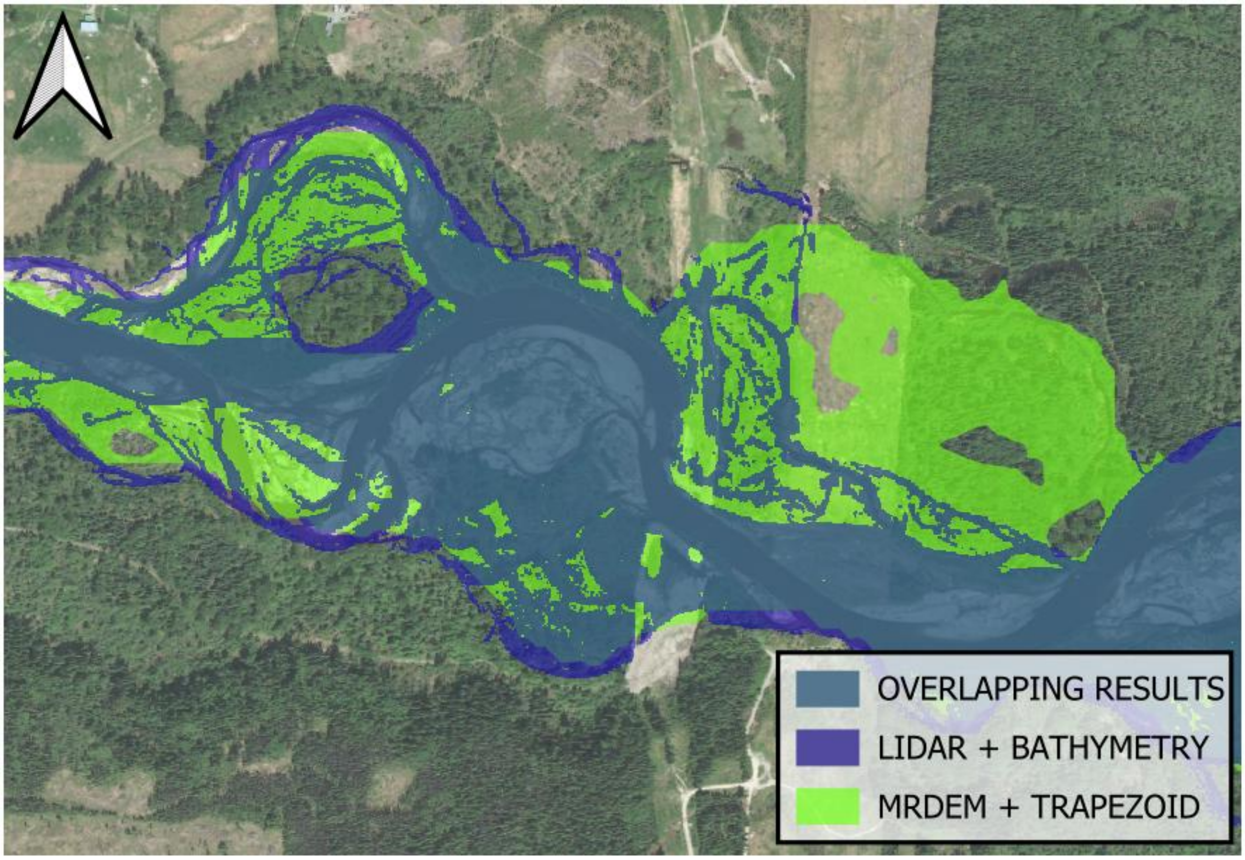

Figure 6-7: Area of interest along the Salmon River with MRDEM and Calculated Trapezoid Bathymetry

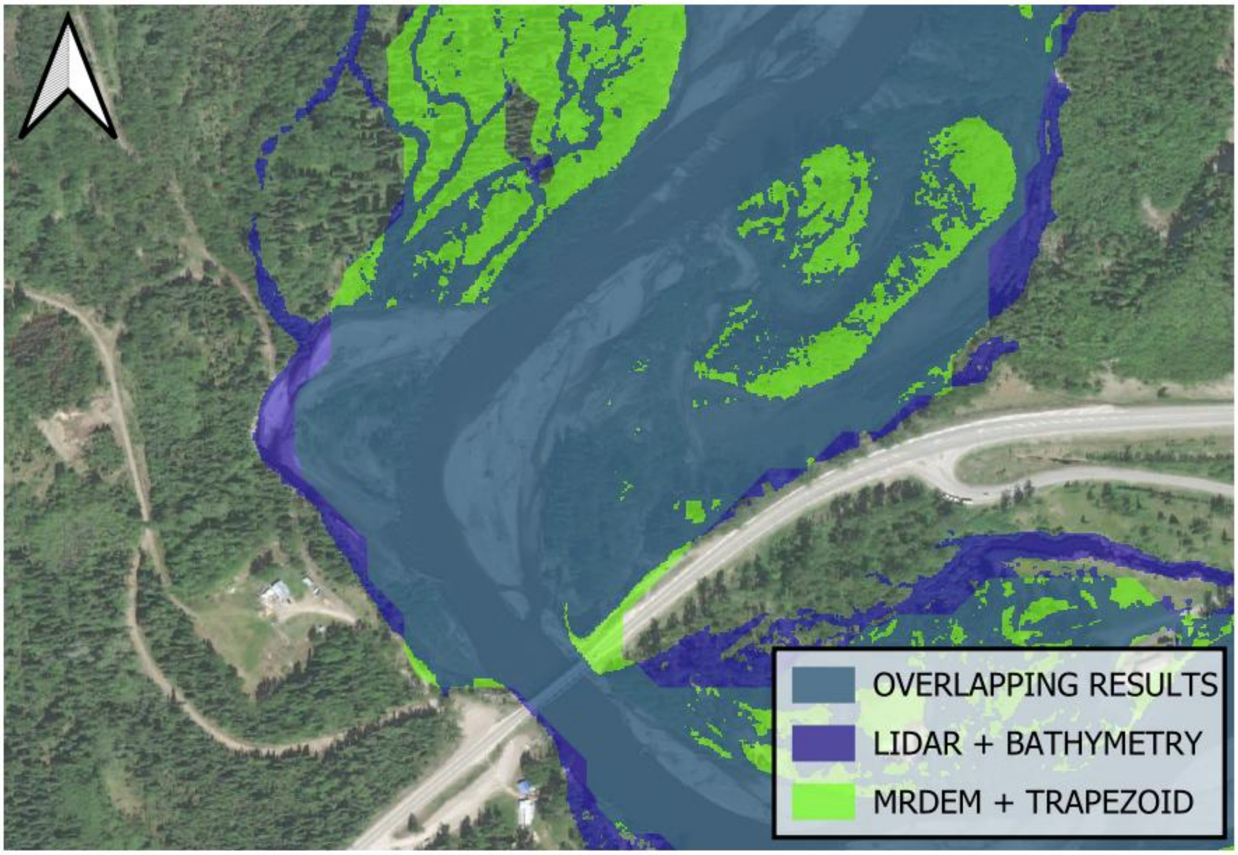

Figure 6-8: Area of interest along the Salmon River with Lidar DEM and Calculated Trapezoid Bathymetry

The average water level with the calculated trapezoid bathymetry and MRDEM was on average approximately 40 cm higher than the baseline model. Due to the nature of the 2D model, it was difficult to burn in a consistent trapezoid in HEC-RAS 2D that conveyed the appropriate flow. Additionally, the lack of resolution within the MRDEM led to higher channel inverts, higher water levels, and larger extents throughout the model when compared to baseline. For average velocity, the MRDEM with the trapezoid bathymetry is lower by an average of 0.4 m/s when compared to the baseline model. Overall, the addition of the trapezoid to the MRDEM had more similar results to the baseline model when compared to the pure MRDEM model, highlighting the importance of channel modifications when survey is not available.

6.2 MRDEM Only

6.2.1 Study Area 1: South River, Antigonish, NS

This scenario represents a situation where there is neither high resolution DEM or bathymetry data available, and hence only the nationally available DEM is used for modelling. The MRDEM has a 30m resolution, which is wider than the study river and many rivers in NS. This results in uncertainty of the thalweg, banks, and river bed variation of the river. Bridge structures were left in the model, as they may be available from record drawing information. Figure 6-9 shows the variation between 1m lidar (pink) and the MRDEM for a particular modeled cross section. The Figure shows how the MRDEM does not capture the river banks or cross-sectional channel, and that there are large differences in elevation. The MRDEM was not manipulated for this scenario, although, if certain elevation points were known, it is recommended that the MRDEM be adjusted to be more representative of those known point locations.

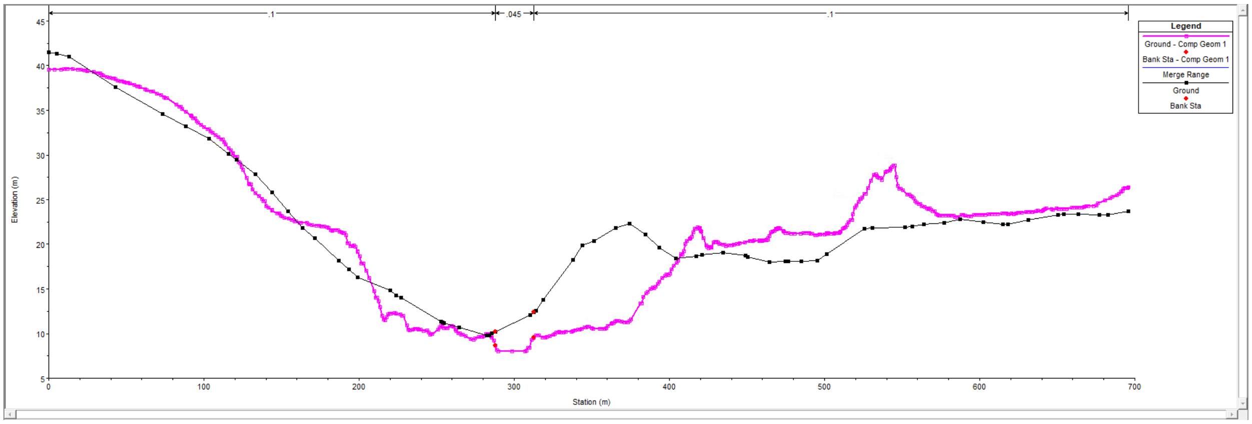

Figure 6-9: Difference between lidar (pink) and MRDEM (black) ground surface elevations

Figure 6-10 shows the difference in water level from changing the high resolution DEM survey to the MRDEM without bathymetry, and Figure 6-11 shows the change in velocity. This scenario resulted in the highest change in water levels and velocities, with a maximum water level change of 5.4m and maximum velocity change of 2.9 m/s.

The peak flood extents for this scenario exceeded those for both the baseline (Figure 6-12) and the MRDEM with modified bathymetry (surveyed and calculated). The location of the channel was also often skewed compared to the baseline model due to the lower resolution of the DEM, resulting in notably different flood extents.

