Flood Hazard Modelling Sensitivity Pilot Study

Phase I

Environment and Climate Change Canada
Environnement et Changement climatique Canada

Canada

Cat. No.: En56-370/1-2026E-PDF
ISBN: 978-0-662-87252-8

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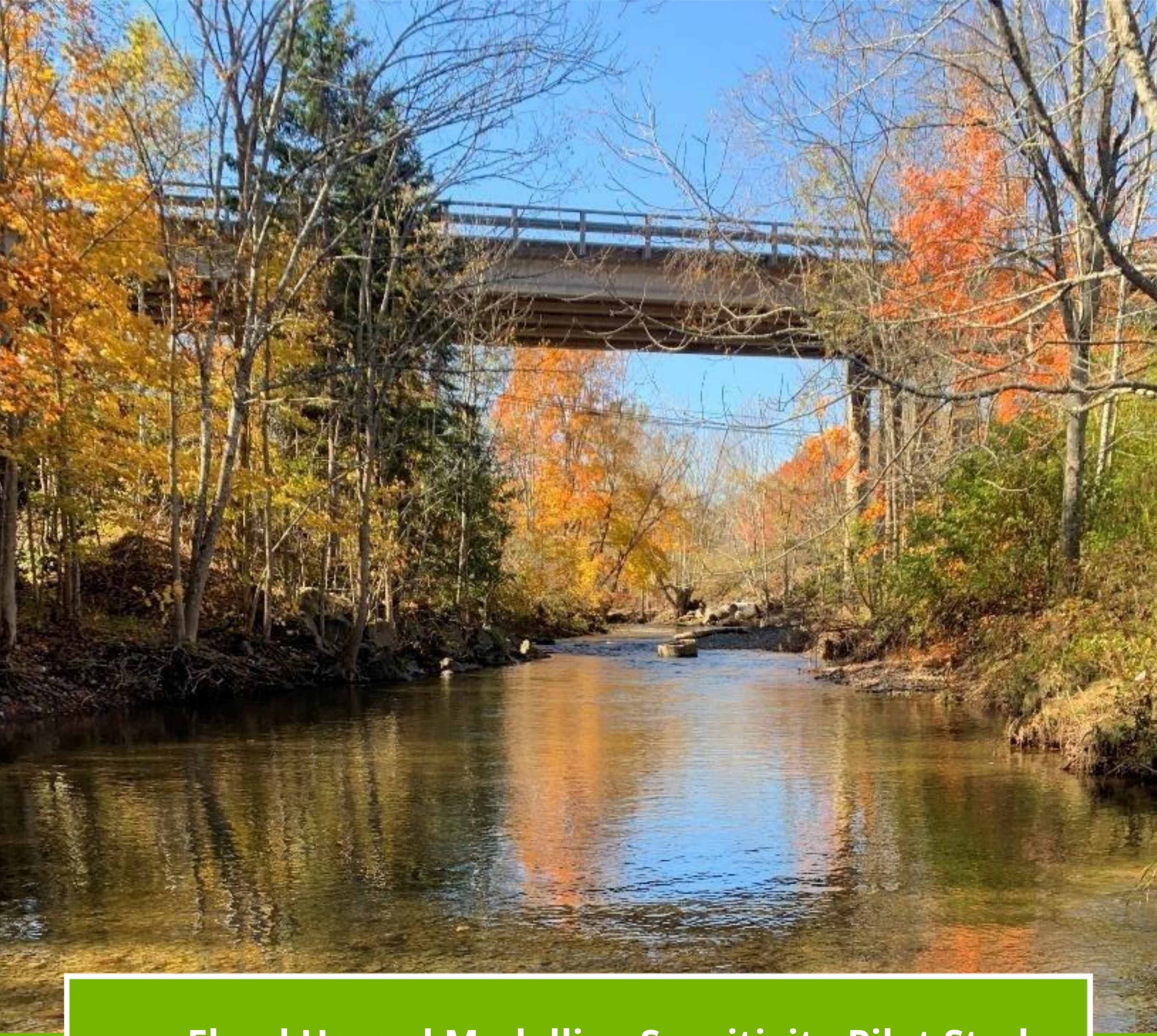

Flood Hazard Modelling Sensitivity Pilot Study

Final Report

Environment and Climate Change Canada

241213.00 • February 2025

03	Final Report	A. Wilson M. MacLatchy	28-Feb-2025	A. Oliver A. MacIsaac
02	Draft Report Ver.2	A. Wilson M. MacLatchy	6-Jan-2025	A. Oliver A. MacIsaac
01	Draft Report	A. Wilson M. MacLatchy	3-Dec-2024	A. Oliver A. MacIsaac
Rev.	Issue	Reviewed By:	Date	Issued By:

Project No. 241213.00

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February 28, 2025

Joel Trubilowicz PhD, P.Eng
National Hydrological Service
ECCC

Dear Mr. Trubilowicz:

RE: Flood Hazard Modelling Sensitivity Pilot Study Final Report

CBCL is very pleased to submit this Flood Hazard Modelling Sensitivity Pilot Study final report. The final report includes an updated conclusions and recommendations section providing high level interpretation and guidance regarding the uncertainty identified in the hydrologic, hydraulic and GIS parameter testing. Comments on other sections have also been addressed.

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.: 241213.00

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1 Introduction

The project team conducted a systematized sensitivity analysis on parts of the flood hazard identification, modelling, and mapping processes completed for two selected flood studies, one in Nova Scotia, and one in British Columbia. 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 map. The focus was not on quantifying the uncertainty related to each parameter, but rather to test the impact of the variability of parameter selection on the resulting flows, water levels and flood maps.

The methodology presented in the following chapters focuses on dominant parameters used in the hydrologic analysis, hydraulic modeling calibration and flood mapping phases of the example flood mapping projects.

Conclusions, recommendations and study limitations are included in the final section of this report.

2 Selected Flood Studies

The project team selected two flood studies in vastly different geographic regions to perform the sensitivity analysis. To mitigate any risk of the project files becoming unavailable through the project, the project team has been given permission by the project owners (i.e. clients) to use the two proposed flood mapping studies for this analysis.

The first flood study involves the South River, Antigonish County, Nova Scotia, Canada and the second study involves the Fraser River and Salmon River near Prince George, British Columbia, Canada. These two selected studies provide valuable diversity in watershed characteristics and hydraulic conditions, which mitigates the risk of executing a sensitivity analysis that is only appropriate to a narrow region in Canada. The two proposed mapping studies have also been carefully selected to represent a range of hydrologic and hydraulic characteristics, based on differences in the underlying terrain and differing flood mechanisms. Both studies have been completed to the latest respective provincial and federal flood mapping guidance documents and standards. The unique hydrologic and hydraulic characteristics of each flood study are outlined below.

2.1 Study Area 1: South River, Antigonish County, NS

The South River is located in the Antigonish County of northern Nova Scotia (**Figure 2-1**). At its mouth, the South River watershed drains an area of 200 km^2. It can be described as having a single main stem flowing north without any major branching or tributaries. The start of its main stem is at the South River Lake, which covers 350 ha of water. Regarding the watershed land cover, it is predominantly forested with agricultural lands mainly in its valleys and lower floodplains. The average watershed slope is 1.8%, with an average river slope of 0.2%. The river has an active Water Survey of Canada (WSC) streamflow monitoring station (gauge) in the study area, which supported the hydrologic model calibration. In 2022-2023, CBCL completed a flood mapping study for the area as part of the provincial Municipal Flood Line Mapping program of the Nova Scotia Department of Municipal Affairs and Housing and supported by the Flood Hazard Identification and Mapping Program (FHIMP) initiative. This project supported the local Eastern District Planning Commission in developing new flood hazard zoning for their jurisdiction.

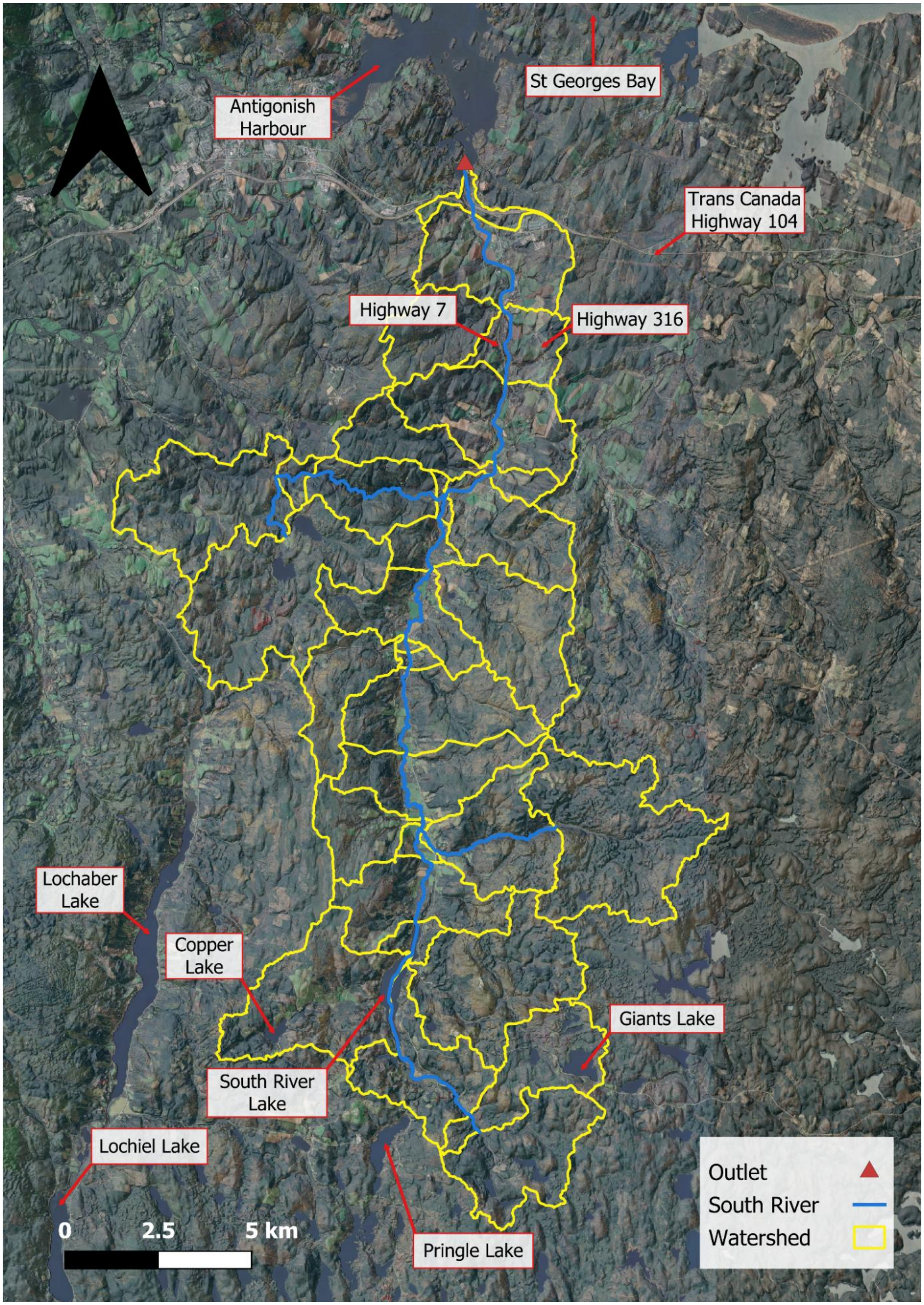

Figure 2-1: Study Area 1 – South River Model Extent.

1. The South River study area is an ideal site for sensitivity analysis due to its physiographic characteristics as well as its high data availability and number of previous studies. The following are key attributes of the South River that are relevant to this analysis. The study has been completed following current best practices including the Nova Scotia Flood Line Mapping Technical Specifications. The project was reviewed by Environment and Climate Change Canada (ECCC) 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.
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
    c. through the fall months.
    d. Rain on frozen ground events in early winter.
    e. Mid-winter rainfall with snowmelt
    f. Ice jamming.
    g. 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 Collegeville Climate Station located in the watershed has over 100 years of rainfall data while the Water Survey of Canada's South River at St. Andrew's Gauge (01DR001) has over 74 years of data. These have been used to calibrate the hydrologic 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 is 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. HEC-RAS hydraulic model (version 6.3)[1] was used to create flood mapping for the 31 km river length, based on 197 cross-sections and nine hydraulics structures (bridges). Channel bathymetry and structures have been topographically surveyed.
7. All models and mapping have been developed using recent LiDAR Digital Elevation Model at 1 m grid size in Canadian Vertical Geodetic Datum (CGVD) 2013.

[1] https://www.hec.usace.army.mil/software/hec-ras/

2.2 Study Area 2: Upper Fraser River and Salmon Rivers

The second flood study area includes the Fraser River and Salmon River near Prince George, British Columbia (Study Area 2). The Fraser River Basin includes a complex network of rivers stretching hundreds of kilometers, including the Fraser River and the Salmon River. Associated Engineering (B.C.) Ltd. was contracted in 2022 to complete four flood mapping studies for the British Columbia Flood Hazard Identification and Mapping Program (FHIMP) initiative; the project is currently in its completion phase, community consultation and feedback. The main objective of this project is to develop high quality, standardized, consistent floodplain mapping for higher-risk communities in B.C. that lack recent flood maps.

Two connected river reaches were used for this sensitivity study: the Fraser River at Prince George and the Salmon River at the Community of Salmon River Valley. These two river reaches were selected to provide contrast with Study Area 1 in Nova Scotia and allow for sensitivity analysis of several, varying topographic regions. The two river reaches are described below.

Fraser River Reach

The Fraser River reach is a 45 km length between the Salmon River Valley and Buckhorn, British Columbia. This river reach includes a heavily incised and confined mountain valley floodway, an urban environment at Prince George and complexity of confluence where the Fraser River meets the Nechako River in Prince George, BC. The river has a contributing watershed of approximately 32,400 km^2 and experiences peak flood events during freshet.

Salmon River Reach

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.

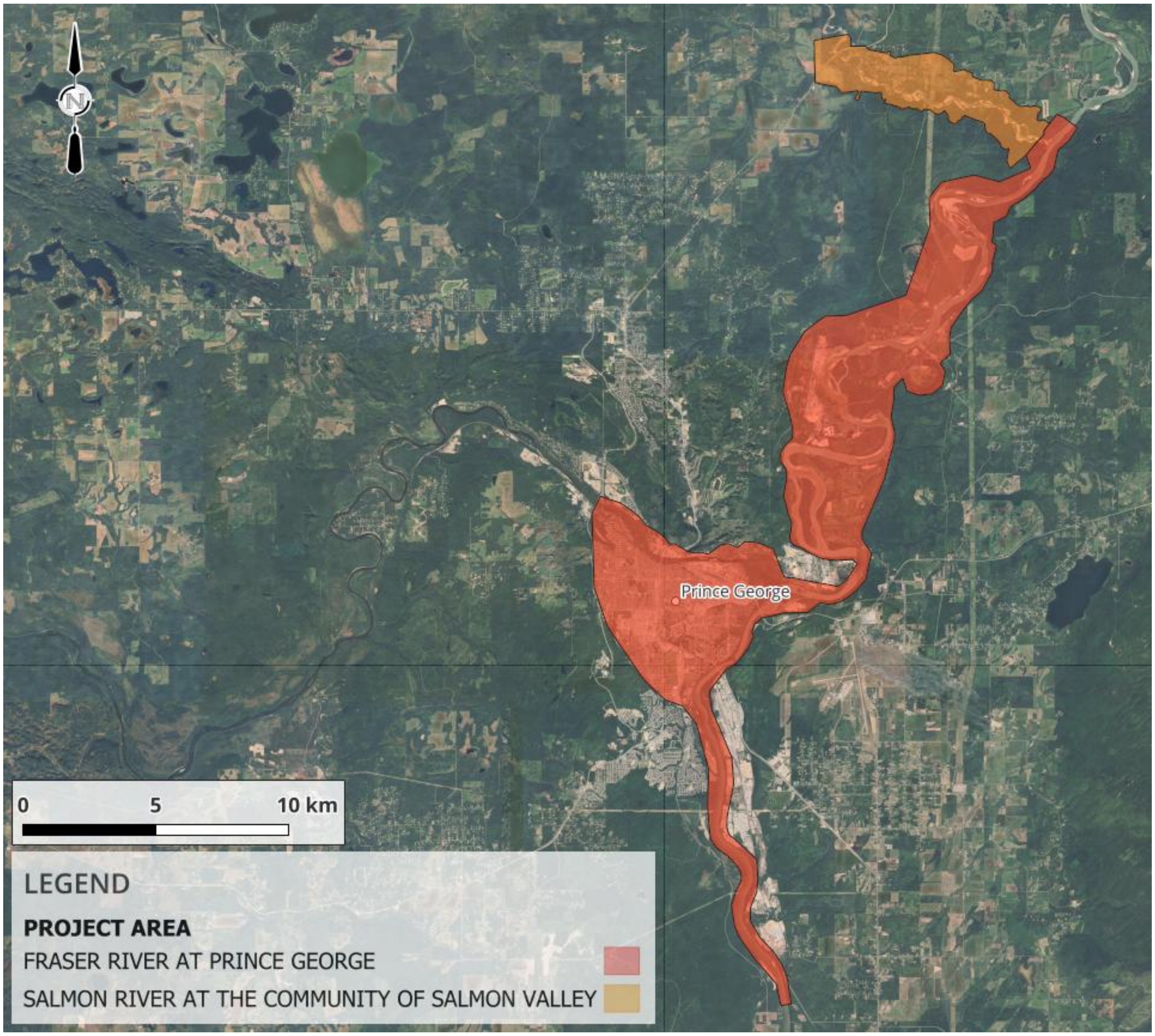

Figure 2-2: Study Area 2 – Salmon River and Fraser River Model Extents.

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 oversite committee that including ECCC staff.
2. The study area represents typical physiographic conditions for mid-to-large-sized western Canadian watersheds. These are freshet, snowmelt-driven systems with mountainous, forested headwaters and well-defined watershed boundaries.
3. Climate and flood regimes within the river watersheds are common to those experienced throughout mountainous British Columbia and other Canadian topographic regions with extensive snowpack. Spring freshet is the primary flood mechanism.
4. The river reaches demonstrate two different river channels and floodplains: one with a highly incised, mountainous river with limited floodplain and the other a typical alluvial morphology, with a well-defined valley floor, and meandering channel. Both floodplains have mixed land cover including forest, agriculture, and residential land use.
5. Some review of the impact of flood defence is included in this assessment, as the Upper Fraser River includes both railway berms and official dyking. The Salmon River reach is unrestricted.
6. Both river reaches have excellent hydrometric data coverage. Water Survey of Canada hydrometric stations are located very near the upper end of each reach of interest and provide both annual daily maxima and peak instantaneous flow data. These stations have been used for flood frequency analysis and derivation of the flood mapping design flows.
7. The river reaches demonstrate two common downstream boundary conditions: a confluence with another river and a run-of-the-river normal flow condition.
8. Detailed HEC-RAS 2D (version 6.3) hydraulic models were created for both reaches in Study Area 2. Channel bathymetry and all bridge structures have been topographically surveyed.
9. All models and mapping have been developed using recent LIDAR Digital Elevation Models at a 1 m grid size in CGVD 2013.

3 Uncertainty in Design Flow Estimation

Design flow estimation presents perhaps the largest source of uncertainty for flood mapping studies. Study Areas 1 and 2 used contrasting methods for estimating design flows. This allows the exploration of sensitivity of a range of parameters, not only within a single model, but also between the differing methods listed below.

1. **Hydrological modelling** of rainfall-runoff used to generate inflows for the South River flood study.
2. **Flood frequency analysis (FFA)** of historical streamflow records used as inflows for the Fraser River and Salmon River flood studies.

Results are presented in the form of bar charts and tables, showing impacts on peak flows and peak water depths at regular points within the watercourse length, and figures of flood extents showing selected areas which illustrate findings. Impacts on peak flows as well as water depths and water extents are presented, in order to show which mechanisms are contributing to changes in flood extents. For example, an increase in watershed surface roughness will slow down flows, likely reducing the peak, by increasing the time of concentration of the watershed. Any decrease in water depth will then depend on the watercourse cross-section and hydraulics (e.g. if water backs up), so water depth change may not vary correspondingly with flow changes. Similarly, impacts on flood extents will depend on the watercourse edge slopes, which will differ along the watercourse. The various mechanisms at play will be further discussed in the summaries of results for each testing category.

3.1 Hydrological Modelling Methods (Study Area 1)

3.1.1 Description of Study Area: South River in NS

The South River Flood Study utilized a 1-Dimensional US EPA SWMM5[2] model that combines hydrologic and hydraulic calculations, with the PCSWMM[3] software to support a GIS interface.

The focus of the sensitivity analysis for hydrologic modelling is on the generation of rainfall hyetographs as well as the model parameters and assumptions. The calibrated South River is used as the base model, and one variable is change at a time to estimate the sensitivity of each selected variable. Details of the selected variables to analyse are presented below.

Results are presented for 17 nodes (**Figure 3-1**), which represent approximately 1 node for every 10 nodes in the model (total of 174). This will ensure that the effects of changing model parameters throughout the entire watershed is shown for both water level and flow, in a more readable manner. A summary of results is found in Section 3.1.5, along with discussion on overall hydrologic model sensitivity.

Table 3.1 displays all the test parameter scenario runs with corresponding upper bound and lower bound in the resulting flows and water levels calculated. Note that the baseline model is the calibrated model used to run scenarios in the original project and uses the 100-year return period, 24-hour Chicago design storm derived from the ECCC rainfall data, with a simulation period of 4 days. Increases and decreases to each parameter were tested with the model (**Table 3-1**). The changes selected are intended to represent reasonable modelling choices, within a range typically considered acceptable, that could be made for each parameter, for this specific study area.

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[2] https://www.pcswmm.com/Downloads/USEPASWMM
[3] https://www.pcswmm.com/

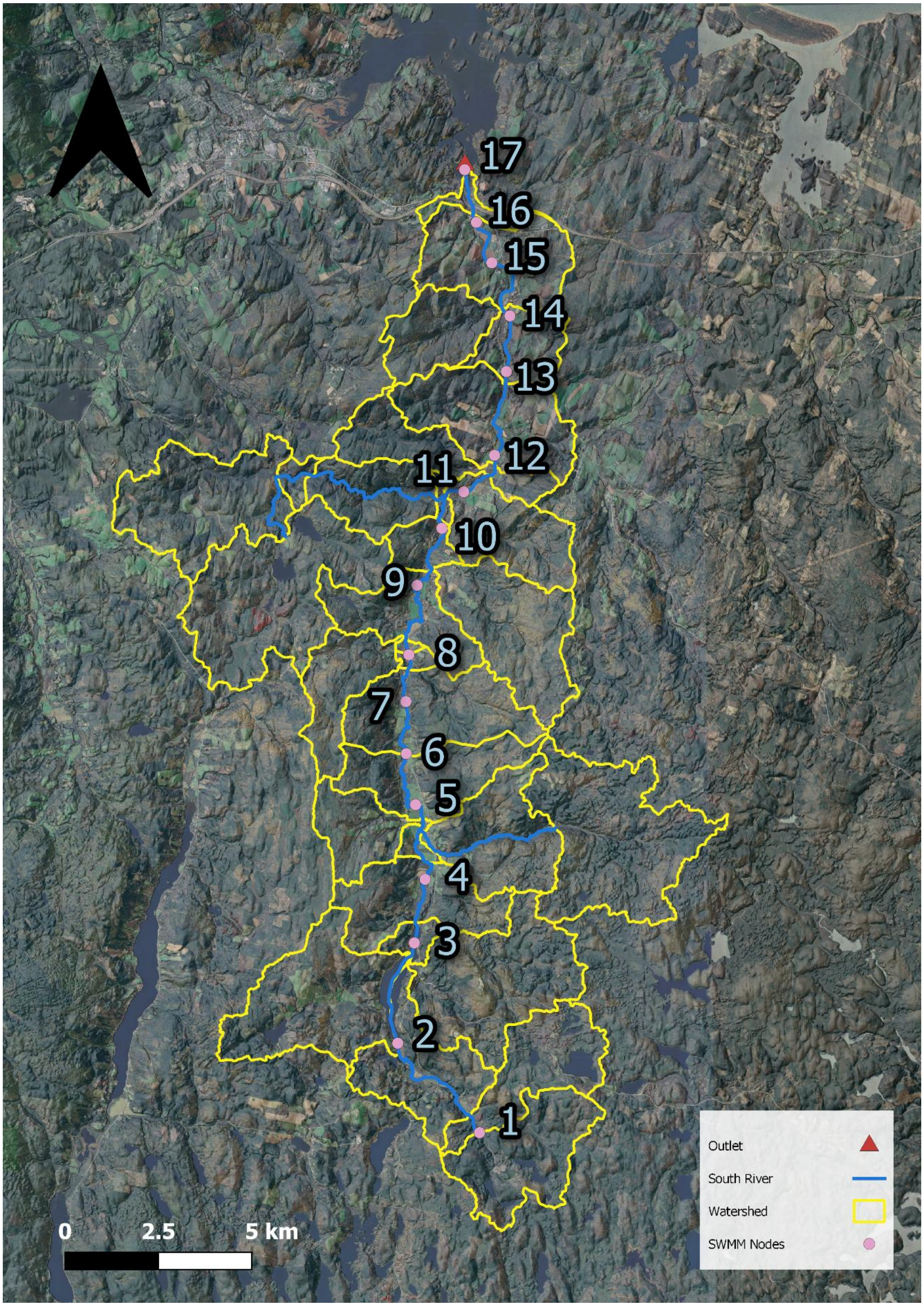

Figure 3-1: Study area showing the seventeen (17) selected nodes for reporting.

Table 3-1: Study Area 1 Hydrologic Test Parameter Upper and Lower Bound Values

Test Parameter	Reference	Lower Bound	Upper Bound
Hyetograph Shape	Baseline Model (ECCC total, with Chicago distribution)	ECCC total, with uniform intensity (block)	ECCC total, with SCS distribution
Rainfall Data Source	Baseline Model (ECCC Chicago)	Northeast Chicago	Western Chicago
Conductivity	Baseline Model	0.1 × Baseline Model	10 × Baseline Model
Initial Deficit	Baseline Model (0.35)	0.01	0.8
Flow Length	Baseline Model	0.2 × Baseline Model	5 × Baseline Model
Subcatchment Discretization	Baseline Model (31)	4	52
Model Calibration	Baseline Model (calibrated with Nov 2021 event)	Calibration with Hurricane Fiona Event	Alternative Calibration with Nov 2021 Event

3.1.2 Estimation of Uncertainty in Rainfall Hyetographs Generation

- Rainfall hyetographs are used in hydrologic models as inputs. To generate the rainfall hyetographs, the IDF curve parameters were obtained from a given source and a given distribution was followed to create the applicable hyetograph. The following sources for IDF curve parameters and storm distributions was considered for this sensitivity analysis:
  Design storm distributions with an event duration of 24 hours:
  - Chicago distribution.
  - Block hyetograph (i.e. constant intensity rainfall over time).
- A typical distribution to use for areas bordering the Atlantic seaboard (i.e. SCS Type III). IDF rainfall data sources:
  - The closest long term ECCC IDF data (Tracadie climate station [8205895]).
  - University of Western Ontario (Western): interpolated IDF info for the Centre Point of the study area (Lat: 45.480050, Long: -61.92991).
  - Northeast Regional Climate Centre (Northeast): interpolated IDF info for the Centre Point of the study area (Lat: 45.480050, Long: -61.92991).

A total of six model scenarios were run to represent all options for rainfall hyetographs, considering a return period of 1-in-100 years (1% AEP) and a 24 hour storm event duration (i.e., Three IDF Rainfall Data Sources and three Rainfall Distributions including the baseline model). IDF curve parameters and return period rainfall amounts from all sources were originated from the same distribution (i.e. Gumbel distribution) to remain consistent such that differences are directly related to interpolation methods rather than the statistical distributions. To generate the hyetographs from the IDF rainfall data, the Chicago distribution method requires a, b, c or a, b coefficients, the SCSIII method requires the 24 hour, 100-year precipitation amount, and the block method requires the 25 hour and 25 minutes (time of concentration of the overall watershed), 100-year precipitation intensity, which is plotted as a straight-line distribution. Design storm input values for each scenario are displayed in **Table 3-2** and **Table 3-3**. **Figure 3-2** to **Figure 3-6** display each design storm rainfall hyetograph that was used in the model.

Table 3-2: Design Storm Inputs with Varying Distributions

Rainfall Source	Rainfall Distribution	Inputs for 100-year return period, 24-hour duration storm:
ECCC	Block	Intensity = 5.78 mm/hr
ECCC	Chicago	a = 400.85, b = 0, c = 0.577
ECCC	SCS Type III	Total rainfall = 138.7 mm

Table 3-3: Design Storm Inputs with Varying Rainfall Source

Rainfall Source	Rainfall Distribution	Inputs for 100-year return period, 24-hour duration storm:
ECCC	Chicago	a = 400.85, b = 0, c = 0.577
Northeast	Chicago	a = 504.08, b = 0, c = 0.580
Western	Chicago	a = 524.06, b = 10.2, c = 0.697

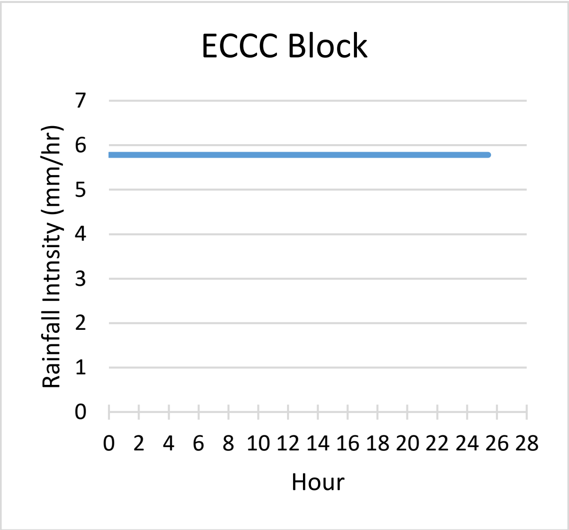

Figure 3-2: ECCC Block Design Storm.

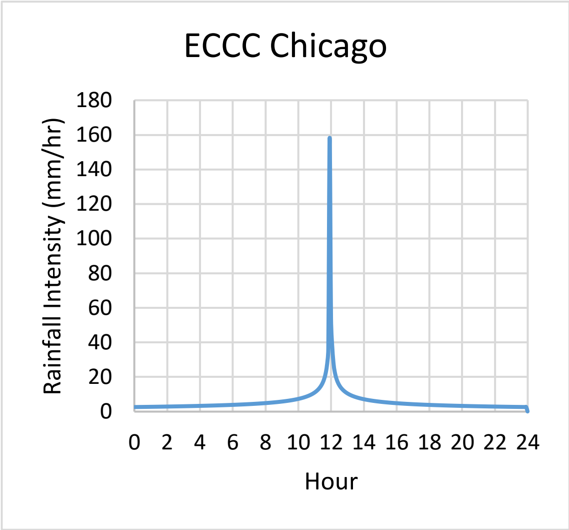

Figure 3-3: ECCC Chicago Design Storm.

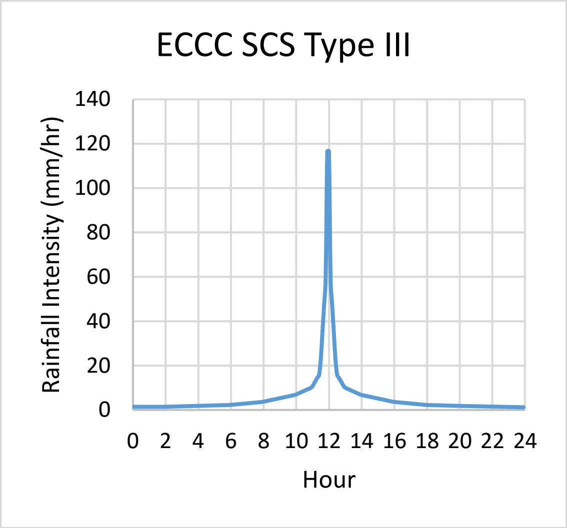

Figure 3-4: ECCC SCS Type III Design Storm.

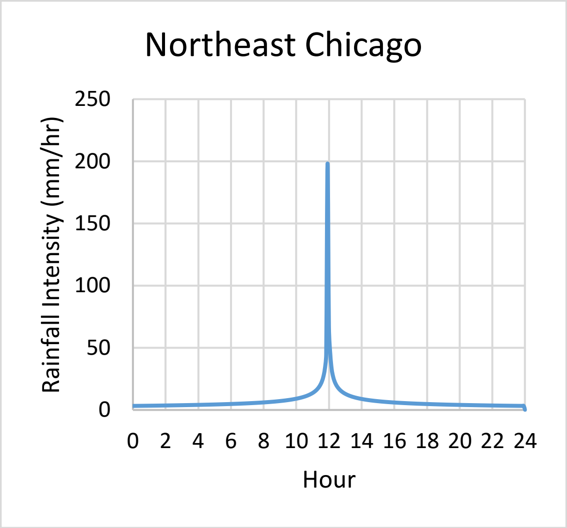

Figure 3-5: Northeast Chicago Design Storm.

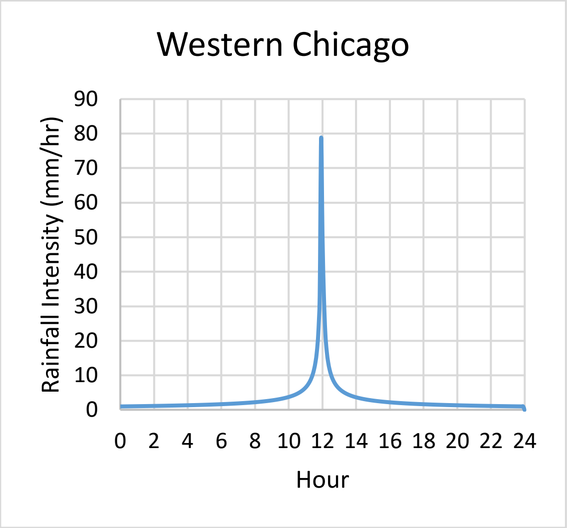

Figure 3-6: Western Chicago Design Storm.

Model scenarios focused on differing rainfall data source selection, rather than rainfall data source location. The 100-year, 24-hour duration rainfall amount at the Tracadie station was compared with the rainfall amounts of two additional closest ECCC IDF stations, i.e. Eddy Point station (53.15 km from the study area) and Caribou Point station (66.70 km from the study area). **Table 3-4** shows that the Tracadie station leads to the most conservative 100-year, 24-hour duration rainfall amount, with an 18% and 22% decrease in total rainfall amounts using the Eddy Point or Caribou Point station data respectfully. It is presumed that any change in flow due to these modelling choices would be generally proportional to the difference in total rainfall amount. This comparison illustrates the importance of considering the rainfall data station's proximity to the study area. When the nearby climate stations lead to vastly different rainfall amounts (for a given return period), further analysis would be recommended to analyze the corresponding rainfall patterns, accompanied with regional IDF data, to estimate their suitability to represent the study area watershed.

Table 3-4: 100-year, 24-hour Duration Rainfall Amount Comparison

ECCC Climate Station	Distance (km) from Centre Point of Study Area	100-year, 24 hour Duration Rainfall Amount (mm)
Tracadie	24.15	138.7
Eddy Point	53.15	114.3
Caribou Point	66.70	107.7

Figure 3-7 displays the impact, as a % change on peak flows, of replacing the hyetograph type, from the original Chicago distribution, with either a block hyetograph or an SCS Type III hyetograph, for the 17 representative nodes. It is noted that all three distributions have the same total amount of rainfall, so any changes are purely a results of the hyetograph shape. Choosing the block hyetograph rather than the baseline Chicago distribution results in a decrease to peak flows at each node, while choosing the SCS Type III hyetograph results in an increase in peak flows at each node. Changing the rainfall hyetograph type has less impact at the nodes around the South River Lake, presumably as a result of its higher time of concentration and associated residence time.

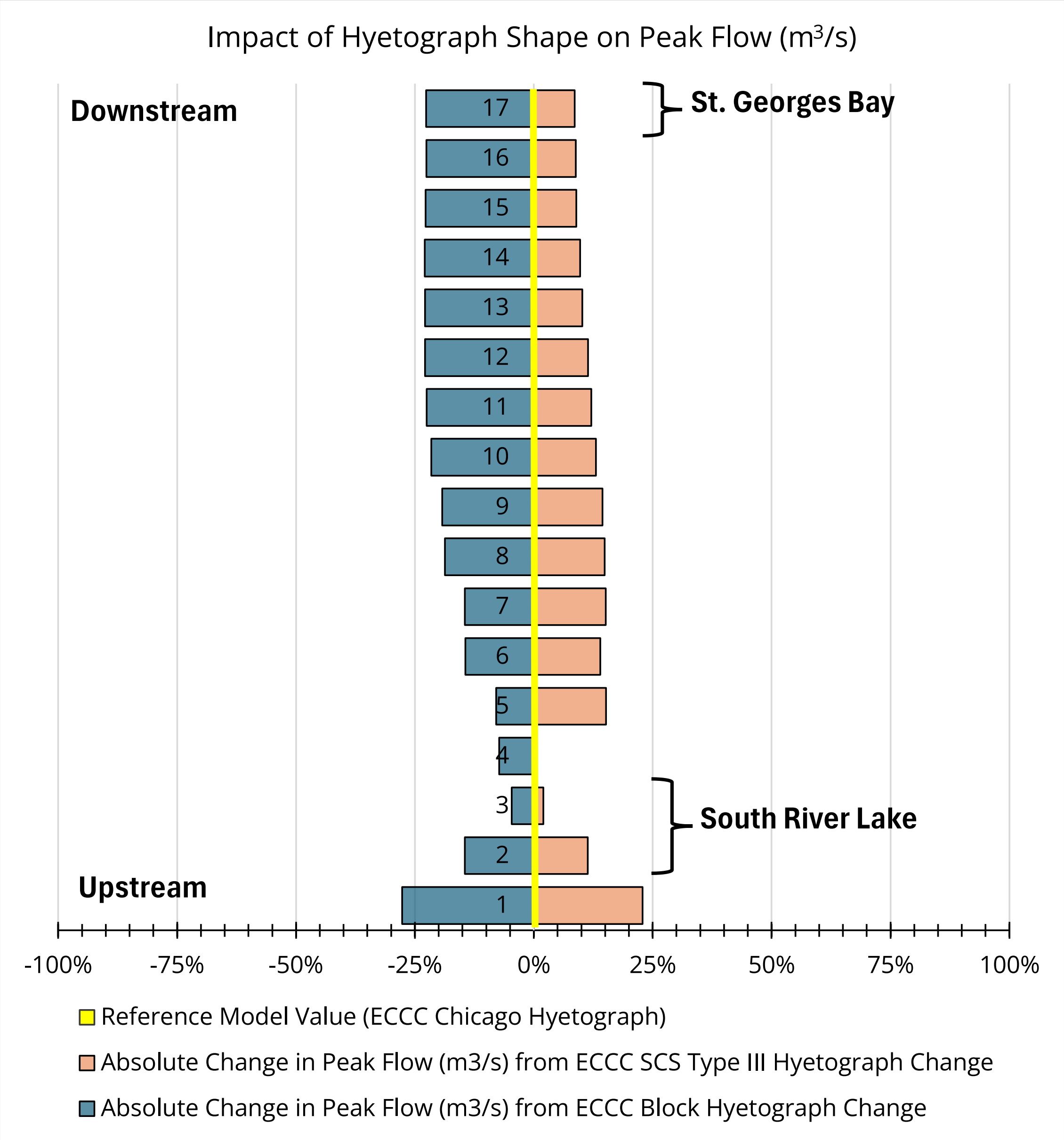

Figure 3-7: Impact of Hyetograph Type (Block or SCS Type III) on Peak Flow compared to Reference Model (ECCC Chicago Hyetograph).