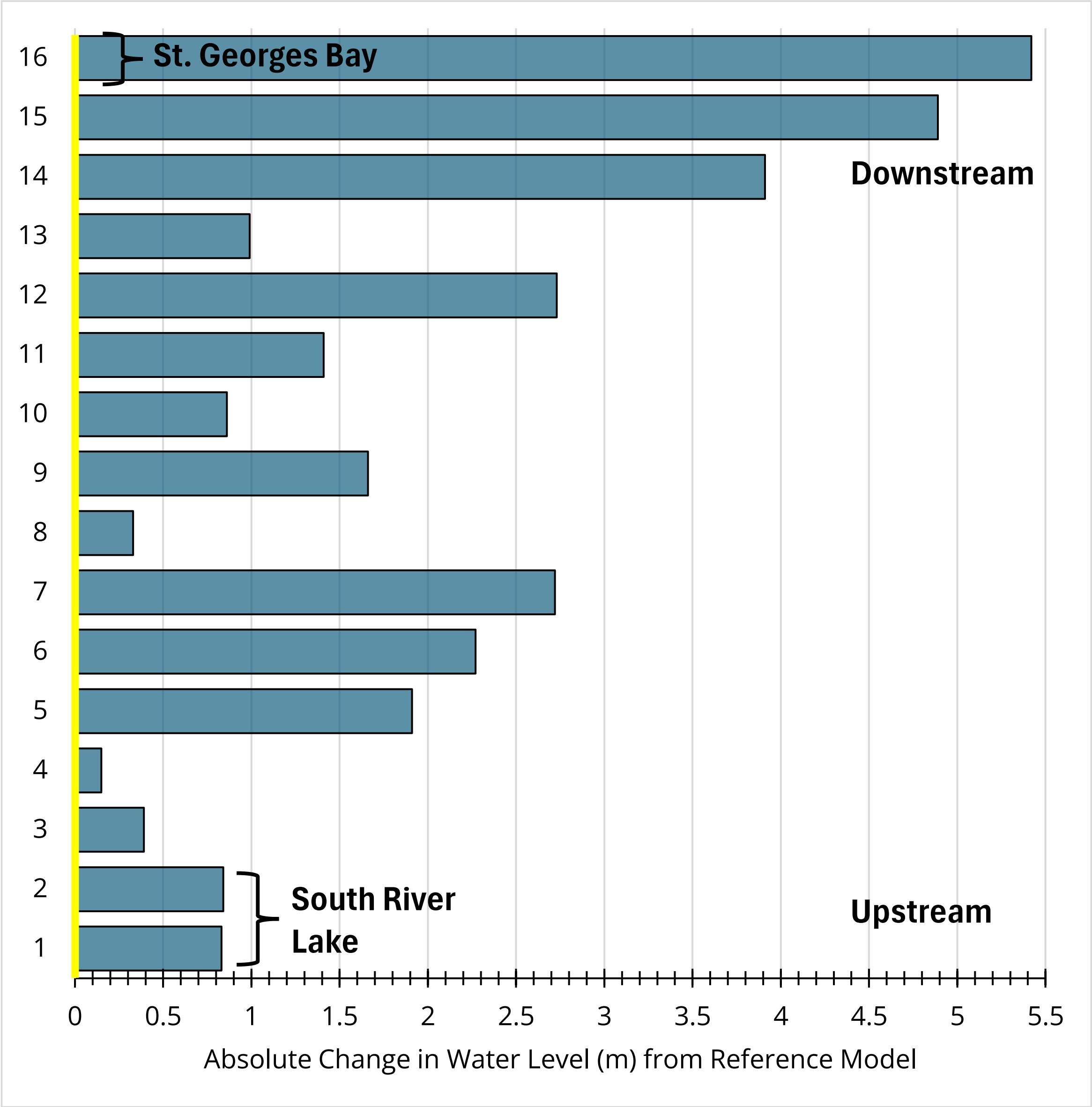

Figure 6-10: Removal of Channel Bathymetry and Adjusting DEM Resolution to 30m Testing Results showing change in WSEL

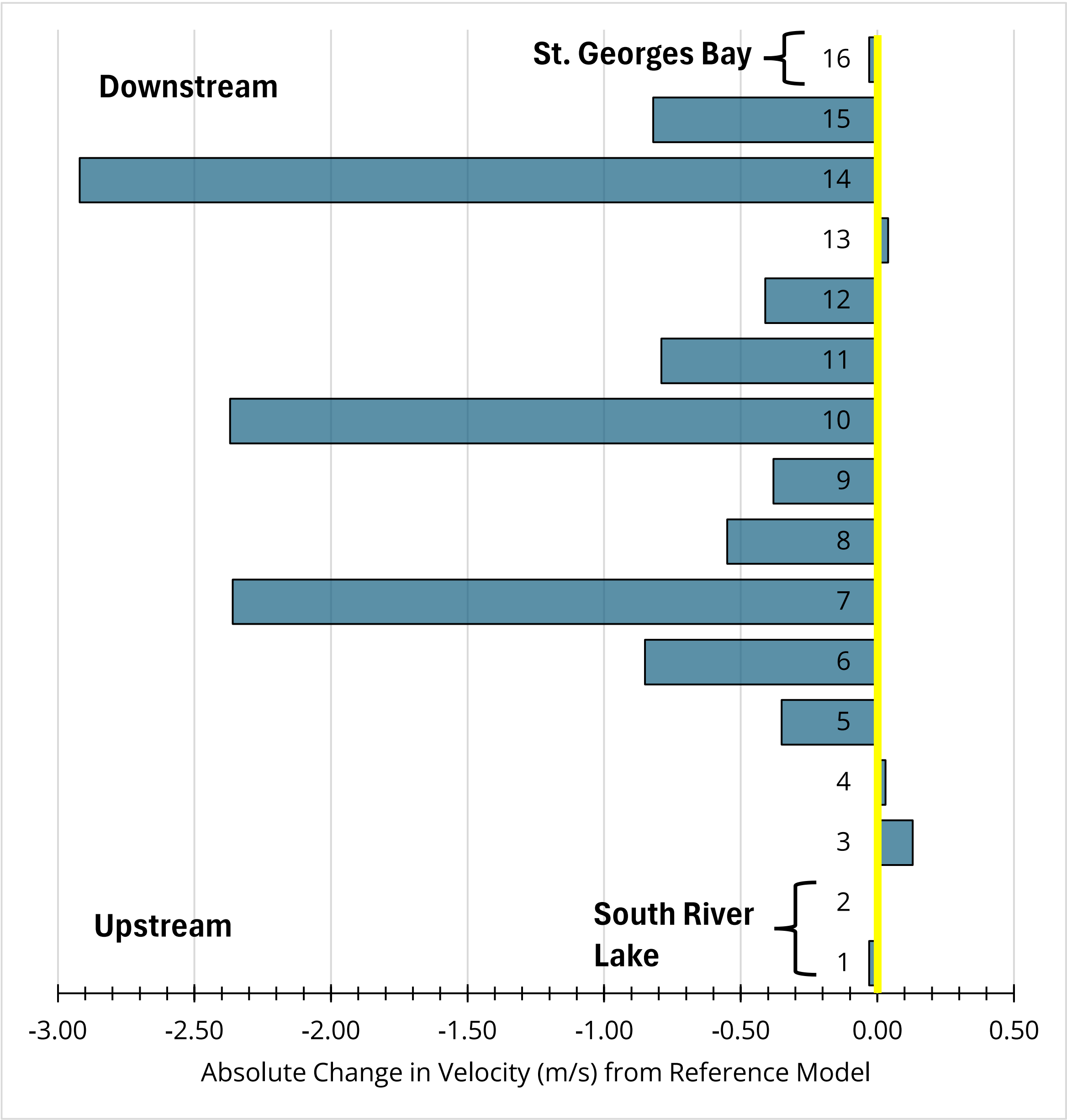

Figure 6-11: Removal of Channel Bathymetry and Adjusting DEM Resolution Testing Results showing change in Channel Velocity

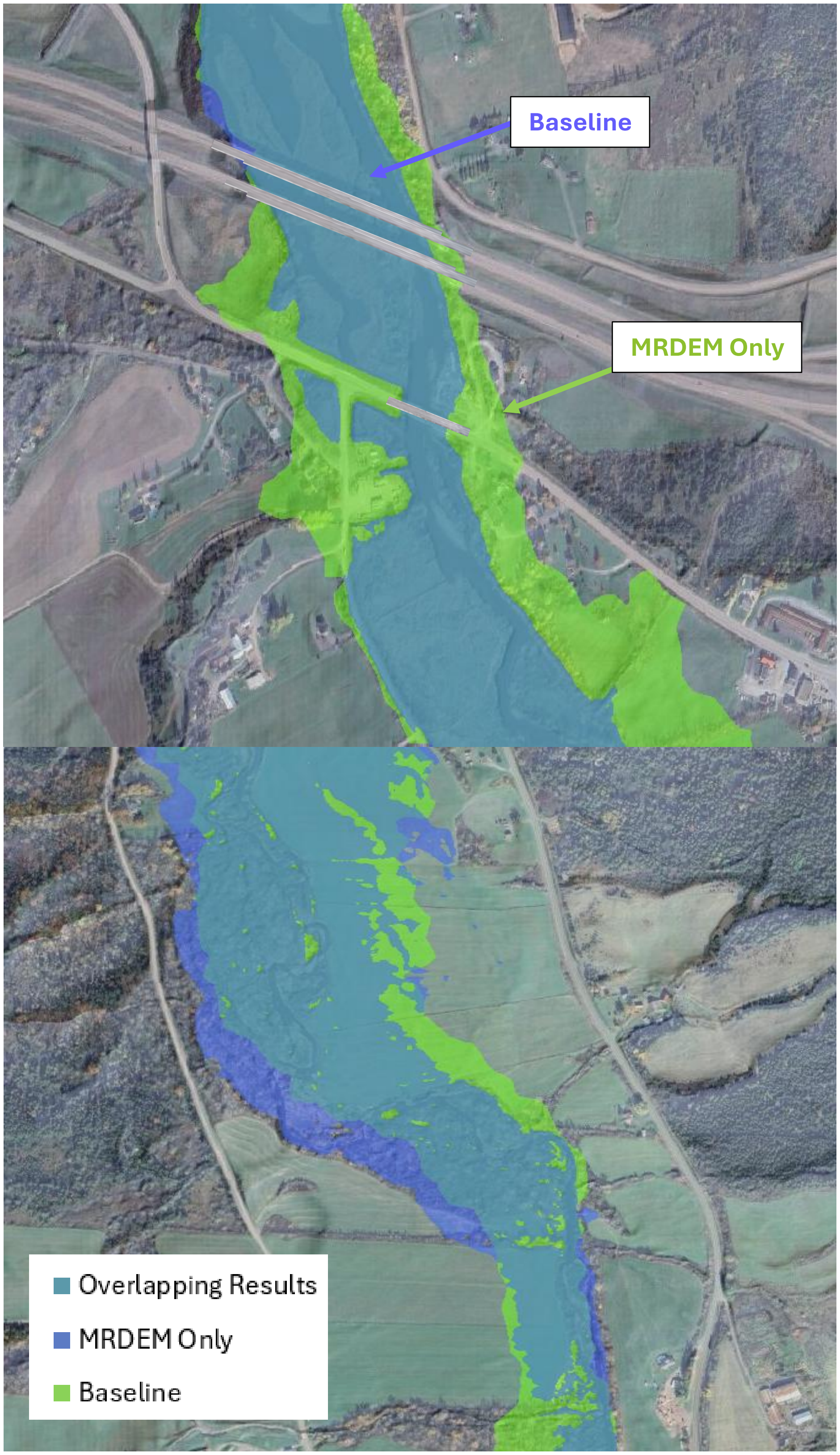

Figure 6-12: Flood extents for MRDEM Only vs Baseline

6.2.2 Study Area 2: Salmon River near Prince George, BC

As water level and flow data may not be available to conduct a calculation of a channel shape such as a trapezoid, the impact of using only the MRDEM was investigated with no bathymetry added, as shown in Figure 6-11.

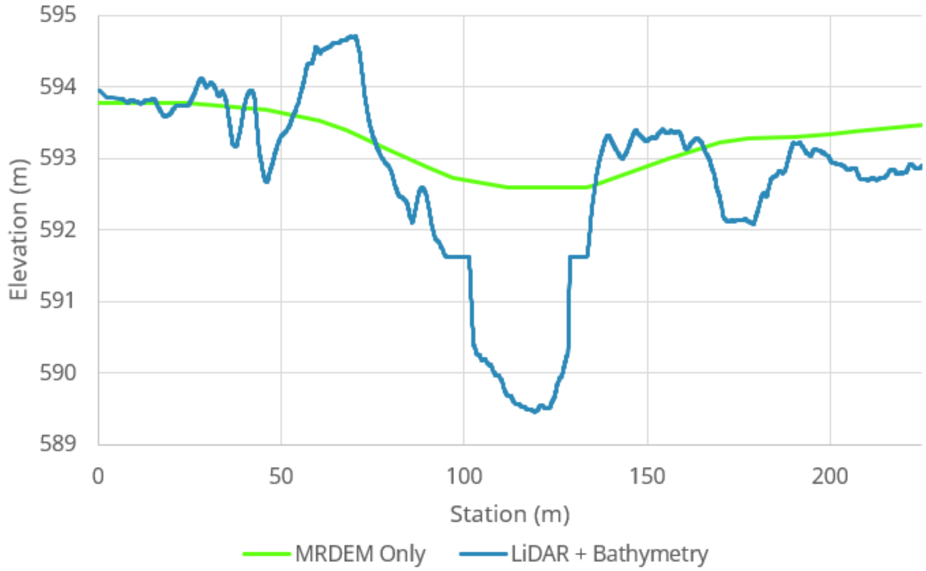

Figure 6-13: Sample Cross-Section along the Salmon River with MRDEM Only

Figure 6-14 and Figure 6-15 show the difference from the reference model in water surface elevations and velocities at corresponding sample cross-section locations for the MRDEM Only model runs. Additionally, Figure 6-16 and Figure 6-17 show the water surface extents at areas of interest along the Salmon River.

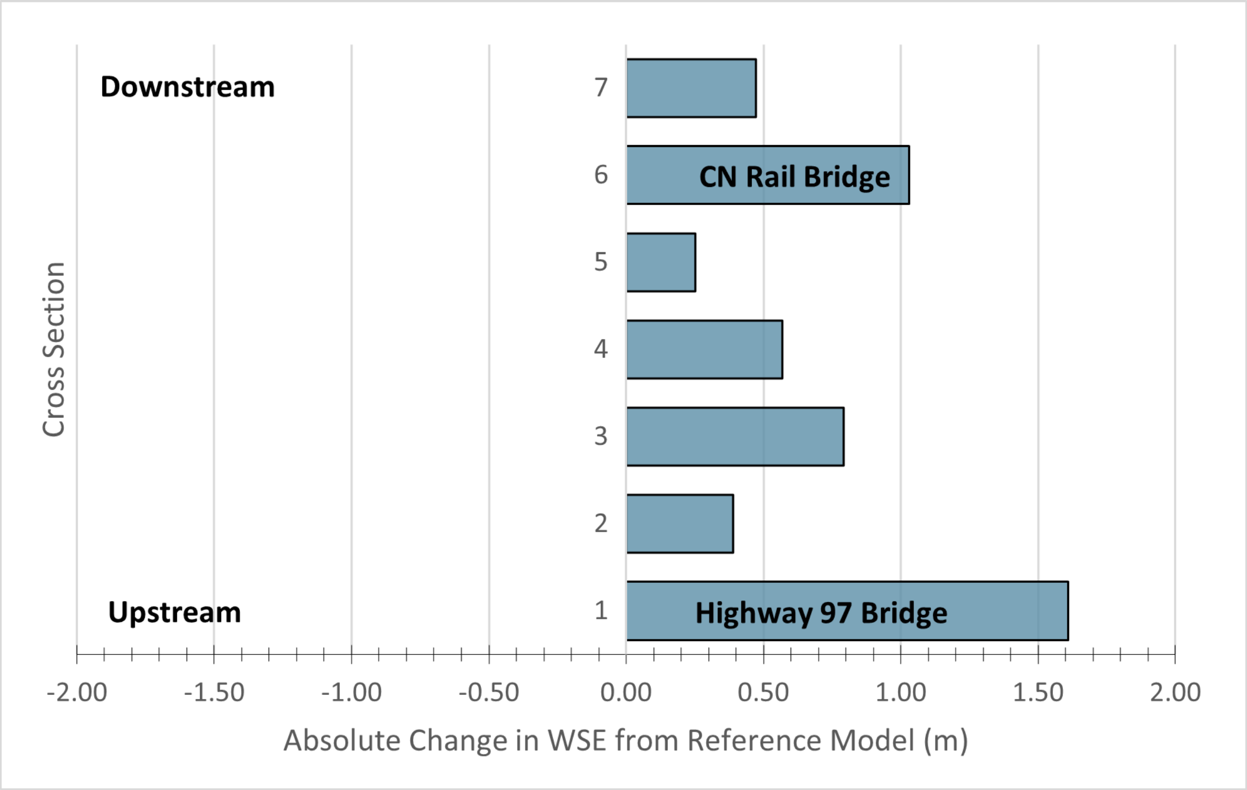

Figure 6-14: Impact of Using MRDEM Only on Water Surface Elevations at Sample Cross Sections along the Salmon River

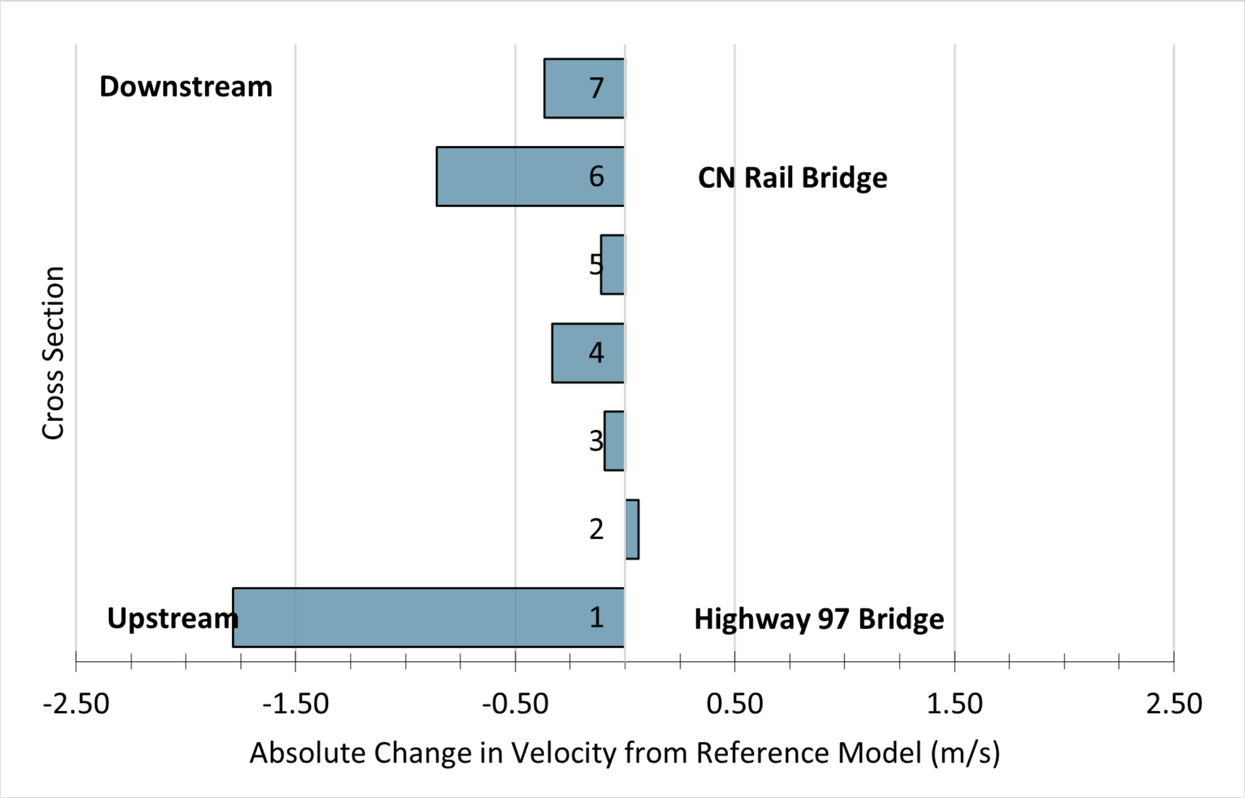

Figure 6-15: Impact of Using MRDEM Only on Velocities at Sample Cross Sections along the Salmon River

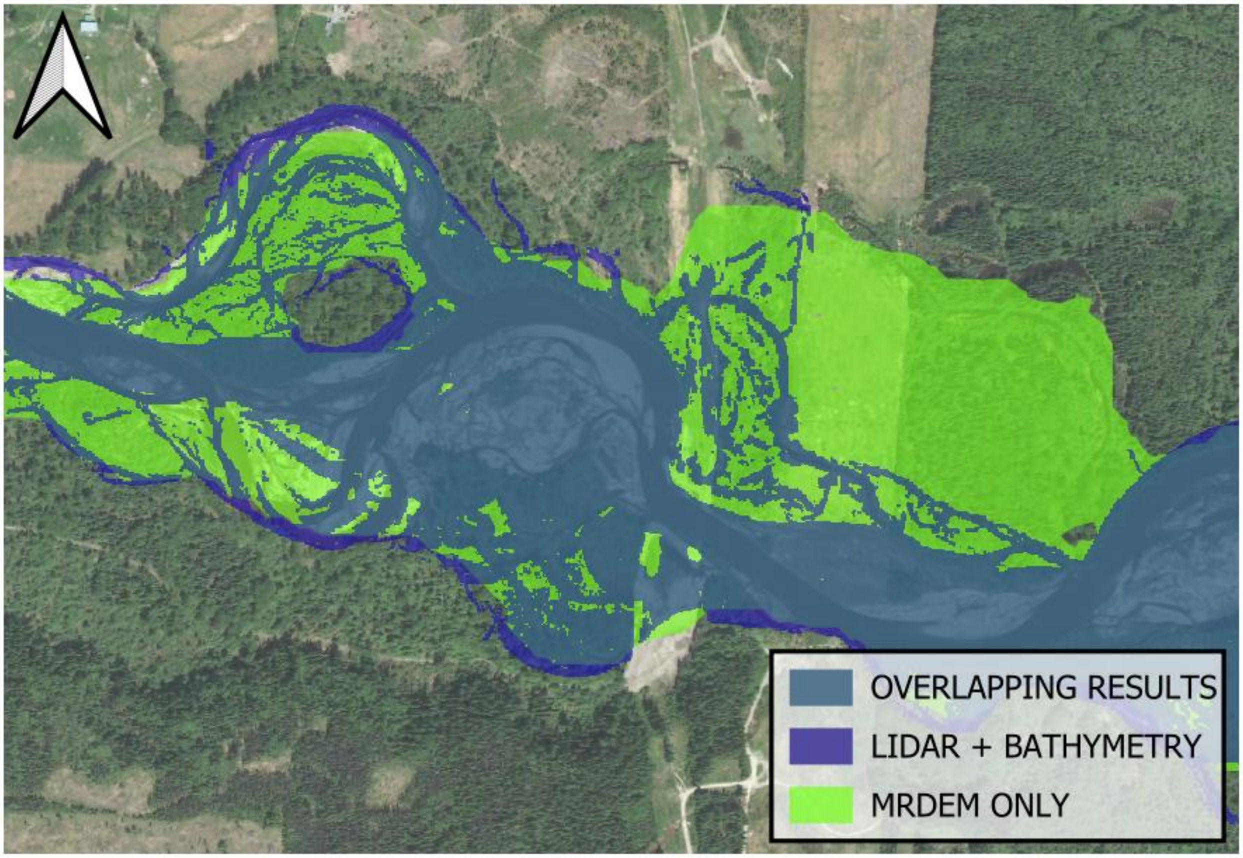

Figure 6-16: Area of interest along the Salmon River with MRDEM Only

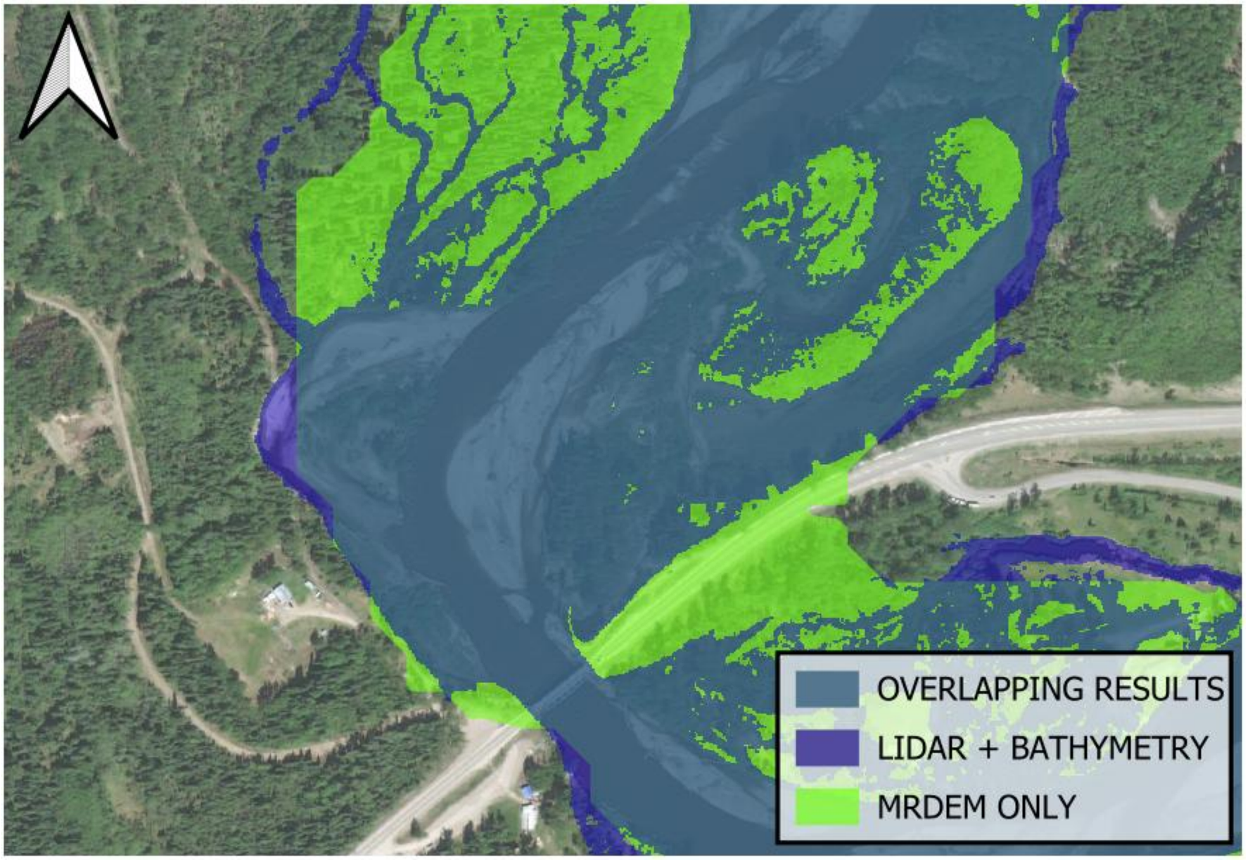

Figure 6-17: Area of interest along the Salmon River with MRDEM Only

The MRDEM Only model had an average increase in water level of approximately 70 cm. Larger differences of up to 1.6 m were observed at critical locations upstream of bridges. For average velocity, the model is lower by an average of 0.5 m/s when compared to the baseline model. Generally, the extent of the MRDEM Only model was significantly larger than the baseline model. Figure 6-13 highlights a case where the MRDEM model's coarse resolution failed to accurately represent the highway embankment, resulting in simulated overtopping that does not occur in the baseline model. The MRDEM is often conservative in extents and depth, but unpredictable due to the lack of detailed features (i.e. road embankments).