Figure 3-8 shows the impact of the different hyetograph types (Block or SCS Type III vs. Chicago) on peak water levels at the 17 reference nodes. The impact of the Block hyetograph on peak flow is to slightly decrease it generally, with the largest decrease occurring at the most upstream node. Using the SCS Type III hyetograph results in slight increases to the peak water levels, also with the largest increase occurring at the most upstream node.

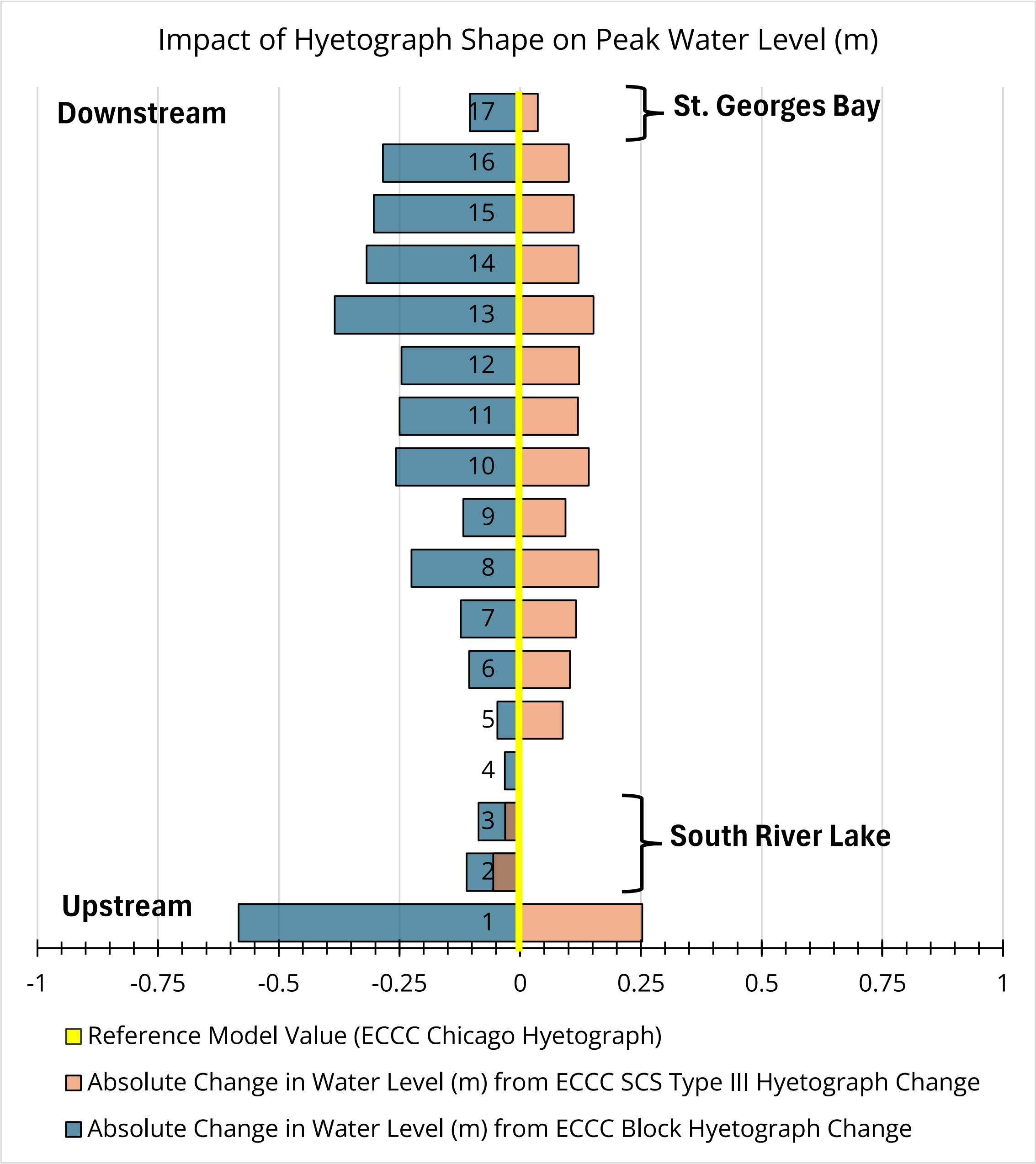

Figure 3-8: Impact of Hyetograph Type (Block or SCS Type III) on Peak Water Level compared to Reference Model (ECCC Chicago Hyetograph).

One of the main reasons why the change seems to be quite limited, even with large changes in the hyetograph shape, is likely related to the fact that the time of concentration of the overall watershed area is 25 hours and 25 minutes, which is close to the design rainfall event duration of 24 hours.

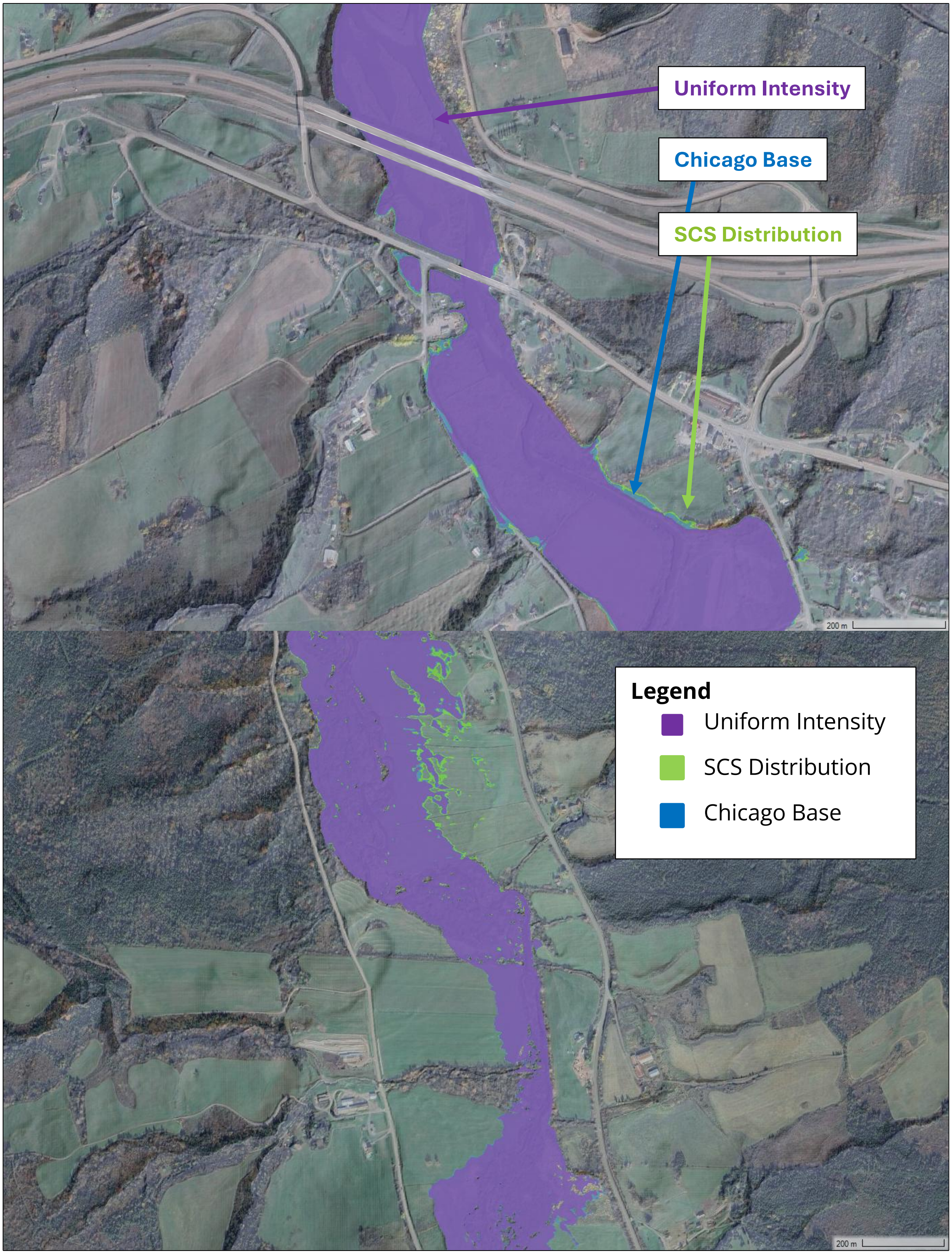

Figure 3-9: Flood Mapping showing changes in Flood extents for 3 Rainfall Distributions.

Rainfall Data Source (same location and distribution) Testing

Using the Western University IDF tool as the rainfall data source results in decreased peak flows, while using the Northeast Regional Climate Centre tool results in increased peak flows, with these percentages differences both getting larger at the nodes around South River Lake (**Figure 3-10**).

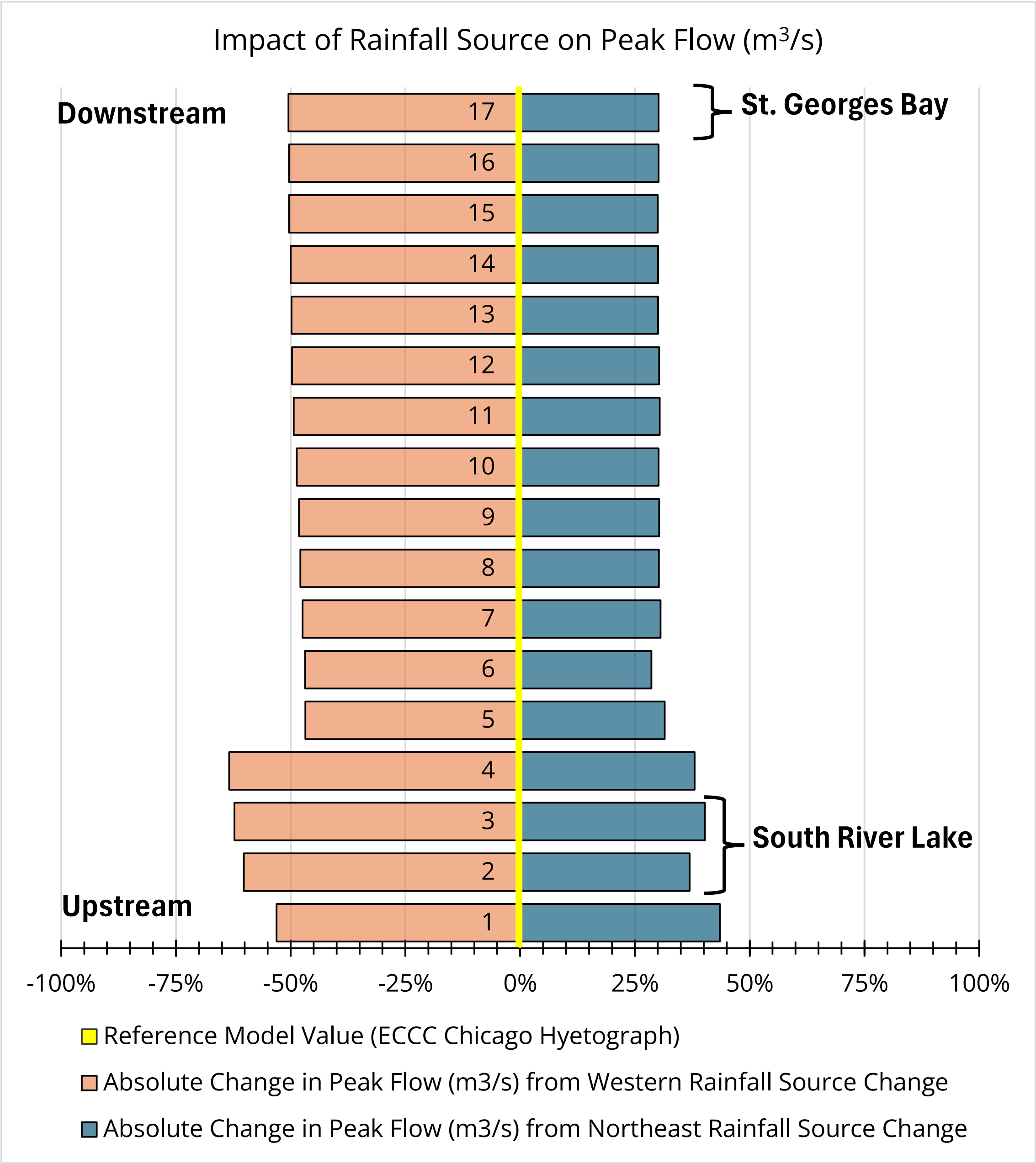

Figure 3-10: Impact of hyetograph source (Northeast or Western tools) on Peak Flow compared to Reference Model (ECCC Chicago Hyetograph).

Figure 3-11 shows the impact of hyetograph source (Northeast or Western tools vs. ECCC rainfall data) across the 17 nodes on peak water levels. The Figure shows that by choosing the Northeast tool as the rainfall source, peak water levels are generally increased at all nodes and increased most at nodes surrounding South River Lake. Choosing the Western tool as the rainfall source results in generally decreased peak flows, and decreased most at nodes surrounding South River Lake, presumably due to lake flow dampening effects. The differences arise because of the change in total precipitation amount (which is the only aspect changed in this testing) and it is interesting to note the variation on peak flows and water levels across the watercourse features.

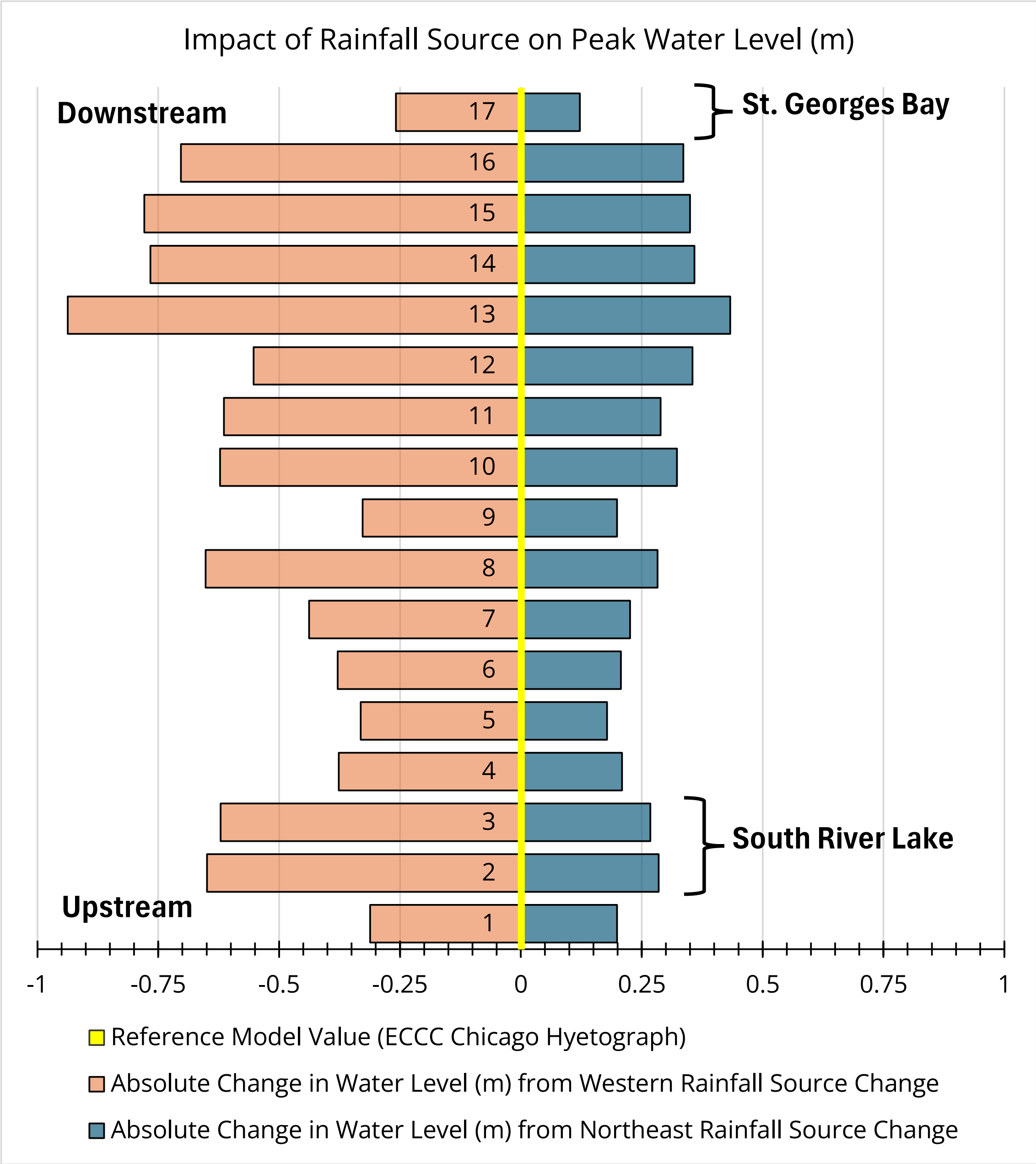

Figure 3-11: Impact of hyetograph source (Northeast or Western tools) on peak water level compared to Reference Model (ECCC Chicago Hyetograph).

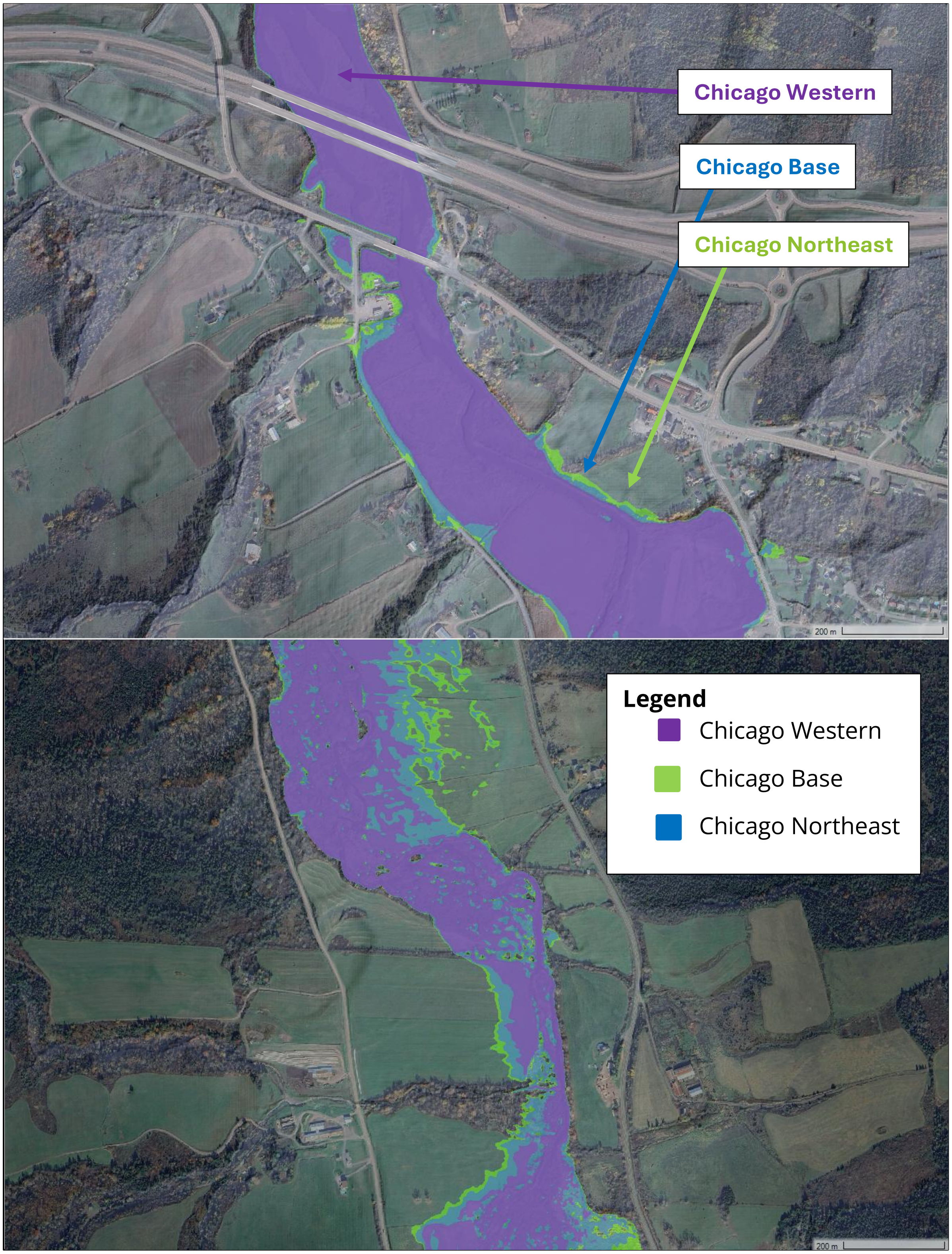

Figure 3-12: Impact of hyetograph source (Northeast or Western tools) on peak flood extents.

Overall, the choice of design storm rainfall hyetograph greatly affects average water level in the modelled watershed. **Table 3-5** highlights the importance of choosing a conservative, yet realistic design storm. It should also be noted that the block hyetograph shape does not have a pronounced peak, rather a constant rainfall intensity, which is not physically realistic.

Table 3-5: Average Water Level Change Across all Modelled Nodes due to Rainfall Hyetograph Changes

Test	Rainfall Source	Hyetograph Type	Total Rainfall Amount (mm)	Peak 100-yr Storm Rainfall Intensity (mm/hr)	Average Water Level Change (m)
Reference Scenario					
	ECCC	Chicago	138.7	158.7	-
Comparative Scenarios					
Rainfall Source	Northeast Tool	Chicago	178.2	198.2	0.272
	Western Tool	Chicago	78.7	78.6	-0.548
Hyetograph Shape	ECCC	SCS III	138.7	116.508	0.096
	ECCC	Block	138.7	6	-0.21

3.1.3 Estimation of Uncertainty in Hydrologic Parameters

There are various parameters used in PCSWMM models to determine hydrologic characteristics. The following are considered for this sensitivity analysis since they are the main parameters that can have major impacts on the resulting flows. Three points are tested for each parameter to assess its sensitivity on the modelling results to estimate a general lower and upper bound (within typical ranges) from the original calibrated values.

- Soil infiltration and soil moisture conditions.
- Discretization level of the subcatchments (subcatchment size).
- Subcatchment flow path lengths.

3.1.3.1 Soil Conductivity

Soil conductivity was spatially weighted to each subcatchment using the Canadian Soil Information Service (CANSIS). Soil conductivity was subsequently adjusted during the model calibration. Such an adjustment can lead to large changes in water level and flow results, reflecting the highly variable nature of soil conductivity. Three models were created, one for reference conductivity (the calibrated value), one for 10 times more than the reference conductivity, and one for 10 times less than the reference conductivity.
The average calibrated conductivity in the model is 0.19 mm/hr, which is low (reference for clay is 0.25 mm/hr), and could mean that there is very little capacity for the soil to get any lower in conductivity. Increasing the conductivity would encourage more infiltration, and less surface runoff, thus leading to a lower peak flow and lower water level as well.

Figure 3-13 and **Figure 3-14** show the impact of those changes on flows and water levels at key points along the river.

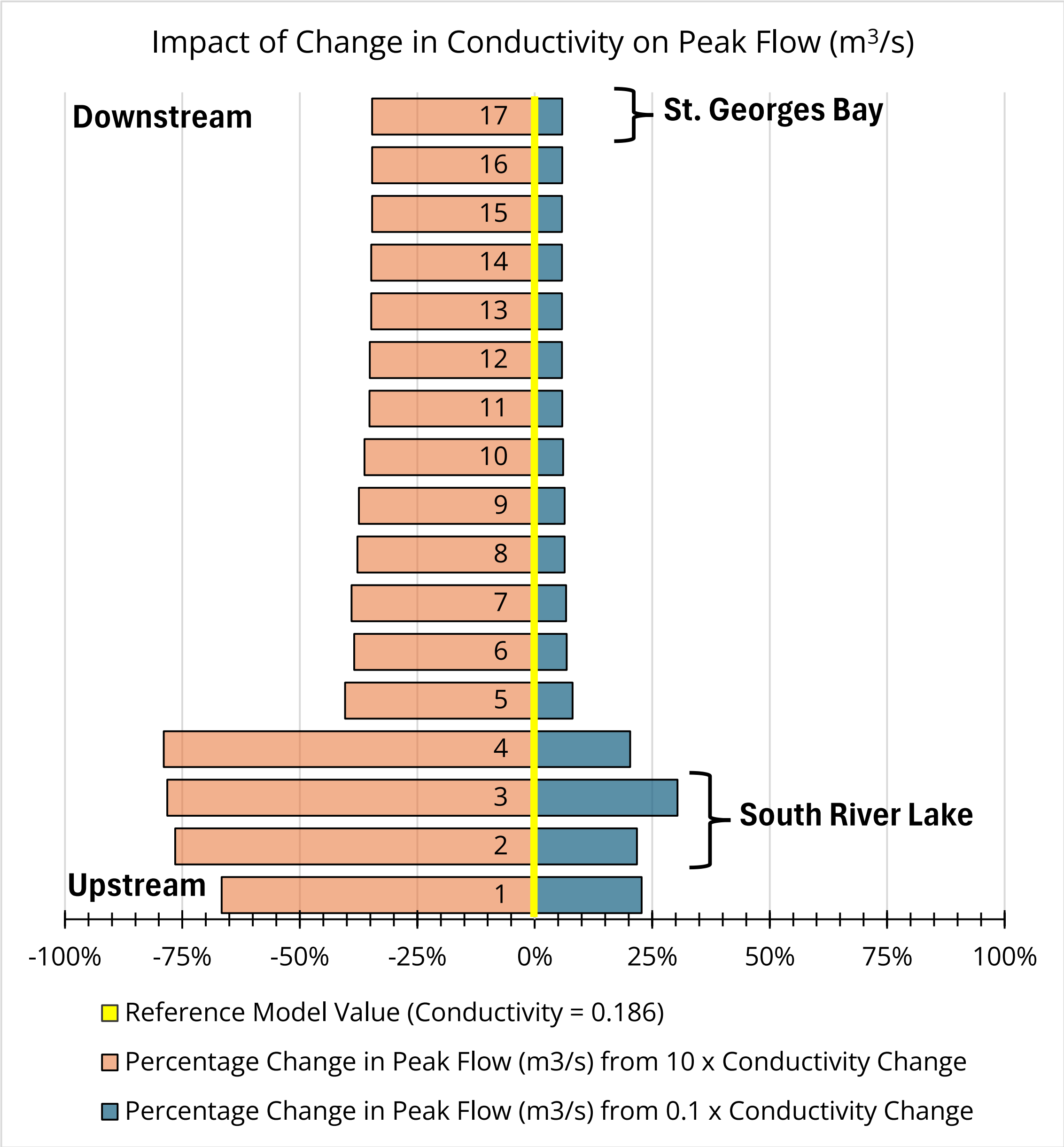

Figure 3-13: Impact of 0.1X and 10X Conductivity on Peak Flows compared to Reference Model (Average Conductivity Value = 0.186).

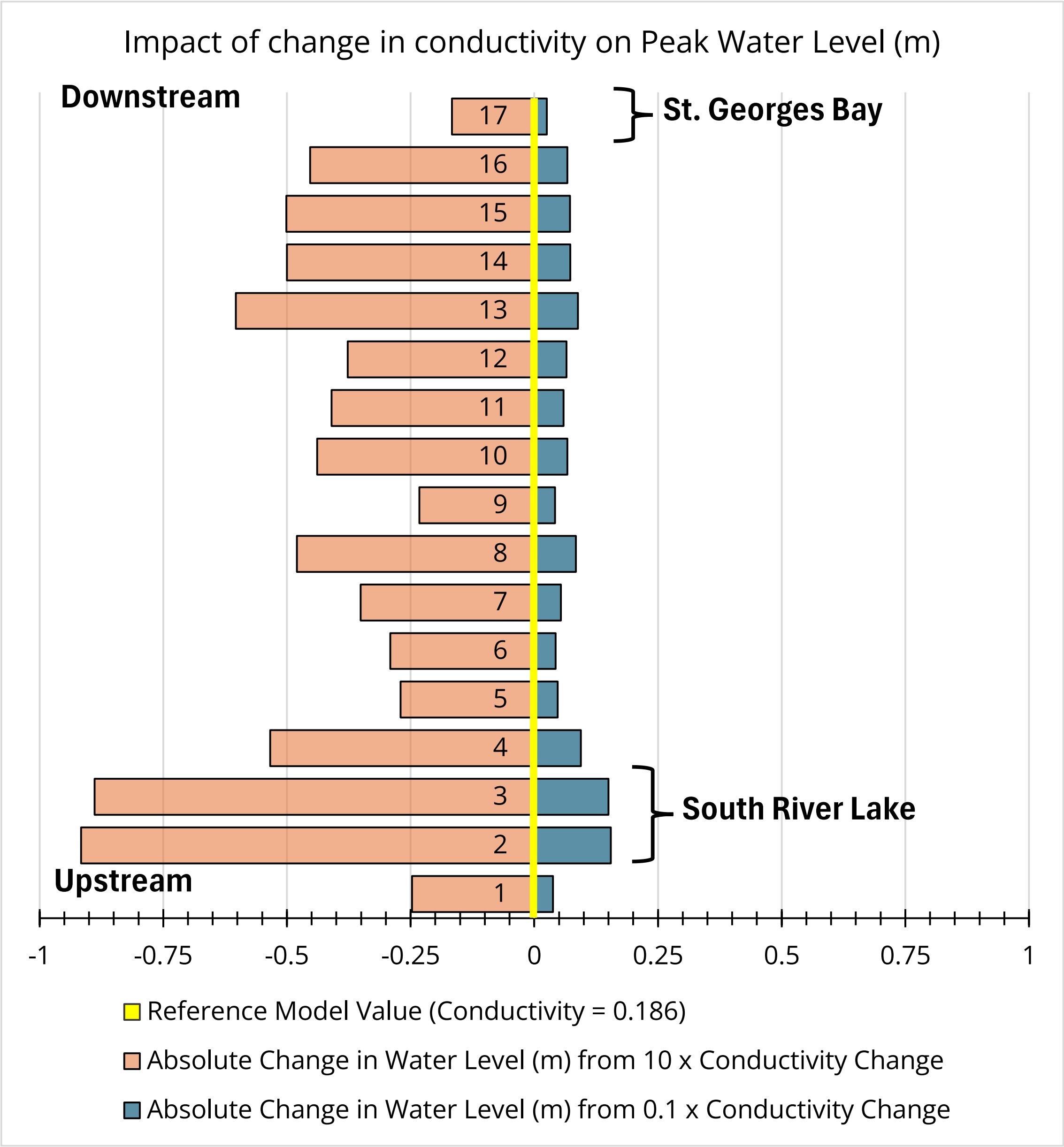

Figure 3-14: Impact of 0.1X and 10X Conductivity on Peak Water Level compared to Reference Model (Average Conductivity Value = 0.186).

It can be observed from the figures above that increasing the soil conductivity by 10 times has a large effect on peak flow (up to ~ 80% in the upper reaches of the watershed) while decreasing the conductivity by 10 has a lesser, but still notable, impact on peak flows (up to ~30%). There are larger percent changes at the nodes surrounding South River Lake, which highlights the importance of slight changes in conductivity in areas where water flows slowly (which allows a longer infiltration time).

Considering water levels, similar trends can be observed, with a lesser magnitude.

In general, hydraulic conductivity is one of the most influential parameters on runoff, and in turn peak flows, and hence on water levels. Its high level of uncertainty makes this parameter one of the key calibration parameters and highlights the importance of flow calibration (vs estimating infiltration based on soil type) and of obtaining good quality measured flow data to support model calibration.

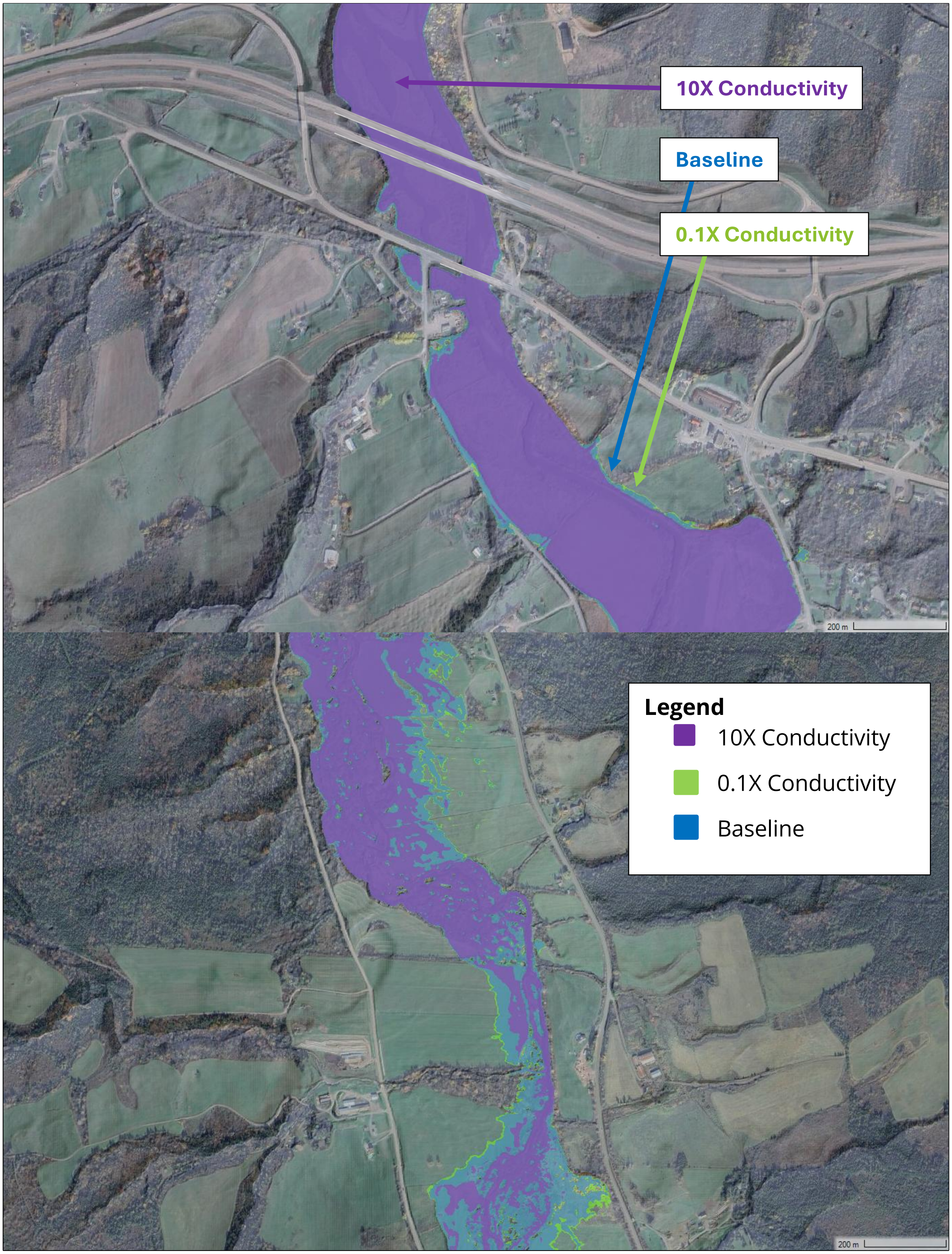

Figure 3-15: Impact of Conductivity (0.1 X Base and 10 X Base) on peak flood extents.

3.1.3.2 Initial Deficit

Upper and lower bound values for Initial Soil Moisture Deficit (as a fraction) were selected to represent both a very dry initial soil moisture (moisture deficit fraction of 0.8), average conditions (moisture deficit fraction of 0.35), and almost completely saturated soil conditions (moisture deficit fraction of 0.01).

Changes to initial soil moisture deficit resulted in zero change to peak flow and water level (**Figure 3-16** and **Figure 3-17**). This was found to be caused by the fact that initial deficit only impacts soil moisture conditions at the model start, and that the rainfall at the start of the event is absorbed by the soil and allows it to reach saturation very quickly, with a negligible impact on runoff volume and in turn peak flows.

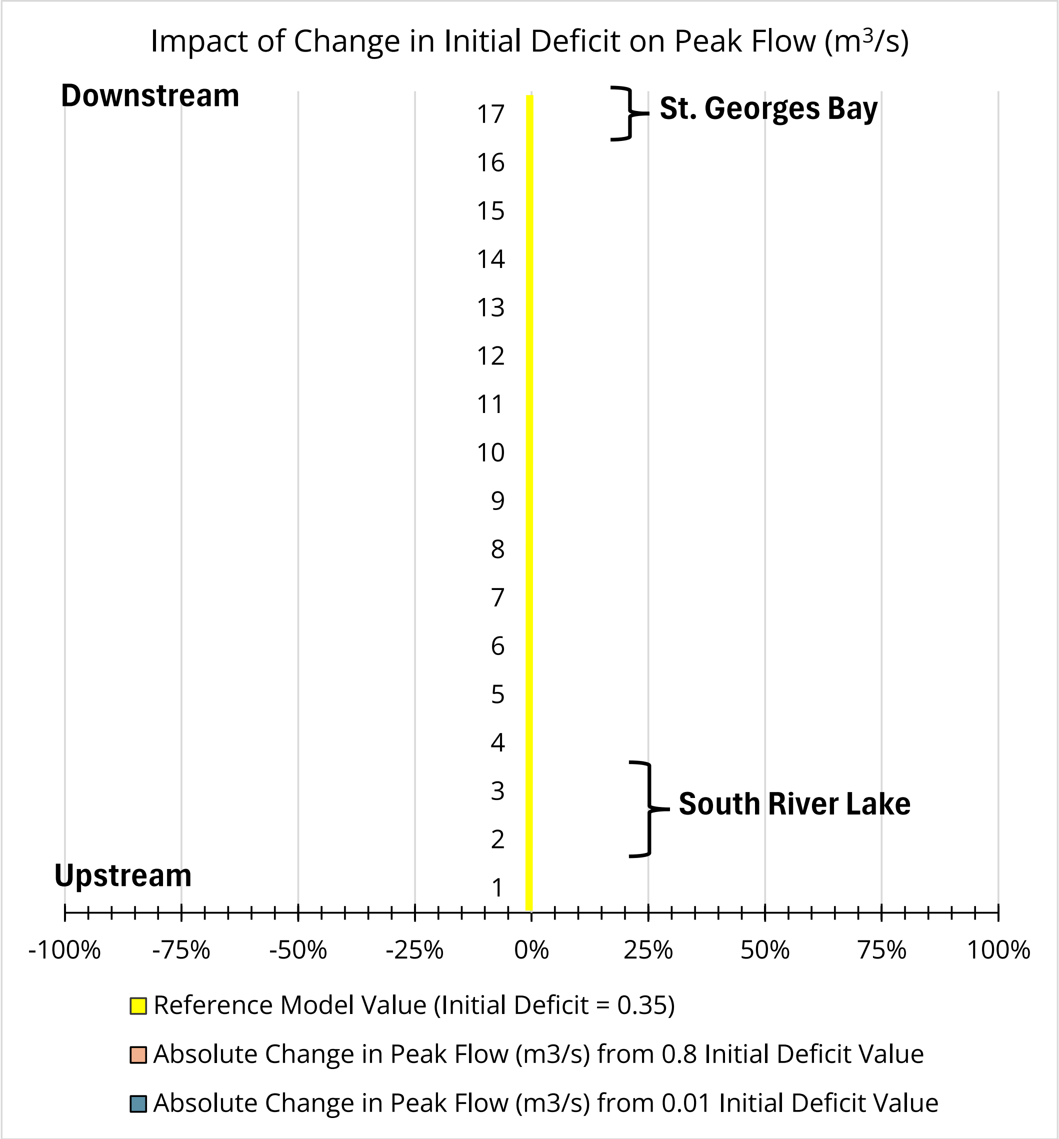

Figure 3-16: Impact of Initial Deficit values of 0.01 and 0.8 on Peak Flow compared to Reference Model (Initial Deficit Value = 0.35).