7 Summary of Results

This chapter summarizes the results of the sensitivity testing for both Study Area 1 and Study Area 2, and also presents a comparison between the two areas.

7.1 Study Area 1: South River, Antigonish, NS

Figures 7-1 and 7-2 show the average change in peak water level and velocity respectively for the entire watershed due to each change made to the baseline model. Changing the supporting DEM from the baseline of 1m lidar with survey throughout the entire river, to using the MRDEM only with no bathymetry, made for the largest difference in both water level (increase of 1.95m) and velocity (decrease of 0.71m/s). These values are significantly larger than all other scenarios, which emphasizes the importance of understanding the limitations of using the MRDEM on its own as a source of channel and floodplain topographic data.

Results of the tests conducted above show that there is a notable improvement in the accuracy of the floodline extents, water levels and velocities, when either a bathymetric survey or a calculated bathymetry channel is added to the MRDEM. In Study Area 1, the model results show that using the MRDEM with surveyed bathymetric data only slightly improves water level and velocity values compared to the results from the MRDEM with inferred channel bathymetric data, resulting in water levels 0.06m closer to baseline and velocity 0.01 m/s closer. Figure 7-1 below illustrates the differences between those scenarios.

A similar result was found when the supporting DEM was lidar data, where Study Area 1 testing found minimal difference between the results of surveyed and inferred bathymetry.

The results also showed that reducing the number of surveyed bathymetry points made a negligible difference to flood extents, water level and velocity. When bathymetric data was completely removed from the model, however, leaving only the lidar DEM, the change in peak water level from the baseline was higher than the change in the other lidar scenarios, but smaller than the change in the MRDEM scenarios.

Removing structures had little effect on flood extents, water levels and velocities for the modelled 1-in-100 year (1% AEP) and 1-in-500 year (0.2% AEP) events, however, local effects were observed in the model results of Study Area 1, increasing water levels by up to 0.17 m and velocity by 0.11 m/s in the 1-in-100 year (1% AEP) event, and increasing by 1.31 m and 0.5 m/s at the same bridge in the 1-in-500 year (0.2% AEP) event.

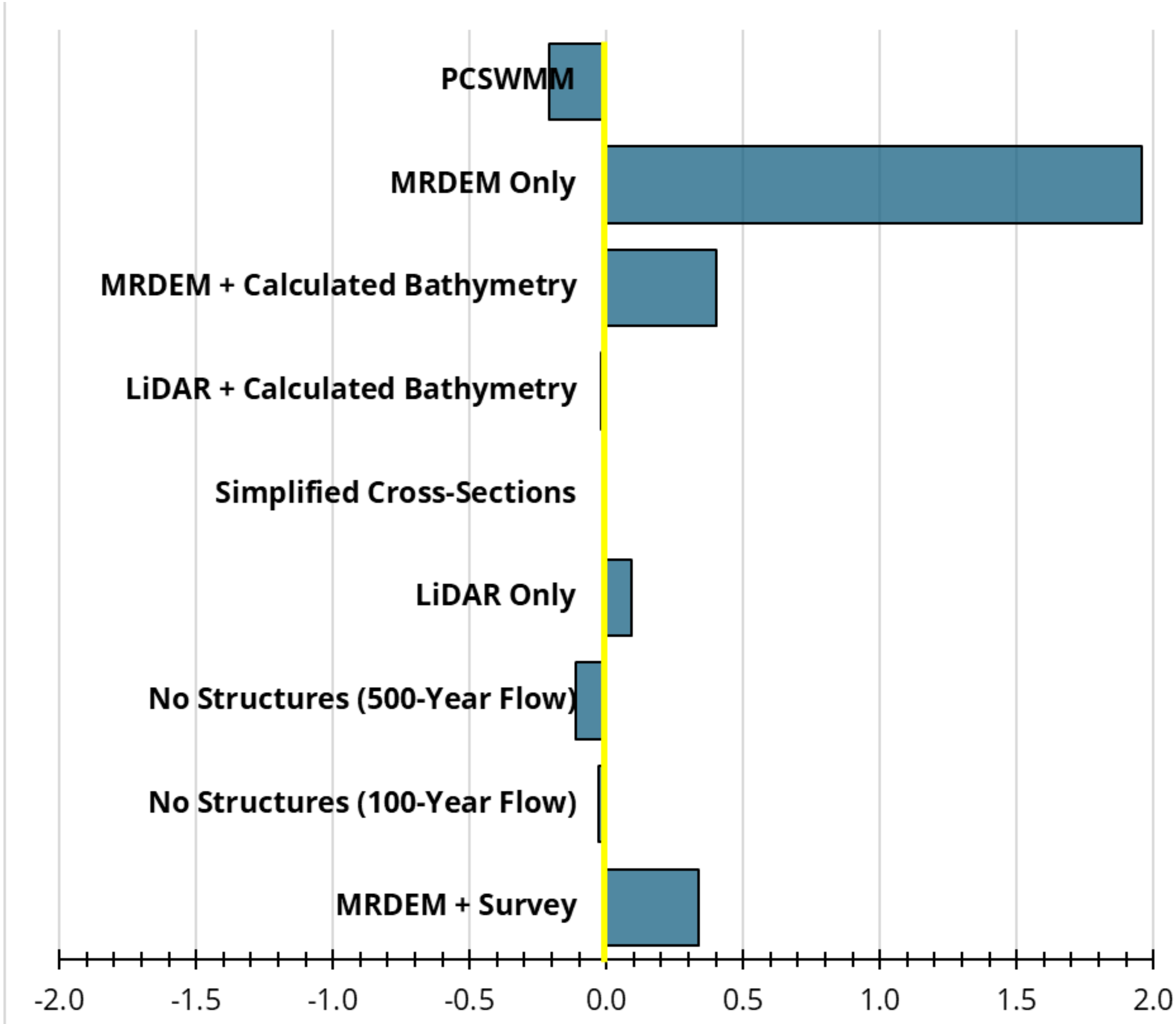

Figure 7-1: Summary of Average Changes to Peak Water Level (m)

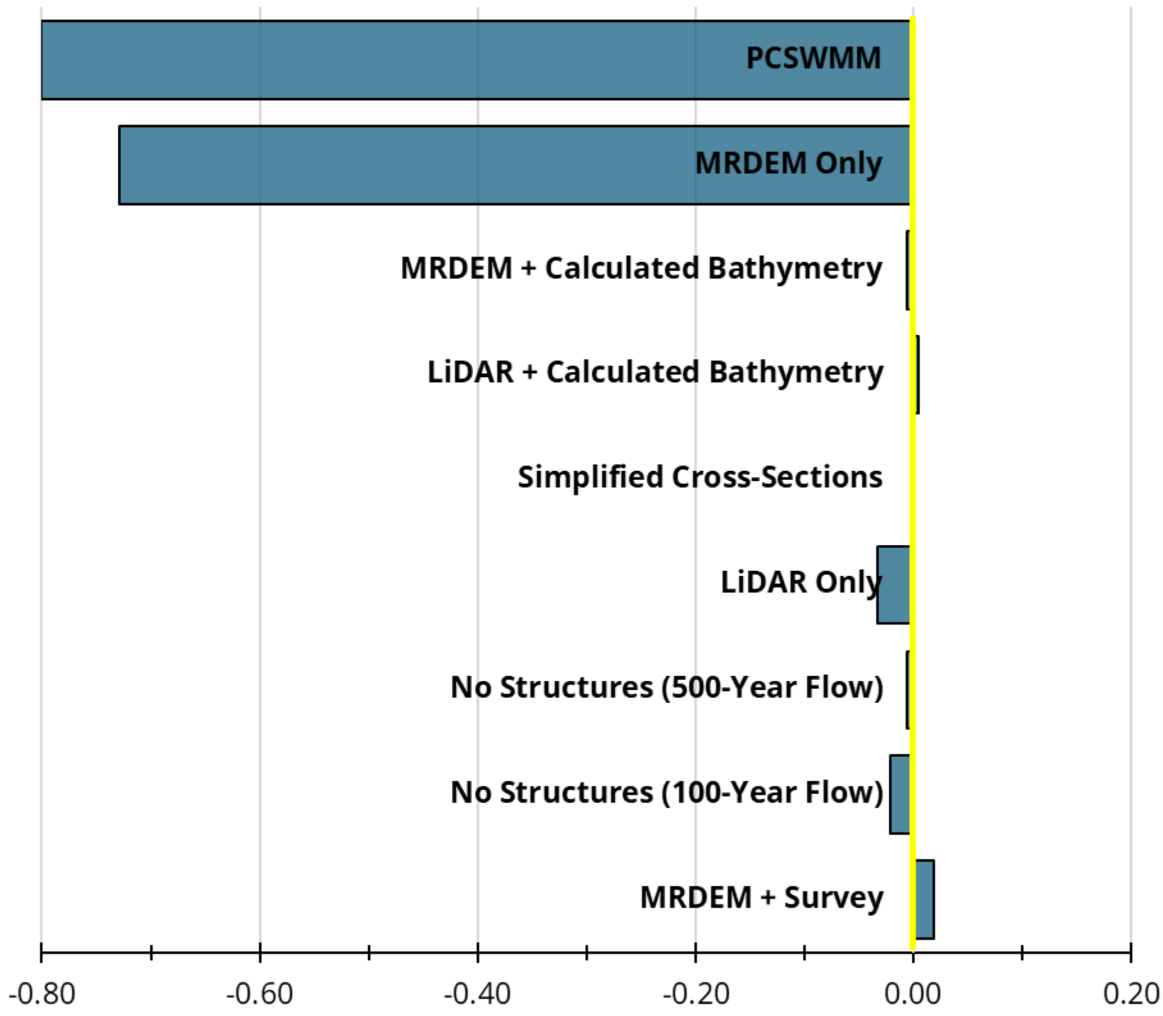

Figure 7-2: Summary of Average Changes to Channel Velocity (m/s)

7.2 Study Area 2: Salmon River near Prince George, BC

Figure 7-3 and Figure 7-4 show the average change in peak water level and average velocity at the sample cross-section along the Salmon River. The figures present a comparison between the baseline HEC-RAS 2D model and the results from various test scenarios, including simulations with MIKE+ 2D, removal of hydraulic structures, and modifications to the DEM and bathymetry. It should be noted that this figure provides an overall view of the magnitude of changes along the study area. It may not illustrate localized impacts such as at bridges. These results show that the use of the MRDEM Only (no added bathymetry data) showed the greatest overall impact to extents. Implementation of calculated trapezoidal channels, every test scenario utilizing the MRDEM, and the Lidar Only test scenario also show high magnitude impacts over the study area. It should be noted that all of these scenarios had larger differences upstream of bridges, further highlighting the importance of attention to detail at critical flow locations, such as hydraulic structures.

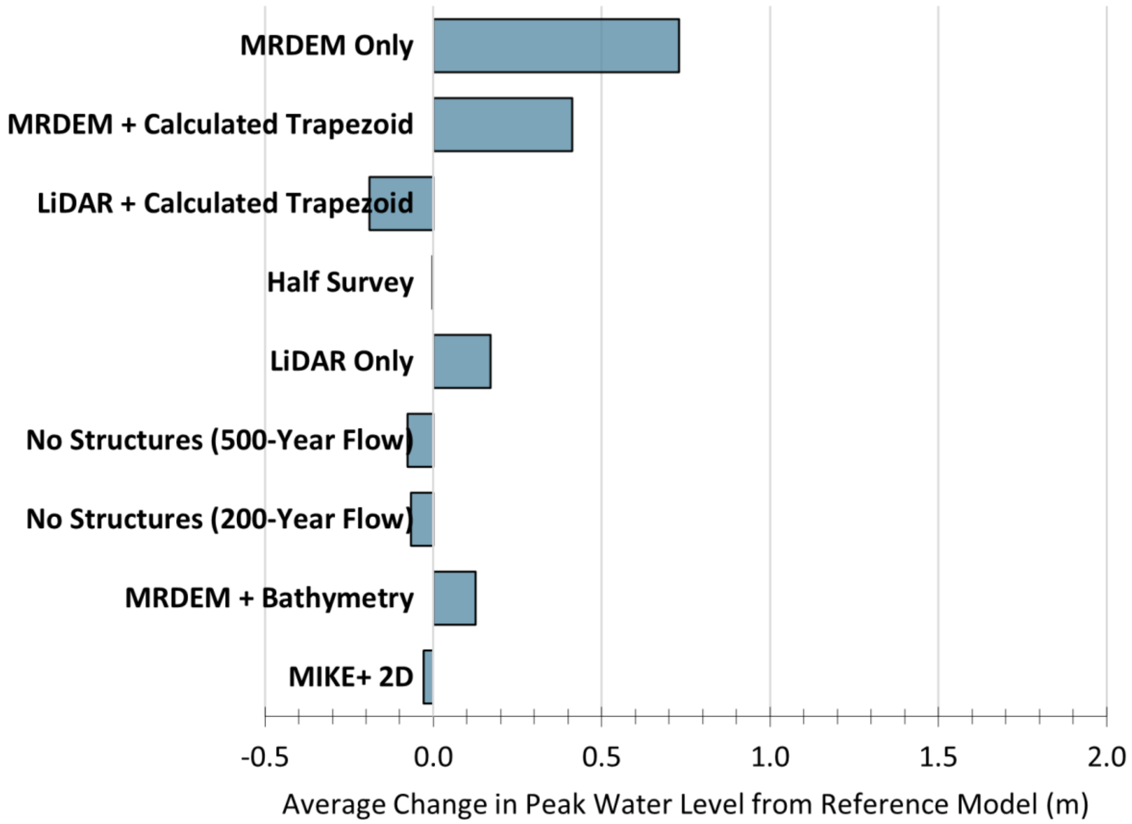

Figure 7-3: Summary of Average Changes to Peak Water Levels along the Salmon River

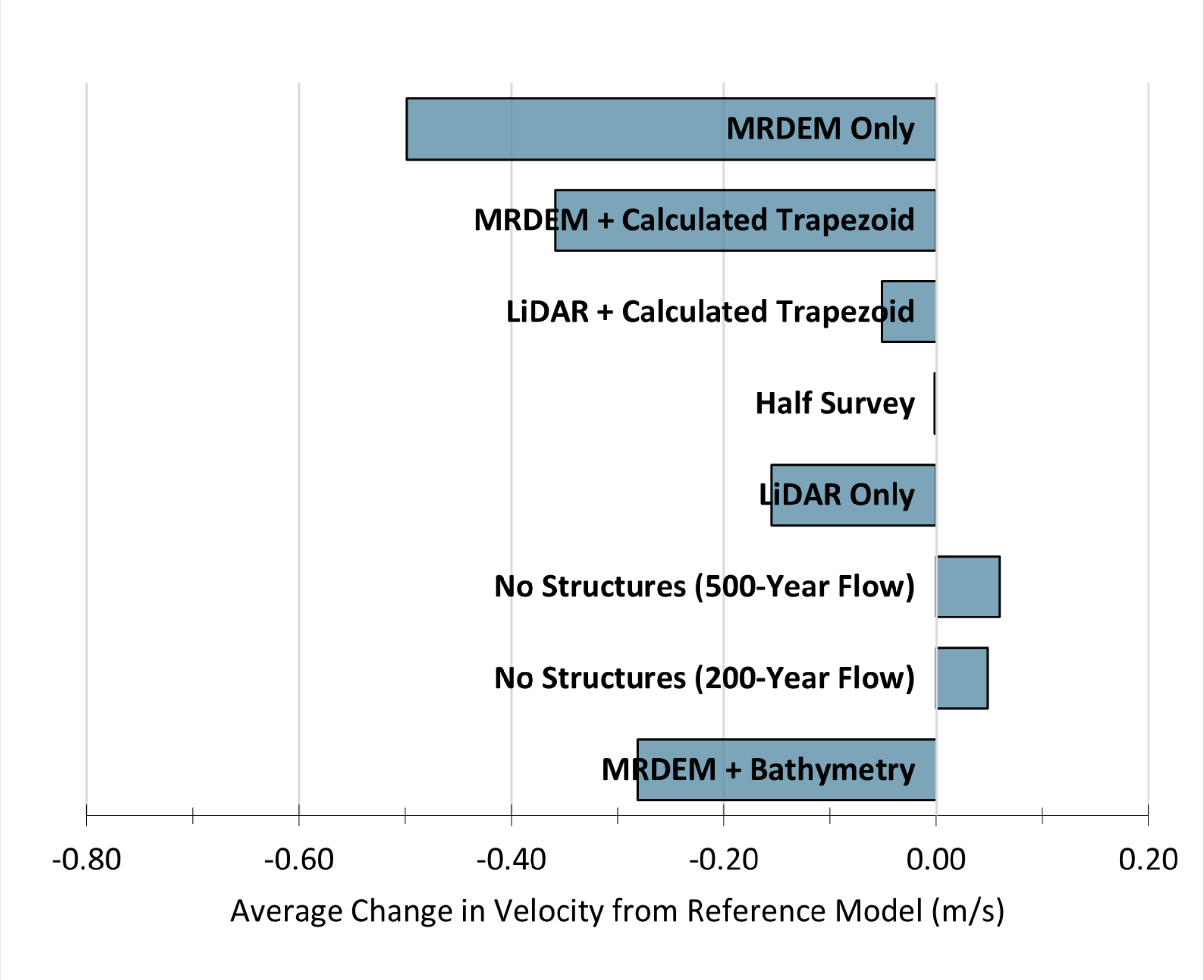

Figure 7-4: Summary of Average Changes to Channel Velocity along the Salmon River

The largest difference was caused by the MRDEM Only scenario, which on average had higher water levels of 0.73 m when compared to the baseline model with high resolution DEM and bathymetry. As this value is much higher than the rest of the test parameters, it signifies the importance of caution when using the low-resolution MRDEM. The addition of the calculated trapezoid with the MRDEM reduced water levels but still resulted in an average of 0.41 m higher water levels than the baseline model. Conversely, the calculated trapezoid with the lidar DEM resulted in lower water levels than the baseline model (-0.19 m). While this suggests that simulated channel geometries can be useful for modelling, achieving consistent implementation of the simulated channel in HEC-RAS 2D was challenging. It should be noted that only one type of simulated channel geometry was explored.

Several issues were identified during the use of the MRDEM. The MRDEM uses a projection designed for national-scale coverage, which can cause local distortions. In Study Area 2, this resulted in an offset of about 50 m in both X and Y directions when compared to the high-resolution lidar DEM. To resolve this, we applied a horizontal shift to align the MRDEM with the lidar and bathymetry datasets. Additionally, HEC-RAS exported the raster results from the MRDEM scenarios in a 30 x 30 m grid. This is not how the results are displayed in HEC-RAS, due to their visualization processes which include a dynamic map that interpolates the terrain and results based on level of zoom. If a part of the cell has water in it, the entire cell is shaded in the exported raster. The "Inundation Boundary Polygon Export" seems to be the best way to export the inundation boundary, as shown in Figure 7-5.

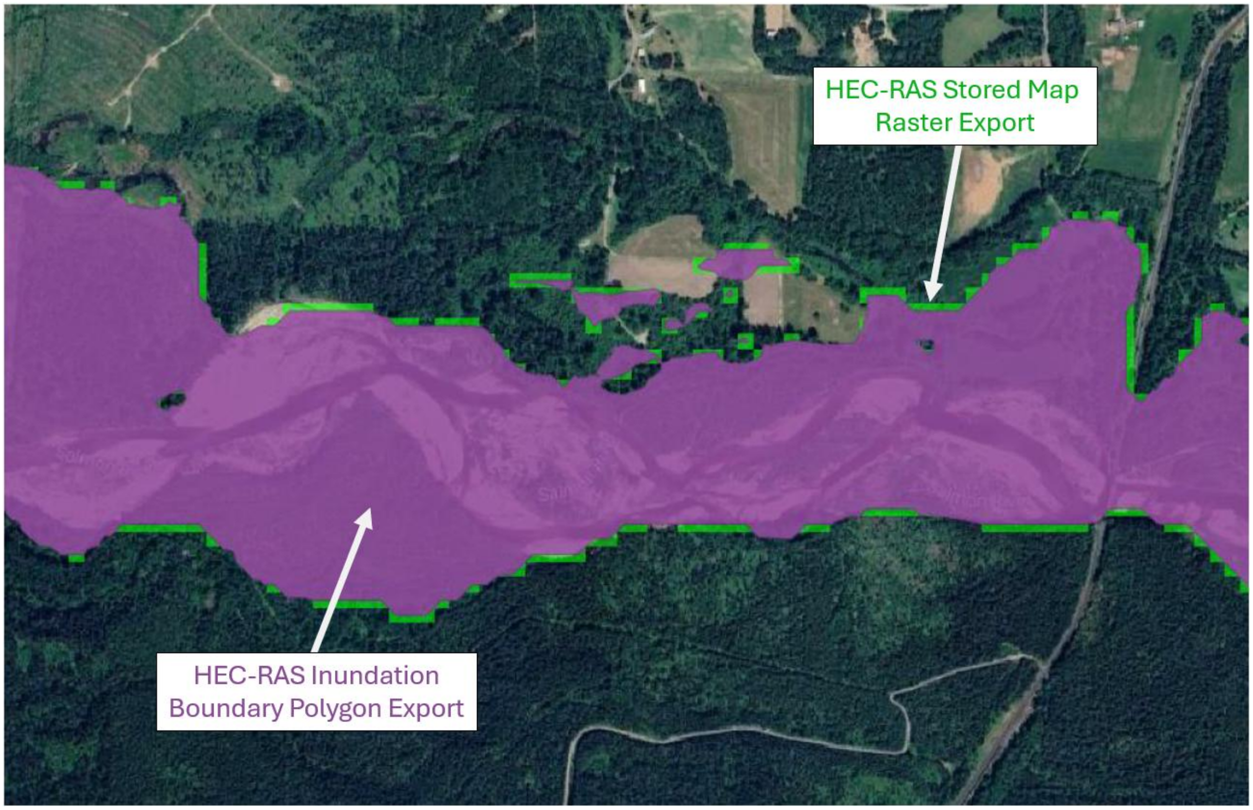

Figure 7-5: HEC-RAS Inundation Boundary Polygon Export versus Stored Raster Export

The largest issue found with the MRDEM was that important terrain features are missed. As shown in Figure 7-6, the railway bridge that was accurately described in the high resolution lidar DEM was almost completely missed in the MRDEM. The largest difference in terrain elevation between the two scenarios is approximately 5 meters, highlighting the need for attentiveness when using the MRDEM, particularly in areas with distinct features such as roads and channels. Guidance associated with limited data availability for practitioners is further discussed in Section 8.2.

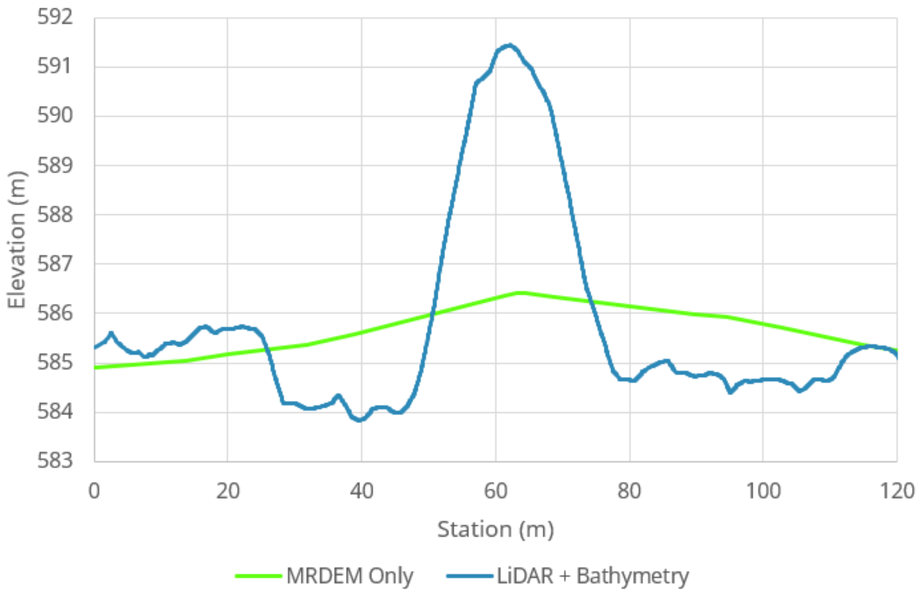

Figure 7-6: Sample MRDEM Lack of Detail at Railway Bridge

7.3 Study Area Comparison

Study Areas 1 and 2 are vastly different in climate, river type and length, watershed area, slope and topography, and land cover. It is important to compare the results from each watershed in order to understand the differences and similarities in results at each case study location.