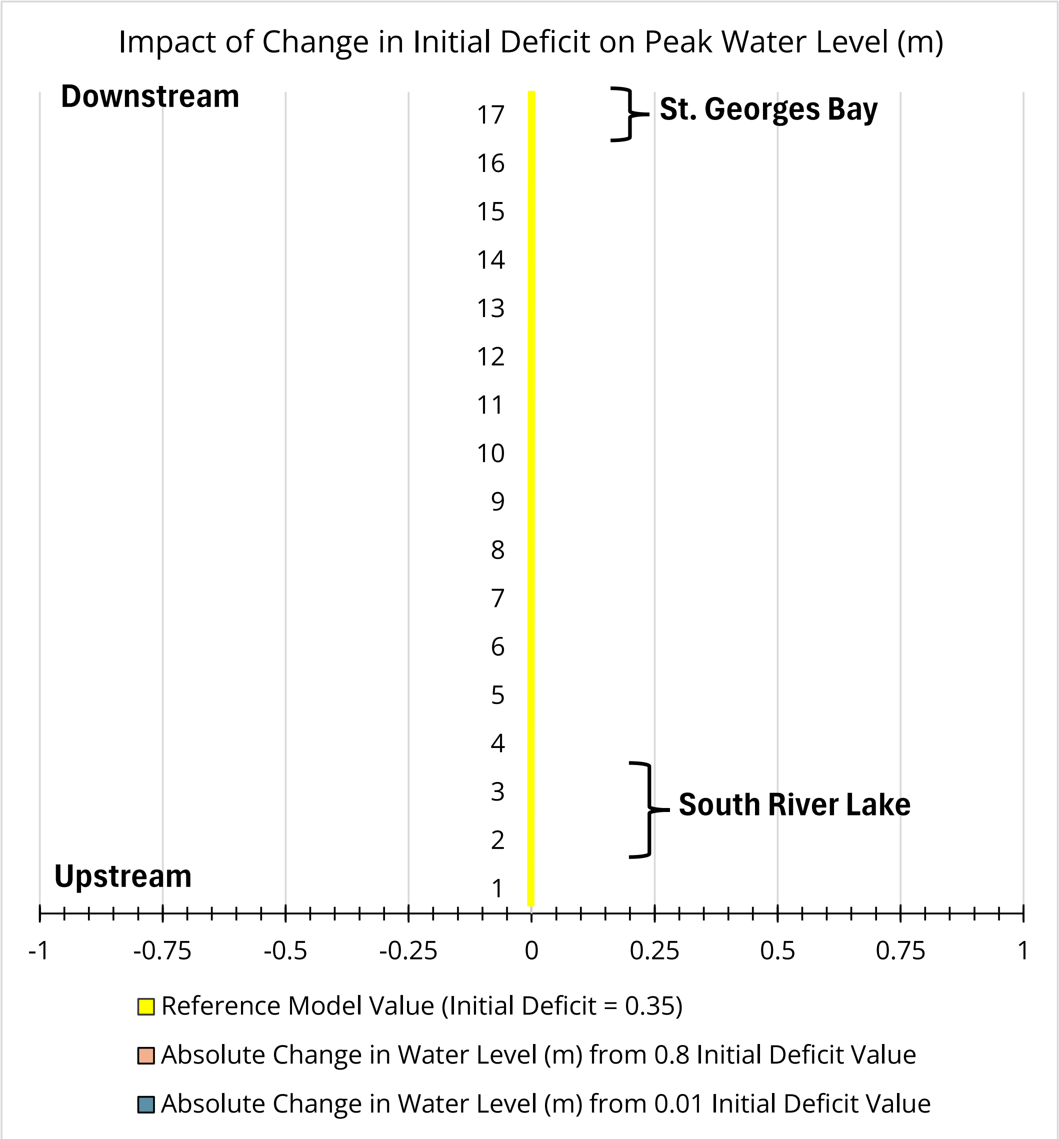

Figure 3-17: Impact of Initial Deficit values of 0.01 and 0.8 on Peak Water Level compared to Reference Model (Initial Deficit Value = 0.35).

The present testing results therefore indicate that the peak flows and peak water levels are not sensitive to variations in the Soil Moisture Deficit parameter in the Green-Ampt formulation within the SWMM model.

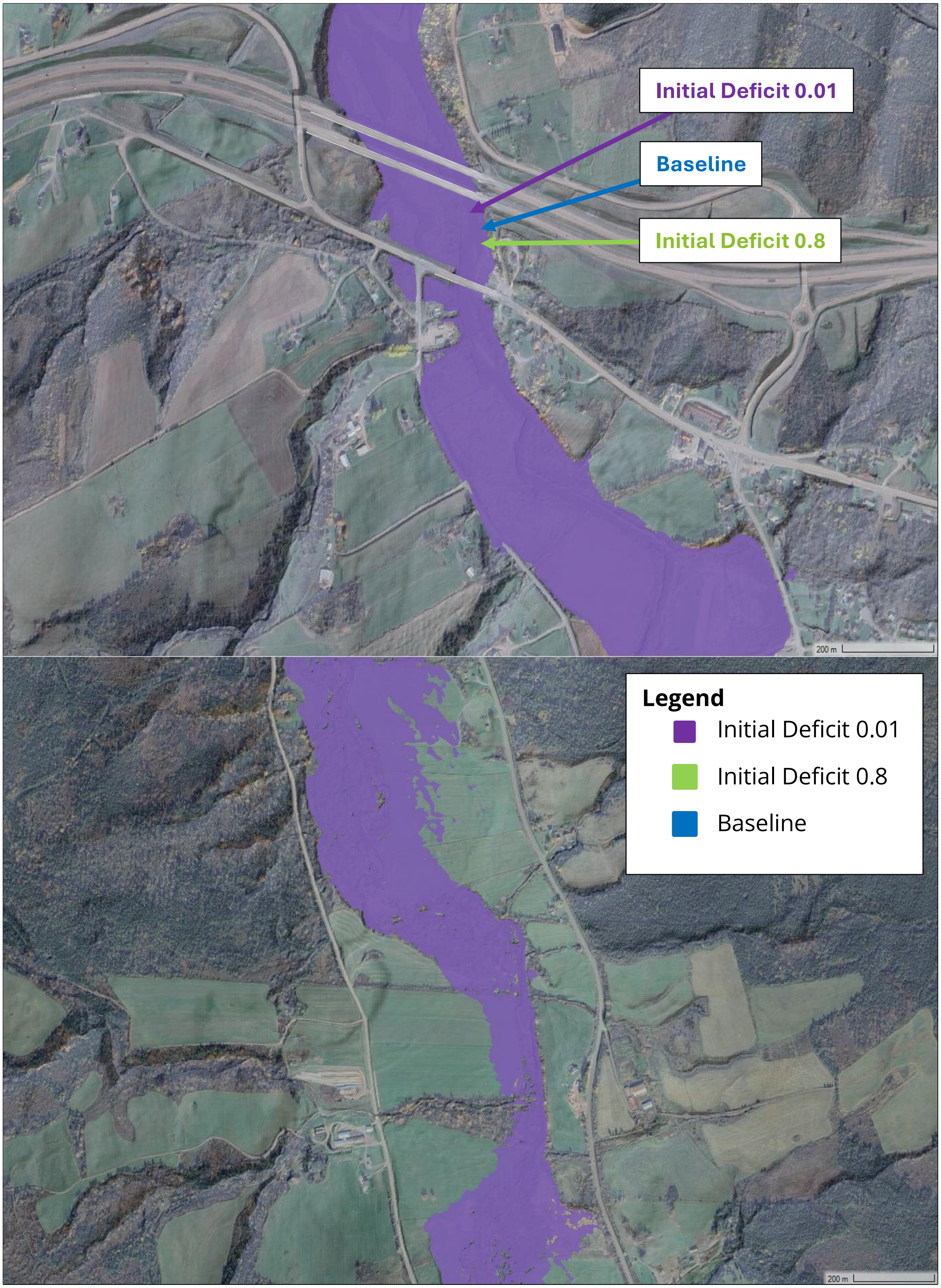

Figure 3-18: Impact of Initial Deficit (0.01 and 0.8) on peak flood extent.

3.1.3.3 Maximum Overland Flow Length

The maximum overland flow length is a parameter that is very subjectively estimated for any model and which can have a high amount of uncertainty. While it can be estimated by hand or with the support of a spatial model, there are many possible approaches that can produce very different results (e.g. drawing a single representative flow pathway vs all the possible flow pathways, drawings relatively straight lines vs meandering around all the ground sinuosities, etc.). Three models were created to propose variations on the reference (calibrated) maximum overland flow length (denoted as “flow length” in the model): 5 times larger than reference, and 5 times smaller than reference. **Figure 3-19** shows that there is a larger impact by multiplying flow length by a factor of 0.2 at the upstream nodes compared to the downstream nodes, and that there is more variance in peak flow caused by multiplying flow length by a factor of 0.2 than multiplying flow length by a factor of 5 across all nodes.

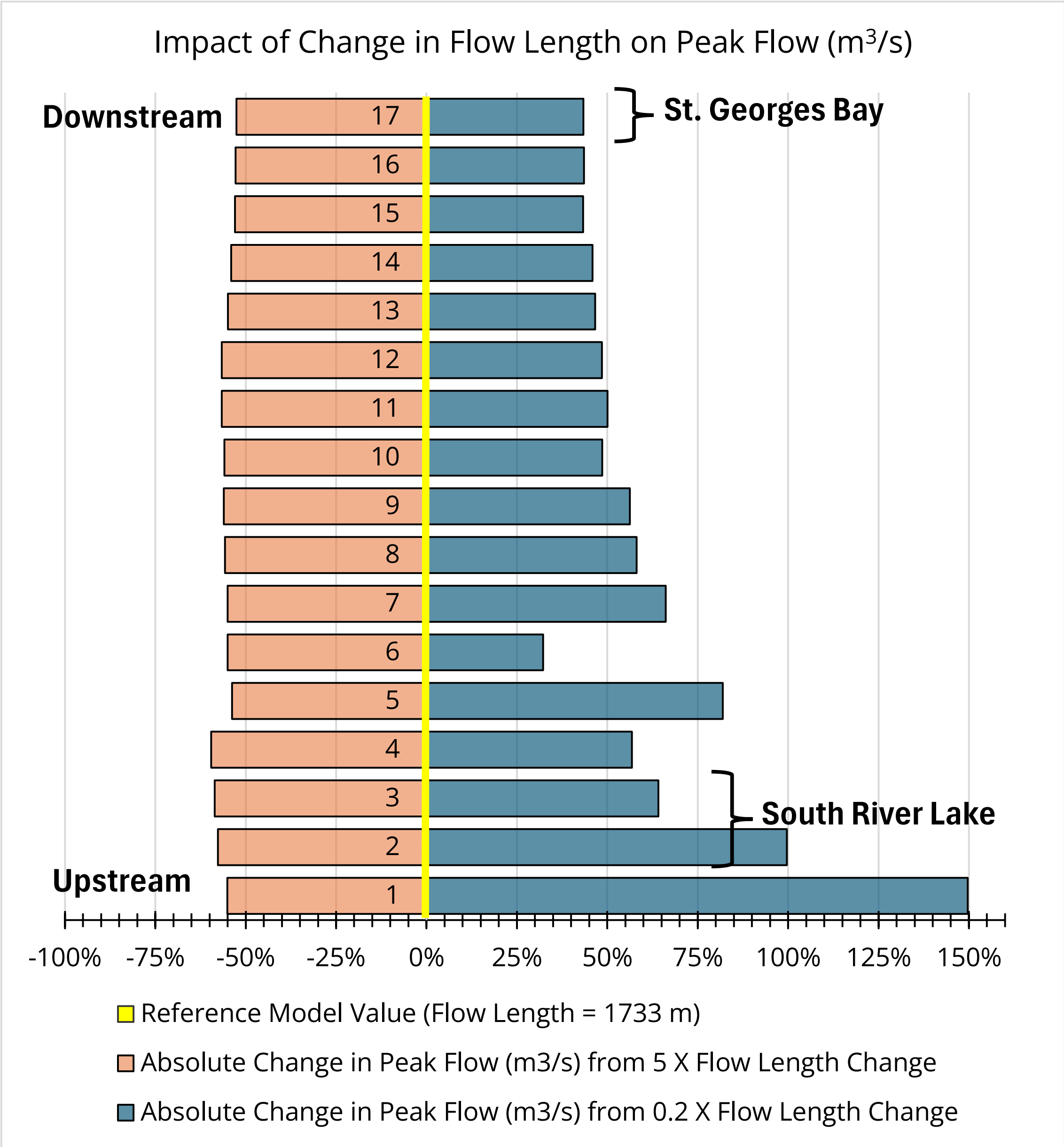

Figure 3-19: Impact of 0.2X and 5X Flow Length on Peak Flow compared to Reference Model (Average Flow Length Value = 1733 m).

Figure 3-20 shows the impact of scaling flow length on water level, which is fairly consistent across all nodes. Increasing flow lengths by factor of 5 in turn decreases peak water level at all nodes on average by 27% and scaling it by 0.2 increases peak water level by 21% on average.

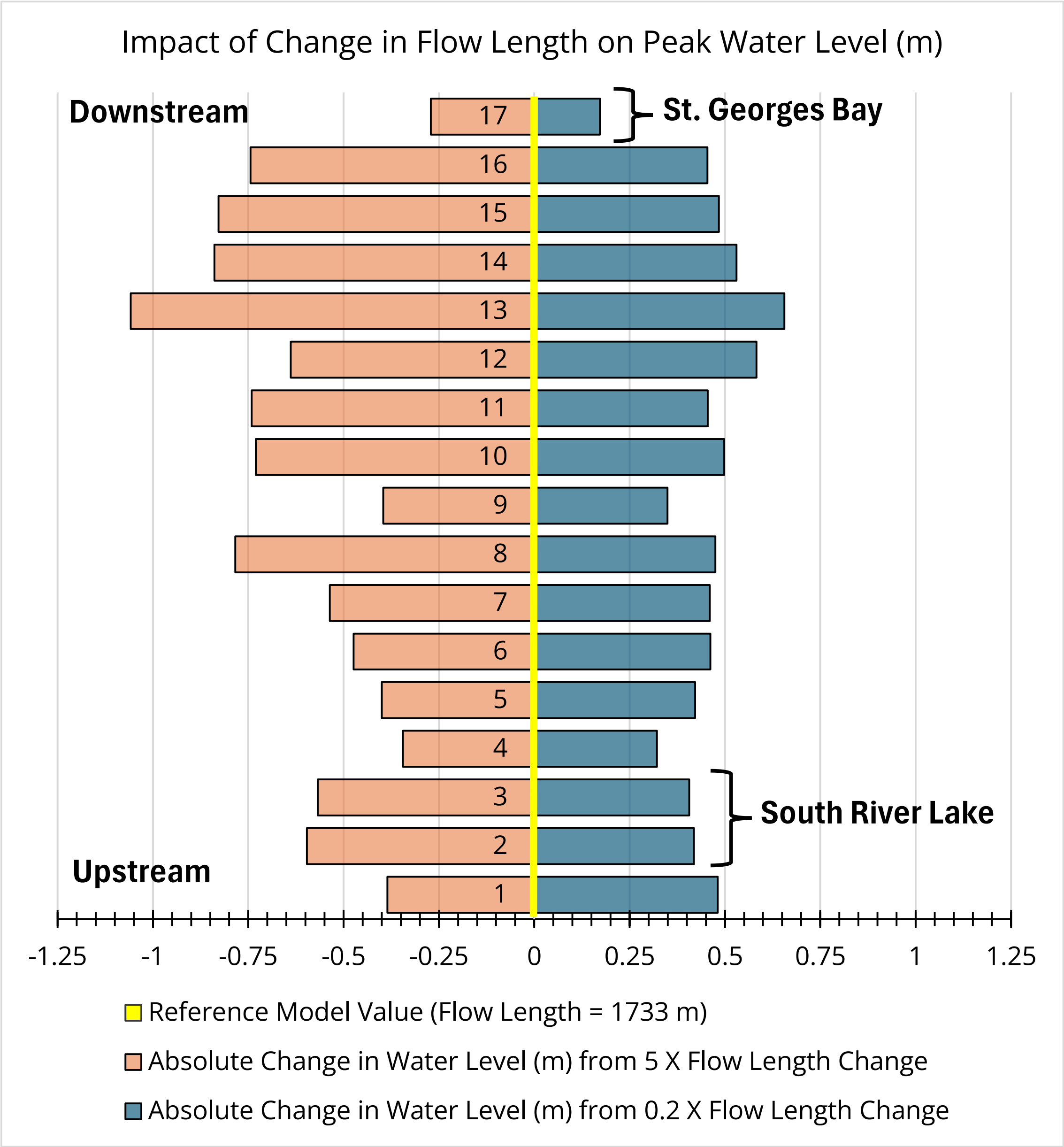

Figure 3-20: Impact of 0.2X and 5X Flow Length on Peak Water Level compared to Reference Model (Average Flow Length Value = 1733 m).

The high impact on flows and water levels resulting from variations in this parameter demonstrate the importance of its careful selection, and the value of calibration. Since it is such an uncertain parameter, it is a potential candidate for model calibration.

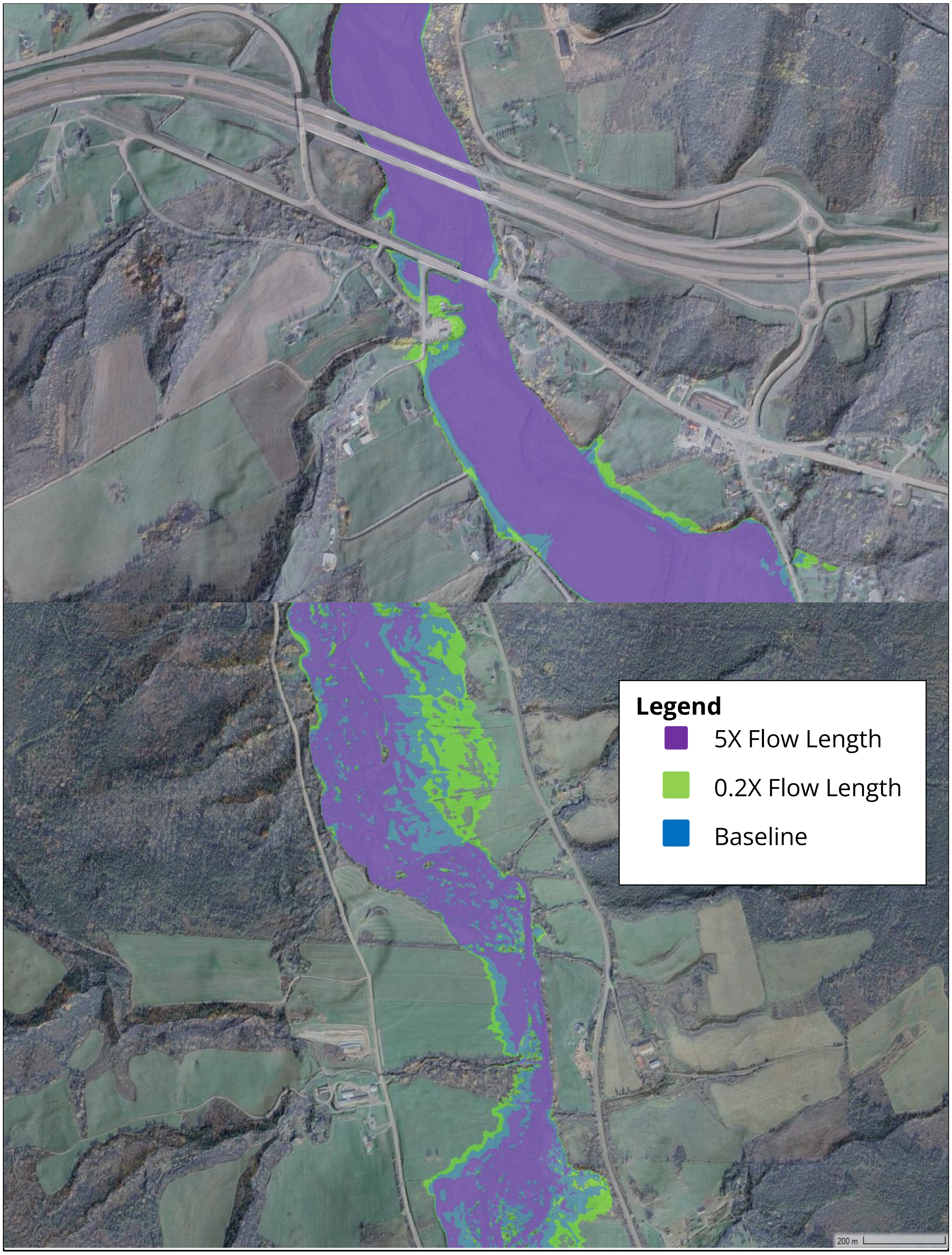

Figure 3-21: Impact of change in Flow Length (0.2X and 5X) on peak flood extents.

3.1.3.4 Discretization Level of Subcatchments

The amount of subcatchment discretization is also a parameter largely left to the modeller to decide upon. While there is no hydrological reason supporting the fact that subdividing a watershed into smaller subwatersheds should change its flow response, the reality is that in the modelling framework, results are different. Tests were therefore conducted with various discretization levels that are within typical approaches.

Three scenarios were created: for a reference amount of subcatchments (31 subcatchments), higher discretization (52 subcatchments), and lower discretization (4 subcatchments) (**Figure 3-22**). For all models, the hydrologic parameters were assigned in the same manner as for the reference model. A soils layer was used to spatially weight values for soil conductivity, suction head, and transect Mannings roughness, and an initial deficit value was set to 0.35 to replicate the characteristics of the baseline model. A land cover layer was used to spatially weight percent impervious, impervious Mannings roughness and impervious Mannings roughness.

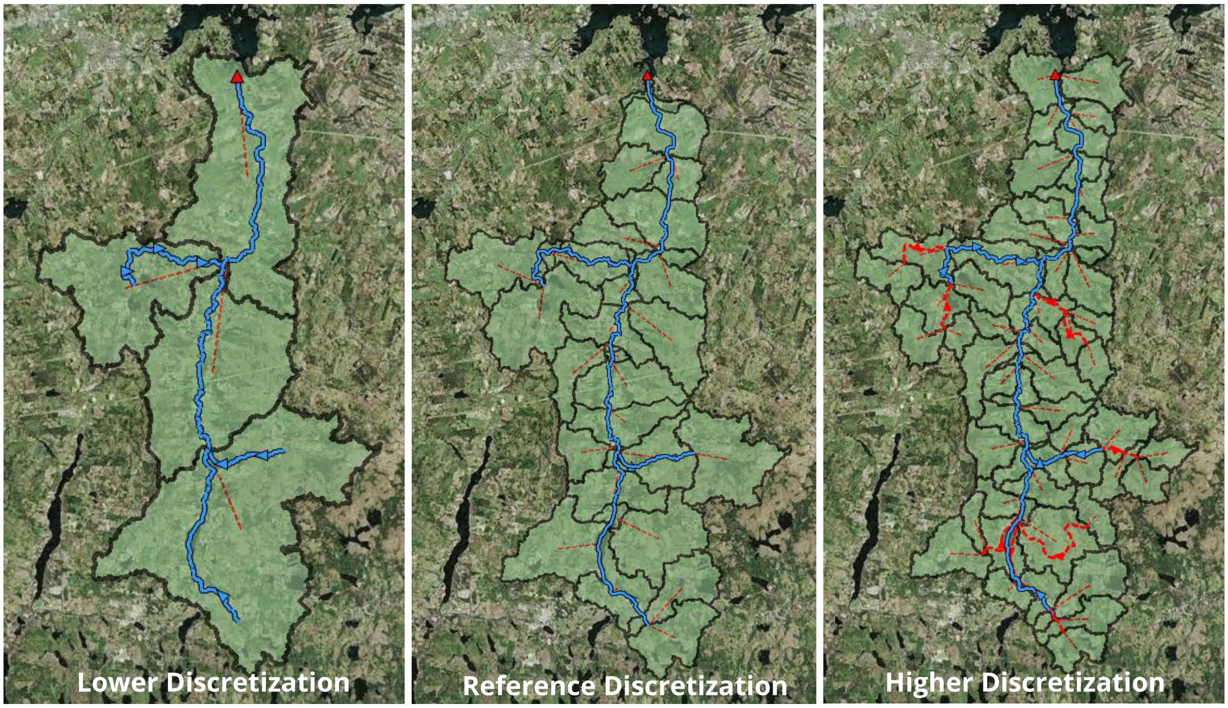

Figure 3-22: Subcatchment extents for lower discretization (4 subcatchments), reference discretization (31 subcatchments), and higher discretization (52 subcatchments).

When the discretization level is low, resulting in large subcatchments, flow inputs to the hydraulic model directly depend on the location of the subcatchment outlet (**Figure 3-23**). For example, flows will stay generally steady along the river between two flow input locations, meaning that they will not be able to gradually increase, and that flow will generally be increasingly underestimated with the distance from the flow input locations.

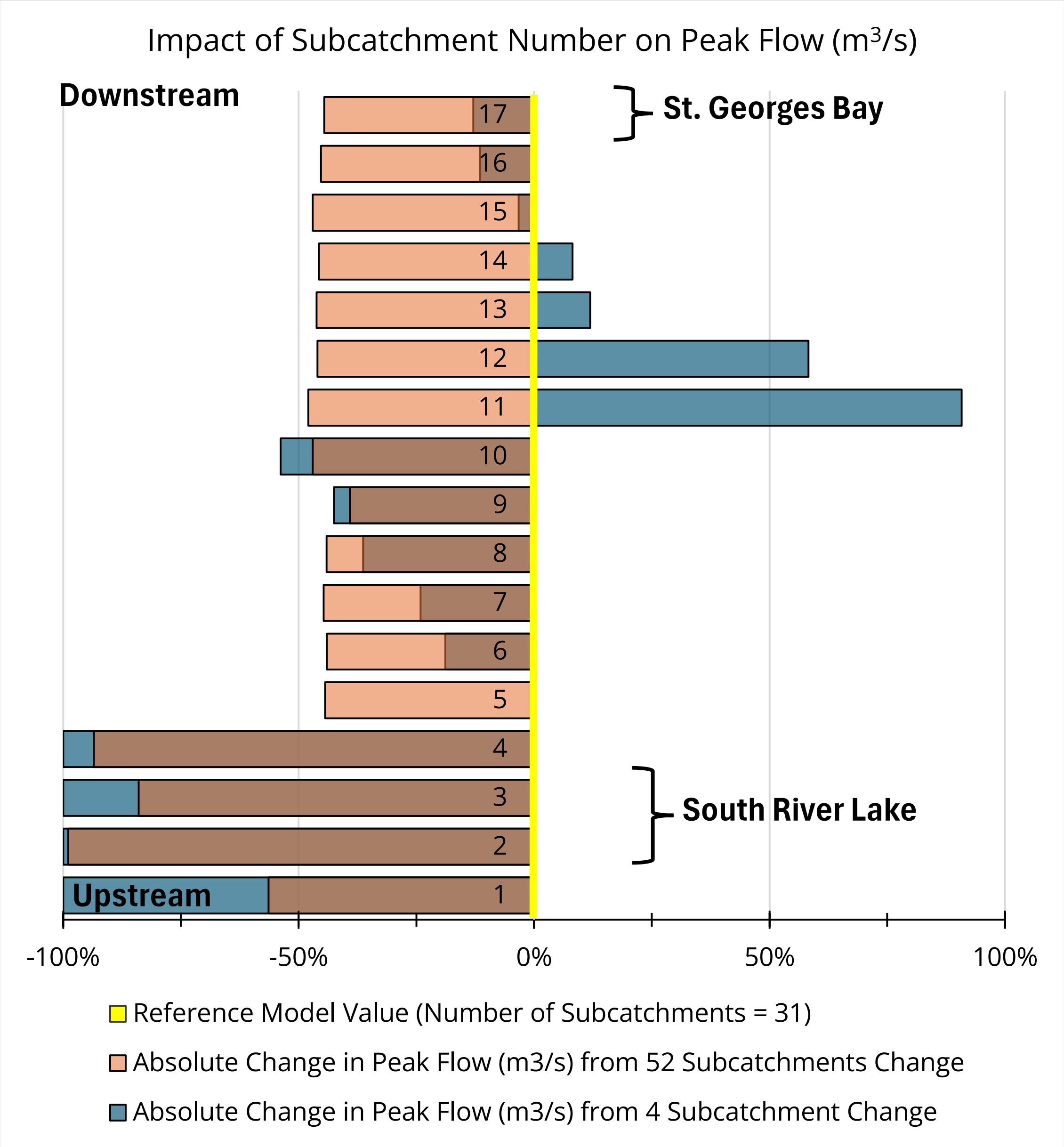

Figure 3-23: Impact 4 and 52 Subcatchments on Peak Flow compared to Reference Model (Number of Subcatchments = 31).

It is noted that there are additional changes in the results beyond discrepancies associated with distance between nodes. This could be due to changes in the representation of watershed time of concentration in the modified, uncalibrated, models. Results should therefore be interpreted more by the relative changes between nodes, rather than the absolute differences against the reference model.

Figure 3-24 shows the impact of subcatchment size on water level at all nodes, generally staying consistent for the 52 subcatchment scenario by decreasing 20% and increasing around the South River Lake to 90%. The 4 subcatchment model resulted in great variability in peak flows and water levels between nodes, whereas the 52 subcatchment model showed results that were more consistent with the reference model.

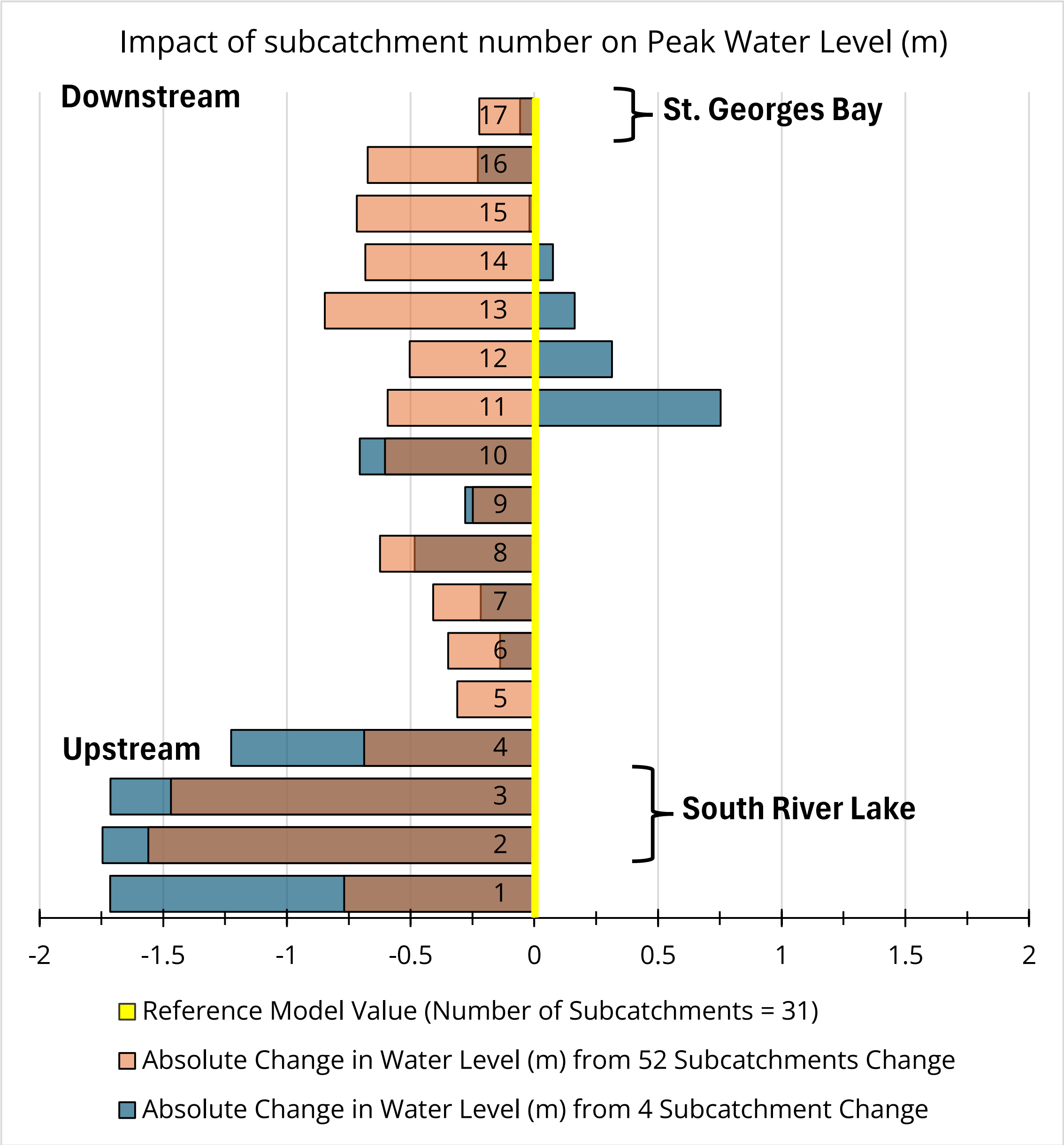

Figure 3-24: Impact 4 and 52 Subcatchments on Peak Water Level compared to Reference Model (Number of Subcatchments = 31).

The main finding of the model results is that it is valuable to discretize as much as reasonably possible the watersheds in a study area, if results are sought along the length of the study area. Insufficient discretization will result in potentially high discrepancies between the expected gradual increase in flows, and the model results. The present testing also highlighted the impact of not further calibrating the models following a modification in subcatchment discretization.

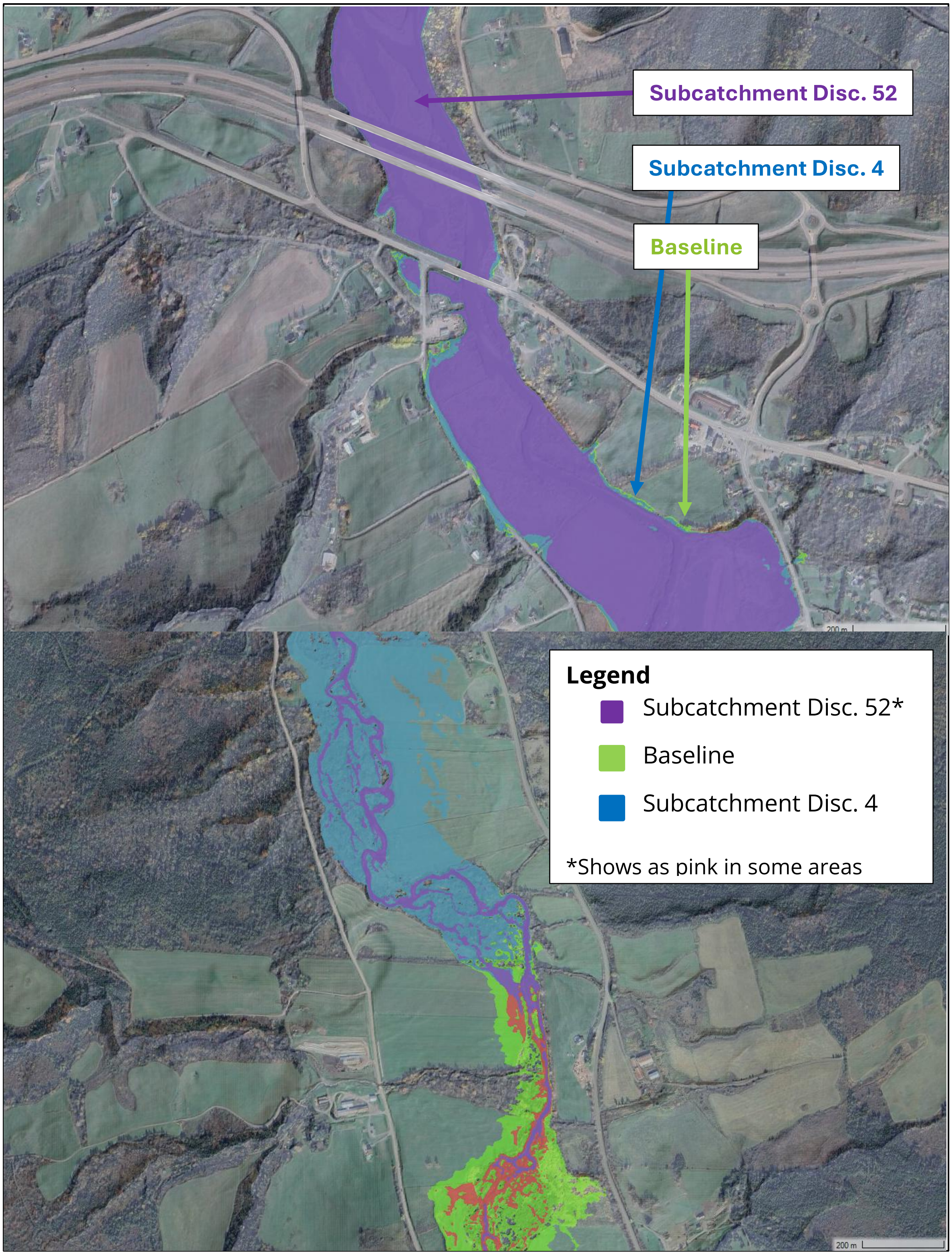

Figure 3-25 Impact of change in subcatchment discretization (4 and 52) on peak flood extents.

3.1.4 Estimation of Uncertainty in Model Calibration

Alternative Calibration to the Same Measured Flow Event

For this comparison, the baseline model, which was calibrated to a November 2021 rainfall event, was calibrated a second time to this event using different parameters, and an additional calibration was performed on the baseline model for a separate rainfall event, Hurricane Fiona, which occurred in September 2022.

For the second calibration using the November 2021 event, the Sensitivity Based Radio-Tuning Calibration (SRTC) tool in PCSWMM was used to automatically adjust parameters in the model, within a given range of uncertainty for each parameter (**Table 3-6**). This provided an unbiased (free of modeller habits and preconceptions) approach to an alternative calibration.

Table 3-6: SRTC Tool Uncertainty Inputs

Parameter	Uncertainty	Reasoning for uncertainty chosen
Flow length	200	Highly uncertain parameter.
Slope	200	Slope estimates can vary widely based on the method of measurement.
Imperviousness	50	delineated by area weighted land use layer.
N Impervious	50	Somewhat subjective estimates based on reference photographs (e.g., Chow, 1959).
N Pervious	50	Somewhat subjective estimates based on reference photographs (e.g., Chow, 1959).
Dstore Impervious	100	Uncertain parameter.
Dstore Pervious	100	Uncertain parameter.
Conductivity	100	Can range by a large amount, even though spatially weighted from a soils layer.
Initial Deficit	100	Highly variable and subjective parameter.
Suction Head	100	These can range by a large amount, even though spatially weighting from a soils layer.

The original model calibration was completed by adjusting flow length, then conductivity. The second calibration involved adjusting conductivity (dividing by a factor of 8) and Manning's roughness (n) for pervious surfaces (dividing by a factor of 1.65).

Alternative Calibration a New Measured Flow Event

Calibration of the model to recorded flows during the Hurricane Fiona rainfall event between September 23rd and 24th, 2022, was chosen as an alternative calibration data source. This was a well-known hurricane that produced a total rainfall amount of 124 mm. Flows from the same WSC gauge that was used in the previous calibration event, the South

River at St. Andrew's Gauge (01DR001), were obtained for this event, and prorated by watershed area. It should be noted that this calibration event took place in September after a relatively dry summer, causing stream flows to be lower than expected from such a rainfall event. This calibration was done by multiplying conductivity by 8 and multiplying flow lengths by 2.5, compared to the original calibration.

Figure 3-26 shows the comparison of each calibrated model's response to the 100-year design storm at the model outlet. The figure shows that by using the same calibration event with different parameters, the resulting hydrograph for the chosen design storm is very similar. The resulting hydrograph from the Hurricane Fiona calibrated model, however, has a much lower (95 m^3/s compared to 250 m^3/s) peak flow at the gauge location that the other models. This demonstrates the importance of choosing a representative rainfall event for model calibration. Rainfall events are typically more favourable for model calibration when both the rainfall event and the associated flood have a similarly high return period, and that the model is able to adequately represent all the relevant hydrologic and hydraulic processes.

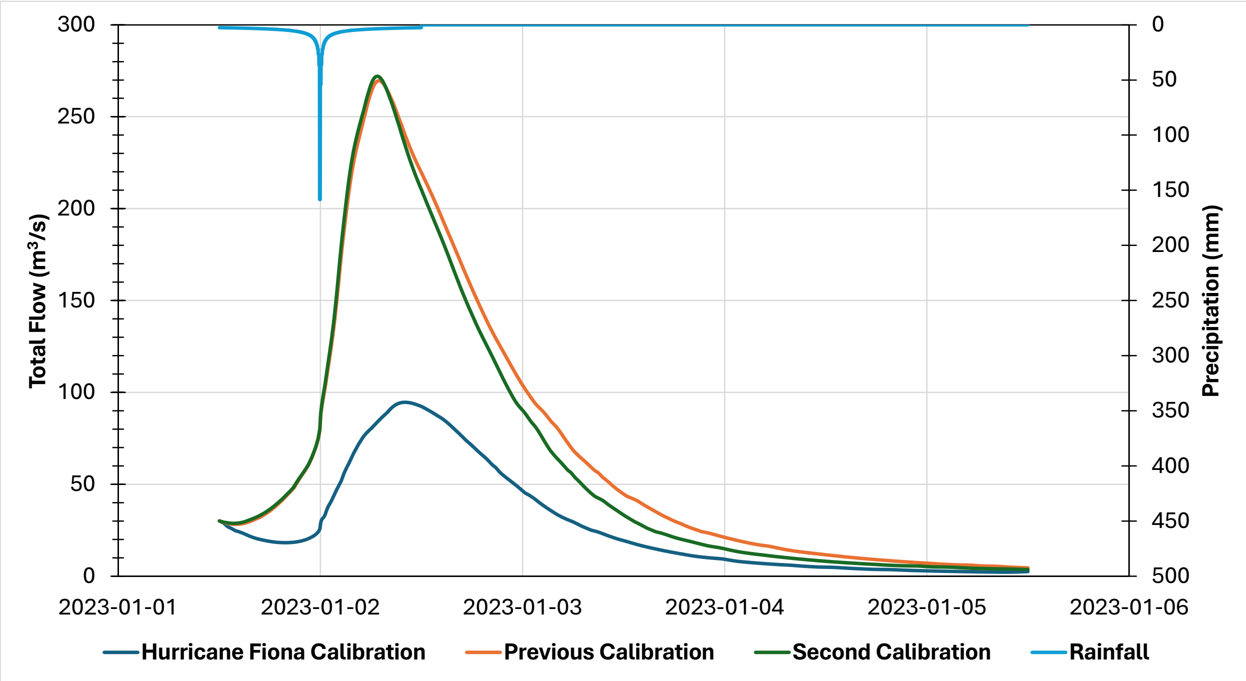

Figure 3-26: Comparison of hydrographs responses to a 1 in 100 year design rainfall event at calibrated node J116 for previous calibration, for the alternative calibration for the November 2021 rainfall event, and for the Hurricane Fiona calibration.

Figure 3-27 shows the comparison of the previous November 2021 calibration with the alternative calibration and observed flow, while **Figure 3-28** shows the calibrated model flows with observed Hurricane Fiona flows.

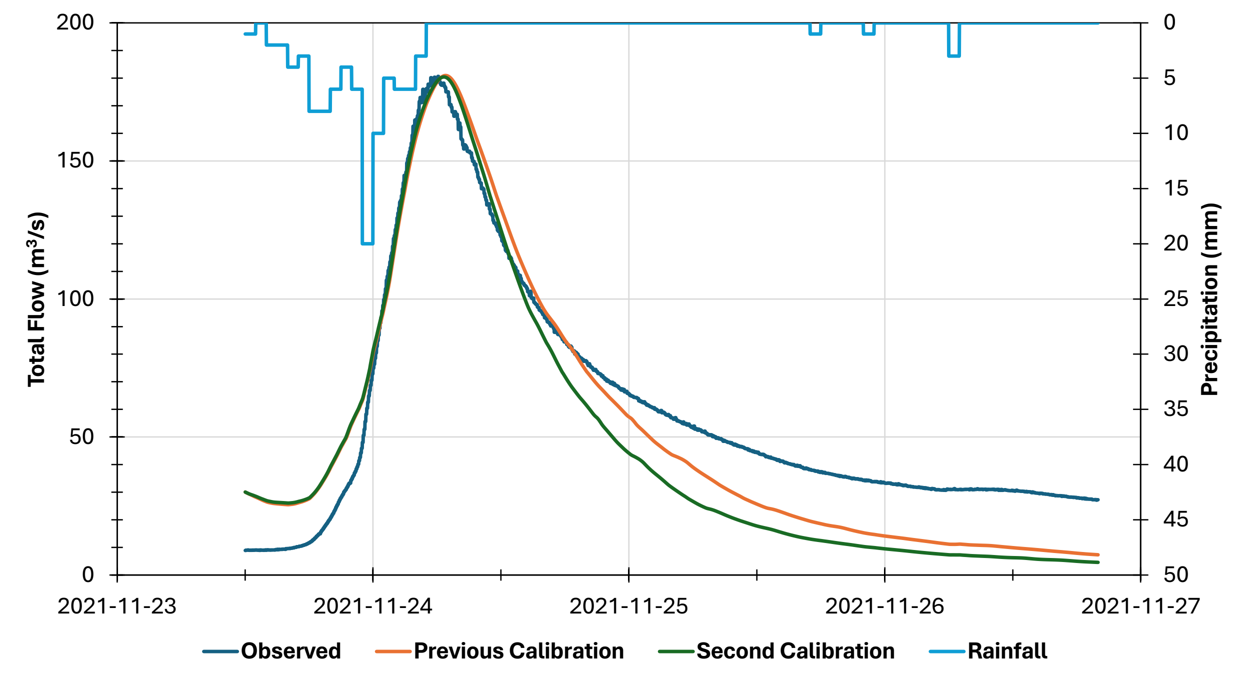

Figure 3-27: Comparison of Previous November 2021 calibration to alternative calibration and observed flow.

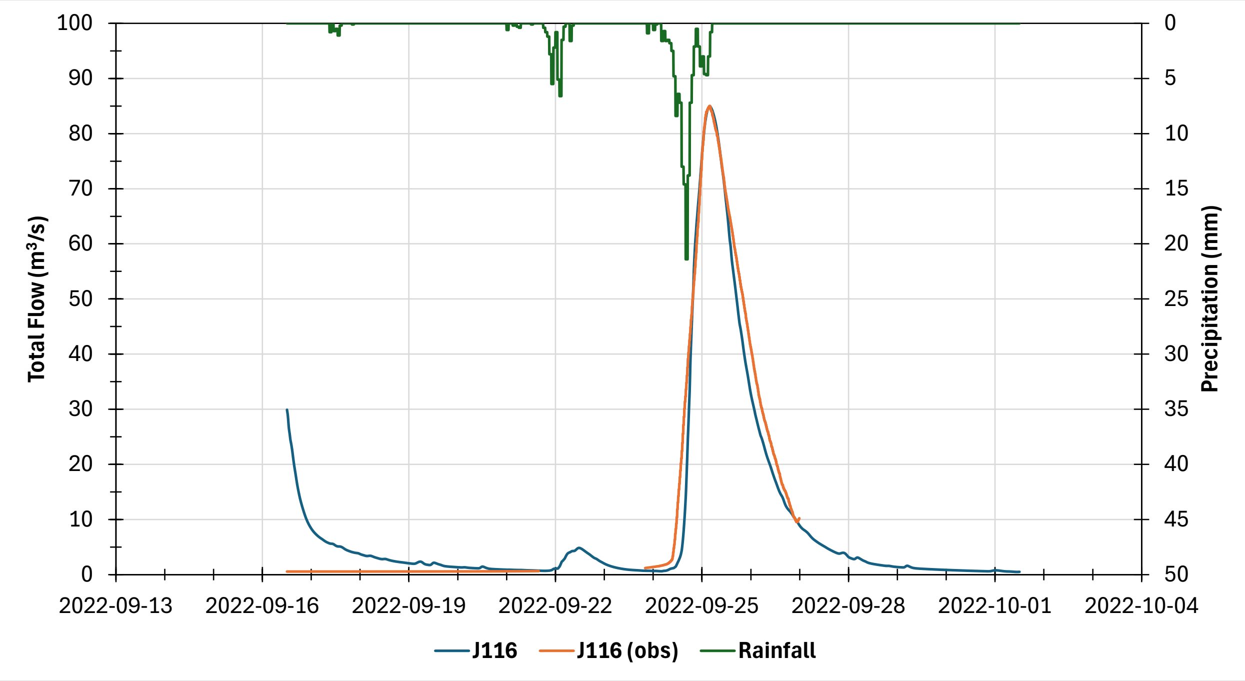

Figure 3-28: Hurricane Fiona Calibration compared to observed flow.

Figure 3-29 shows that the Hurricane Fiona calibrated model has a far greater effect on peak flows along the river than the alternative calibration model. The alternative calibration only slightly impacted peak flows, increasing them generally by 1%, and decreasing them by up to 10% around South Lake River. The Hurricane Fiona calibrated model, however, resulted in a decrease in peak flows of approximately 65% on average, and a decrease of approximately 83% around the South River Lake.

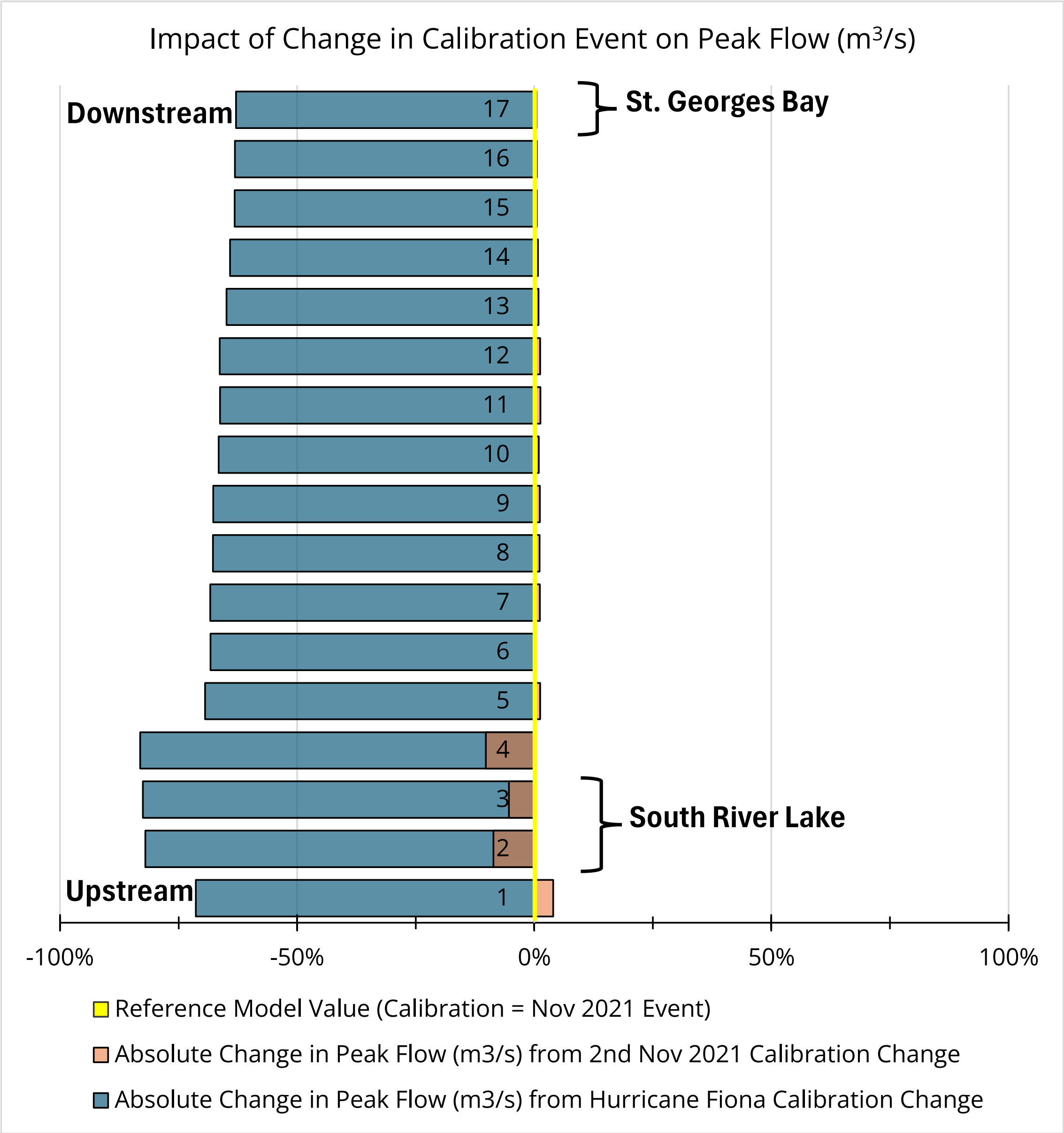

Figure 3-29: Impact Different Calibration Events on Peak Flow compared to Reference Model (Calibration = Nov 2021 Event).

Figure 3-30 shows that the alternative calibration had a very slight impact on peak water levels, whereas the Hurricane Fiona calibrated model results produced a generally consistent reduction in peak water levels by 36%, and slightly more at the nodes around the South River Lake.

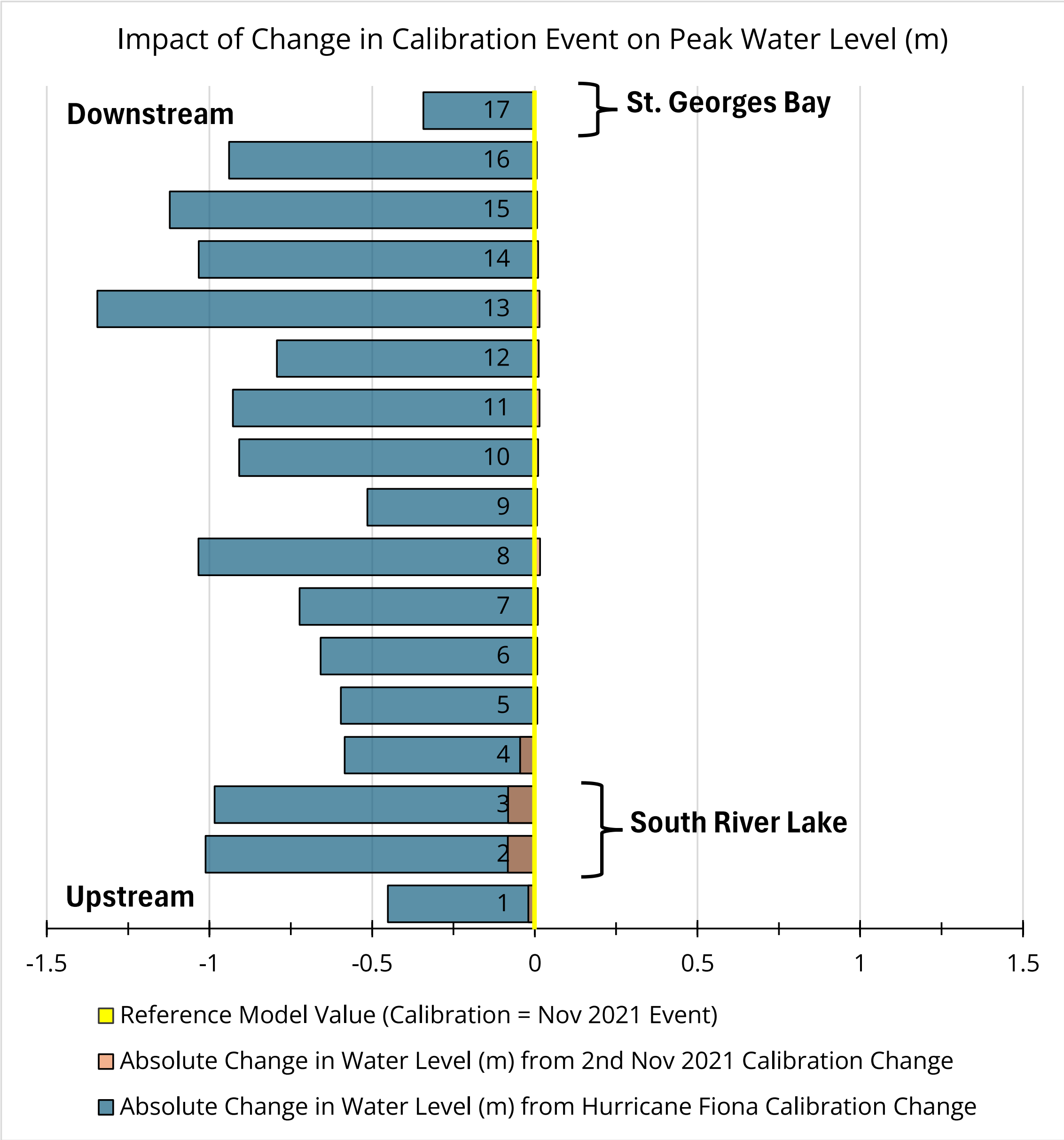

Figure 3-30: Impact Different Calibration Events on Peak Water Level compared to Reference Model (Calibration = Nov 2021 Event).

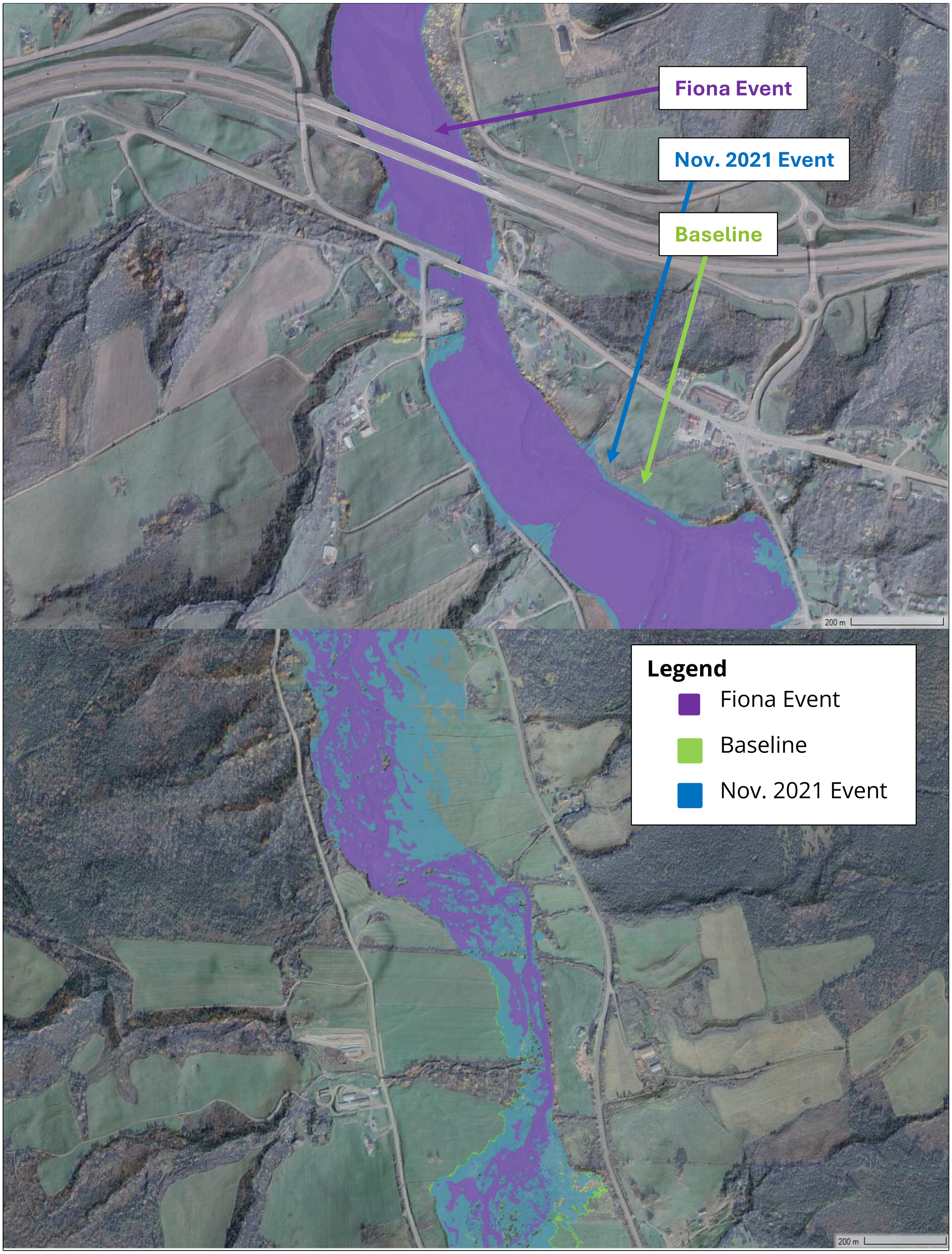

Figure 3-31: Impact of change in Calibration events (Nov 2021 and Fiona Event) on peak flood extents.

3.1.5 Summary of Results

The results of the sensitivity testing were averaged for all the 17 representative nodes and compared by parameter, presented in the set of figures and table below.

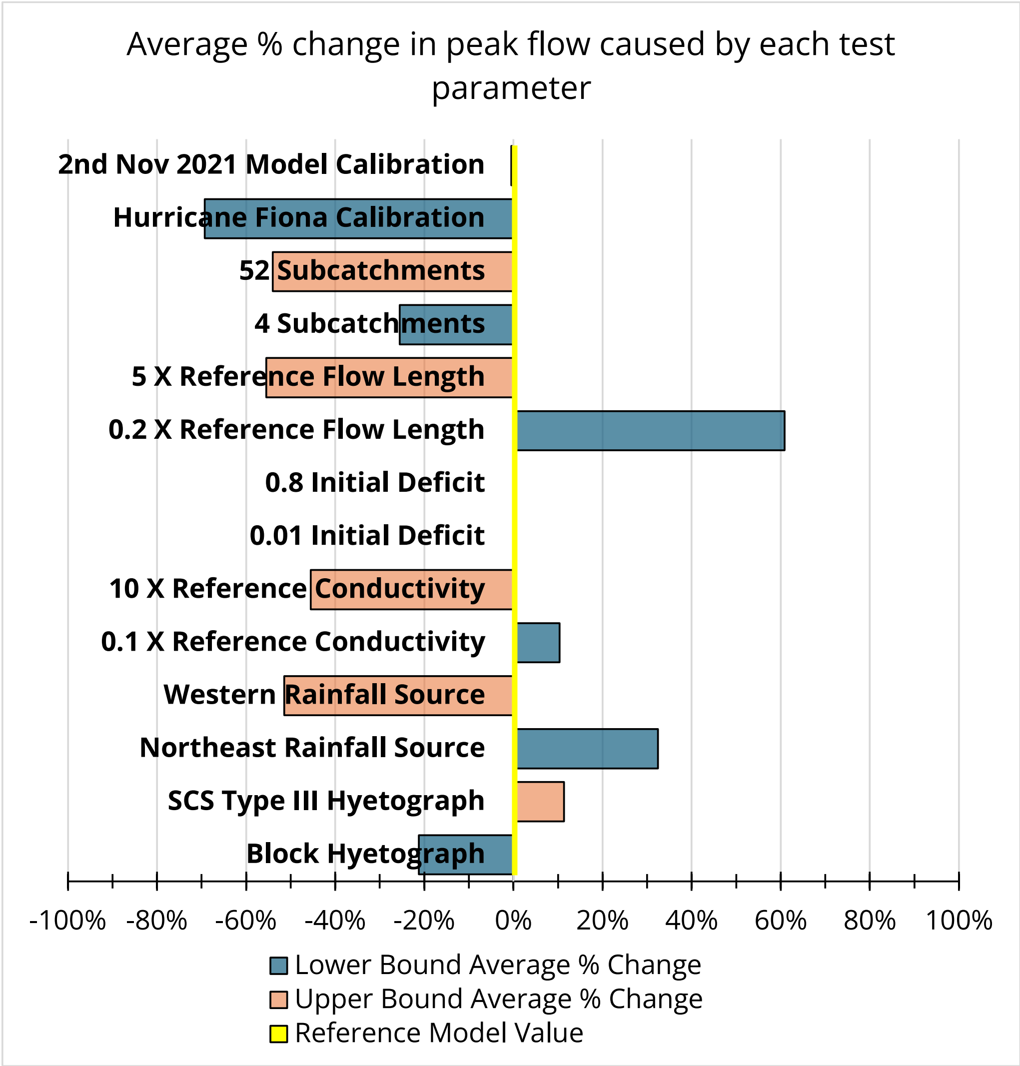

Figure 3-32: Summary of average changes on peak flow.

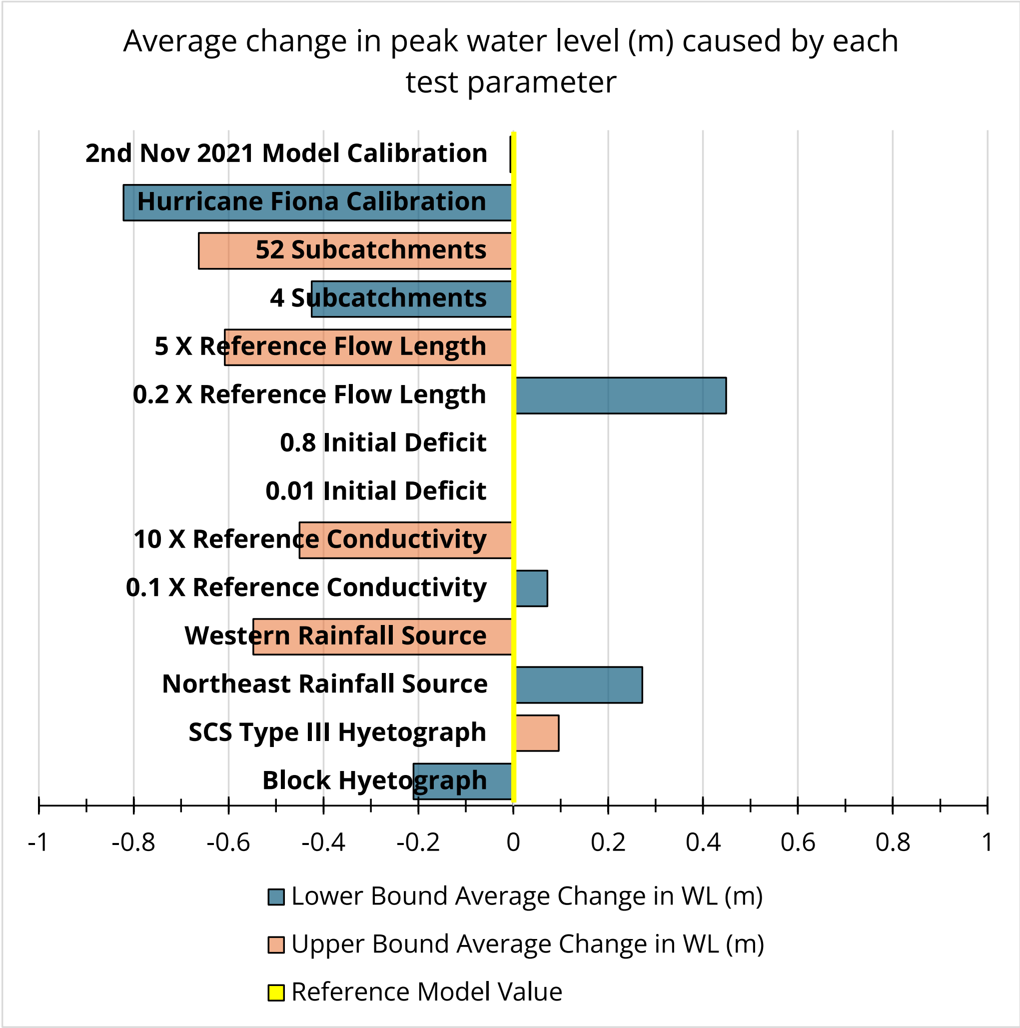

Figure 3-33: Summary of average changes on peak water level.

Table 3-7: Summary of results

Test Parameter Change	Average % Change in Peak Flow	Average Change in Water Depth (m)	Average Change in Flood Extents (Ha)
Block Hyetograph	-21%	-0.21	17.82
SCS Type III Hyetograph	11%	0.096	-9.88
Northeast Rainfall Source	32%	0.272	-28.99
Western Rainfall Source	-51%	-0.548	82.05
0.1 X Reference Conductivity	10%	0.072	-10.02
10 X Reference Conductivity	-45%	-0.247	75.09
0.01 Initial Deficit	0%	0	0.08
0.8 Initial Deficit	0%	0	-0.13
0.2 X Reference Flow Length	61%	0.449	-49.34
5 X Reference Flow Length	-55%	-0.608	95.58
4 Subcatchments	-26%	-0.425	68.85
52 Subcatchments	-54%	-0.663	141.25
Hurricane Fiona Calibration	-69%	-0.822	151.51
2nd Nov 2021 Model Calibration	0%	-0.006	1.18

The descriptions presented below are organized in order of the parameter that had the largest impact, to the parameter that had the least impact.

It was found that changing the calibration event to Hurricane Fiona resulted in the largest change to peak flows, with a 69% change (which denotes the importance of selecting a representative calibration event), while the 2nd calibration using the same event and different parameters resulted in no discernable change to peak flows. This is quite informative, given that calibration is a very subjective process. This result points to the fact that a change in the rainfall-runoff relationship directly impacts the resulting flows for the same design rainfall event. In the case of Hurricane Fiona, since a large rainfall amount resulted in a minor flood response, the design rainfall event produced a much reduced flow response compared to the original model calibration. Selecting a calibration event that has a representative rainfall-runoff response is therefore an essential part of the modelling exercise.

The change to Hurricane Fiona also resulted in the largest change to peak water levels (reduced peak water levels by 0.82 m), while the alternative calibration using the same event and different parameters resulted in a -1% change to peak water levels on average. This shows that the large change in peak flows (69%) resulting from the alternative calibration event directly impacts the water levels and flood extents in the model results.

It was then found that the flow length parameter also had a large impact on peak flows (increasing by factor of 5 decreased peak flows by 55% and decreasing it by a factor 5 increased peak flow by 61%). This is caused by the fact that a longer maximum overland flow length will increase the time of concentration of a watershed (for the same watershed area), which dampens further the flow response, and therefore decreases its peak flow. Increasing the flow length by a factor of 5 produced a decrease in water levels of 0.61 m, while decreasing the flow length by a factor of 5 resulted in an increase in water levels of 0.45 m. The impact on water levels is, in this case as well, directly connected to the change in flows resulting from the change to the time of concentration of a watershed.

Adjusting the level of discretization of subcatchments also had a notable impact, although perhaps biased by the absence of subsequent calibration of the models. The enhanced discretization (52 subcatchments) resulted in a 54% peak flow reduction on average, while the simplified discretization (4 subcatchments) resulted in a maximum change of 26% peak flow reduction, although changes to peak flow varied greatly (up and down) between nodes. The main reason for the decrease in peak flows is likely the fact that the newly delineated subcatchments were populated with standard parameter values for flow length, roughness and infiltration, which produced lower peak flows than the calibrated parameters. In a relative sense, the difference between the 4 and 52 subcatchment models is meaningful in that the higher subdivision of watersheds produced a runoff response that exhibited a doubling of the flow reduction compared to the model with 4 watersheds. This shows that a greater subdivision of watersheds allows the model to deliver more of the runoff response to the hydraulic channel network (since a greater channel network is needed to carry the water from a greater number of watersheds), which slows down the response. The hydraulic channel network will allow flow dampening through filling up the channel volumes and flow routing (which spreads the peak flow), akin to increasing the maximum overland flow length. From an overall modelling perspective, even though calibration will correct this effect on the peak flows, it is valuable to bear in mind that the shape of the response hydrograph will be different depending on the approach taken, and that the various parameter choices have to be made in the greater context of the approach to hydrologic modelling.

The increased discretization (52 subcatchments) resulted in a 0.66 m decrease in peak water levels on average, while reduced discretization (4 subcatchments) resulted in a 0.43 m water level reduction on average. The change in peak water levels is, in this case, only partly related to the change in flows, since the additional channel volume introduced with further discretization spreads out the water volume. This means that in there is also a hydraulic component to the change in water levels in the system. In general, it is also noted that more regular inputs from the hydrologic components into the hydraulic components of the model reduces the fragmentation of the flow hydrographs, resulting in a smoother, more representative and gradual, change in flows along the hydraulic network.

Increasing the conductivity had a greater impact on peak flows than reducing it (10X increase in conductivity resulted in a 45% reduction in peak flows, but a 0.1X change in conductivity resulted in a 10% increase in peak flows). This is likely a result of the low conductivity assigned to the watersheds through the process of calibration, whereby an already high runoff coefficient could not be increased much further. Nevertheless, the high sensitivity of the peak flows to a change in soil conductivity is quite meaningful in that it will directly impact the volume of rainfall water lost to infiltration, and in turn the volume of water available to contribute to flooding. The 10-fold increase in conductivity reduced peak water levels by 0.25 m, while applying a factor of 0.1 to conductivity values increased peak water levels by 0.07 m. This change is a result of the reduced flows from lower runoff, filling a smaller portion of the channel as it is routed through the channel system.

Using a block hyetograph (constant rainfall over the time of concentration) reduced peak flows by 21%, while using the SCS hyetograph increased peak flows by 11%. This is a result of the fact that the peak intensity of the rainfall hyetograph typically has a direct impact on the peak flow response. This result is quite important since it shows that the selection of a design hyetograph is an important modelling decision. Using the block (uniform rainfall over the time of concentration) hyetograph reduced peak water levels by 0.21 m on average, while using the SCS hyetograph shape increased peak water levels by 0.10 m on average. The peak intensity of the hyetograph, impacting the peak flows, impacts the water levels in a similarly proportional manner.

Changing the rainfall source to the Western University IDF Tool decreased peak flows by 51% on average, while using Northeast Regional Climate Center tool increased peak flows by 32% on average. In this case, the total amount of rainfall was modified, using the same rainfall hyetograph distribution. This shows that the total amount of rainfall is directly related to the peak flow, which is logical, as more rainfall volume will increase the volume of water flowing through the watershed.

Changing the rainfall source to the Western University IDF Tool decreased peak water levels by 0.55 m, while using the Northeast Regional Climate Center tool increased peak water levels by 0.27 m on average. Similarly, the change in flows resulting from the change in rainfall volume impacts proportionally the peak water levels.

Changes to values of initial soil moisture deficit resulted in no change in peak flow, as the soil moisture deficit was eliminated in the initial minutes of the rainfall event and did not impact peak flows. It was found that no changes to soil moisture deficit impacted peak flow unless the rainfall event peak was altered to occur earlier in the event duration. Changes to the peak of the rainfall event to 6 hours earlier, 9 hours earlier, and 12 hours earlier reduced the peak flow by 9%, 18% and 54% respectively, and reduced maximum water level by 0.023 m, 0.050 m, and 0.163 m respectively. Changes to values of initial soil moisture deficit resulted in no change in peak water levels, as the soil moisture deficit was eliminated in the initial minutes of the rainfall event and did not impact peak water levels.

It is noted that some limited testing of combinations of parameter variations was conducted, including decreasing conductivity, flow length and increasing watershed slope. It was found that the combined effect on flows, water levels and flood extents was less than the sum of the individual effects (by approximately 10%). This is likely a result of the fact that some characteristics interact with each other, for example, with decreased conductivity, the increased runoff would travel faster and would interact with the flow length. Similarly, the increase in slope would change the associated response from the other parameters.

3.2 Flood Frequency Analysis (Study Area 2)

3.2.1 Description of Study Area: Fraser River and Salmon Rivers in BC

The Fraser River and Salmon River Study utilized FFAs of historical streamflow records to determine flood design flows. This hydrologic sensitivity is therefore focussed on methods and decisions made throughout the FFA process, specifically reviewing the data for outliers, reviewing different FFA methods and statistical distributions, analyzing confidence bands, reviewing alternative estimators, and assessing different approaches to coincident flow analysis.

Two stations with long-term records Water Survey of Canada (WSC) 08KC001 (Salmon River near Prince George) and WSC 08KB001 (Fraser River at Shelley) were selected for the original FFAs. The baseline scenario for both stations was based on FFAs completed on the available annual maximum daily discharge records from WSC.

Six theoretical distributions were fit to the observed annual daily maximum discharge records and the final distribution was selected by reviewing visual fit, goodness-of-fit statistics, and considerations from previous studies. The maximum daily 200-year return period design flows were estimated to be 480 m^3/s for the Salmon River based on the Gumbel distribution and 5,455 m^3/s for the Fraser River based on the Log-Pearson Type 3 distribution.

The following flood frequency analysis methodologies were tested:

- Exclusion of outliers or extreme events.

- Dataset gaps and adjustments.
- Distribution selection.
- Confidence intervals.
- Alternative regional FFA-based estimators.
- Peak day coincident flows vs. coincident flow windows.

The changes and methodologies selected are intended to represent reasonable flood frequency analysis choices, within a range typically considered acceptable for this specific study area.

3.2.2 Data Outliers and Extreme Events in FFA

Outliers and extreme events can influence frequency analyses by significantly decreasing or increasing the design flow estimates. For this study, the Grubbs-Beck test was used to identify low outliers and the Creager C value was used to identify high outliers and extreme events. In addition, a visual assessment of the recorded data against the plotted theoretical distributions was completed. No outliers were identified in the records for either river based on the Grubbs-Beck test and Creager C value. A potential outlier, an extreme event, was visually identified in the Salmon River dataset, where the flood of record (2007) plots lower than all fitted theoretical distributions (**Figure 3-34**).