Testing bathymetry sources in Study Area 1 revealed that results from using a calculated bathymetry are very similar to those from using surveyed bathymetry data, and that adding bathymetry of any kind improved results overall. This may be due to the un-braided nature of the river, and consistency of the river bathymetry shape throughout the watershed. For Study Area 2, the calculated bathymetry results were less similar to the results from using surveyed bathymetry. This may be related to the fact that deep braided channels will all be active during flood events, and that the simplified approach of deepening one of the river channels may not be hydraulically representative. This was especially notable when applied to the lidar DEM, with a limited effectiveness of the approach. However, incorporating the calculated bathymetry into the MRDEM showed greater improvement in the model results compared to using the MRDEM alone. This put into perspective the significant challenge of implementing a consistent, calculated bathymetry in HEC-RAS 2D. Although overall results from both study areas were similar, more challenges arose when using calculated bathymetry on the 2D model of the braided morphology of the Salmon River.

Simplifying the survey by reducing the number of surveyed points (along cross-sections) by half in Study Area 1 had negligible impacts on flood extents. This could be due to the relative size of the cross-sections in the river and density of the original survey data. Study Area 2 also showed overall negligible differences resulting from the reduction in survey points. However, localized variations in water levels and inundation extents were observed near bridges, highlighting the importance of detailed survey at these locations. The region of study had little impact on density of survey points needed for modelling. It is however recognized that several provinces have specific guidelines for number of survey points per cross-section in flood mapping projects, and this number will depend on size of the river, budget constraints, and detail level of the study.

Removing nine structures on the river in Study Area 1 indicated only localized effects on water level and velocity for both the 1-in-100 year (1% AEP) and 1-in-500 year (0.2% AEP) design storms. Study Area 2 demonstrated a similar pattern in the results when removing the two structures on the river. Unlike bridges in Study Area 1, low chords for the bridge girders in Study Area 2 were typically at a much higher elevation than even the 1-in-500 year (0.2% AEP) design flood water levels due to the topography of the region. This reduced the difference to flood lines when structures are removed from the model. In Study Area 1, there is typically less freeboard than bridges in Study Area 2, making the effect of removing structures in the model more impactful, particularly for storm events larger than the design event of the bridge.

Removing the structures in Study Area 2 still influenced the results because of differences between 2D and 1D calculations at the bridge and the loss of pier modelling at the CN Rail Bridge. (Bridges in HEC-RAS 2D are modelled as SA/2D Area Connections where HEC-RAS uses the input data to develop 1D rating curves for the bridge.) We believe this difference is in part due to variations in Manning's roughness coefficients used in the 2D versus 1D hydraulic modelling. While 1D roughness coefficients must include energy losses due to bedform complexity not captured in the simplified 1D cross sections, 2D modelling describes much of this bedform complexity directly. Typically, the more complex the channel bedform, the greater the difference between 1D and 2D roughness coefficients. Braided rivers have highly complex bedforms, so selecting an appropriate Manning's roughness coefficient is essential to accurately represent the area. The difference in the Manning's roughness coefficient between 1D and 2D is further discussed in the Guide to Bridge Hydraulics, Third Edition (Transportation Association of Canada, 2025).

Study Area 1 and Study Area 2 results indicated that the scenario using only the MRDEM (no bathymetry data) yielded the greatest difference in results from the baseline model. The MRDEM was not corrected for positioning or elevation in Study Area 1, however, it was corrected in Study Area 2. As a result, in Study Area 1, this change might have slightly affected the positioning of the thalweg of the river, shifting the floodlines, which was not the case in Study Area 2. Also, in Study Area 2, since the topography encompasses more extreme valleys and mountains, the MRDEM may have exhibited more evident dampening of sharp features, leading to further misrepresentation of flooding extents. Professional judgment is needed to assess whether correcting the MRDEM will significantly improve the results and whether that level of accuracy is necessary for a specific project area.

8 Recommendations

Based on the results from the above testing scenarios in two significantly different watersheds, recommendations are presented on best practices on model selection and flood mapping for various scenarios of data availability.

8.1 Guidance Associated with Modelling Software Selection

The testing conducted in the previous sections compared modelling results obtained with software that is typically considered similar, both in a 1D setting and a 2D setting.

1D Setting

The testing compared two commonly used 1D software for hydraulic modelling and floodplain mapping: HEC-RAS 1D and PCSWMM 1D. The two software both derive river channel bathymetry and floodplain geometry from cross-sections through the river and floodplain areas (whether obtained through topographic survey, pre-existing DEM or otherwise). A summary of differences in model setup and characteristics is presented below in Table 8-1.

They differ in how the channel between the cross-sections is modelled, in that one software gradually adjusts the channel shape (and conveyance capacity) between cross-sections, while the other maintains a fixed channel shape (and conveyance capacity) with sharp transitions at cross-section changes. One software used dynamic (unsteady) routing, which allowed changes in flow, velocity and water buildup over time, while the other used steady-state routing, which assumes constant values for those aspects through the simulation. Hydraulic parameters such as surface roughness are interpreted slightly differently in both software which would also be a source of expected differences in results between the two approaches. While SWMM uses an area-weighted composite Manning's N value for the overall channel roughness, HEC-RAS uses a conveyance-weighted composite Manning's N value, which can result in a slightly lower average value, and hence result in slightly lower water levels. Finally, it is noted that when the software was changed, the flow inputs were kept the same, but the model was not calibrated again for water depth results, with the same channel and floodplain surface roughness values used.

Table 8-1: Software setup and characteristics used in the comparison

Characteristic	SWMM	HEC-RAS
Channel Geometry	Fixed geometry along length of conduit; sharp transitions	Gradually adapting geometry to match next cross-section shape
Routing	Dynamic	Steady-State
Composite Manning's N	Area Weighted	Conveyance Weighted
Calibration	Flows were not re-calibrated	Calibrated flows

While the results found a slight increase in water levels with the use of the SWMM model (with fixed cross-sections and dynamic routing), results were generally consistent. It is unclear how any differences can be attributed to specific modelling aspects, and it is considered that since those difference were found to be minor, no advantage is found between the two 1D modelling approaches. It is also noted that the flows input into the HEC-RAS steady-state model were obtained from the output of SWMM, an unsteady hydrologic and hydraulic model, which is expected to have yielded more consistent flows and water levels between the two approaches as a result. Generating flows from a purely hydrologic model (e.g. HEC-HMS) for direct input into a steady state model risks overlooking the impact of bridge constrictions on the flows, which would have further impacts on flows and water levels.

It is expected that the selection of the software for hydraulic modelling in 1D, provided that it is an industry-recognized and proven software, need not be the primary focus of a hydraulic routing and floodplain mapping exercise, as a suitable model calibration should allow the production of representative results.

In terms of ease of setup, model assembly and preparation of flood maps, this can be a consideration that is worth noting. In order to make the fixed cross-section model better adapt to the changing shape of the channel bed and floodplain, as well as to provide more data points for flood mapping, a significantly larger number of cross-sections was used in the SWMM model compared to the HEC-RAS model. This results in a notably larger level of effort to create the cross-sections, assign their hydraulic parameters and then to extract the results for flood mapping.

2D Setting

The testing in the British Columbia study compared two commonly used 2D software for hydraulic modelling and floodplain mapping: HEC-RAS 2D and MIKE+ 2D. Both software have similar inputs such as topography, boundary conditions, and surface roughness. The boundary condition and terrain inputs were consistent between the models. They also both include a mesh-based approach that calculates flow between cells. However, HEC-RAS 2D utilizes an implicit mesh design to determine horizontally varying water surface characteristics such as elevation and velocity based on underlying terrain at a sub-mesh level of detail. MIKE+ 2D utilizes an explicit mesh system and does not capture terrain detail at a sub-mesh scale. Due to the nature of the explicit mesh system, the development of the triangular flexible mesh in MIKE+ 2D required more intentional engineer-led review of surface terrain and engineering expertise-led identification of secondary channels with significant hydraulic conveyance.

Both the MIKE+ 2D model and the original HEC-RAS 2D model were calibrated using the same 2022 calibration event and utilized each software's higher order numerical solution. Results of the MIKE+ 2D calibration yielded channel roughness values 10% lower than in the original HEC-RAS 2D model. Although the original HEC-RAS 2D model was calibrated using the same event, the resulting roughness values did not yield consistent results when applied in MIKE+ 2D.

Although the MIKE+ 2D results showed both increased and decreased water levels and extents in certain areas, the overall results were very similar to HEC-RAS 2D. It is assumed that much of the difference is the result of using an explicit mesh instead of an implicit mesh. First, the implicit mesh does not preserve the 0.3 m (channel) to 1.0 m (lidar) DEM surface details within each mesh cell in the same way as the implicit HEC-RAS 2D. To do so the MIKE+ 2D model would require a prohibitively large number of discrete cells (i.e. a mesh cell width of 0.3 m in the main channel and 1.0 m over the remainder of the flood plain for this particular DEM). As the MIKE+ 2D cells are larger than these values, they do not capture as much bedform detail as the HEC-RAS 2D cells. The larger MIKE+ 2D cells may lose detail (i.e. additional hydraulic conveyance) in the dozens of secondary and tertiary side channels within the Salmon River when compared to HEC-RAS 2D. We posit that in other locations or at different cell densities, a MIKE+ 2D model may require a higher Manning's roughness than in HEC-RAS 2D to compensate for the lack of sub-cell bedform roughness in the model or due to differences in selection of numerical solutions or approaches within the two software packages. As discussed in Section 3.2, there may be some advantage to using an implicit mesh approach in river reaches with braided channels and other bedform and flow complexities to improve model accuracy while minimizing iterative model refinement.

The difference in calibrated Manning's roughness values underscores the importance of model-specific calibration. Even if roughness parameters are calibrated in another model software, they may not be directly transferable or suitable for use with all software.

For ease of setup, HEC-RAS 2D appeared to offer a more user-friendly interface for model development and calibration. The HEC-RAS 2D interface also allowed for rapid terrain editing and modification, which is pertinent for the limited data analysis discussed in Section 8.2, below.

Generally, however, it is expected that the selection of the software for hydraulic modelling in 2D, provided that it is an industry-recognized and proven software, need not be the primary focus of a hydraulic routing and floodplain mapping exercise, as a suitable model calibration should allow the production of representative results.

8.2 Guidance Associated with Limited Data Availability

8.2.1 If the MRDEM is the only DEM available, or is the highest resolution available, but river bathymetry can be surveyed

In this case, the second set of tests conducted (details presented in Section 4.1.1 and 4.1.2 above) offers valuable information. This involved replacing the lidar DEM (1m resolution) with the NRCan MRDEM (30m resolution), while keeping the surveyed bathymetry data. This would occur in areas where access and budgets permit surveying activities, but more detailed DEM data is not available, and obtaining lidar data is not feasible.

In the 1D model, findings from this test showed that in general, the resolution of the results, as expected, was greatly decreased. From an overall perspective, it was found that water levels were raised, but flood extents were not necessarily increased as well, since the MRDEM is also at a somewhat higher elevation (given that low elevation features in the river channels and valleys are averaged with higher elevation banks and slopes). The overall MRDEM surface in the BC study area was shifted horizontally by 50m to better match the lidar surface at local features. However, the thalweg location still did not match the actual thalweg location in many locations. Introducing a high resolution (from the survey) bathymetry introduced unexpected artifices, such as making the floodlines disappear (where the water would be entirely contained in the surveyed channel and be at a lower elevation than the MRDEM), or showing flooding in two apparent rivers, where there is only one actual river.

In the broader context, however, the floodlines were still generally similar to the original high-resolution results. This means that while there is a fair degree of uncertainty introduced with the use of the MRDEM, the resulting floodlines still have some value. If a floodplain horizontal extent uncertainty is acceptable, then the MRDEM may be a suitable basis for preparing floodlines. It may also be reasonable to extend the field campaign to include some salient floodplain features such as elevations of embankments, bridges, roadways and other hydraulically-relevant features, which would in this case significantly improve the accuracy of the floodplain extent results. Naturally, if the cost of this is the same or higher than the cost of obtaining lidar data, lidar data would be preferred since it captures a lot of the ground's varying topographic details.

In the case of a 1D model, an extended survey effort may produce a sufficiently representative river and floodplain topography to reduce or eliminate the need for an MRDEM. In a 1D setting, the level of effort to collect additional floodplain data is only marginally higher than collecting data solely for a bathymetric survey, which would make it advantageous. The modelling would then rely mostly on the surveyed cross-sectional data, and the mapping would be at the correct extents at the cross-section locations, and, if needed, be informed by the MRDEM between the cross-sections (where some manual adjustments would likely be necessary).

In a 2D setting, while the MRDEM is less detailed than higher resolution DEM, modifications can be made to add some of the necessary detail for flood mapping and increase accuracy in analysis. A 2D model represents the whole floodplain surface, so every land feature in the floodplain (major or minor) is to be represented. In this case, the proposed steps to implement the use of an MRDEM in Flood Mapping are as follows:

1. Confirm the MRDEM projection and coordinates within the study of area of interest. If necessary, adjust the MRDEM coordinates with a local adjustment to the latitude, longitude or both. We recommend that the practitioner review georeferenced aerial photography, local survey or local municipal GIS layers and confirm or adjust the local projection based on terrain features visible in both the locally georeferenced information and the MRDEM. These supplemental sources should be as recent as possible to improve model accuracy.

2. Confirm the MRDEM vertical elevation to match open, relatively flat terrain in areas important to the community. If necessary, adjust the MRDEM with a global vertical conversion to improve the overall accuracy of the MRDEM terrain in the study area of interest. It is important that this completed in a relatively flat, featureless area as it is difficult to compare the MRDEM in areas with rapid changes in terrain due to the coarseness of the data set.

3. Collect field survey at critical infrastructure that bisects or impinges upon the floodplain or river system, especially any road or infrastructure that bisects the floodplain and any hydraulic structures on the river, such as bridges or dikes.

4. Use terrain modification tools within the GIS software or directly within the hydraulic software selected by the practitioner to incorporate the bridges, roads, highways, and other critical terrain features and hydraulic infrastructure into the MRDEM surface.

The MRDEM is less accurate than higher resolution DEM, but it can be greatly improved with a review of aerial photography, identification of critical terrain features and infrastructure, some basic survey and terrain modifications. It is noted that DEM surface modifications can now be achieved with relative ease through hydraulic model software interfaces.

It should be noted that this methodology focuses on improving accuracy for detailed flood modelling and mapping in small to medium sized study areas. Single horizontal or vertical corrections may not be sufficient for regional flood study areas (on the order of 100 km of river reach or greater). Other recommendations in this methodology may be difficult to implement at a regional scale.

8.2.2 If no cross-section survey or bathymetry data is available

This situation would occur for example where an area is not accessible, or the level of effort to access and survey an area is prohibitive.

In this context, the modeller relies solely on the available DEM to assemble the model and prepare the flood maps. The model tests conducted above show that a significant amount of detail can be lost, especially if the MRDEM (30m resolution) is the only DEM data available. It was found that a horizontal uncertainty in the range of 50m, and a vertical uncertainty in the range of 2.0 m could be created (compared to the 1m lidar data with complete survey of channels). This amount of uncertainty may be worth considering as a minimum when conducting modelling and floodplain mapping in a given area where no field data can be collected. Uncertainty is likely to vary by study location and study area characteristics, so it is possible that uncertainty may substantially exceed the values determined in this study. However, if a level of uncertainty can be defined and determined to be acceptable, the MRDEM may be used to create initial flood maps. These initial flood maps may provide a high level understanding of flood risks before more detailed mapping can be undertaken.

If the DEM is available at a high resolution, such as a lidar 1m grid, then the amount of resulting uncertainty is quite different, as most of the floodplain features will be modelled and mapped in a representative manner, and it is mainly the channel bathymetry that will lack information. Where rivers or estuaries are deep, the missing data can be critical, and lead to a notable amount of uncertainty (even though in the tests conducted above, a 0.1m to 0.2m water level uncertainty was found for a range of river depths). When planning a flood mapping study, a valuable step is to have a preliminary look at the rivers and estuaries, and review their existing in-channel depths and other critical features for channel conveyance. This information can be combined with engineering judgment and a review of the existing lidar to determine if bathymetric data collection is necessary for a study. In ideal conditions where lidar was collected at low flow without backwater conditions, the critical channel features may have been captured.

For example, Study Area 1 has relatively small watersheds (e.g. less than 500 km^2), the channel slopes are generally shallow, the river bed is quite mobile, and the river bed depth is quite limited. The river is somewhat wide and shallow. In this and similar cases, if the lidar is collected while water levels are low, the lidar data may be sufficiently representative of the river bedform to produce meaningful results in the absence of bathymetric data. Based on results from Study Area 1, it was estimated generally (to be confirmed with engineering judgement) that a depth lower than 1m may be acceptable to omit river bathymetry in the modelling. However, it is important to note that specific minimum water depths are difficult to generalize across different study areas.

In terms of level of effort associated with modelling and mapping a floodplain based on a DEM only, it can be noted that the amount of effort expended in data preparation, model assembly and flood mapping will be reduced.

If bathymetric data is considered necessary, while not obtainable, it is still possible to manipulate the data to produce more representative results. As discussed by Choné et al. (2018), it is possible to infer a bathymetric depth from water level and flow gauging measurements (although the methodology followed in this report was simplified). Adjusting the DEM surface to include this inferred bathymetry (called "burning in channels") has the ability to greatly reduce the uncertainty in modelling results. For example, with the MRDEM, the adjusted surface allowed the uncertainty to be reduced from an average of 2.0 m to 0.4m in Study Area 1, and from 0.73m to 0.41m in Study Area 2. It is noted that, as expected, the more representative the flow and water level gauging data is to the modelled river (ideally the data would be available on the modelled river itself), the more representative the inferred bathymetric depth will be. It is also noted that since the water level and flow information does not need to represent peak flows, but rather average flows, temporary flow gauging during average flow conditions (even a spot measurement), if feasible, may be sufficient to provide suitable supporting data for bathymetric depth inference. It is also noted that although temporary flow gauging can assist in calculating bathymetry for certain channels, it is likely not effective for braided channels and other highly complex bedforms, as their geometry varies throughout the length of the channel and these channels tend to be highly morphologically active.

In the scenarios tested where lidar data was supplemented with inferred bathymetry, the uncertainty was reduced (between using no bathymetry data and using the inferred bathymetry) from an average of 0.15m to -0.01m in Study Area 1. However, in Study Area 2, this uncertainty changed from 0.17m to -0.19m. This result draws out an issue that arises in more intricate situations, where a 2D model is used to represent a deep and braided river bed. In this case, it is impractical to apply an inferred bathymetric depth to a number of parallel channels, and the result may focus disproportionately on a given river channel at the expense of others.

Although it was not explored in this study, practitioners working with complex bathymetry such as braided channels may also consider the use of flow subtraction as an alternative to calculated bathymetry. Should the date of terrain data collection be known, the average flow value at the time of terrain data collection could be subtracted from all design flow modelling to compensate for the lack of bathymetric data. This approach is most effective where inflow points are limited in number, confidence in the quality and accuracy of flow data on the day of terrain collection is high, and flows are relatively consistent over the period of terrain data collection.

These considerations highlight the fact that innovative techniques can allow the modeller to greatly reduce the potential uncertainty associated with lack of bathymetric data. The modeller needs to retain, however, a generous amount of caution before deciding to implement such techniques, and should conduct an initial overview of the estimated channel characteristics and depth of water at time of terrain data collection. This overview can be completed using available satellite imagery and existing terrain data, which should provide the necessary information without field work.

8.2.3 If no structure survey data is available

The model testing conducted above showed that omitting the bridge structures (deck and piers) from the modelling geometry (i.e. by using the unmodified lidar surface), could have a minimal impact on the overall magnitude of modelled flood water levels. This result is contingent on the characteristics of the structure, where large piers and/or a low deck elevation, that would not allow sufficient capacity for the modelled flood event(s), would not have their impact adequately represented in flood extents, if omitted.

In the testing conducted, the 1D modelling results showed an average of 0.02m difference during the design flow event, and a 0.1m difference during a greater (1 in 500 year) event. The 2D modelling results showed an average difference of 0.07m during the design event, and a 0.08m difference during a greater event. In the cases of both models, changes in water surface elevations and flow depths are more substantial in close proximity to the bridges.

While this may be true on average, the modelling results showed that there can be large discrepancies locally, in the following instances:

- For undersized structures,
- Where piers and abutments encroach on the channel, limiting hydraulic conveyance, or
- Where the flood flow event exceeds the design event of the structure (and the design clearance depth is minimal)

Where the bridge is located above a deep river valley, the deck is far above the water surface and there are minimal piers or other hydraulic impingements within the channel, omitting the bridge in the model geometry may have negligible impacts on the modelled water levels.

If a bridge survey or general dimensions can not be collected, it is still recommended to obtain wherever possible record drawing information on the structure, so that the modeller can evaluate the potential restricting effect the bridge may have on the flow and water levels in the river system. Some limited improvements on bridge geometry can also be achieved by using elevations from surrounding roads to estimate the elevations of the abutments.

It should be noted that this discussion relates specifically to the bridge deck, piers and other detailed features of the crossing. In all cases, the road and any raised embankment on either side of each bridge was retained within the model (as it is part of the DEM). These embankments and the general bridge opening (i.e. channel width) were not varied and, where they restrict the natural river channel width, can have a substantial impact on flood extents. Please refer to Phase 1 of this study for further details.

8.3 Guidance Associated with Time or Resource Constrained Flood Mapping Development

In order to maximize the quality of flood mapping within given time or resource constraints, a number of approaches can be taken, which are described below for consideration. The guidance and numbers provided are based on the results of the examples tested in the previous sections, in two pilot study areas, one in Nova Scotia and one in British Columbia respectively, and as such represent singular test results rather than ensemble testing. The Nova Scotia setting is reflective of ~200km^2 watershed areas in relatively flat, tilly watersheds with a few lakes, while the British Columbia setting is reflective of ~4,000 km^2 mountainous watersheds with freshet dominated peak flows. More details on the respective settings are provided in Chapter 1.

1) The highest resolution DEM available is to be used. Vertical Datum, as well as horizontal accuracy of the DEM, are to be checked and adjusted if necessary. If the DEM resolution is not considered to be sufficiently detailed to meet the flood mapping objectives, further data collection will be necessary. In order to identify whether lidar data collection or ground surveying is the most suitable approach, it will first be necessary to decide whether the entire floodplain should be mapped (e.g. if 2D modelling is necessary), or if only cross-sections at specific locations are sufficient. Considerations of access, localized versus wide area topographic surveys, and quality of data collection (leaf cover, GPS satellite coverage, etc) are to be taken into account. The next point discusses bathymetric data collection.

2) Regarding bathymetric data collection, as noted in Section 7 above, a careful examination of the river using satellite imagery and the current available surface topography data to identify areas of notable water depth (suggested greater that 1m) or areas of significant braiding may indicate (if no such instances are present) that bathymetric data collection is not necessary, thereby reducing potentially substantial bathymetric survey efforts. Practitioners may also consider whether a sufficient quality of flow data was available for the period of topographic data

collection to allow for flow subtraction as an alternative to bathymetric survey.

3) Where areas of significant depth are present, and the collection of bathymetric data is to be avoided if possible, consideration for a water level uncertainty of 0.1m to 0.2m (if lidar data is available), or 0.6m to 2.0m (if only the MRDEM is available) in the modelling results is necessary at a minimum. As these values are based on only the two study areas included in this study, engineering judgement and available data sources should be used to assess whether there is greater risk of uncertainty within each proposed study area. Reducing this type of uncertainty can be achieved using the following methods:

   a) It may be valuable to consider implementing an inferred bathymetric depth into the DEM, based on back-calculating the depth using flow and water level data. If suitable flow and water level information is available to support this process (or if it can be collected), the above test results indicate that this approach has the potential to reduce the uncertainty by a factor of 2 to 5. An alternative to inferred bathymetric depth not included in this study would be to use flow subtraction to compensate for this same challenge.

   b) If the uncertainty is to be further reduced, a field survey may need to be conducted. Some efficiencies can be achieved by collecting a minimized number of points along the cross-section (testing presented above showed no notable difference by collecting only half the number of points along cross-sections), or collecting cross-sectional data only once in regularly shaped sections of the river, or at key river bed changes. Increasing surveying detail and coverage will gradually minimise the remaining uncertainty in results associated with the representation of the ground surface.