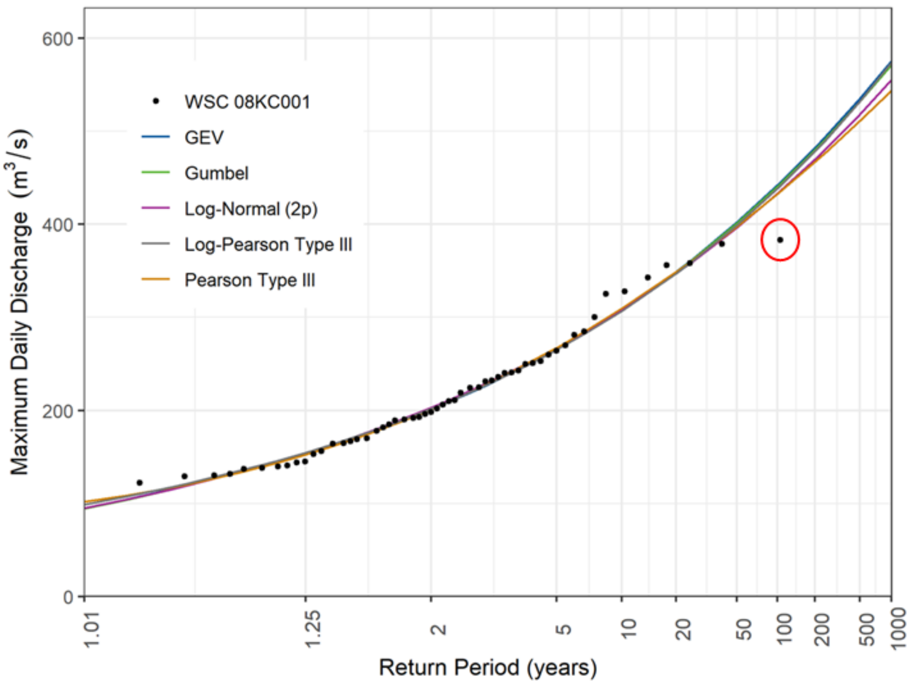

Figure 3-34: Flood Frequency Distribution Curves for Salmon River and Potential Outlier / Extreme Event (circled in red).

A frequency analysis was completed in the Salmon River dataset excluding the 2007 event for sensitivity analysis. Excluding this event decreases the 200-year return period design flow by 3% to 467 m^3/s. This limited change suggests that while the 2007 event is an extreme event, it is not an outlier to the data set. It should also be noted that the data set in question is relatively extensive; the more data available for a FFA, the less that the addition or removal of one point is likely to impact results. In a FFA, however, even if a high outlier is identified in the dataset, these values are included in the analysis as they are important to inform the upper tail of the distributions (i.e., extreme peak flows). Overall, excluding this extreme event from the dataset does not largely change the peak flow.

3.2.3 Dataset Gaps and Adjustments

When dataset gaps occur during known important flood years, dataset adjustments might be necessary to account for the influence of missing records.

Salmon River Data Gaps

Significant flood events occurred in the Salmon River during four years within a seven years data gap in Salmon River records (i.e., 2005 and 2008 to 2013). A review of nearby WSC hydrometric stations with near complete long-term records that included the 2005 to 2013 missing period were identified. This was done to assess the influence that the missing period of record at the Salmon River may have on the resultant design flow estimates. The Tsilcoh River near the Mouth station (WSC 08JE004) is located near Stuart Lake along the west boundary of the Salmon River watershed, has a drainage area of 431 km^2 and records available from 1976 to 2021. Therefore, this station was used to account for the missing period of record at the Salmon River station based on a ratio of the frequency analysis result with and without the missing record.

Consideration of the missing records (i.e., seven years including 2005 and 2008 to 2013) based on WSC 08JE004 records leads to an increase of 4% in the 200-year return period design flow estimate (i.e., 499 m^3/s).

Fraser River Data Gaps

Significant flood events occurred in the Fraser River before the period of record for the project hydrometric station (WSC 08KB001), including the historical maximum flood in 1894 (estimated by NHC [2009] to be 5,790 m^3/s) and major events in 1936 and 1948 recorded at Fraser River at Big Bar Creek (WSC 08MD013). The WSC 08KB001 record was extended to 1935 based on a linear regression of annual maximum daily discharges for Fraser River at Shelley (WSC 08KB001) and Fraser River at Big Bar Creek (WSC 08MD013) and the 1984 maximum flood added based on the NHC (2009) estimate.

Consideration of the missing records (i.e., 17 years including 1984 and 1935 to 1949) leads to a 7% increase in the 200-year return period design flow estimate (i.e., 5,837 m^3/s). This difference in flood extent is shown in **Figure 3-35**, and represents a substantial change in final mapped extents.

Figure 3-35: Study Area 2 on the Fraser River comparing dataset gaps.

3.2.4 Distribution Selection

Distribution selection can influence the final design flow estimates. Generally, visual fitting assessments and goodness-of-fit statistics are used to inform final distribution selection. Whereas the GUM distribution was selected for the Salmon River baseline scenario, selecting a different distribution could represent changes from -9% (438 m^3/s, Gamma) to <1% (482 m^3/s, Generalized Extreme Value) in relation to Gumbel. Whereas the LP3 distribution was selected for the Fraser River baseline scenario, selecting a different distribution could represent changes from -2% (5,355 m^3/s, GAM) to 9% (5,945 m^3/s, GUM) in relation to LP3.

3.2.5 Confidence Intervals

Flood frequency analyses include uncertainty from the statistical models used to fit observed data. Confidence intervals represent the amount of statistical uncertainty related to the use of observed datasets that represent only a small portion (i.e., sample) of an entire population of events. Three confidence intervals were selected for sensitivity analysis: 75%, 90%, and 95% confidence intervals.

The table below shows the baseline scenario, upper and lower limits of the confidence intervals for both the Salmon and Fraser Rivers. The 95%, 90%, and 75% confidence intervals result in approximately ±15%, ±13%, and ±9% differences changes in flow.

Table 3-7: Upper and Lower Confidence Interval Bounds for the Salmon and Fraser Rivers

Flow Estimate	Salmon River	Fraser River
200-year design flow (baseline scenario)	480	5,455
95% Upper Bound	559	6,327
90% Upper Bound	544	6,160
75% Upper Bound	523	5,921
75% Lower Bound	439	5,003
90% Lower Bound	423	4,836
95% Lower Bound	413	4,728

3.2.6 Estimation of Uncertainty in Alternative Estimators

In ungauged watersheds, alternative estimators such as regional hydrologic models and regional FFAs can be used as a surrogate to estimate design flows. Two BC provincial level flood estimators were tested for this sensitivity analysis:

- The regional analysis equations developed for the BC Extreme Flood Project[4] (NHC 2021).
- The British Columbia River Forecast Center CLEVER[5] model estimates.

NHC (2021) provides predictive regional equations for BC using regional FFAs according to Ecozones or Ecoprovinces. The Salmon River is located in the Nechako Plateu Ecoprovince (14.1) and the Fraser River is located in the Upper Fraser Ecoprovince (14.4). The equations for prediction of the 1-day 200-year return period flows for each respective ecoprovince were applied to the drainage areas of the Salmon River and Fraser River study area reaches.

The regional equation estimate for the Salmon River was -10% lower compared to baseline (i.e., 434 m^3/s). The regional equation estimate for the Fraser River was -22% lower compared to the baseline scenario (i.e., 4,241 m^3/s).

The British Columbia River Forecast Center provides design flows estimates up to the 100-year return period based on the CLEVER hydrological model, which uses third-party data as input to provide flood forecast. Results from the CLEVER model were extrapolated to obtain a 200-year return period flow. The 200-year return period estimates from the CLEVER model were 6% higher than the baseline design flow on the Salmon River (i.e., 509 m^3/s) and 2% higher than the baseline design flow for the Fraser River (i.e., 5,569 m^3/s).

[4] https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-data-tools/provincial-hydrology-program/resources/british-columbia-extreme-flood-project
[5] https://bcrfc.env.gov.bc.ca/freshet/map_clever.html

3.2.7 Estimation of Uncertainty in Coincident Flows

Study Area 2 includes the confluence of the Salmon and Fraser Rivers and therefore requires the analysis of coincident flows. Historically, the Salmon River has peaked approximately 40 days before the Fraser River (**Figure 3-36**).

The closest peak dates occurred in 1966 when the Fraser River peaked on May 11th and the Salmon River peaked on May 12th. However, in general, it is unlikely that both rivers will peak simultaneously.

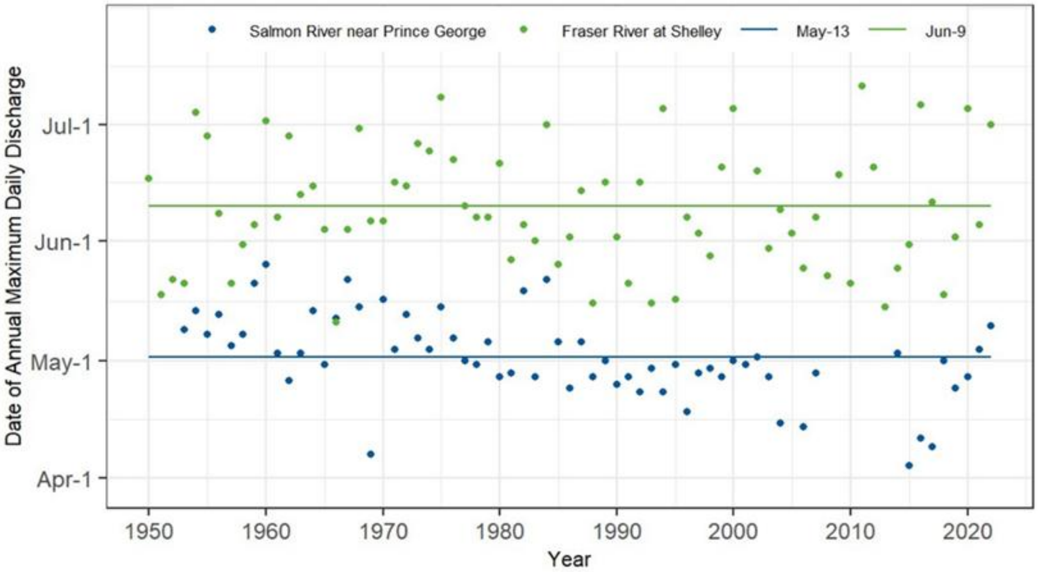

Figure 3-36: Salmon River vs. Fraser River Annual Maximum Discharge Dates.

Due to the difference in river flow scale (a factor of 10 separates design events on these two rivers), the Fraser River creates a backwater effect on the lower Salmon River and substantially impacts the Salmon River flood extents.

During the period of record, the Fraser River above Salmon River discharge at the time of Salmon River peaks has ranged from 564 m^3/s to 2,647 m^3/s, with an average of 1,539 m^3/s (**Table 3-8**).

Table 3-8: Fraser River Flows during Salmon River Peak Event Flows Statistics

Statistic	Fraser River Coincident Daily Discharge (m^3/s)
Minimum	564
Median	1,465
Average (Baseline Scenario)	1,539
75th percentile	1,734
90th percentile	2,393
Maximum	2,859

Coincident flows on the Fraser River were determined based on the day of Salmon River peak flows (**Figure 3-36**). For sensitivity analysis, coincident flows on the Fraser River were also determined based on a week, one month, and two month window around the day of Salmon River peak flows. The results show that Fraser River coincident flows increase by 4% when looking at a one-week period, and decrease by 13% and 17%, respectively, when looking at the one-month and two-month window.

3.2.8 Summary of Results of Flood Frequency Analysis

A summary of the results of the various FFA methodologies and sensitivity analysis are included in **Table 3-9**, below. In general, the greatest ranges in river flows were observed using the 95% confidence intervals and when using the alternative, regional FFA-based estimator. This is in keeping with the fact that use of either an alternative regional estimator or the 95% confidence intervals represent departures from the typically recommended FFA methodology; in particular, the use of a regional estimator may not be appropriate or representative of flows within a given watershed. The smallest changes in river flows were observed in the data outlier/extreme event and several of the alternative distribution methodologies, which better represent refinements of the typical FFA methodology.

Table 3-9: Percent Change in Peak Flow for Fraser River and Salmon River with Different Changes in Test Methodology

Methodology Reviewed	Fraser River % Change in Flow	Salmon River % Change in Flow
Excluding data outliers	-	-3%
Extending dataset and adjustments	7%	4%
Distribution selection	-2% to 9%	-9% to <1%
Confidence intervals (max range 95%)	-13% to 16%	-14% to 16%
Alternative estimators	-22% to 2%	-10% to 6%

Both points-of-interest had long-term historic data from WSC available for analysis, which is considered to be a best-case scenario for estimating peak flows. Both datasets, however, had missing records during known important flood years. Adjusting the datasets to account for these missing records did not result in a major increase in the design flow (i.e., 4% for Salmon River and 7% for Fraser River). The adjustments, however, did help increase confidence in the estimated design flows. These differences can also increase when a climate change factor is being applied to the estimated design flows.

It was also found that at both points-of-interest, selecting a different distribution resulted in approximately ±10% difference in relation to the selected design flows.

At both points-of-interest, the 95% confidence interval resulted in approximately ±15% difference in relation to the baseline design flows.

Use of Alternative Estimators for FFAs:
The regional analysis equations developed for the BC Extreme Flood Project (NHC 2021) underestimated the baseline design flows by -10% on Salmon River and -22% on the Fraser River. If considering the extended records, these differences become even larger (i.e., -15% on Salmon River and -37% on Fraser River). *These results indicate that large scale regional analyses do not seem applicable for large watersheds, such as the Fraser River.*

Extrapolated results from the CLEVER hydrological model were similar to the baseline FFA results (i.e., based on maximum daily WSC records only). However, the model includes a disclaimer that the theorical floods are not to be used for design purposes. Therefore, additional analysis or modeling would be necessary to confirm these initial estimates.

Resulting Water Depths
Upper and lower bound scenarios as well as the baseline scenario were run through the project HEC-RAS 2-D hydraulic model to understand how the range of flow sensitivity effects final water depths. The upper and lower bound values are shown in **Table 3-10**, below. Upper bound values for both the Fraser and the Salmon Rivers were provided by the 95% upper confidence interval. The lower bound value for the Fraser River was provided the regional FFA estimator; the lower bound value for the Salmon River is the 95% lower confidence interval. Water depth results for these two events and the baseline scenario are shown in **Table 3-11**. Figures **Figure 3-37** and **Figure 3-38** show the results of this upper and lower bound at a communities along the Salmon and Fraser Rivers.

Table 3-10: Salmon and Fraser River Upper and Lower Bound Flows Compared to the Baseline

River	Upper Bound (m^3/s)	Baseline Scenario (m^3/s)	Lower Bound (m^3/s)
Salmon	552	480	455
Fraser	6,327	5,455	5,355

Table 3-11: Salmon and Fraser River Depths for the Upper Bound, Lower Bound and Baseline Flow Scenarios

Sample Cross-Sections	River	Depth Results (m)			Depth Difference from Moderate Results (m)	
		Lower Bound Flow	Baseline Flow	Upper Bound Flow	Lower Bound Flow	Upper Bound Flow
1	Salmon	4.05	4.13	4.42	-0.08	0.29
2		3.23	3.29	3.49	-0.07	0.20
3		4.03	4.09	4.32	-0.07	0.23
4		3.02	3.08	3.29	-0.06	0.21
5		4.36	4.45	4.69	-0.09	0.24
6		5.77	5.85	6.06	-0.08	0.21
7		2.57	2.63	2.80	-0.06	0.17
8	Fraser	8.91	8.99	9.67	-0.08	0.68
9		17.51	17.60	18.29	-0.08	0.69
10		12.26	12.34	13.04	-0.09	0.69
11		11.27	11.35	12.03	-0.08	0.68
12		9.74	9.83	10.63	-0.10	0.79
13		14.40	14.49	15.13	-0.08	0.64
14		15.53	15.61	16.28	-0.09	0.67
15		11.38	11.42	11.83	-0.04	0.42
16		13.40	13.48	14.13	-0.08	0.65
17		9.98	10.05	10.66	-0.07	0.60

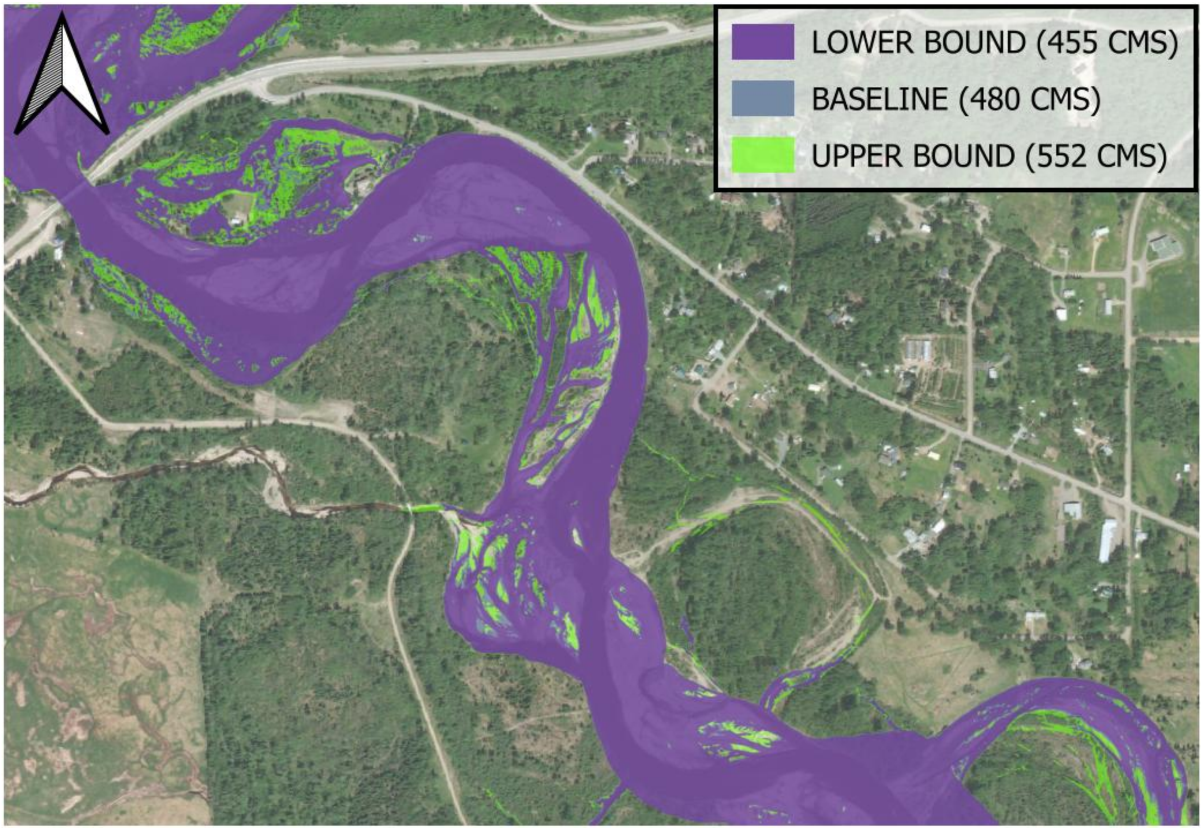

Figure 3-37: Salmon River upper / lower bound flow events compared to baseline.

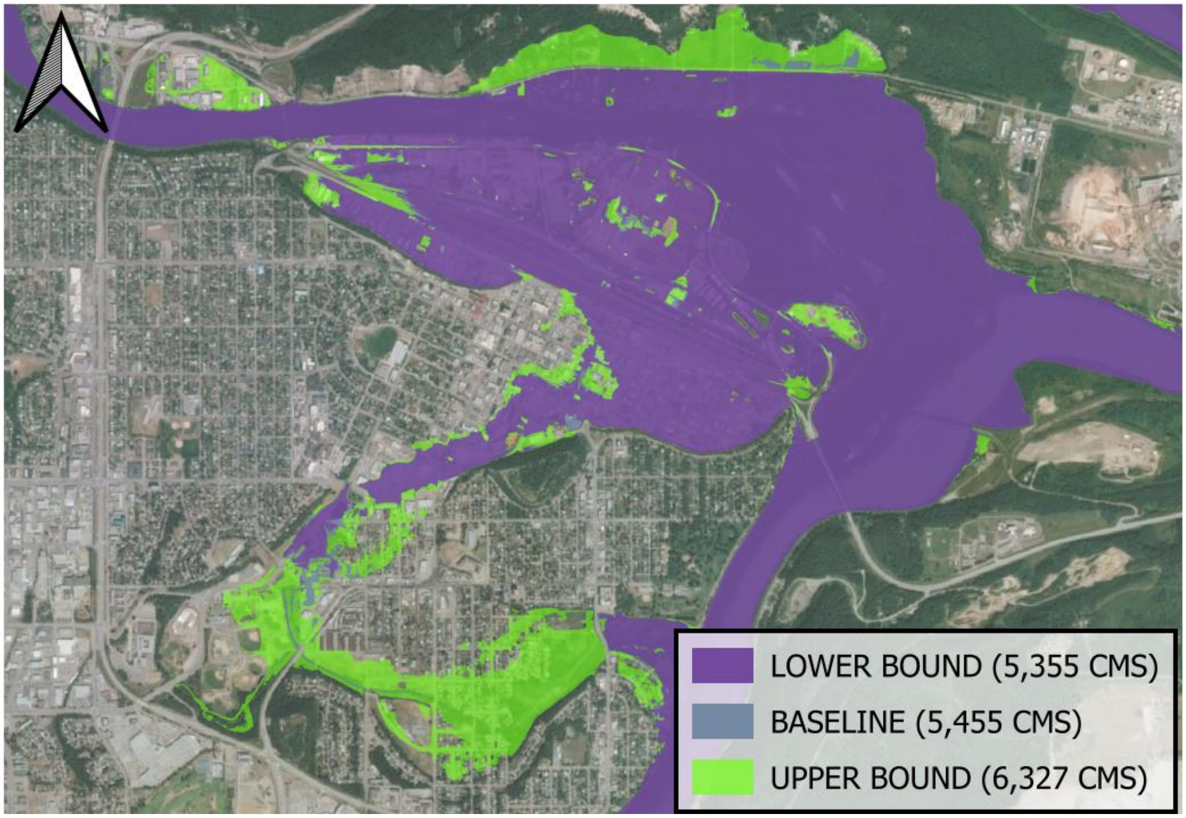

Figure 3-38: Fraser River upper / lower bound flow events compared to baseline.

In addition to the design flows, this review also identified that coincident flow period and statistics play a large role in the determining coincident flow for the Salmon River downstream boundary at its confluence with the Fraser River. Values for flow coincidence ranged widely and have a large impact on the backwater effect from the Fraser River onto the Salmon River.

4 Uncertainty in Hydraulic Model Parameters

An evaluation of uncertainty in hydraulic modelling is also presented here. In this regard, the two separate study areas offer opportunities to test differences in regional physiographic characteristics, as well as differences in modelling methodologies. Study Area 1 in Nova Scotia utilized a one-dimensional (1D) HEC-RAS model, whereas Study Area 2 in British Columbia utilized a two-dimensional (2D) HEC-RAS model.

Uncertainty in hydraulic modelling is most commonly related to the design flows, or Manning's roughness. However, there are many other impacting factors, including built infrastructure that can highly affect localized conditions, or the selection of modelling choices that may affect the final water elevations and velocities. Details of the selected factors to analyse for hydraulic modelling are presented below.

4.1 Estimation of Uncertainty in Input of Design Flow

Design flows from hydrologic modelling (Study Area 1) and FFA (Study Area 2) are the main input for the hydraulic modelling to calculate the resulting water depths and flood extents. Assumptions and decisions have to be made to select locations for input of steady and unsteady flows in the hydraulic model. Testing different locations for the selection will help evaluate the effects of routing attenuation and backwater effects.

Different scenarios were developed for the two different study areas, due to the very different scales of the upstream watersheds and their contributing flow areas.

Study Area 1

To comprehensively assess the hydraulic behaviour of the system under different flow conditions, three distinct modelling scenarios have been developed:

Scenario 1: Four- Flow Data Input Locations: In this scenario, four specific locations within the study area will be designated as input points for both steady and unsteady flows.

Scenario 2: Seventeen- Flow Data Input Locations: This scenario involves a more detailed approach, utilizing seventeen input locations to capture the spatial variability of flow conditions.

Scenario 3: All Cross-Section Flow Data Input Locations (reference model): This scenario represents the most comprehensive approach, incorporating flow input at every cross-section within the hydraulic model.

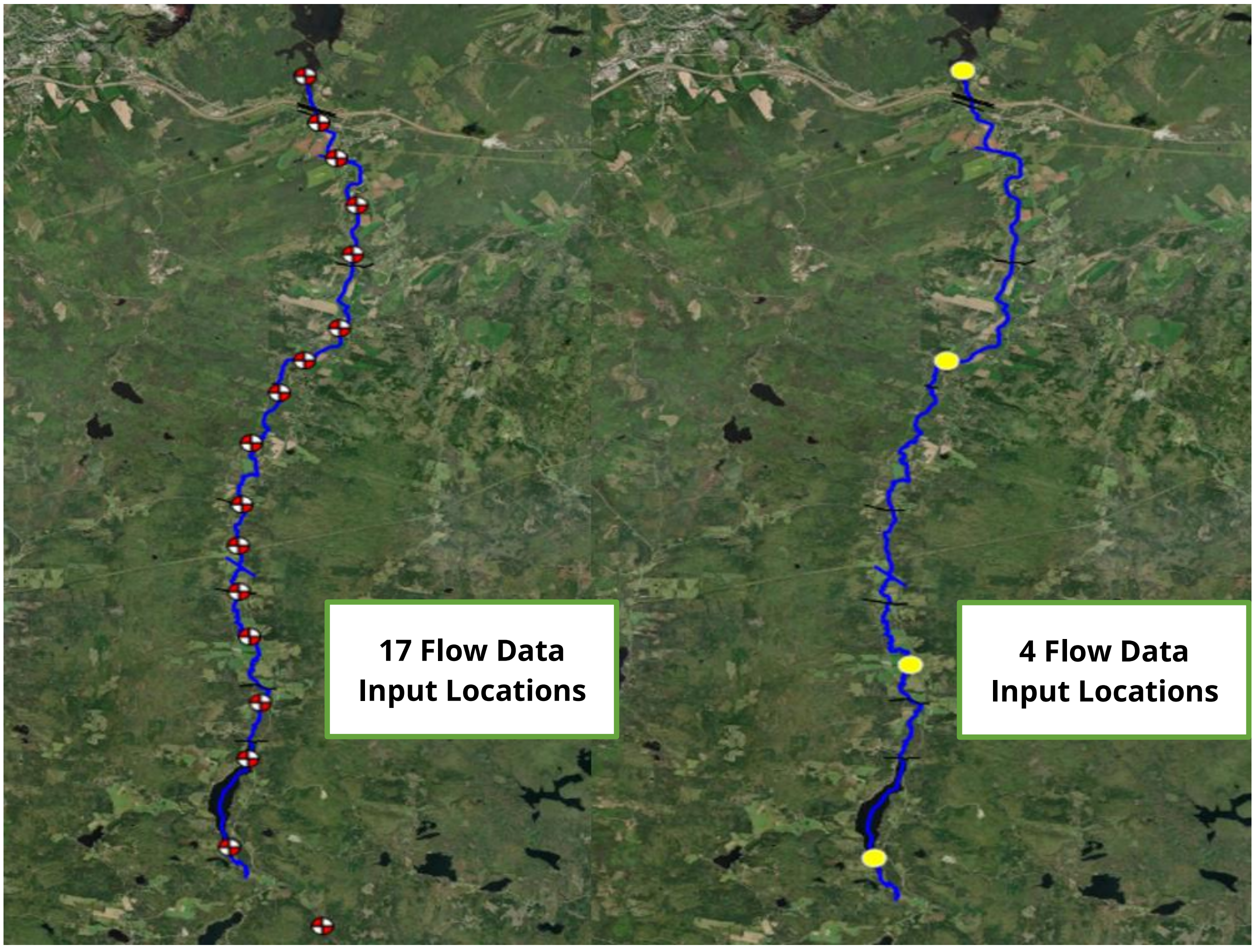

Figure 4-1: 4 points and 17 Points Flow Data Input Locations.

Table 4-1: Average Water Depth and Flood Extents Change with Number of Flow Data Input Locations

Base Model Flow Data Input Location	Average Water Depth Change (m)	Change in Flood Extents (ha)
4-point Flow Data Input Locations	0.5	-50.78
17-point Flow Data Input Locations	0.27	-2.47

To analyze the impact of varying flow locations on inundation patterns, flood maps were generated for three distinct scenarios. As illustrated in **Figure 4-1**, the resulting maps exhibit high variability across different locations while maintaining similarity in others. This result indicates that it is important to closely monitor changes in flow locations and incorporate as many input points as feasible to generate more precise flood maps.

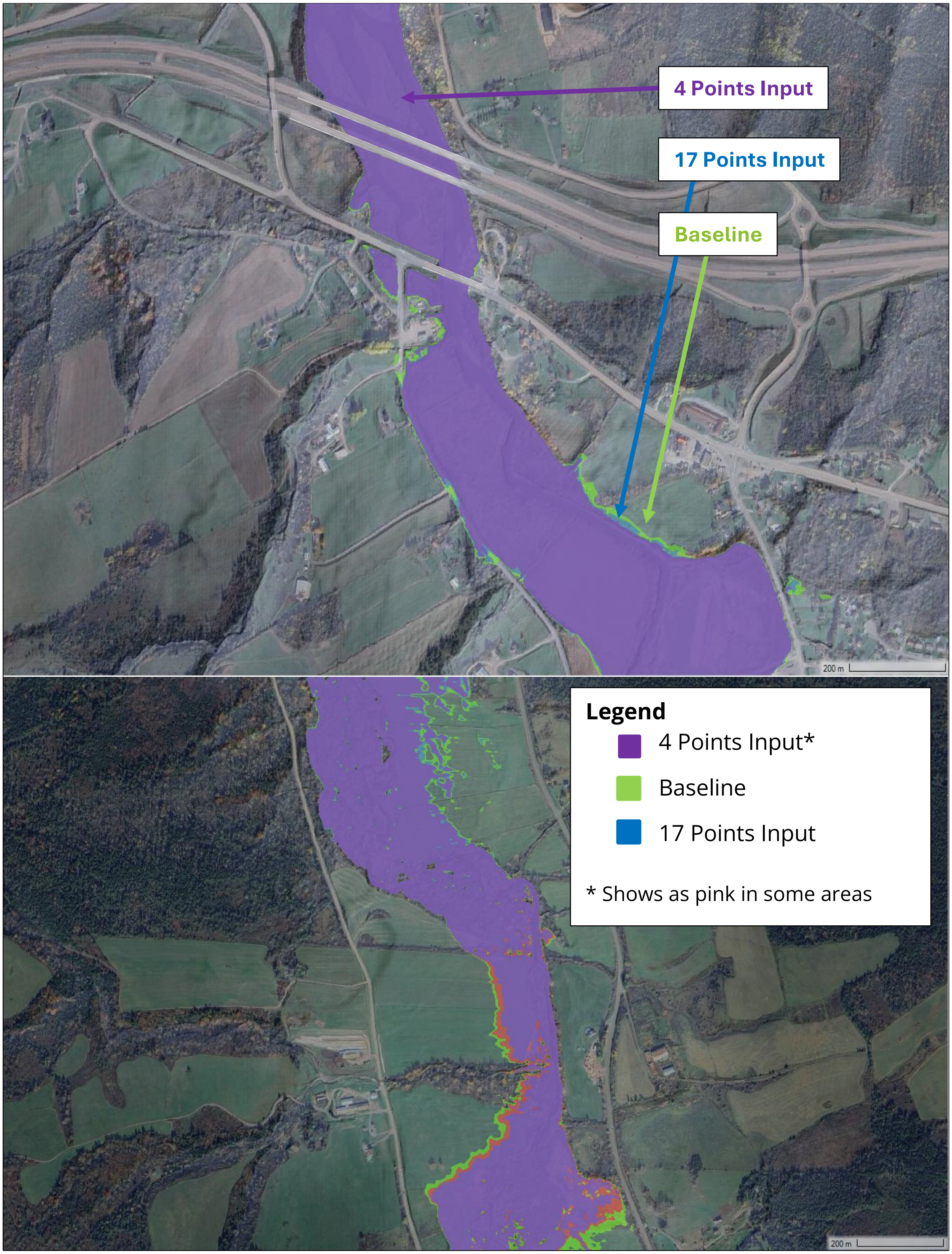

Figure 4-2: Impact of different Input locations (All XS, 17 points and 4 points) on peak flood extents.

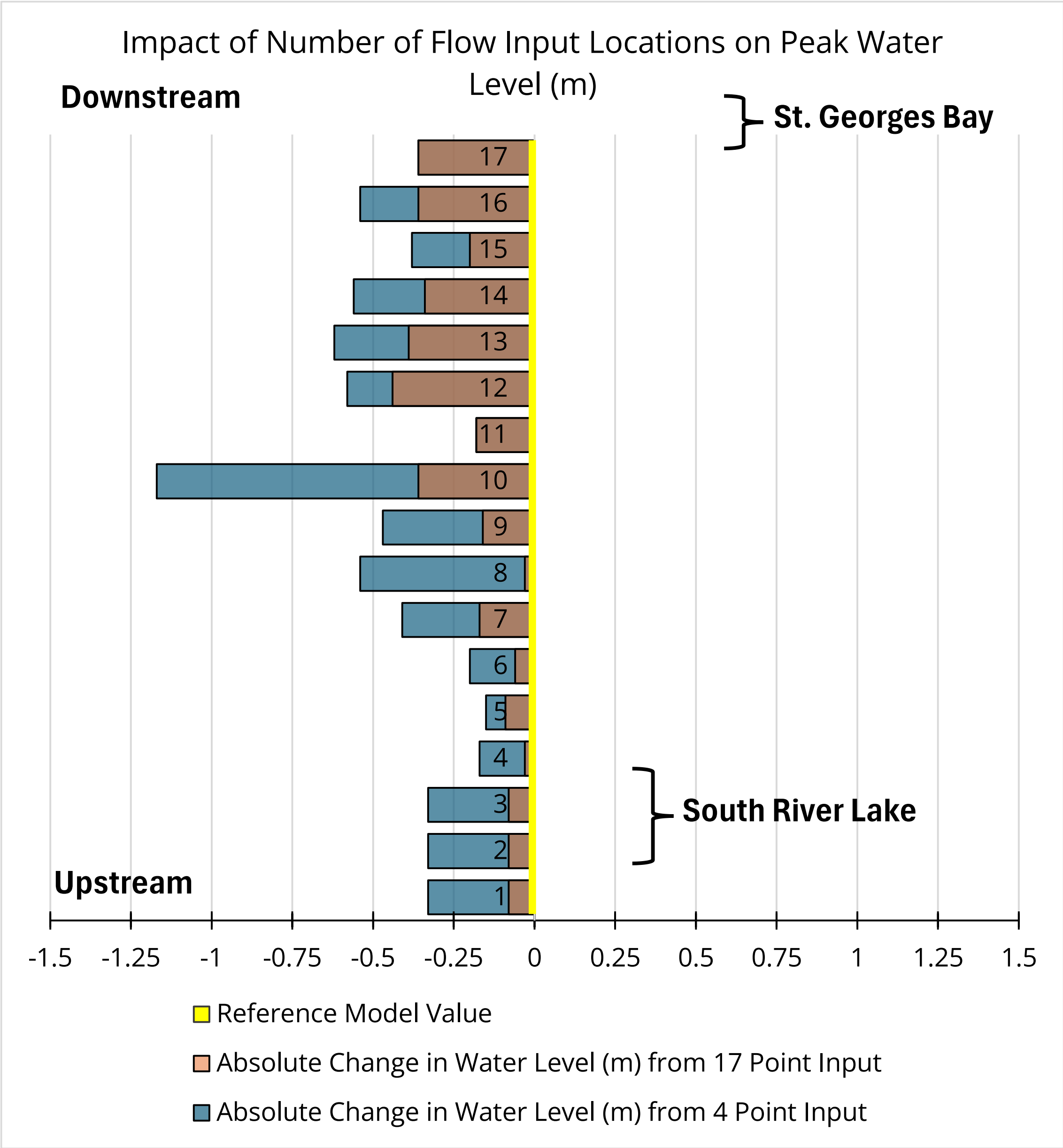

Figure 4-3: Impact of different Input locations (17 points and 4 points) compared to Base model (188 points) on peak flood extents.

4.1.1 Study Area 2

Options for secondary inflow points within Study Area 2 are far more limited than those reviewed in Study Area 1. Both the Salmon River and Fraser Rivers have very large upstream watersheds (4,200 km^2 and 32,400 km^2 respectively). Neither river has significant flow contributions along reaches, except for defined confluences with other rivers (i.e. the confluence of the Salmon River where it joins the Fraser River). This limits inflow point sensitivity review to defining the upstream inflow and upper extent of the reach of interest.

To comprehensively assess the hydraulic behaviour of the system under different flow conditions, two distinct modelling scenarios have been developed:

Scenario 1: The location of the Salmon River input flow in the existing model is approximately 2.1 km upstream of the John Hart Highway Bridge.

Scenario 2: The location of the Salmon River input flow is directly upstream (200 m) of the John Hart Highway Bridge.

The Fraser River inflow location was not changed, as this river reach begins just above the confluence with the Salmon River.

Table 4-2 shows the water depths at corresponding sample cross-section locations for the inflow directly upstream of the Salmon River bridge and in the existing model. As shown in the table, moving the inflow location closer to built infrastructure has a negligible impact on water levels at the bridge or downstream and there is no change to the final flood map extents.

Table 4-2: Water Depth Results at Sample Cross-sections along the Salmon River with the Inflow Directly Upstream of the Bridge Compared to the Existing Model

Sample Cross-Sections	River	Depth Results (m)		Depth Difference from Existing Model Results (m)
		Inflow Directly Upstream of Bridge	Inflow in Existing Model Location	Inflow Directly Upstream of Bridge
1	Salmon	4.22	4.20	0.01
2		3.35	3.35	0.00
3		4.15	4.16	0.00
4		3.13	3.13	0.00
5		4.52	4.52	0.00
6		5.91	5.91	0.00
7		2.67	2.67	0.00

4.2 Estimation of Uncertainty in Manning's Roughness

The Manning's roughness coefficient is a fundamental parameter in hydraulic modelling, playing a pivotal role in determining the simulated water depths, water surface elevations and flow velocities within river channels and open channel systems. This coefficient quantifies the resistance to flow encountered by water as it moves through a channel, stemming from factors such as channel morphology, bed material, vegetation, and other obstacles. A higher Manning's roughness coefficient signifies greater resistance to flow, leading to increased water depths and reduced flow velocities. Conversely, a lower Manning's roughness coefficient indicates less resistance to flow, resulting in decreased water depths and increased flow velocities. An example of Mannings n range is given the table below.

Table 4-3: Manning's n range based on Channel Types

Channel Type	Manning's n Range
Natural Streams	
Clean, straight, full stage	0.035
With more stones and weed	0.045
Artificial Channels	
Concrete lined	0.014
Floodplains	
Cultivated land	0.040
Mature Crops	0.045
Brush	0.05
Trees	0.1

To assess the sensitivity of the model to variations in the Manning's roughness coefficient and the peak flow rate on the water levels, a sensitivity analysis was conducted.