4) Within areas of river braiding or other high bedform complexity (with several active channels or flow directions), and 1D modelling is not considered suitable, some of the multiple channels or flow paths may not be suitably represented using inferred bathymetry methods (which would focus on only one channel). If flow data of sufficient quality is not available to use for flow subtraction as an alternative approach and vertical uncertainty is to be reduced further, field collection of the bathymetry data may be necessary.

5) To minimize the survey effort, data collection at structures can also be minimized, recognizing that the culvert embankments and bridge abutments, which are a critical source of the structure's impact on the flow, are already included in the DEM data. Additional information is therefore only needed to obtain the girder and deck thickness, as well as more detail on abutment shape, number of piers, pier dimensions and spacing or the exact culvert size. This can be investigated following various approaches:

a) An exhaustive search for record drawings, previous reports, or historic information may produce dimensional data on structures along the river to be modelled and mapped.

b) A review of the structures along the river can help identify structures that may not need to be included in the model. The testing conducted above shows that clear span structures high above the river in deep river valleys (e.g. at least 10m above the estimated top of bank height) likely do not need to be included. A structure should only be excluded from a model if it has no elements which impinge on the primary hydraulic flow conveyance, such as piers. Then, if the flow event for flood mapping is equal or less than the design event of the structures, they will likely have capacity to pass the flow without surcharging or overtopping. Those structures may therefore also be considered for elimination from the model. In exercising of engineering judgement, it may be prudent, however, to include in the model any structure that may be perceived as causing a hydraulic restriction to the flow of water during extreme events.

8.4 General Recommendations for Flood Mapping

Flood modelling and mapping includes a number of inherently highly uncertain processes. While it may often be expected that uncertainty be minimized wherever possible, it may also be acceptable to assume a certain amount of uncertainty, particularly where the most detailed maps may not be necessary for their intended purpose, or where an existing source of uncertainty would far outweigh a given additional uncertainty considered for inclusion in the process. Given project-specific limitations of access (seasonal, property-related, safety-related or distance-related), scheduling, budgets, surveying capacity, or other, it may be necessary or valuable to consider conducting flood mapping with limited data availability, and making informed decisions about the associated uncertainty.

In such cases, the guidance presented above will be helpful to inform flood mapping practitioners, as well as project managers preparing the scope of a flood mapping project, whether facing limited data availability, or time and resource constraints. Step by step approaches are presented above to incrementally reduce the uncertainty of flood mapping results, while increasing the associated level of effort. The findings of the testing suggest that while general trends are evident (e.g. less data generally results in more uncertainty), an understanding of river hydrodynamics, combined with an investigation of the river characteristics, can offer potential opportunities for savings in time and effort. This is true for example where missing river bathymetry may be suitably inferred with available flow gauging data, which may eliminate the need for river cross-section surveys. However, where river braiding occurs with multiple active channels, or flow data at the time of topographic data collection is ill defined, this method becomes notably less effective. The characteristics of the watershed and floodplain play an important role in the behaviour of the watercourse, and methods that may be applicable in certain areas of Canada may not be so in others.

It is always important to consider what data is readily available and what its resolution is as well as the level of effort needed to obtain higher resolution data. In a broad sense, it is important to use the highest resolution DEM available, and if only a coarse resolution DEM exists, to give consideration to obtaining lidar data in the floodplain. A review of the watercourse characteristics, as well as the hydraulic structures that may pose restrictions to the flow of water, will be very helpful in identifying potential opportunities for data collection optimization. Given uncertainties in methods for inferring river bathymetry, it is still recommended that river bathymetry be obtained using field surveying methods, bearing in mind that those can also be optimized. Reducing the density of points collected for cross-sections, or reducing the number of cross-sections (if engineering judgment allows this) may reduce field survey costs with minimal impacts on uncertainty. If no field data collection is feasible, however, the inference of river bathymetry was found to greatly reduce the uncertainty associated with using only the DEM (whether lidar or MRDEM) for bathymetric data. It will be important to first, however, confirm if opportunities for reducing data collection will be limited by jurisdictional requirements, which will need to be carefully reviewed to ensure compliance.

It is therefore fundamental to exercise dutiful engineering judgement based on experience and expertise to inform decisions on whether to expend the additional effort associated with the gathering of additional field data, even when this data may necessitate a very high amount of effort to collect. In a client / consultant relationship, both parties should be involved in discussions and in the decision-making process. If the choice is made to reduce or forego the collection of supporting data, clear discussions should be included in the associated reports to explain such decisions and the accepted amount of uncertainty resulting from those decisions. Discussions about the additional efforts to reduce the resulting uncertainties should also be included in the reporting, should they be needed in the future.

8.5 Limitations and Opportunities for Future Research

8.5.1 Limitations

- This sensitivity analysis involved testing of only select parameters, for select flood mechanisms, in two study areas (in 2 Canadian provinces) and 2 river reaches with watershed-specific characteristics. The report therefore does not represent expected responses for any other study area, or any of the parameters not studied here. The intent is solely to provide the reader with two study area examples of alternative modelling methods and various changes to the amount of data available.

- No discussion has been included regarding the uncertainties which surround the changing Canadian climate.
- This assessment reviewed the PCSWMM, HEC-RAS 1D, HEC-RAS 2D, and MIKE+ 2D software packages; some recommendations may not apply to the application of other hydrologic / hydraulic software programs.
- Recommendations are limited by the scope of the study and the experiences and expertise of the professionals involved in its development.
- A comprehensive sensitivity analysis on the modelling parameters was not completed as part of this study.
- The MIKE+ 2D mesh developed for this project could have been refined further to better capture features such as secondary and tertiary channels; however, the model was developed to a level deemed optimized and sufficient for the purposes of this study. As noted earlier, achieving a mesh with detail comparable to HEC-RAS 2D requires significantly more computation power, run time and attention to detail in MIKE+ 2D.

8.5.2 Opportunities for Further Research

- Further research opportunities to directly supplement the test scenarios included in the Phase 2 study include the following additional testing:
    - Conducting the same tests in a wider range of physiographic regions to form a more representative envelope of results
    - Adjustments in model resolution, e.g. cross-section spacing for 1D models, mesh size or shape or orientation for 2D models
    - Impacts of removing culverts of various sizes on flood characteristics, since the two study areas did not include culvert structures
    - The accuracy of calculating bathymetry for braided channels and different methods for calculating bathymetry in braided channels.
    - Use of flow subtraction (i.e. determining the flow at the time of LiDAR capture and subtracting this from all flow hydrographs) as an alternative to calculated bathymetry in reaches with complex flow paths such as braided channels.
    - Differences between equations used at structures in HEC-RAS 2D and adjustments to Manning’s roughness coefficients to address these differences.
- Opportunities for future research include analysis of Canadian regions with different topographic, hydraulic and hydrologic flood mechanisms. These include, but are not limited to regional hydrologic and hydraulic challenges associated with the Prairie Pothole Region and the Canadian North, ice and ice jam flooding, and complex downstream boundary conditions such as Canadian tidal ranges.
- Opportunities also include more detailed assessment of the sensitivities associated with highly developed areas, especially those with extensive flood protection structures such as dikes and road/railway berms.

- Future research could also include the sensitivity / application of different computational equations within a software package.

Recommendations and overall guidance could then be updated to encompass the results of any future research to improve general applicability and practicality of implementation.

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APPENDIX A

Additional Information

Table A-0-1: Flow Prorating Areas

HEC-RAS River Station	PCSWMM Junction Number	Upstream Subcatchment Area (m^2)
31079	J31079	1.894E+07
30639	J30639	2.232E+07
27667	J27667	4.467E+07
25744	J25744	5.535E+07
22791	J22791	8.594E+07
20571	J20571	9.228E+07
18784	J18784	9.674E+07
17346	J17346	1.018E+08
14699	J14699	1.121E+08
12575	J12575	1.239E+08
10963	J10963	1.588E+08
9425	J9425	1.715E+08
6788	J6788	1.810E+08
5179	J5179	1.827E+08
3073	J3073	1.902E+08
1610	J1610	1.969E+08

Table 0-2: Statistical Analysis Results

Year	Annual Max (mm)	Empirical Curve, X^-	Rank (m)	Probability of non-exceedance (F)	Y of Gumbel	X	Y	A	B	Gumbel Values	X=AY+B		Probability of non-exceedance (F)	Empirical Curve, X^-	Gumbel Values
2008	67.5	107	1	0.960339943	3.20724499	70.60714	0.549887	17.43122	61.02193	116.928137			0.960339943	107	116.9281
2009	64	100.8	2	0.889518414	2.14493992					98.41085928			0.889518414	100.8	98.41086
2010	86	92.2	3	0.818696884	1.60923109					89.07279865			0.818696884	92.2	89.0728
2011	69.6	89.6	4	0.747875354	1.23608646					82.56843097			0.747875354	89.6	82.56843
2012	100.8	86	5	0.677053824	0.94159699					77.435119			0.677053824	86	77.43512
2013	44.8	69.6	6	0.606232295	0.69216358					73.08718936			0.606232295	69.6	73.08719
2014	42	69.6	7	0.535410765	0.47045006					69.22245133			0.535410765	69.6	69.22245
2015	92.2	67.5	8	0.464589235	0.265788					65.65494107			0.464589235	67.5	65.65494
2016	107	64.2	9	0.393767705	0.07042877					62.24959052			0.393767705	64.2	62.24959
2017	64.2	64	10	0.322946176	-0.1224562					58.88736947			0.322946176	64	58.88737
2018	44.2	47	11	0.252124646	-0.32051102					55.4350314			0.252124646	47	55.43503
2019	69.6	44.8	12	0.181303116	-0.53508008					51.69483013			0.181303116	44.8	51.69483
2020	47	44.2	13	0.110481586	-0.78977758					47.25514078			0.110481586	44.2	47.25514
2021	89.6	42	14	0.039660057	-1.17168018					40.59811099			0.039660057	42	40.59811

Table A-0-3: Statistical Analysis Results on Rainfall Amounts

Return Period (yrs)	EVA Rainfall Amount (mm)
2	67.4
5	87.2
10	100.2
25	116.8
50	129.0
100	141.2
500	169.3

Appendix – Tabulated Results for Each Test in Study Area 2

Max Water Level (m)							
River Reach	Salmon River						
Sample Cross-Section	1	2	3	4	5	6	7
Baseline (HEC-RAS 2D Lidar DEM + Bathymetry)	610.38	608.43	605.55	600.67	595.13	585.61	583.40
MIKE+ 2D	610.29	608.40	605.50	600.61	594.96	585.76	583.44
MRDEM + Bathymetry	611.03	608.56	605.64	600.66	594.82	585.94	583.41
1-in-200 Year (0.5% AEP) Flow Event with Bridges Removed	610.02	608.42	605.54	600.67	595.13	585.52	583.40
1-in-500 Year (0.2% AEP) Flow Event with Bridges Removed	610.18	608.57	605.66	600.84	595.15	585.67	583.51
Lidar DEM Only	610.46	608.60	605.68	600.83	595.38	585.78	583.64
Lidar DEM + Half Points Removed Bathymetry	610.28	608.43	605.54	600.68	595.13	585.70	583.41
Lidar DEM + Calculated Trapezoid Bathymetry	609.96	608.18	605.58	600.63	595.13	585.20	583.16
MRDEM + Calculated Trapezoid Bathymetry	611.43	608.51	606.03	600.98	595.15	586.30	583.65
MRDEM Only	611.99	608.81	606.34	601.24	595.38	586.64	583.87

Average Velocity (m/s)							
River Reach	Salmon River						
Sample Cross-Section	1	2	3	4	5	6	7
Baseline (HEC-RAS 2D Lidar DEM + Bathymetry)	2.4	0.9	1.4	1.3	0.5	1.6	1.0
MRDEM + Bathymetry	1.3	0.9	1.1	1.3	0.5	1.2	0.8
1-in-200 Year (0.5% AEP) Flow Event with Bridges Removed	2.7	0.9	1.4	1.3	0.5	1.7	1.0
1-in-500 Year (0.2% AEP) Flow Event with Bridges Removed	2.8	0.9	1.4	1.2	0.5	1.8	1.0
Lidar DEM Only	2.6	0.9	0.4	1.2	0.3	1.7	0.9
Lidar DEM + Half Points Removed Bathymetry	2.5	0.9	1.4	1.3	0.5	1.6	1.0
Lidar DEM + Calculated Trapezoid Bathymetry	2.8	1.2	0.3	1.4	0.4	1.7	0.9
MRDEM + Calculated Trapezoid Bathymetry	0.9	0.9	1.2	1.1	0.4	1.4	0.7
MRDEM Only	0.7	0.9	1.3	0.9	0.4	0.9	0.6

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