Different scenarios were developed for the two different study areas, due to the very different scales of the rivers and their topographic features.

4.2.1 Study Area 1

Study Area 1 involved creating four different scenarios:

- Increased Manning's Roughness: The Manning's roughness coefficient was increased by 25% compared to the base model.
- Decreased Manning's Roughness: The Manning's roughness coefficient was decreased by 25% compared to the base model.
- Increased Peak Flow Rate: The peak flow rate was increased by 25% compared to the base model.

- Decreased Peak Flow Rate: The peak flow rate was decreased by 25% compared to the base model.

For each scenario, HEC-RAS simulations were performed, and the resulting water depths were compared to the base model. The results, visualized in **Figure 4-4** to **Figure 4-7**, and summarized in **Table 4-4**, provide insights into the impact of these parameter changes on the predicted water depths.

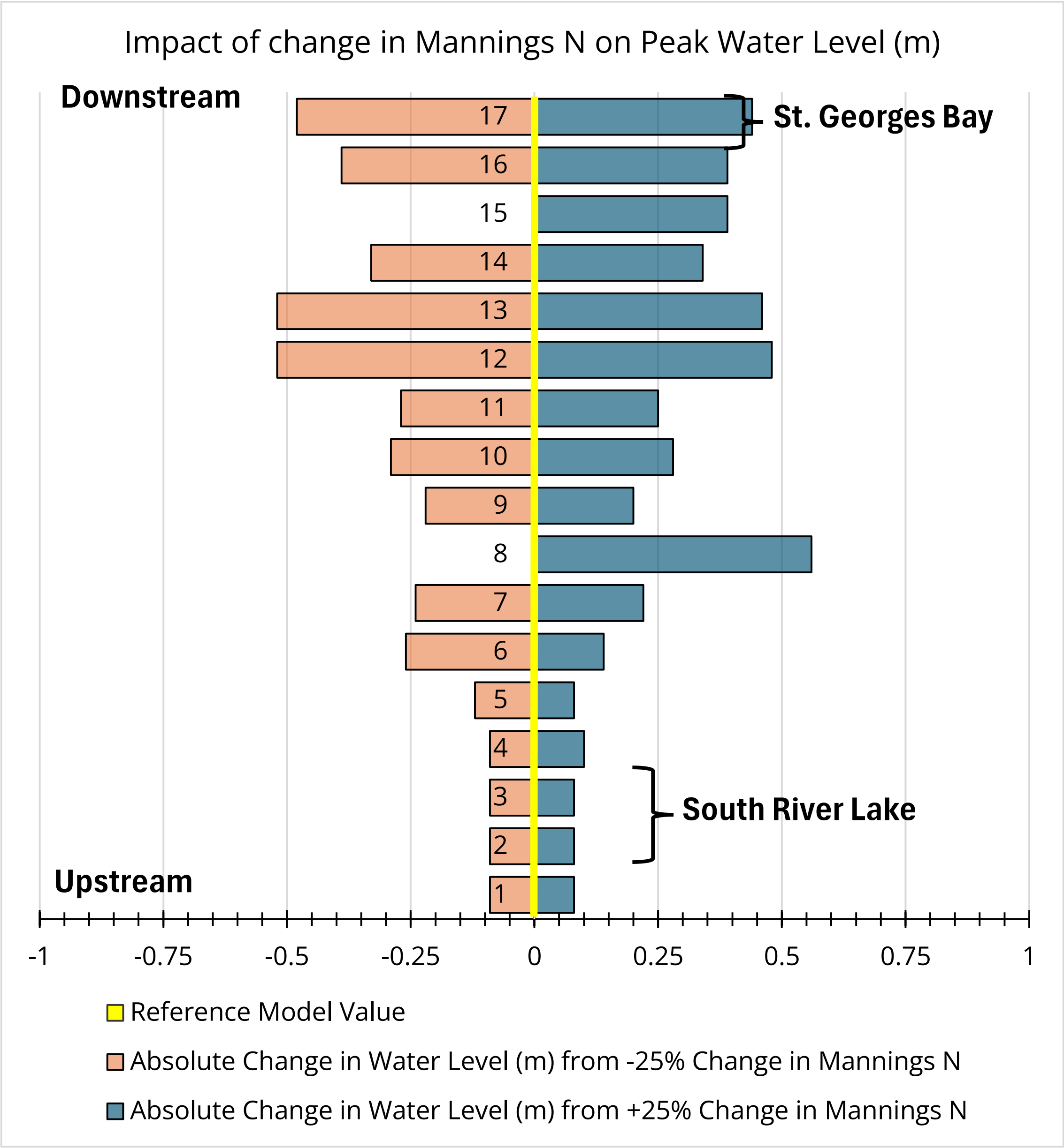

Figure 4-4: Manning's Roughness Parameter Testing Results showing change in WSEL.

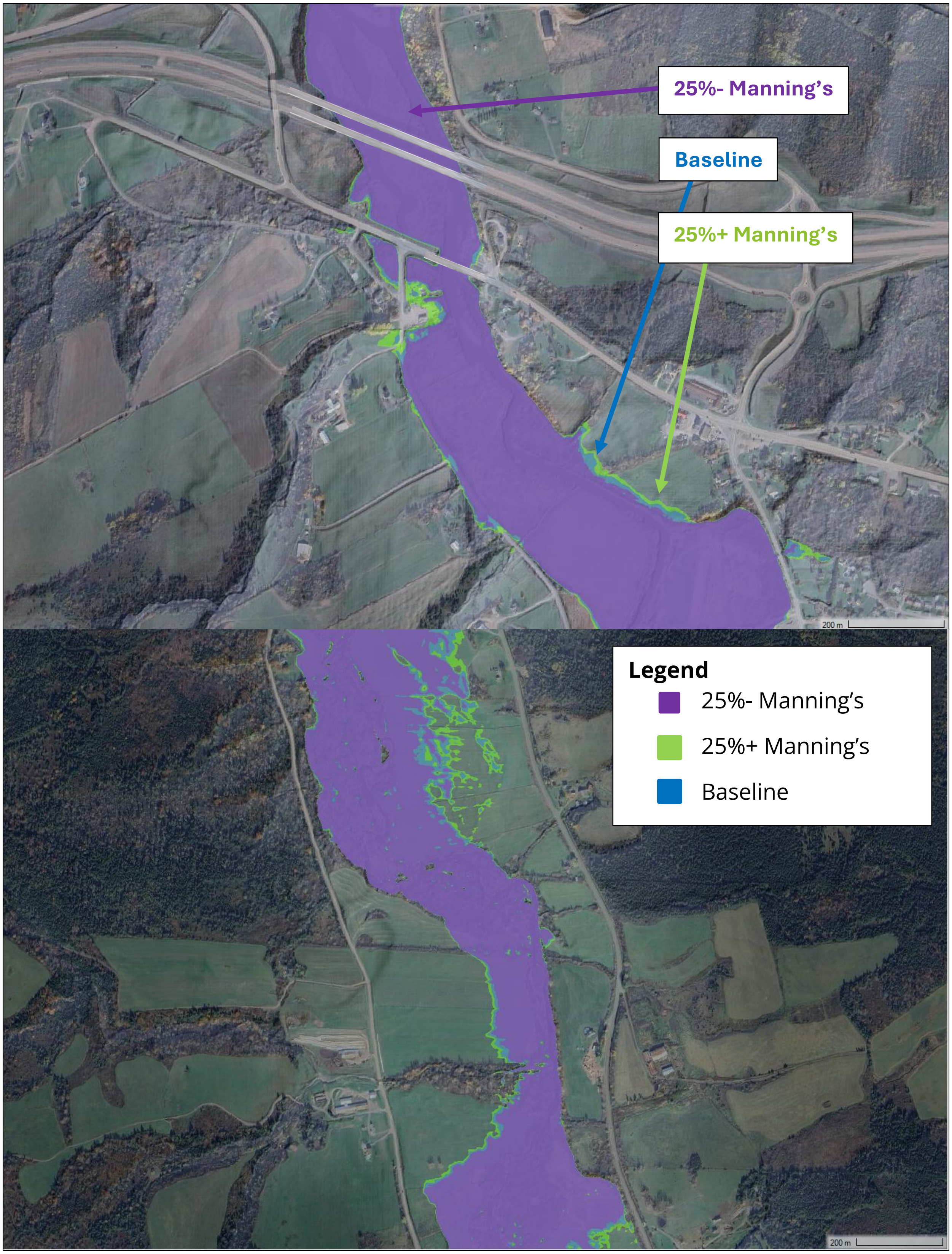

Figure 4-5: Impact of change in Manning's Roughness value (Baseline, 25% increased and 25% reduced) on peak flood extents.

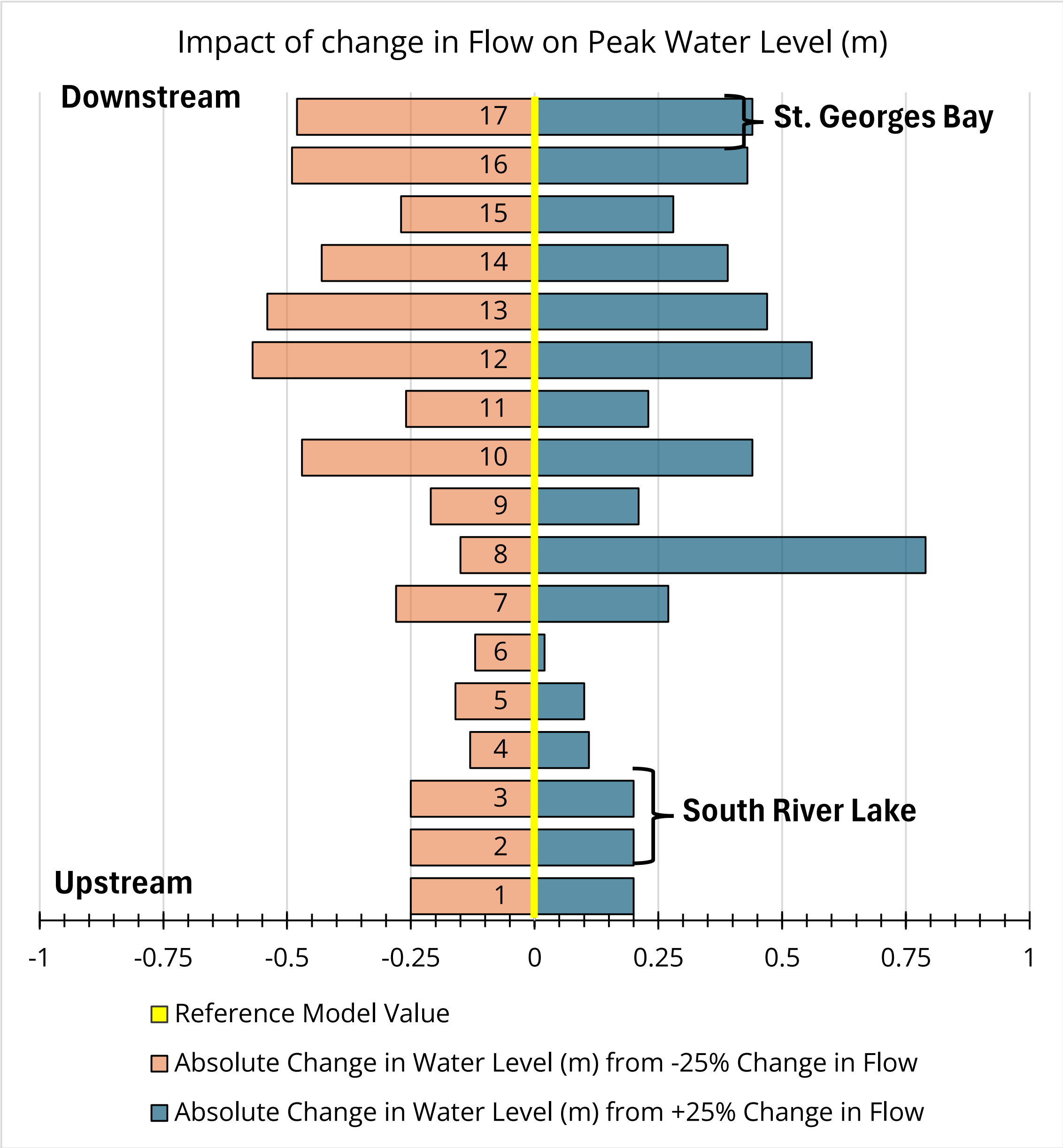

Figure 4-6: Flow Change Testing Results showing change in WSEL

Since some of the values are very small and difficult to quantify from the graph, a table is included below for clarity.

Table 4-4: Model Results showing Average Change in Depth and Flood Extents

	Manning's Roughness Change		Peak Flow Rate Change	
	Manning's Roughness Value (-25%)	Manning's Roughness Value (+25%)	Peak Flow Rate (-25%)	Peak Flow Rate (+25%)
Average Depth Change (m)	-0.26m	0.24m	-0.32m	+0.31m
Maximum Depth Increase (m)	-0.67m	0.64m	-0.76m	1.33m
Flood Extents change (ha)	-23.80ha	20.96ha	-30.06ha	26.68ha

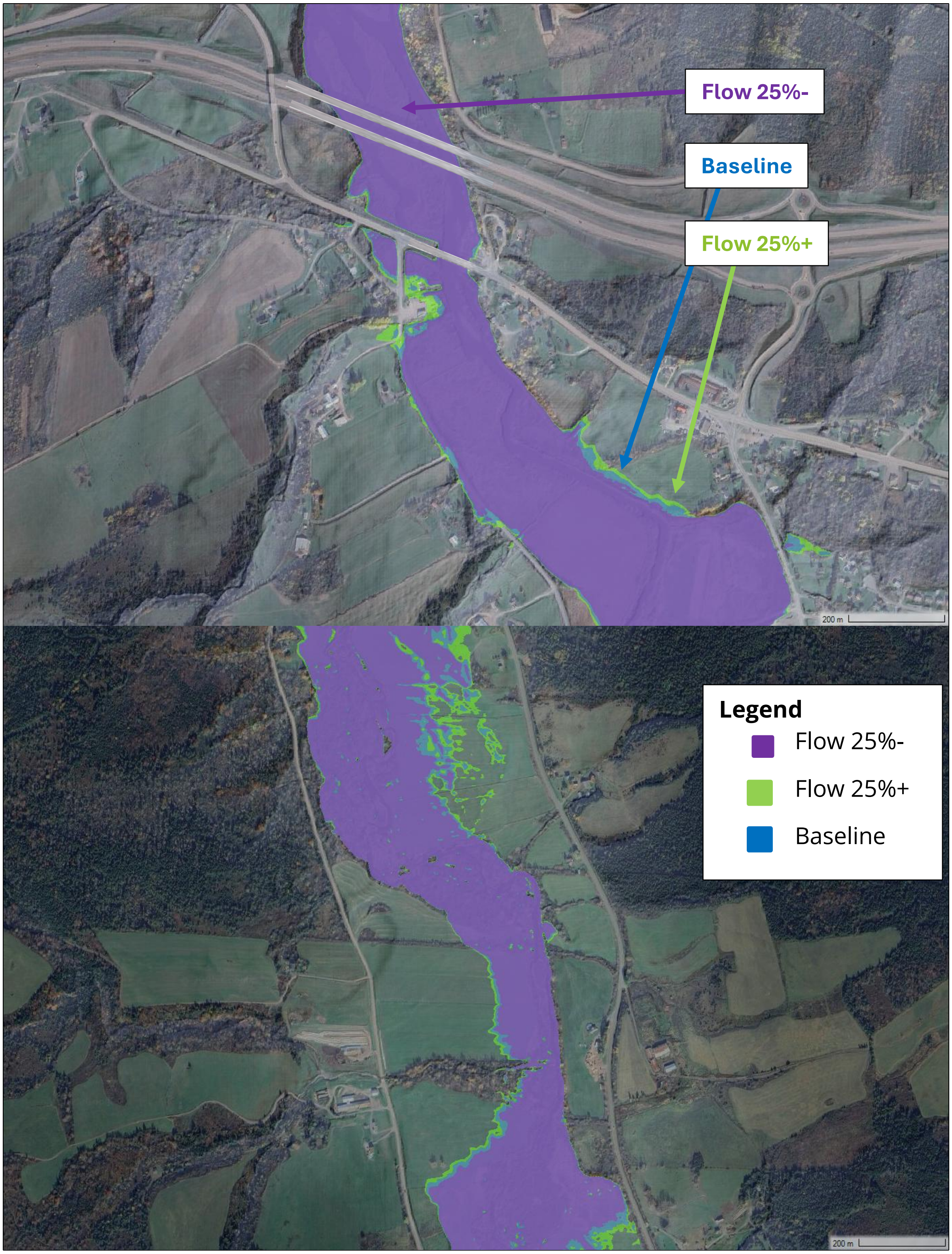

Figure 4-7: Impact of change in Peak Flow value (Baseline, 25% added and 25% reduced) on peak flood extents.

4.2.2 Study Area 2

Both channel and overland Manning's roughness values were tested at three levels in Study Area 2: low, moderate (typical), and high. The three scenarios include:

- High Manning's Roughness: The Manning's roughness coefficient was increased by 10% compared to the base model.
- Moderate Manning's Roughness: Reference calibrated values from the base model.
- Low Manning's Roughness: The Manning's roughness coefficient was decreased by 10% compared to the base model.

Table 4-5 shows the water depths at corresponding sample cross-section locations for the low, moderate, and high roughness model runs. Additionally, **Figure 4-8** and **Figure 4-9** show the water surface extents at areas of interest along the Salmon and Fraser Rivers.

Table 4-5: Water Depth Results at Sample Cross-sections along the Salmon and Fraser Rivers with Low, Moderate, and High Manning's Roughness Values

Sample Cross-Sections	River	Water Depth Results (m)			Water Depth Difference from Moderate Results (m)	
		Low Manning's Roughness	Moderate Manning's Roughness	High Manning's Roughness	Low Manning's Roughness	High Manning's Roughness
1	Salmon	4.13	4.20	4.28	-0.07	0.07
2		3.28	3.35	3.41	-0.06	0.06
3		4.07	4.16	4.25	-0.09	0.09
4		3.03	3.13	3.25	-0.10	0.12
5		4.47	4.52	4.57	-0.05	0.05
6		5.86	5.91	5.96	-0.05	0.05
7		2.61	2.67	2.74	-0.07	0.07
8	Fraser	8.86	9.29	9.70	-0.43	0.40
9		17.59	17.91	18.21	-0.32	0.30
10		12.30	12.65	12.98	-0.35	0.33
11		11.32	11.65	11.97	-0.34	0.31
12		9.74	10.19	10.60	-0.45	0.41
13		14.33	14.79	15.18	-0.46	0.39
14		15.47	15.91	16.32	-0.45	0.40
15		11.33	11.59	11.87	-0.26	0.28
16		13.30	13.76	14.20	-0.46	0.44
17		9.91	10.32	10.69	-0.41	0.38

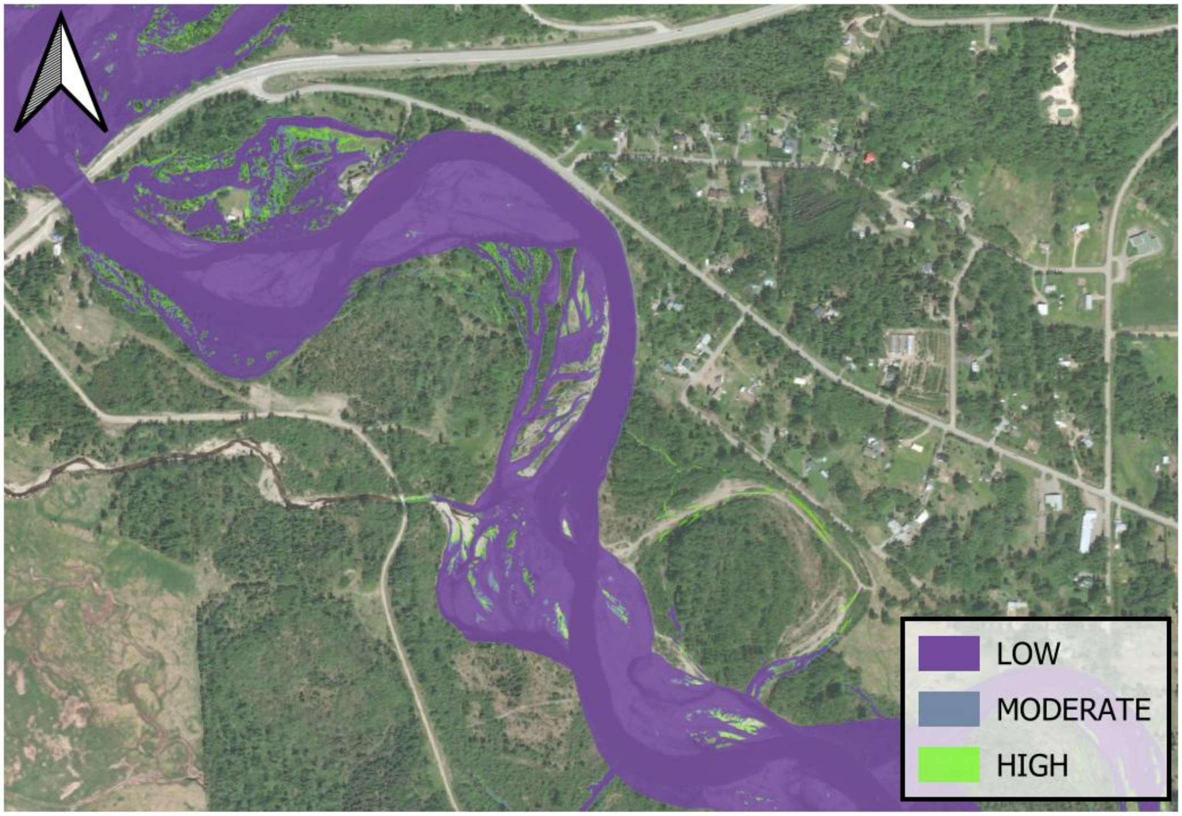

Figure 4-8: Study Area 2 along the Salmon River for Variation in Manning's n.

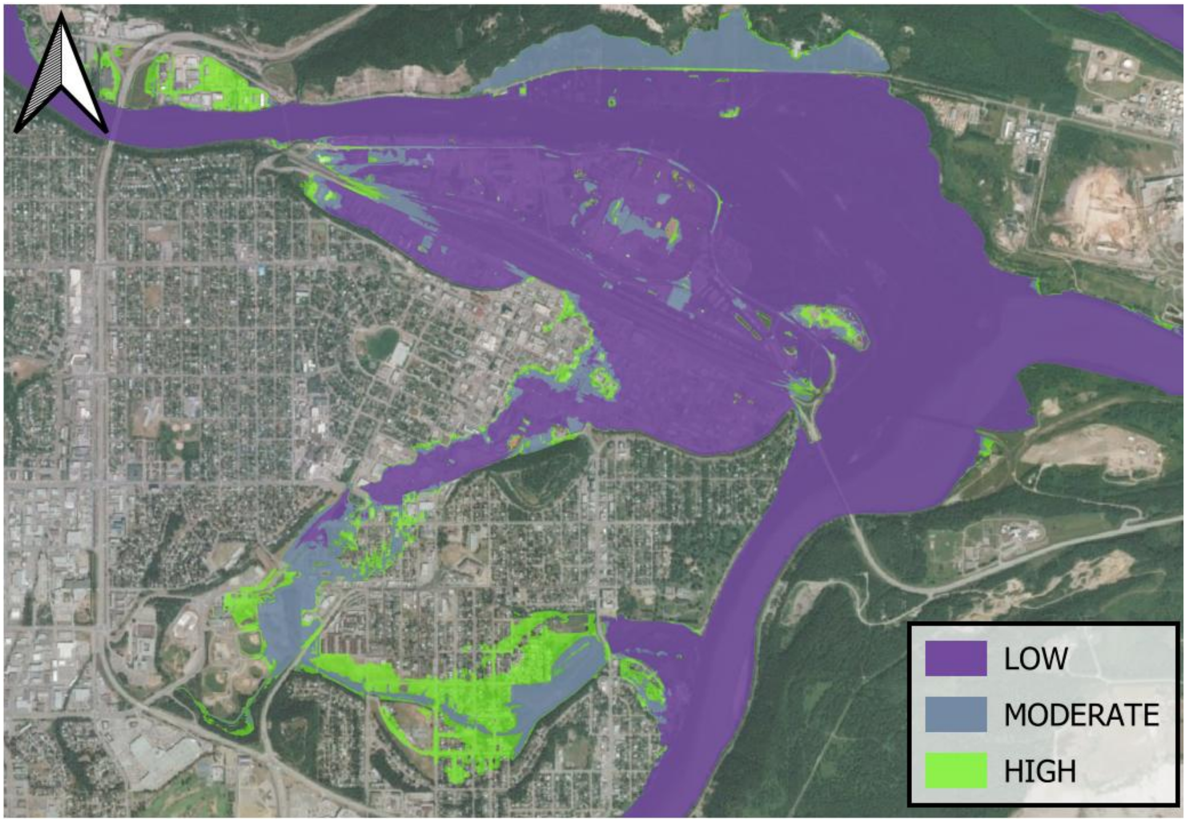

Figure 4-9: Study Area 2 at the Fraser River for Variation in Manning's n.

As shown in the table and figures above, the Fraser River water depths are more greatly impacted by the change in Manning's roughness when compared to the Salmon River. The change in roughness affected the Salmon River water depth on average by 5 cm, while the average change in the Fraser River was about 38 cm. This reflects the larger scale of the Fraser River, as well as the fact that most of the Fraser River reach is highly confined. The Fraser River reach also has a number of bridge crossings which are highly sensitive to the change in roughness. The Salmon River is a smaller scale and has an open, unconfined floodplain, limiting the increase in water levels and instead causing a general increase in flood extents.

4.3 Estimation of Uncertainty in Built Infrastructure

Localized conditions can be highly sensitive to built infrastructure such as bridges, culverts, embankments, and earthen structures. Analyses were conducted to estimate how their functionality in the model can impact the local water level conditions.

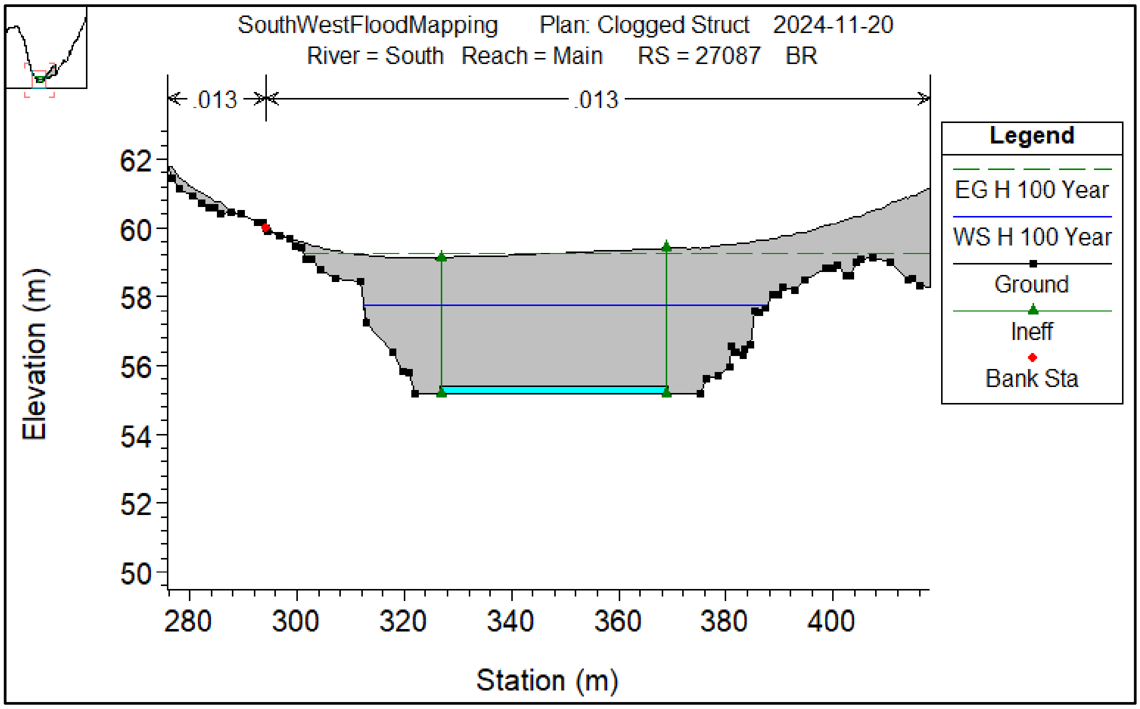

Figure 4-10: Cross-sectional view of a Clogged Bridge with 100 Year Flood Map.

To assess the sensitivity of the model to variations in built infrastructure and the peak flow rate on the water levels, a sensitivity analysis was conducted.

Different scenarios were developed for the two different study areas, due to the very different scales of the rivers and their topographic features.

4.3.1 Study Area 1

For Study Area 1, three distinct scenarios were developed.

- The first scenario, "Clear Span," represents a baseline condition where all structures were assumed to be clear and unobstructed, allowing for unimpeded flow.
- The second scenario, "30% Extra Opening," explores the effect of increasing the opening area of structures by 30%. This scenario aims to simulate the impact of potential scour under the bridge structures, that would increase the available hydraulic opening during an extreme flow event.
- The final scenario, "Clogged Structures," investigates the consequences of reduced flow capacity due to debris accumulation or other obstructions. The clogged structures were left with a minimal opening of approximately 100-300mm to run the model (the HEC-RAS analysis cannot run if the opening is completely blocked.).

By comparing the results of these three scenarios, valuable insights can be gained into the vulnerability of the system to various infrastructure conditions and the potential increase in capacity associated with potential scour.

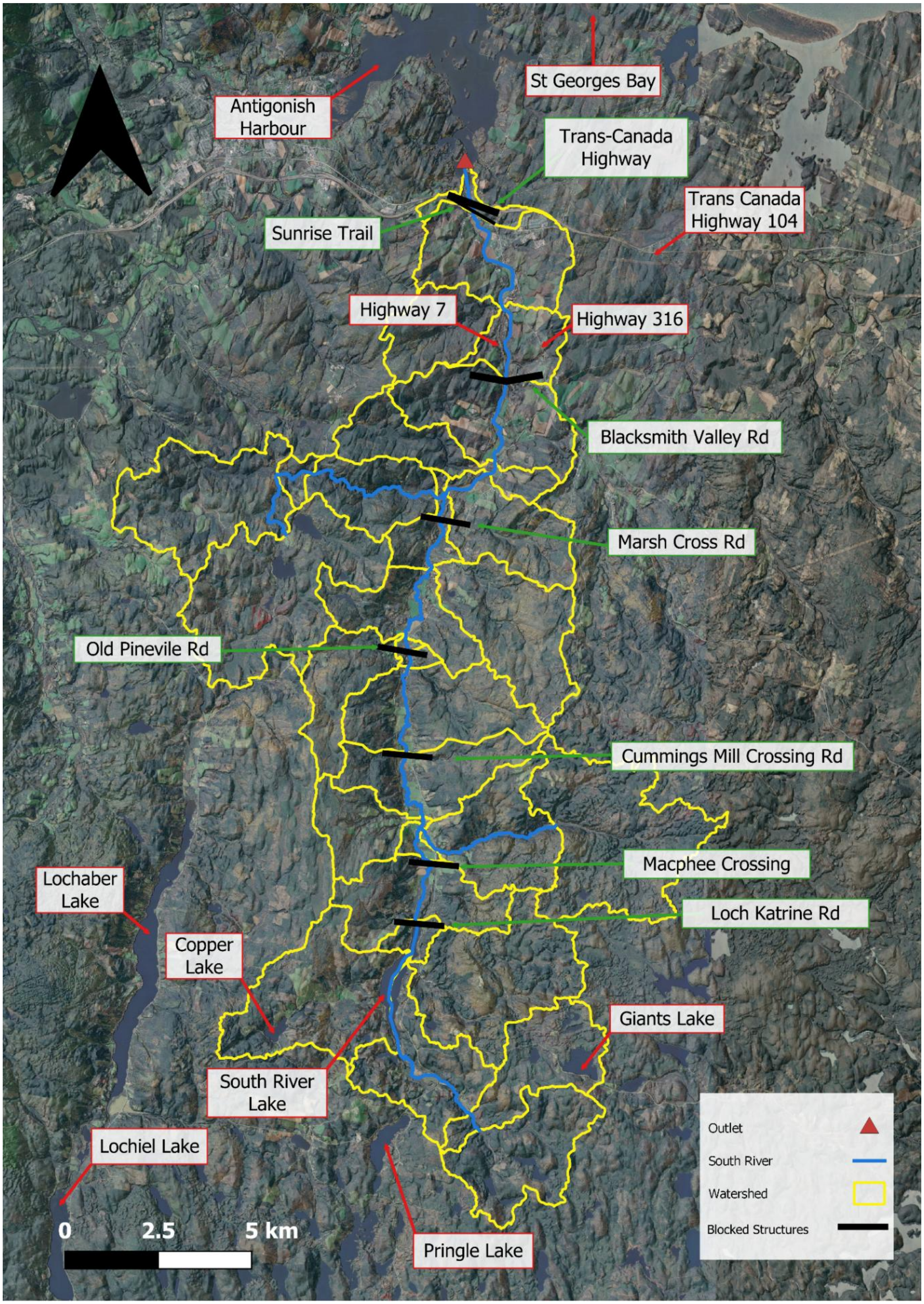

Figure 4-11: Blocked Structures Locations.

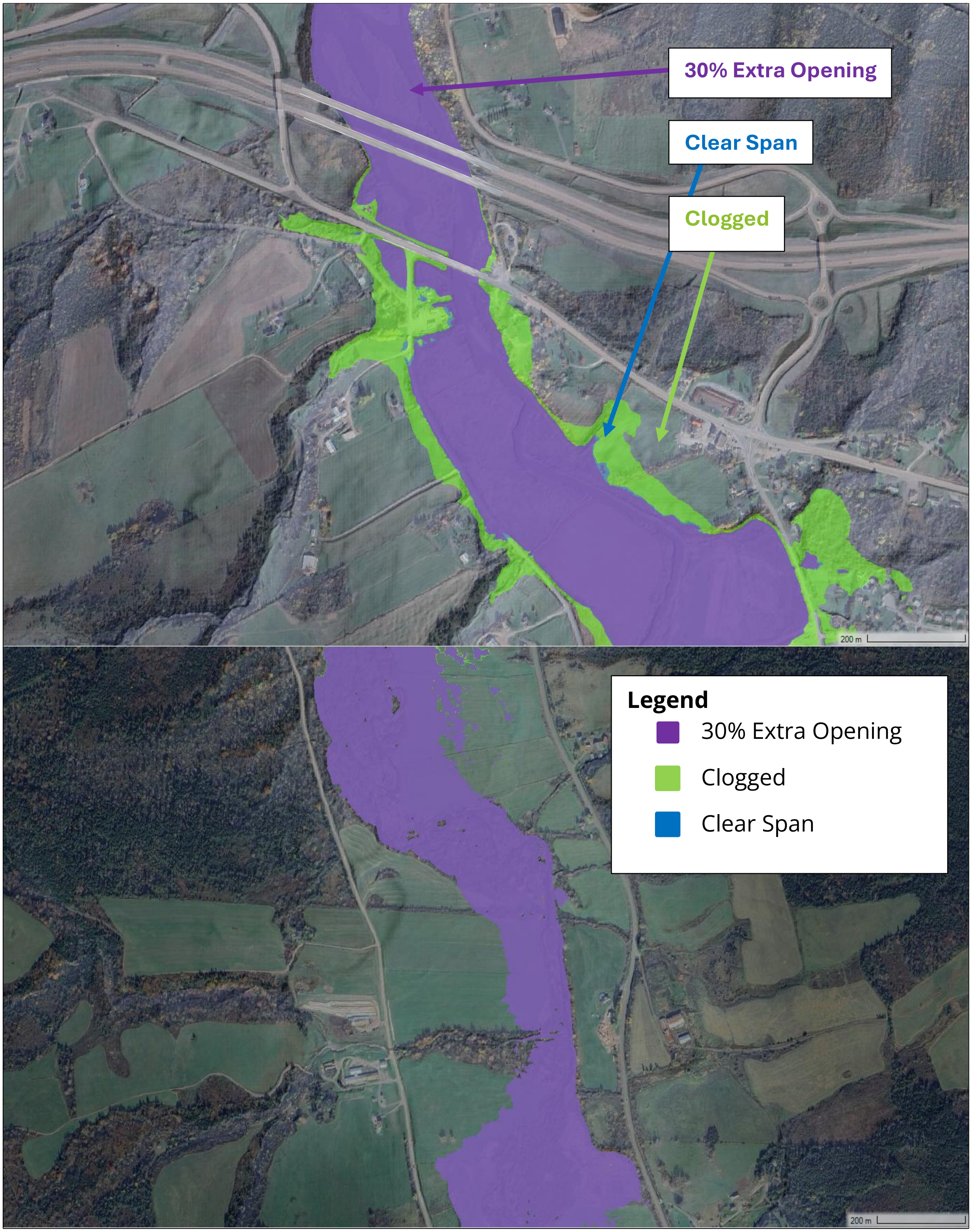

Figure 4-12: Infrastructure Flood map from Clogged Bridges, Clear Span and 30% Extra Opening of Bridges.

The flood map presented in **Figure 4-12** provides a clear visual representation of how built structures and their opening sizes greatly influence flood patterns and extents in surrounding areas.

The "Clear Span" scenario serves as the baseline, illustrating the natural flood extent without any additional infrastructure modifications. In contrast, the "30% Extra Opening" scenario demonstrates the positive impact to conveyance capacity of potential scour. Scour during an extreme flow event can effectively reduce the actual flood footprint compared to the estimated flood footprint based on the surveyed cross-section in low flow conditions.

On the other hand, the "Clogged Structures" scenario highlights the detrimental consequences of obstructed infrastructure. When structures become clogged with debris or other impediments, their capacity to convey water is notably reduced. This can lead to increased water levels, prolonged inundation, and expanded flood zones, as depicted in **Figure 4-12**.

By comparing these three scenarios, it provides valuable information to better understand the range of potential flood extents through a range of natural environmental processes (scour and debris accumulation). This can provide valuable information for lifeline of structures close to vulnerable infrastructure and habitats.

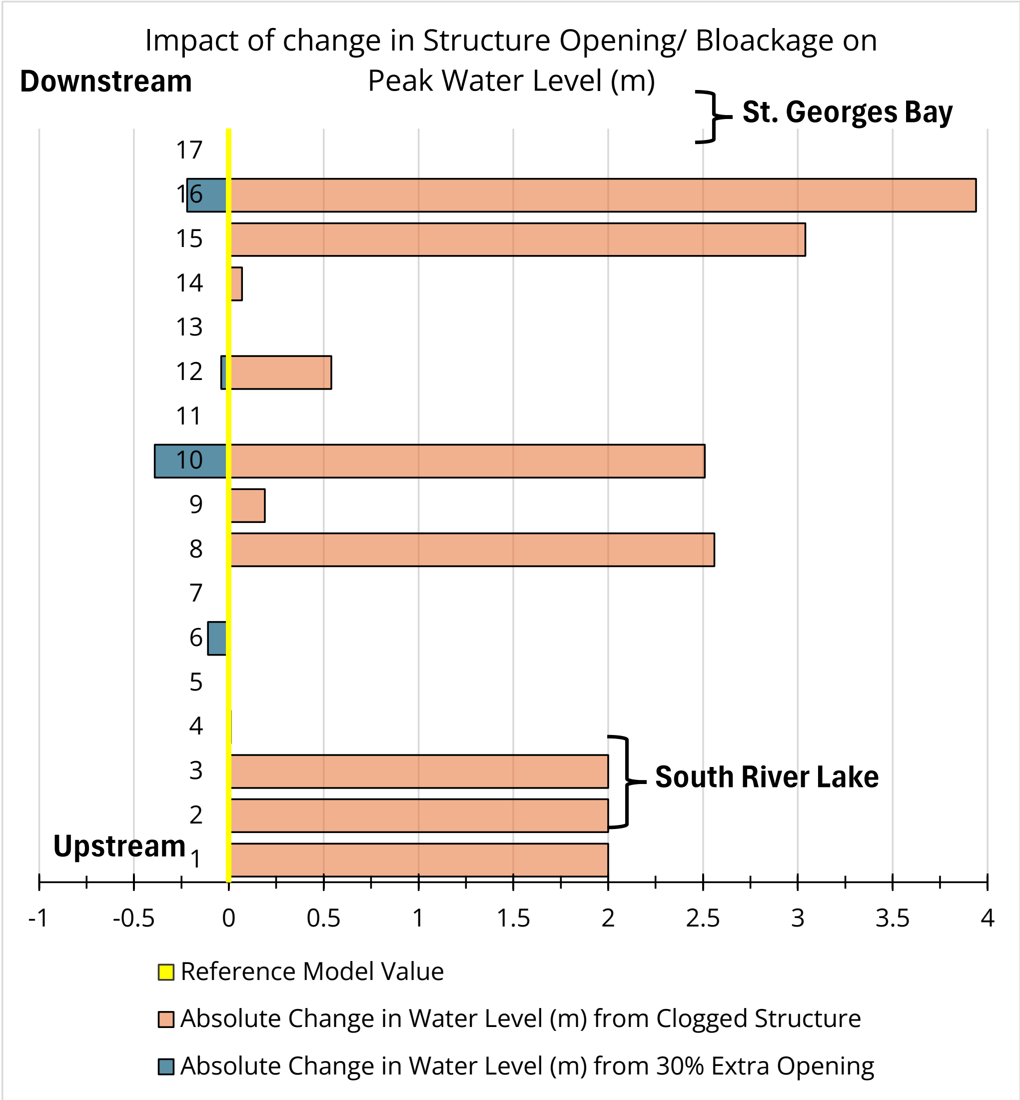

Figure 4-13: Impact of Structure Opening / Blockage Testing Results on WSEL.

4.3.2 Study Area 2

For Study Area 2, three distinct scenarios were developed:

- The first scenario, "Clear Bridges," represents a baseline condition where all structures were assumed to be clear and unobstructed, allowing for unimpeded flow.
- The second scenario, "Partially Clogged Bridges," explores the effect of decreasing the opening area of structures by 50%. This scenario investigates the consequences of some reduced flow capacity due to debris accumulation or other obstructions.
- The final scenario, "Fully Clogged Bridges," investigates the consequences of extreme reduced flow capacity due to debris accumulation or other obstructions. The clogged structures were left with a minimal opening to run the model (the HEC-RAS analysis cannot run if the opening is completely blocked.).

All scenarios were tested for Salmon River, but the Fraser River model proved unstable with fully clogged bridges. The instability is likely the result of numerous bridge crossings along the Fraser River and the heavily confined nature of this river floodplain; this scenario is removed from the results. The locations of the bridges partially or completely blocked for Study Area 2 are shown in **Figure 4-14** and **Figure 4-15**, below.

Table 4-6 shows the water depths at corresponding sample cross-section locations for clear, partially clogged, and fully clogged bridge model runs. Additionally, **Figure 4-16** and **Figure 4-17** show the water surface extents at areas of interest along the Salmon and Fraser Rivers.

Table 4-6: Water Depth Results at Sample Cross-sections along the Salmon and Fraser Rivers with Low, Moderate, and High Manning's Roughness Values

Sample Cross-Sections	River	Depth Results (m)			Depth Difference from Clear Results (m)	
		Partially Clogged Bridges	Clear Bridges	Fully Clogged Bridges	Partially Clogged Bridges	Fully Clogged Bridges
1	Salmon	6.90	4.20	9.11	2.70	4.91
2		3.36	3.35	5.52	0.01	2.17
3		4.15	4.16	4.15	0.00	0.00
4		3.13	3.13	3.13	0.00	0.00
5		4.52	4.52	4.52	0.00	0.00
6		7.32	5.91	12.52	1.41	6.61
7		2.68	2.67	10.02	0.00	7.34
8	Fraser	9.53	9.29	-	0.24	-
9		18.63	17.91	-	0.72	-
10		14.30	12.65	-	1.65	-
11		13.88	11.65	-	2.23	-
12		13.11	10.19	-	2.92	-
13		18.73	14.79	-	3.94	-
14		18.16	15.91	-	2.24	-
15		13.57	11.59	-	1.98	-
16		15.70	13.76	-	1.94	-
17		10.22	10.32	-	-0.10	-

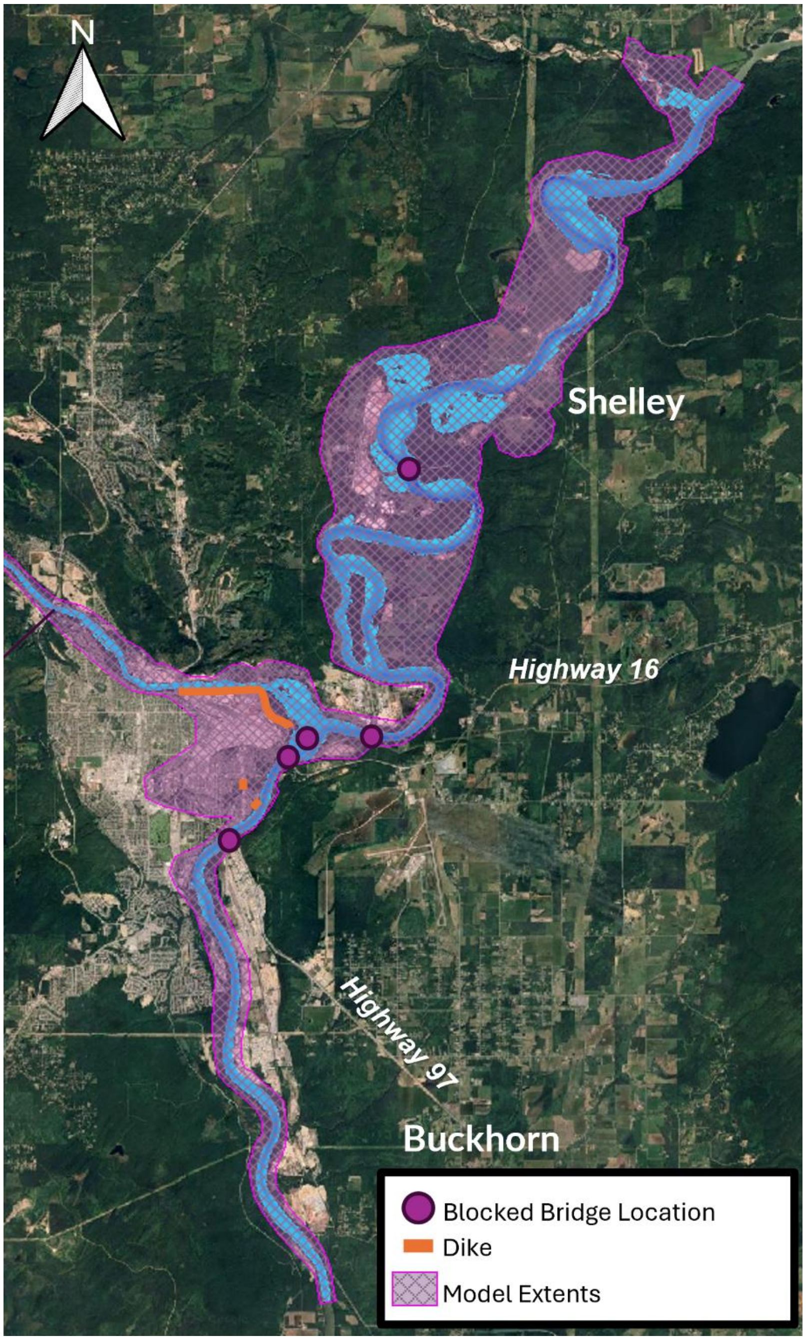

Figure 4-14: Study Area 2 Fraser River Blocked Structures Locations.

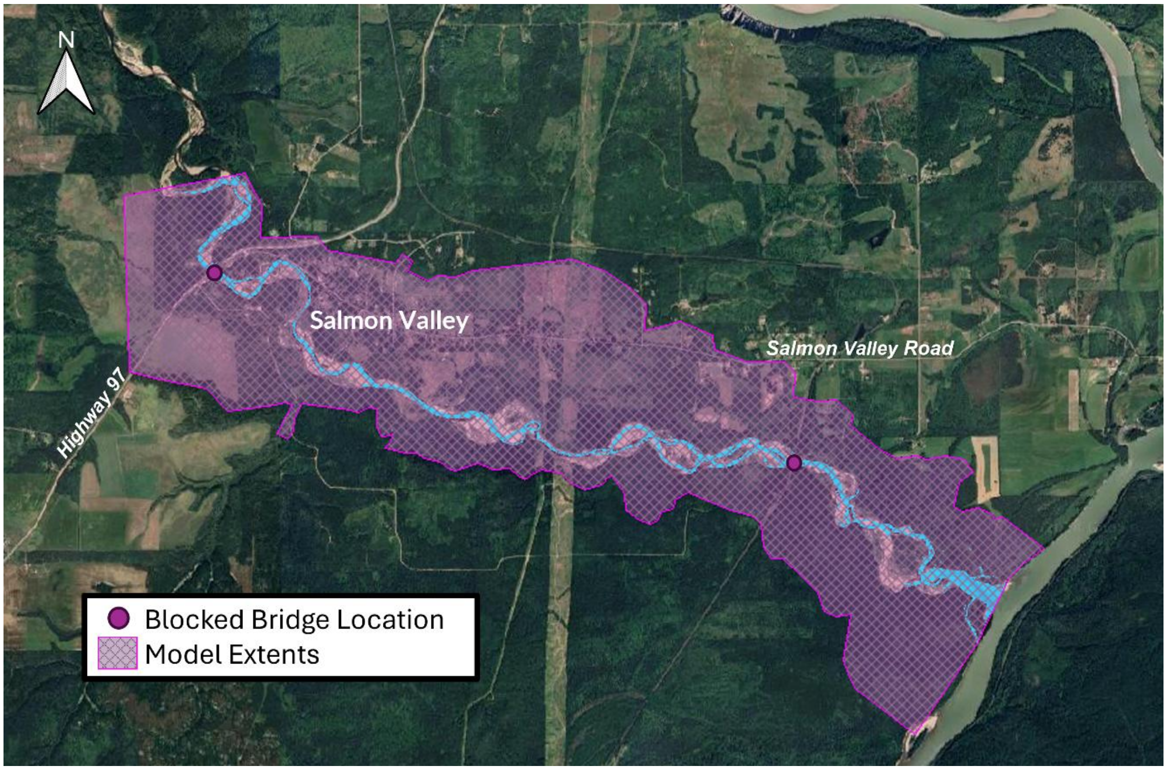

Figure 4-15: Study Area 2 Salmon River Blocked Structures Locations.

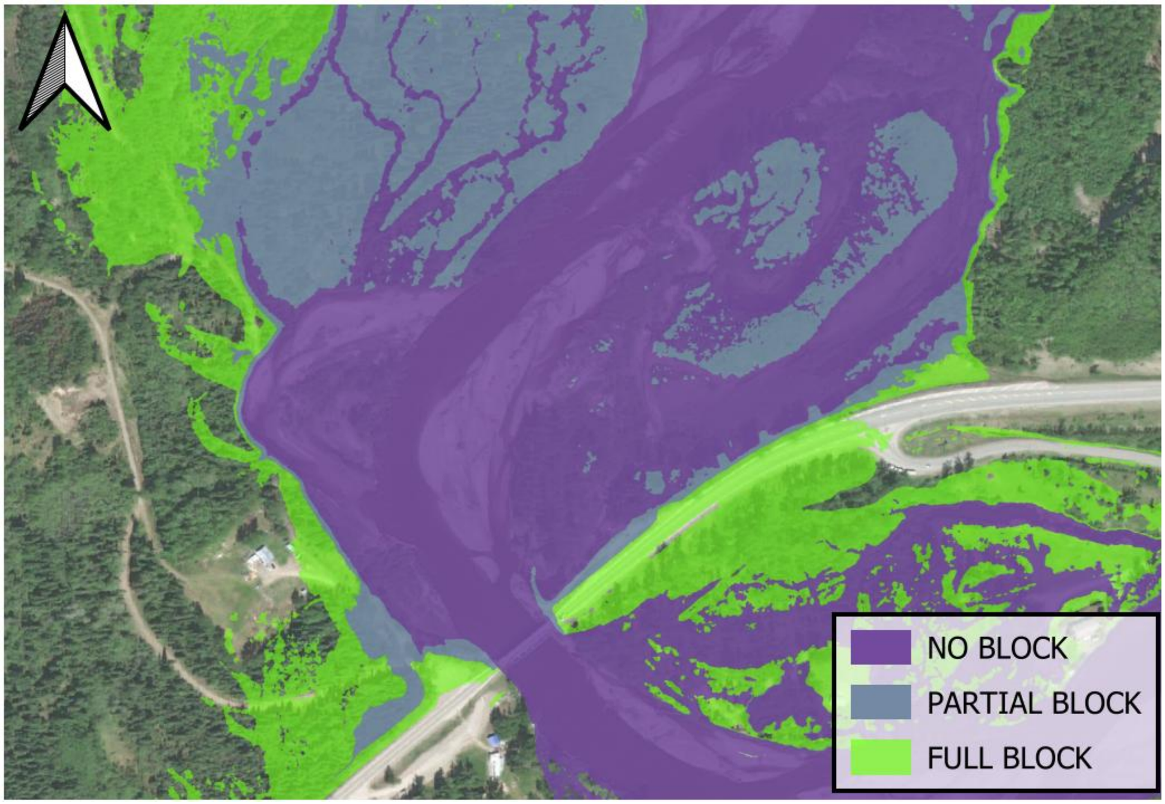

Figure 4-16: Bridge crossing along the Salmon River.

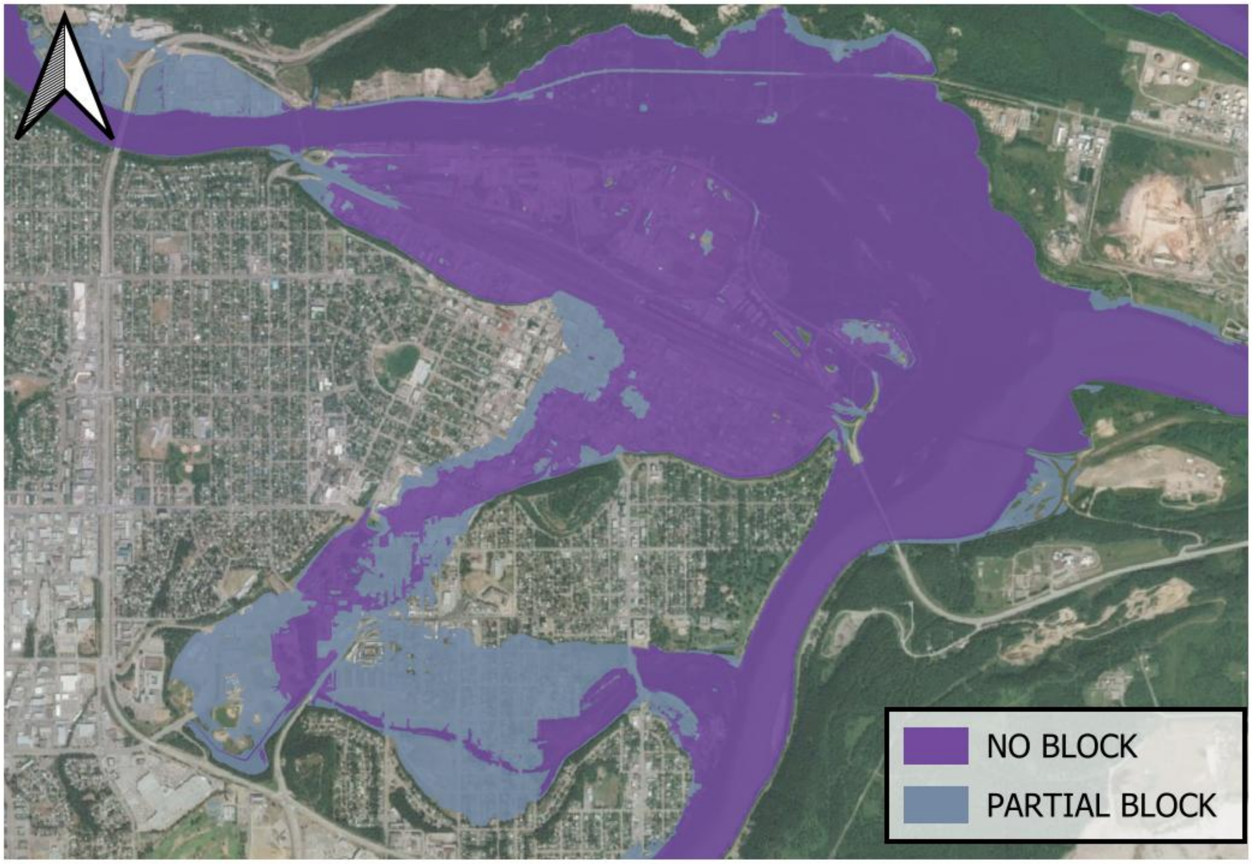

Figure 4-17: Study Area 2 along the Fraser River.

Variations in the model representation of built infrastructure, such as clogging of the bridges, can greatly influence the water depths and the extents. As shown in the figures and table above, both partially and fully clogged bridges increase the backwater upstream of the bridge. In some instances, such as on the Salmon River, fully clogged scenario caused the water to overtop the roads approaching the bridges. Both clogged scenarios cause water levels to increase by meters in multiple locations, as potential flow area in the channel is substantially decreased.

4.4 Estimation of Uncertainty in Modelling Choices

There are various modelling choices that need to be considered and decided in the hydraulic model.

Different scenarios were developed for the two different study areas, due to the very different scales of the rivers and their topographic features as well as the differences in model development (i.e. 1D vs. 2D HEC-RAS).

4.4.1 Study Area 1

For Study Area 1, the steady vs unsteady flow calculations are selected for consideration.

Steady vs Unsteady Flow Calculations

Steady flow assumes that flow conditions do not change with time. This means that the water depth, velocity, and discharge at any given point in the river remain constant over time. Unsteady flow considers the variation of flow conditions with time. This type of simulation is necessary when dealing with transient events like short to medium duration floods, storm surges, or dam breaks, where flow rates and water levels change rapidly.

The scenario Unsteady flow modelling was created to study the effects of choosing unsteady flow conditions in HEC-RAS. The Base model was taken from the Steady Flow scenario and then the Unsteady flow option was used to define the flow hydrograph with various flow data input locations and boundary conditions.

The Time Step selection is crucial in unsteady flow simulations. A smaller time step can provide more accurate results, especially for rapidly changing flow conditions. However, a smaller time step also increases computational costs. Therefore, it is important to balance accuracy and efficiency when selecting the time step. Factors to consider include the steepness of the hydrograph, the complexity of the channel geometry, and the desired level of detail in the results.

For the Unsteady model for this project 3-time steps were primarily chosen. 5 minutes, 1 second and 0.1 seconds. Out of the three options considered, the 5-minute and 0.1-second time steps were found to be unstable, preventing the completion of the HEC-RAS analysis. The model's instability, as indicated by the generated warnings and errors, necessitated adjustments to the model's geometry to enhance its stability and accommodate the selected time step and flow inputs. However, modifying the model's geometry would have compromised the comparability of the results to the base model, rendering the analysis inconclusive.

The HEC-RAS analysis was successfully completed using a 1-second time step. However, upon examining the Summary Output table, certain instabilities were identified within the model's behaviour. These instabilities could potentially be mitigated through adjustments to the model's geometry. Nevertheless, such modifications were avoided as they would have compromised the comparability of the results to the base model, thereby undermining the purpose of the analysis.

By adjusting and recalibrating the model to address the identified instabilities, a more stable unsteady flow analysis could be conducted. The challenge is that a sometimes large amount of effort is needed to eliminate the various instabilities to produce a model that may be more representative in some instances. These include situations where the storage of water created by constrictions is sufficient to dampen the peak flows and reduce water levels.

4.4.2 Study Area 2

For Study Area 2, the following modelling choices were analyzed:

- Grid size: Existing grid sizes (moderate) were increased and decreased by approximately 30% to test the change in water depth and extents. All the channel, overland, and high point grid sizes were scaled.
- Timestep: The existing model timestep was considered moderate, while the low and high timesteps were determined as the next corresponding lower and higher timestep options available in HEC-RAS. For Salmon River, the moderate timestep is 1 second, the low timestep is 0.5 second, and the high timestep is 2 seconds. The Fraser River model has a moderate timestep of 0.5 second, a low timestep of 0.4 second, and a high timestep of 1 second.

4.4.2.1 Grid Size Modifications

The grid size in hydraulic modeling is very important in accurately describing the flow area. More specifically, it is essential to have a grid size that can accurately capture high points, barriers to flow and other critical hydraulic features. The grid sizes were initially tested with both 30% larger and smaller scaling. However, due to the fine detail in the existing models, a 30% increase in mesh refinement (i.e. decrease in mesh size) lead to model instability which prevented the model from running or producing results. This highlights the challenges of running 2D models with very small grid sizes and the important balance between increased refinement to allow for model detail and cell size limitations due to instability. For this reason, the increase in mesh refinement was limited to an increase of 15% (i.e. decrease of 15% in mesh size).

Table 4-7 shows the water depths at corresponding sample cross-section locations for the smaller (15% decrease in size), moderate and larger (30% increase in size) grid size model runs. Additionally, **Figure 4-18** through **Figure 4-20** show the water surface extents at areas of interest along the Salmon and Fraser Rivers, including the high sensitivity of the 1D-2D bridge crossings to mesh size.

Table 4-7: Water Depth Results at Sample Cross-sections along the Salmon and Fraser Rivers with Smaller, Moderate and Larger Grid Sizes

Sample Cross-Sections	River	Water Depth Results (m)			Water Depth Difference from Moderate Results (m)	
		Smaller Grid Size	Moderate Grid Size	Larger Grid Size	Smaller Grid Size	Larger Grid Size
1	Salmon	4.42	4.20	4.27	0.22	0.07
2		3.35	3.35	3.38	0.00	0.03
3		4.19	4.16	4.25	0.04	0.09
4		3.17	3.13	3.14	0.03	0.01
5		4.52	4.52	4.50	0.00	-0.02
6		5.99	5.91	5.94	0.08	0.03
7		2.70	2.67	2.66	0.02	-0.01
8	Fraser	9.31	9.29	9.67	0.01	0.37
9		17.80	17.91	18.08	-0.11	0.17
10		12.71	12.65	13.08	0.07	0.43
11		11.71	11.65	12.22	0.06	0.57
12		10.28	10.19	11.54	0.09	1.35
13		14.85	14.79	16.50	0.06	1.71
14		15.99	15.91	17.42	0.08	1.51
15		11.63	11.59	13.05	0.04	1.45
16		13.89	13.76	16.09	0.13	2.33
17		10.26	10.32	10.35	-0.06	0.03

Figure 4-18: Area of interest along the Salmon River for variation in grid size.

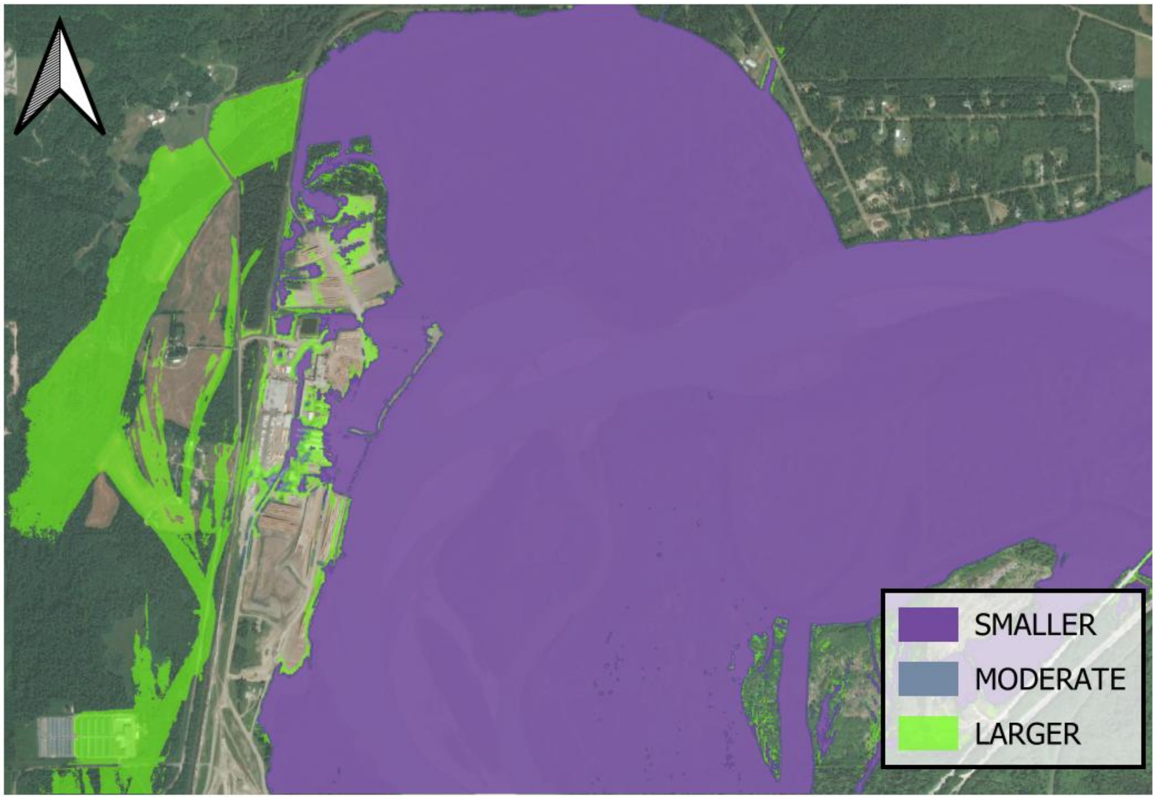

Figure 4-19: Area of interest along Fraser River showing variation in grid size.

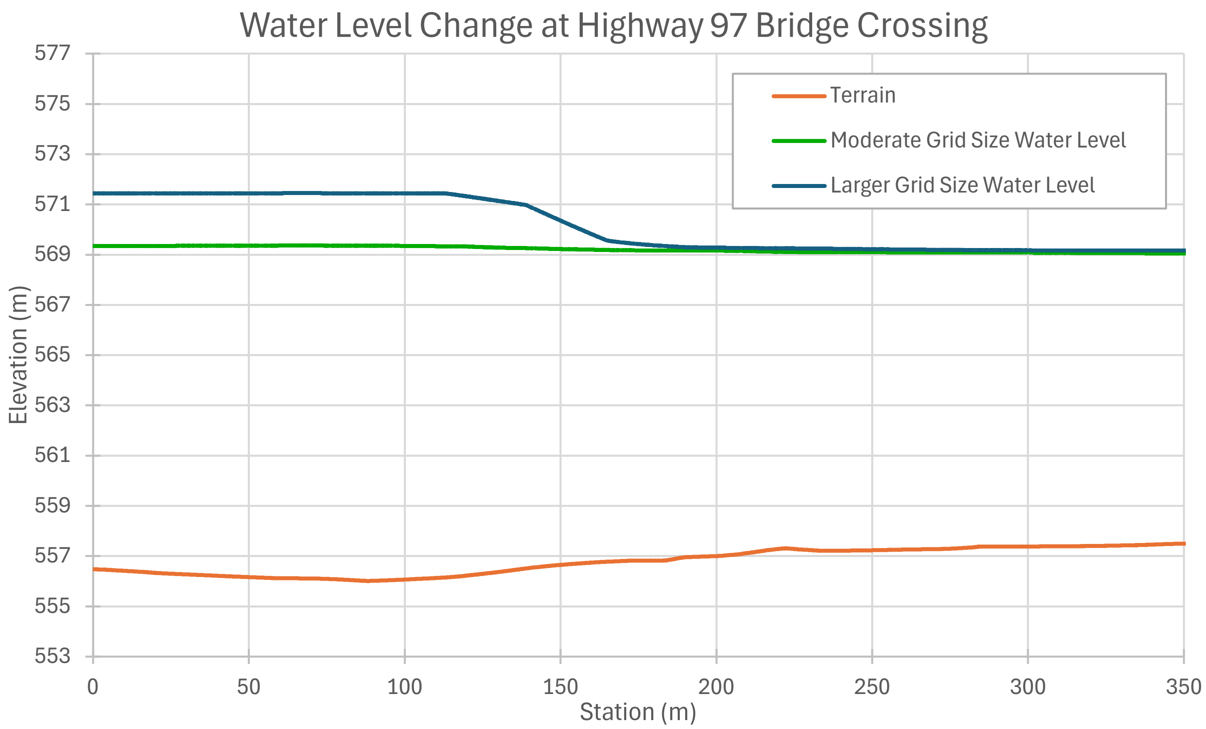

Figure 4-20: Water level change at the Fraser River Highway 97 bridge crossing.

As shown in the figures and table above, the larger grid size typically results in a higher water depths with larger extents. This occurs more dramatically for the Fraser River, specifically within the most developed area of the reach with multiple bridge crossings. Bridge crossings are particularly sensitive to grid size, as shown in **Figure 4-20** where the larger grid size has a drop of more than 2 m in water level across the bridge, causing appreciable backwater upstream. **Figure 4-19** illustrates a high point that loses critical topographic description in the large grid size results, as the larger grid size allows leakage through the high point.

In general, the smaller grid size produced minimal changes in water depths and extents, suggesting that the level of detail in the moderate size mesh was sufficient to accurately describe river topography and bathymetry. This suggests a point of diminishing returns beyond which additional model detail (i.e. mesh refinement) does not yield greater accuracy in model results.

4.4.2.2 Timestep Modifications

In hydraulic modelling, the timestep, also know as the computation interval, is the time between unsteady flow calculations.

Table 4-8: Water Depth Results at Sample Cross-sections along the Salmon and Fraser Rivers with Low, Moderate, and High Timestep Values

Sample Cross-Sections	River	Water Depth Results (m)			Water Depth Difference from Moderate Results (m)	
		Low Timestep	Moderate Timestep	High Timestep	Low Timestep	High Timestep
1	Salmon	4.24	4.20	4.19	0.04	-0.02
2		3.35	3.35	3.34	0.00	0.00
3		4.15	4.16	4.15	0.00	0.00
4		3.13	3.13	3.13	0.00	0.00
5		4.52	4.52	4.50	0.00	-0.02
6		5.91	5.91	5.89	0.00	-0.02
7		2.68	2.67	2.67	0.00	-0.01
8	Fraser	9.30	9.29	9.29	0.00	0.00
9		17.91	17.91	17.91	0.00	0.00
10		12.65	12.65	12.64	0.00	0.00
11		11.66	11.65	11.68	0.00	0.03
12		10.20	10.19	10.18	0.01	-0.01
13		14.80	14.79	14.78	0.01	-0.01
14		15.93	15.91	15.91	0.01	0.00
15		11.60	11.59	11.59	0.00	0.00
16		13.77	13.76	13.76	0.00	0.00
17		10.32	10.32	10.31	0.00	0.00

It can be observed from the table above that these changes in timestep had a much smaller impact on peak water depths or extents than did the mesh size. For example, the largest difference in water depth is 4 cm on the Salmon River. Overall, changing the timestep within the range examined does not notably impact the results of the model. For this reason, no example figures have been included in this section.

4.5 Estimation of Uncertainty in Hydraulic Model Calibration

Model calibration is a process completed by adjusting model parameters to reproduce measured water levels. Typically, this involves adjusting the Manning's roughness values.

For Study Area 2, the Salmon River was selected for model calibration review and had limited data available for calibration. Two calibration events were assessed: the original calibration from the existing model and a secondary calibration from an event originally discounted. The secondary calibration was completed with an event prior to noticeable changes in the bed of the channel in aerial photography, explaining why it was not chosen for the original calibration. The resulting Manning's roughness values in the Salmon River channel for the secondary calibration are 30% lower than the original calibration.

Table 4-9 shows the water depths at corresponding sample cross-section locations for the low, moderate, and high roughness model runs. Additionally, **Figure 4-21** shows the water extents at an area of interest along the Salmon River.

Table 4-9: Water Depth Results at Sample Cross-sections along the Salmon River with Low, Moderate, and High Manning's Roughness Values

Sample Cross-Sections	River	Water Depth Results (m)		Water Depth Difference from Original Calibration (m)
		Secondary Calibration Parameters	Original Calibration Parameters	Secondary Calibration Parameters
1	Salmon	4.63	4.20	0.43
2		3.21	3.35	-0.14
3		3.90	4.16	-0.25
4		2.89	3.13	-0.25
5		4.43	4.52	-0.09
6		5.76	5.91	-0.15
7		2.50	2.67	-0.18

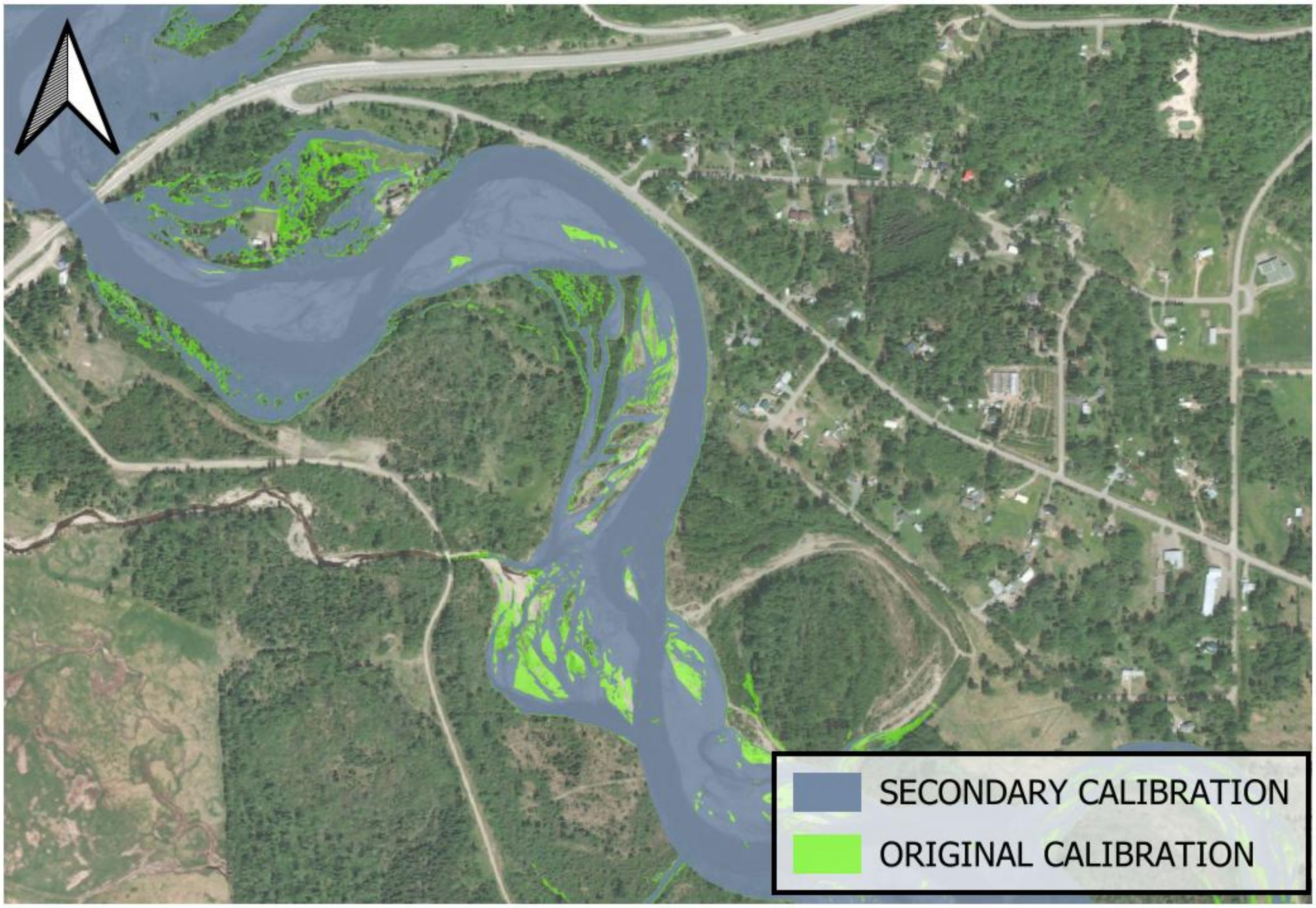

Figure 4-21: Area of interest along the Salmon River with secondary calibration.

As shown in the figure and table above, the water depths and extents are substantially lower within the secondary calibration when compared to the original, due to the Manning's roughness in the channel being lower in the secondary calibration event. For the Salmon River, this corresponds to a large decrease in extents as lower water levels in the channel causes less overbank flow into the floodplain. Modelling of this second, less appropriate calibration highlights the importance of reviewing calibration data for applicability and reviewing hydrometric station locations for changes in bedform or other hydraulic characteristics.

4.6 Summary and Discussion of Results

The sensitivity analysis of hydraulic modelling demonstrated a range of variations in results with changes to each tested parameter.

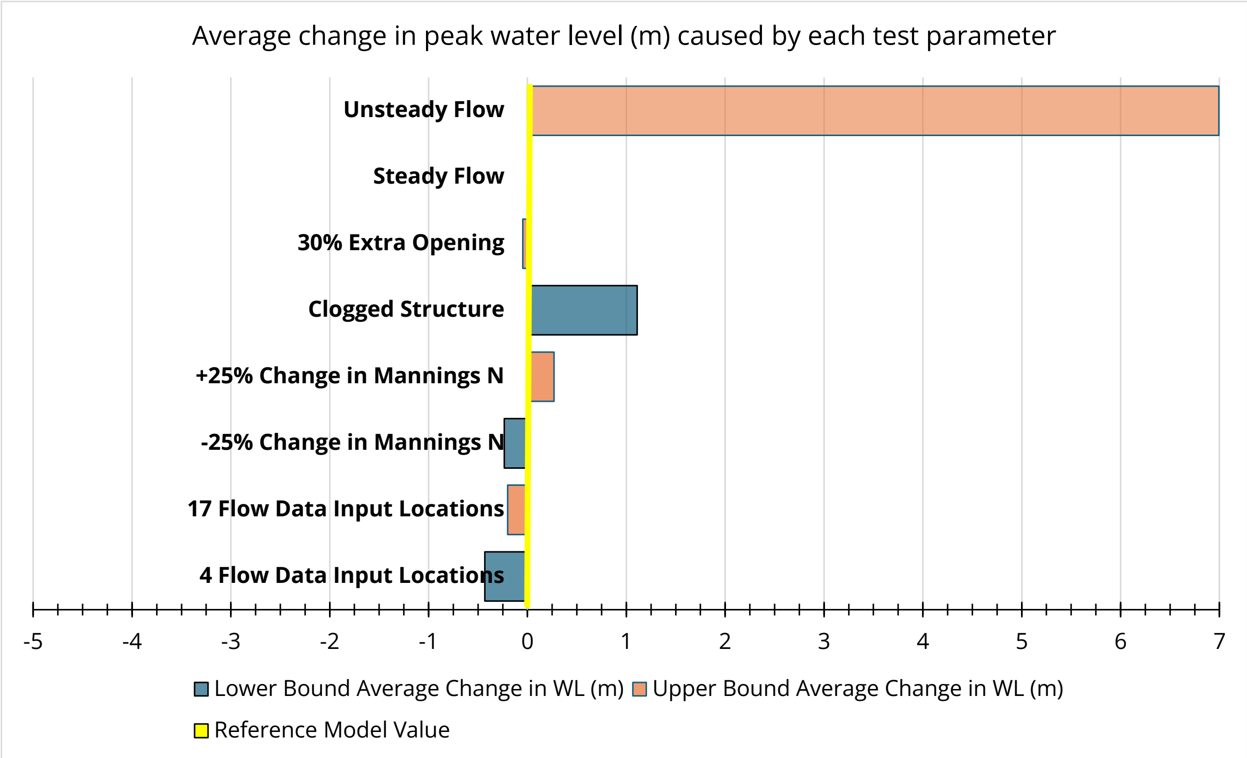

Figure 4-22: Summary of average changes on peak water level.

4.6.1 Input of Design Flow

A closer examination of the Flow Change Location parameter revealed a clear trend: higher values of this parameter generally led to improved results, as evidenced by both water depth values and the corresponding flood maps. This trend suggests that increasing the number of flow data input locations tends to produce more detailed and representative flood maps.

Further analysis indicated that the optimal number of flow data input locations varied depending on the specific characteristics of the study area. However, in general, increasing the number of flow data input locations beyond a certain point did not result in many improvements in model results. This suggests that there is a balance to be struck between the number of flow data input locations and the computational cost of the model.

Generally, it is estimated that model results far from input flow locations are less representative of real-world conditions than model results close to input flow locations, since in real-world conditions, the flows would be gradually increasing along the entire watercourse length, with the main inputs being from groundwater, small tributaries and large tributaries.

4.6.2 Manning's Roughness

The second set of parameter modifications involved altering the Manning's n values and flow rates within the model to assess their impact on simulated water depths. The results unequivocally demonstrate the critical role of both parameters in the accuracy of the analysis. As illustrated in the table, increasing Manning's n values led to a decrease in flow velocity and a subsequent rise in water levels. Naturally, an increased channel roughness will require a higher water depth to convey the same flow. Conversely, decreasing Manning's n values facilitated more rapid water movement through the model. Consequently, meticulous consideration must be given to the selection of representative Manning's n values, tailored to the specific characteristics of the local area.

Not surprisingly, the sensitivity analysis demonstrated that flow rate adjustments largely influenced both water depths and flood map extents. Depths increased, and flood maps expanded, particularly in low-lying regions, with higher flow rates. Conversely, lower flow rates resulted in decreased elevations and smaller flood map areas.

4.6.3 Built Infrastructure

The impact of built infrastructure was also investigated through the following scenarios: 30% Extra Opening (mimicking scour), Clear Span, Partially Clogged, and Clogged Structures. The Clear Span scenario replicated the base flow conditions. The 30% Extra Opening scenarios facilitated increased water flow, resulting in a slightly lower water depth values and a reduced flood map footprint. Conversely, the Clogged Structures scenario, simulating debris accumulation and reduced flow capacity, led to higher water depth values and a substantial expansion of the flood map, affecting a larger portion of the modelled area. The Clear Span scenario served as a baseline, representing the absence of notable infrastructure-related flow obstructions. The 30% Extra Opening scenario introduced additional flow capacity through the infrastructure as a result of scour, leading to improved water flow and reduced flood impacts. In contrast, the Clogged Structures scenario simulated the adverse effects of debris accumulation and reduced flow capacity within the infrastructure, resulting in increased water levels and a wider extent of flooding. This sensitivity analysis not only showed the relative impact that structures can have on flood flows, water levels and extents, but also showed how estimating the width of structures with unknown dimensions (e.g. private structures) is a delicate task that can have notable consequences on the flood mapping results.

4.6.4 Modelling Choices

Within Study Area 1, a comparative analysis was conducted between the Steady and Unsteady model simulations. The Unsteady model exhibited some numerical instability issues, which were only partially resolved through multiple iterations within the HEC-RAS engine.

Within the Study Area 2 2D HEC-RAS models, grid size greatly impacted the water depths and extents. Specifically, increased mesh sizing lead to loss of mesh refinement and description of important topographic and hydraulic structures. Water within the hydraulic models then spread to areas behind berms and other high points. This "leakage" through high points is a common problem in 2D hydraulic models that should be recognized while selecting a grid size at high points. The larger grid size also created extreme increases in bridge crossing energy losses, creating large backwater effects which impacted upstream water levels. Smaller grid size was limited by model instability and produced minimal changes in water depths and extents. This suggests that the level of detail in the original moderate size mesh was sufficient to accurately describe river topography and bathymetry and indicates a point of diminishing returns beyond which additional model detail (i.e. mesh refinement) does not yield greater accuracy in model results.

Within Study Area 2, time steps were varied and simulations were performed with time steps of 0.1 second, 1 second, and 5 minutes. Due to severe instabilities, only the 1-second time step simulation was successfully run. This illustrates the importance of balance in time step, that is, detailed enough to describe changing water levels without being so detailed as to cause calculation instability and error.

4.6.5 Calibration

The event chosen for calibration can greatly impact the overall water extent results. If the "wrong event" is chosen that could potentially represent an inaccurate representation of the channel, the results could also be inaccurate. This highlights the importance of choosing an event for calibration that is representative of flood conditions, and taking note of notable changes to the watercourse over time. Ideally, a calibration event has a flow magnitude similar to the flow magnitude of the flood mapping design event and has taken place recently enough that the river bathymetry, flood plain topography and flood management infrastructure during the event are as representative of present day conditions as possible.

A closer examination of the flood maps generated under different flow rate scenarios revealed several additional insights. In areas with complex topography, such as those with numerous obstacles, the impact of flow rate changes on flood extent was often more pronounced, but highly dependent on the interactions between water depths and obstacle elevations. This is because higher flow rates can more easily overcome topographic barriers, leading to widespread inundation, but only when the change in inflow causes water to reach the threshold elevation necessary to overtop a given barrier. In contrast, in relatively flat areas without obstacles such as roads or flood infrastructure, the impact of flow rate changes on flood extent was more consistent, as the water tended to spread out more evenly. Areas with steep slopes and relatively consistent terrain (i.e. lacking obstacles such as flood infrastructure) also showed a more consistent relationship between flow rate and flood extent. However, in these steeper areas without obstacles, variation in flood extents was observed to be less sensitive to changes in flow than in adjacent reaches with flatter slopes without obstacles.

Complex interactions between various aspects of changing topography (slopes, channel confinement, the presence of obstacles and flood infrastructure) as well as backwater effects from downstream restrictions make it challenging to estimate more site-specific sensitivity of flood extents to flow.

5 Uncertainty in GIS Post-Processing

A number of different GIS post-processing methodologies and practices can be applied during the development of flood hazard maps. These methodologies and practices may change depending on projection location, local best practices and provincial guidance. Practices may also change based on whether the modelling and analysis were completed in 1D of 2D models. For the purposes of this study, each study area has reviewed those post-processing processes which were included in their original study and area considered typical of their province.

The following GIS post-processing methodologies were reviewed:

- Flood extent cleaning (Study Areas 1 and 2).
- Flood extent simplification (Study Areas 1 and 2).
- Inclusion of "protected" areas (Study Area 2).
- Combining multi-hazard scenarios (Study Area 2).
- Isoline generation and smoothing (Study Area 2).
- Comparison of WSEL and EGL (Study Area 1).

The changes and variation considered within each process methodology are intended to represent reasonable flood mapping choices, within a range typically considered acceptable for their specific study area and river reach. Results for this section are discussed in each sub-section.

5.1 Flood Extent Cleaning

Inundation mapping is generated by the difference of modelled water levels and the ground surface Digital Elevation Model (DEM). When high precision DEMs are used, it is common for there to be numerous small islands and ponded areas in the shallow fringes of the flood zone. Furthermore, the high precision DEM typically leads to intricately complex flood line boundaries.

There are varying approaches used in the industry to handle the 'noise' created by overlaying the flood level onto the DEM. One method is to leave as much detail as possible and not manually edit or alter the resulting flood line. A downside of this method is the potential for confusion and misinterpretation of the results at the land use planning stage.

Isolated islands may not technically be flooded but are exposed to flood hazards nonetheless. Another side effect of leaving all features intact, is the potential to create large GIS file sizes with the potential to generate thousands of small individual features, which must be managed.

A pragmatic approach to this challenge often involves removing small disconnected flooded areas and islands under a nominal size (selection varies), such as 500 m^2. Yet still there are subjective decisions to make regarding the minimum size of these features to remove. For example, if during the Lidar data processing, buildings are removed, but the substituted ground elevation is slightly higher than the surrounding elevations, floodlines can appear to surround the building footprints. This is an example where review of the data and re-infilling those gaps may be conducted if necessary.

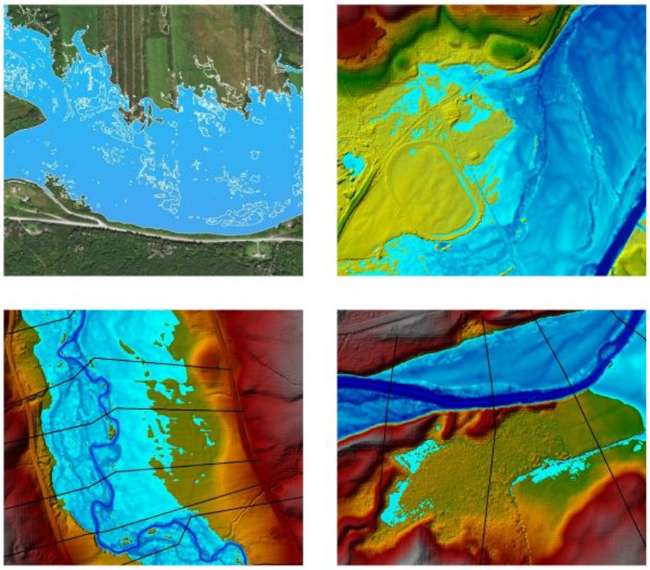

Figure 5-1: Examples of Flood Mapping Uncertainty around Flood Fringes, Disconnected Wet Areas, and Islands

5.1.1 Study Area 1

Study Area 1 employed the HEC-RAS tool to test rendering options. Examples of various flood mapping results that may warrant the selection of appropriate GIS-post processing in various flood studies are displayed in **Figure 5-1**.

Another interfacing software for HEC-RAS called GeoHECRAS from CivilGEO, can be utilised to create and review HEC-RAS modelling results.

For Mapping, GeoHECRAS provides the following options for plotting the flood map based on HEC-RAS analysis results.

- Selection of the type of flood map that is to be generated including EGL or WSEL.
- Selection of the type of computation method to use for generating the flood map. This includes Straight Line, Detailed Intersection (GeoHECRAS exclusive) and 1D Steady State (HEC-RAS method).
- Selection of the underlying terrain surface and the algorithm for generating the flood map, which can be Approximate (Fast) method (uses the default grid resolution of 5 ft to generate the flood map), or the Precise (Slow) option (allows a grid resolution in the range of 1 m to 5 m).
- Clipping of small dry areas (islands) in the floodplain and small ponded areas outside the floodplain can be set by defining a maximum area value, and buildings can also be clipped out from the flood map.

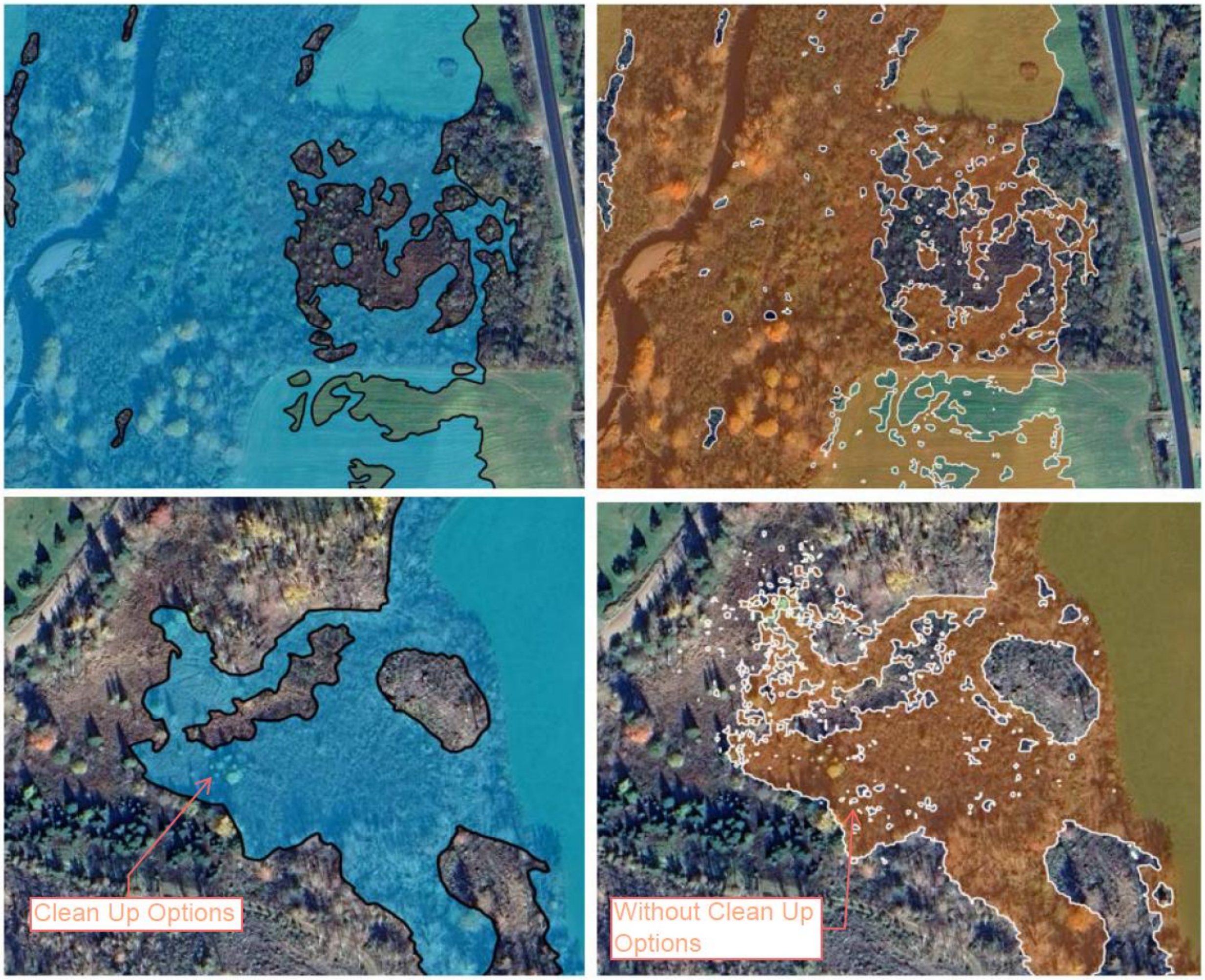

Figure 5-2: Flood Map with and without Cleanup Option (Fill in holes and removal of Ponded regions) of GeoHECRAS.

Table 5-1: Impacts of Extent Cleaning on Flooded Area using GeoHECRAS

Nominal Size for Cleaning (m^2)	Flood Extent Area		
	Sum of Removed Area and Filled Area (ha)	Total Area (ha)	Change in Area From Base Case
None	0	652.45	0%
50	0.947	653.40	0.15%
100	1.549	654.	0.24%
200	2.246	654.701	0.34%
500	2.937	655.392	0.45%
1000	3.371	655.826	0.52%

5.1.2 Study Area 2

Hydraulic models developed with high-resolution DEMs often show numerous small islands and ponded areas in the shallow fringes in the flood zone. To address this 'noise' pragmatically, small, flooded areas and/or islands can be removed under a certain nominal size. Selection of this nominal size will vary depending on the scale of the watercourse / waterbody modeled. Different nominal sizes were tested at three levels: low, moderate (typical), and high. The values of these sizes were selected according to the respective scale of the Salmon and Fraser Rivers.

Table 5-2 shows the flood extent area for each river for the low, moderate, and high nominal sizes. Additionally, **Figure 5-3** and **Figure 5-4** show the cleaned extents at areas of interest along the Salmon and Fraser Rivers.

Table 5-2: Impacts of Extent Cleaning on Flooded Area

Nominal Size for Cleaning (m^2)	River	Flood Extent Area[1]			
		Removed (Puddles) (ha)	Added (Filled Islands) (ha)	Total Area (ha)	Change in Area From Base Case
None	Salmon	0	0	394	0%
800		5	8	397	0.8%
1000		5	9	398	1.0%
20,000		5	33	422	7.1%
None	Fraser	0	0	5320	0%
3000		17.0	37	5340	0.4%
5000		20.7	50.7	5350	0.6%
80,000		39.2	129.2	5410	1.7%

[1] Values have been rounded to reflect the scale of the rivers on which they are calculated. Values on the Salmon River are rounded to the nearest 1 m. Values on the Fraser River are rounded to the nearest 10 m.

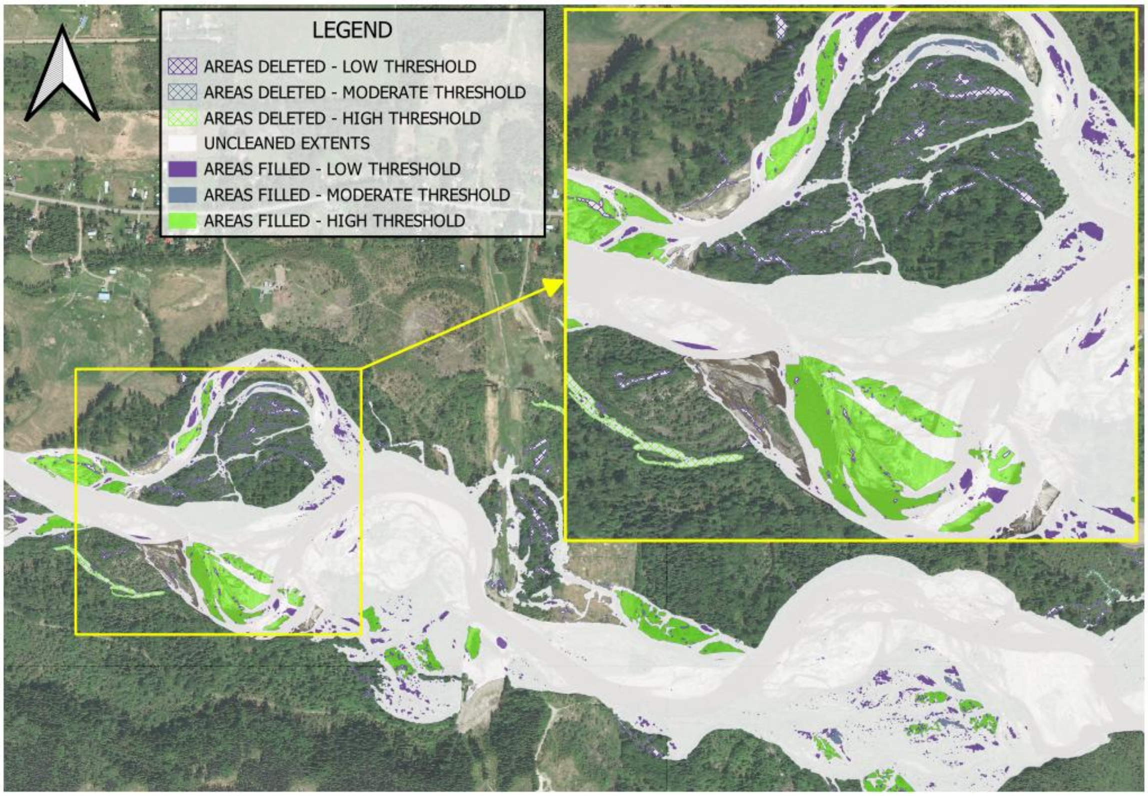

Figure 5-3: Salmon River Flood Extent Cleaning.

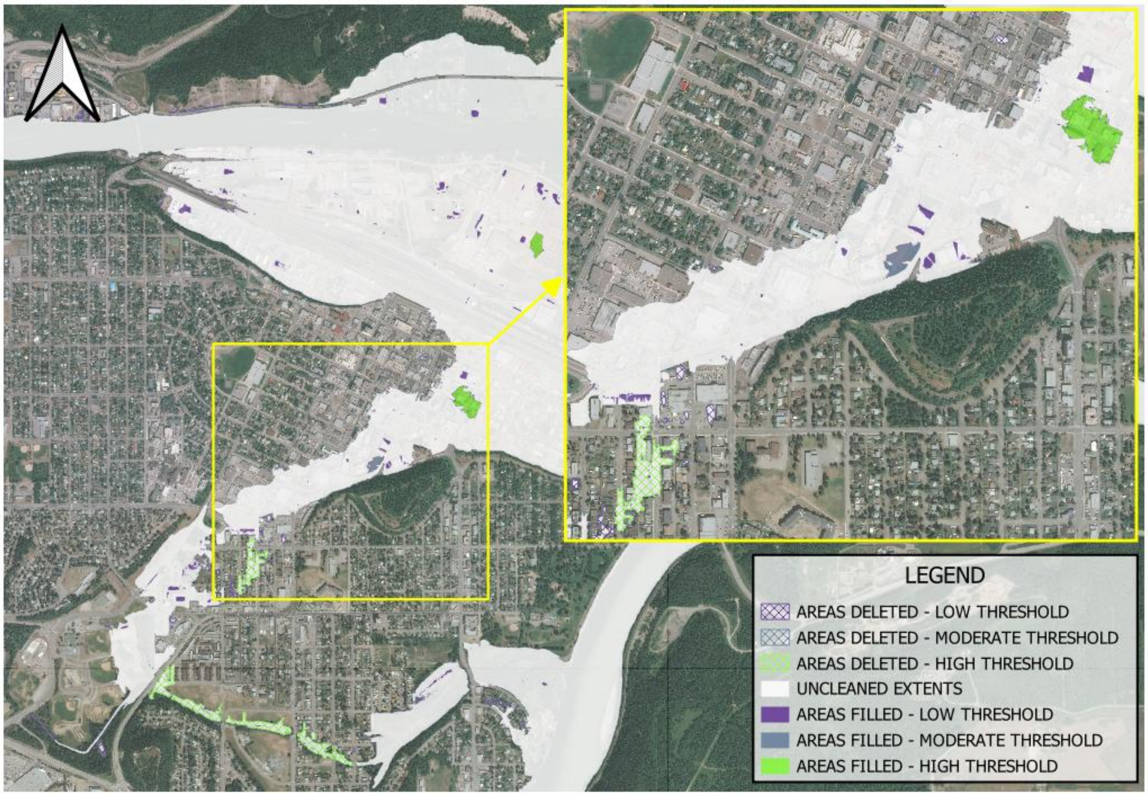

Figure 5-4: Fraser River Flood Extent Cleaning.

Generally, the flood extent cleaning removes noise and improves readability of result extents. Filling islands may artificially increase flooded area and floodplain width, particularly in a wide floodplain where multiple relic channels are engaged during high flow events. This is observed on the Salmon River for the high nominal size (**Figure 5-3**), where the floodplain width increases locally by approximately 50% as a result of the cleaning process.

Neither the Salmon nor the Fraser River experienced significant data loss for the low or moderate nominal sizes. For the high nominal size, some data has been lost in the secondary flow channel at the confluence of the Fraser River with the Nechako River (**Figure 5-4**). Some partially engaged relic channels were removed by this process on the Salmon River, shown in **Figure 5-3.** Data loss due to area removals is most likely in areas that are poorly described by model terrain and/or model mesh.

5.2 Flood Extent Simplification

5.2.1 Study Area 1

The main disadvantage of a flood map created using Straight Line computation is that it cannot follow the underlying terrain elevation geometry and hence cannot identify high elevation areas where floodwaters cannot reach. The Detailed Intersection computation identifies the difference between the flood surface and the ground terrain to create flood maps that follow the terrain. Moreover, it can also detect higher ground elevations within the flood map area and clip it out accordingly. **Figure 5-5** and **Figure 5-6** show the tools selection screen options.

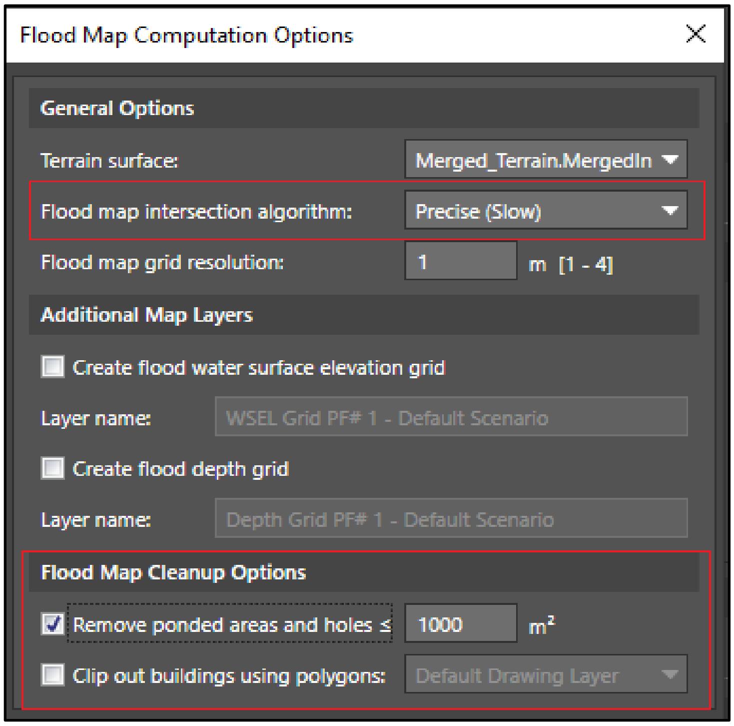

Figure 5-5: Options button in Flood Map GeoHECRAS.

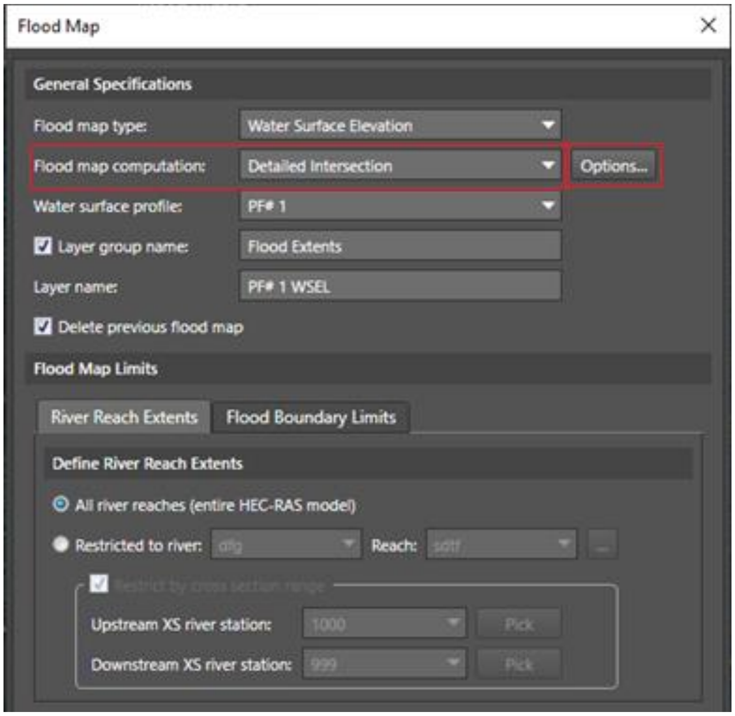

Figure 5-6: Flood Map Option in GeoHECRAS with Detailed Intersection map computation selected.

This was tested with the model to identify any potential differences in the flood map extents generated with and without this option. **Figure 5-7** shows there is very little difference between the two approaches, meaning that it may be acceptable to use the simpler, faster option for mapping of large areas which are already demanding high computational costs.

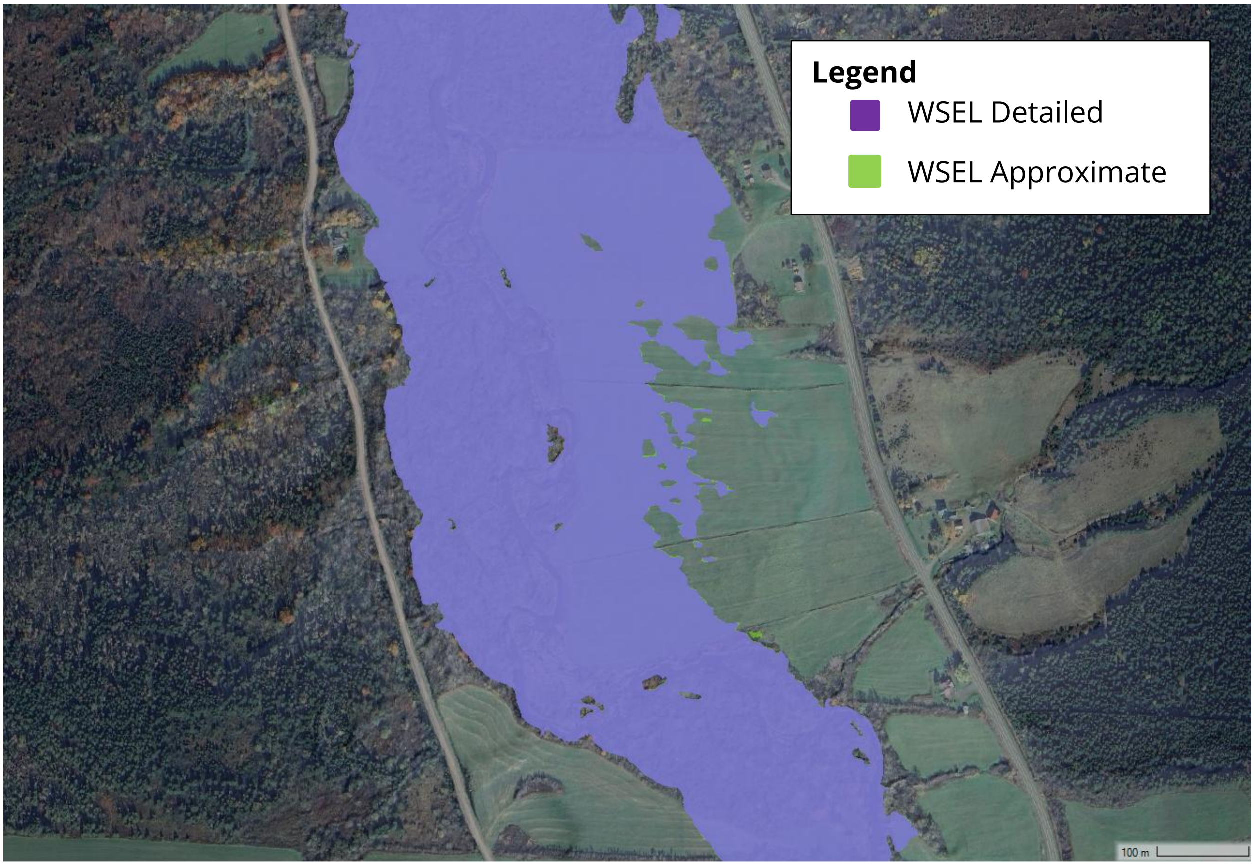

Figure 5-7: Flood Mapping extents with and without the detailed intersection flood map computation.

5.2.2 Study Area 2

Hydraulic models developed with high-resolution DEMs often preserve high-detail flood extents. This detail may provide minimal value for the scale at which the flood extent results are mapped and communicated. Simplification of flood extent areas can be conducted using polygon simplification algorithms in GIS to reduce the complexity of the extents. For this assessment, the Visvalingam-Whyatt algorithm was selected. Different simplification thresholds were tested at two levels: moderate (typical), and high. The values of these sizes were selected according to the respective scale of the Salmon and Fraser Rivers.

Table 5-3 shows the flood extent area for each river for the low, moderate, and high simplification tolerances. Figure 5-8 and Figure 5-9 show the simplified extents at areas of interest along the Salmon and Fraser Rivers.

Table 5-3: Impacts of Extent Simplification on Flooded Area

Simplification Threshold (m²)	River	Flood Extent Area[1]			
		Convex Area Removed (ha)	Concave Area Filled (ha)	Total Area (ha)	Change in Area From Base Case
None	Salmon	0	0	394	0%
8		9	9	394	0%
20		17	16	393	-0.3%
None	Fraser	0	0	5320	0%
12		40	50	5330	0.2%
30		70	80	5330	0.2%

[1] Values have been rounded to reflect the scale of the rivers on which they are calculated. Values on the Salmon River are rounded to the nearest 1 m. Values on the Fraser River are rounded to the nearest 10 m.

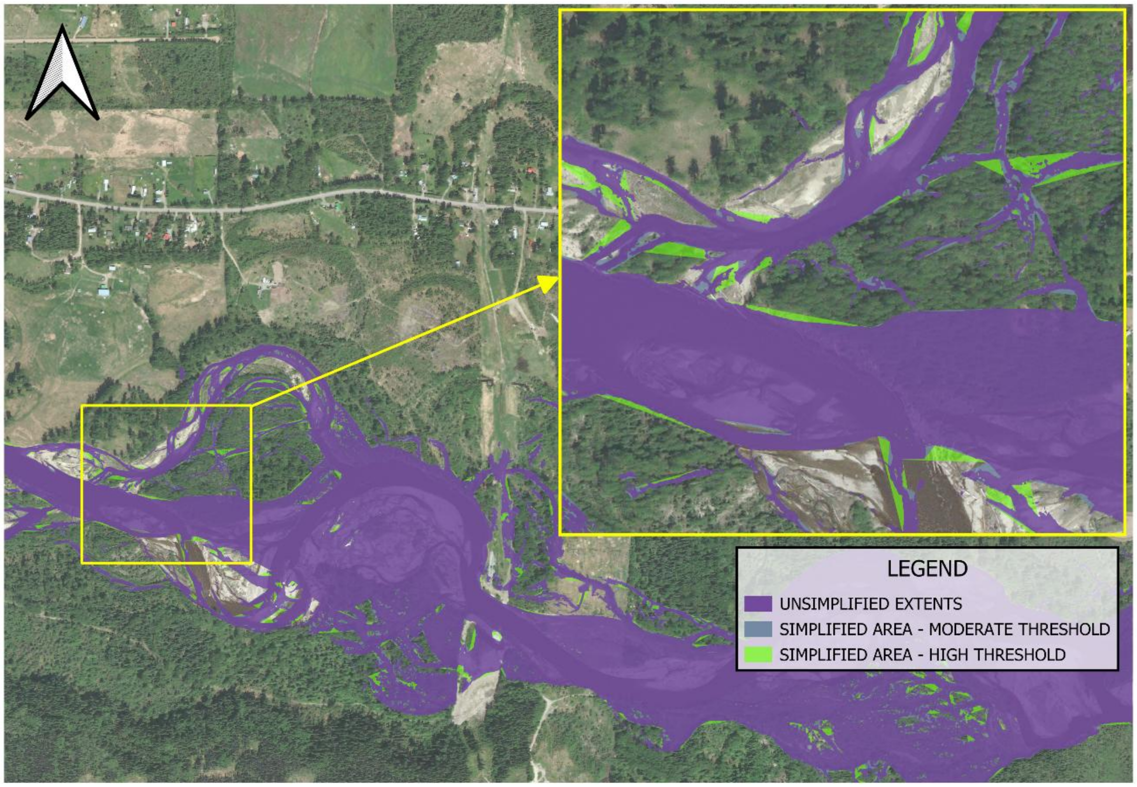

Figure 5-8: Salmon River flood extent simplification.

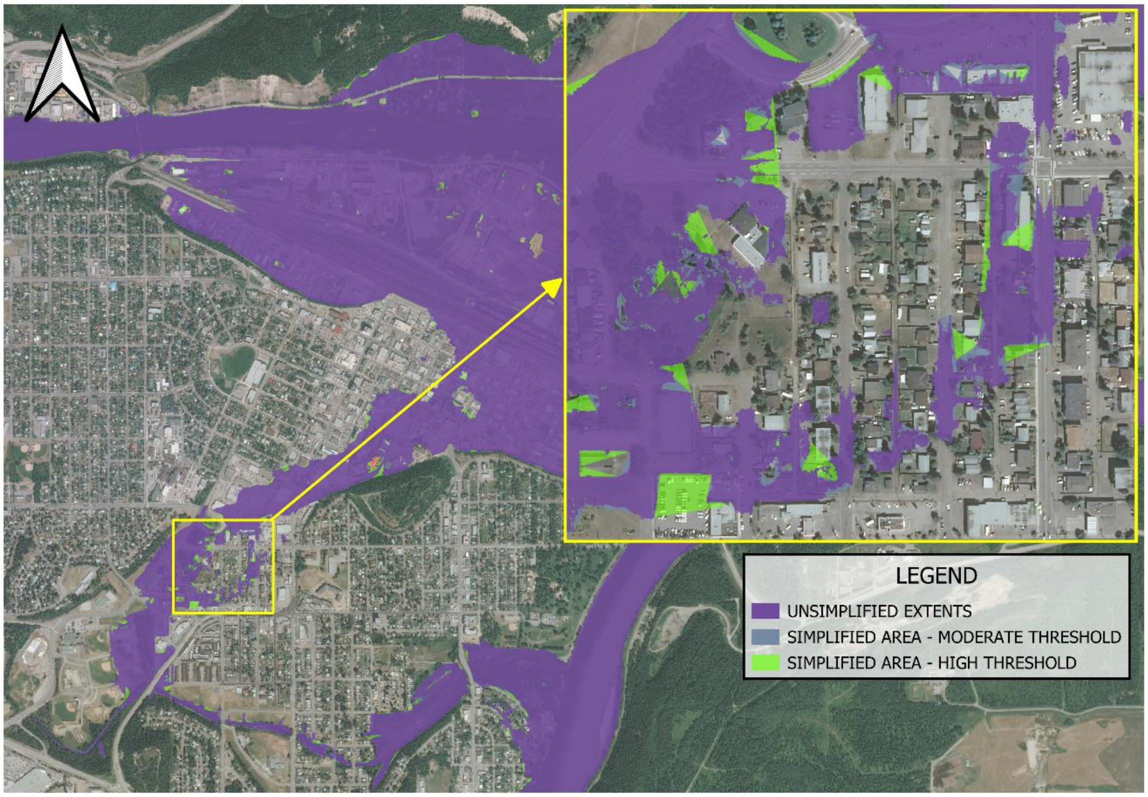

Figure 5-9: Fraser River flood extent simplification.

Generally, simplification of the flood extents does not substantially change the total flooded area, as presented in **Table 5-3.** However, the resulting extents for all thresholds are inorganic shapes and remove some details in the flood fringe. This results in a larger relative change on the Salmon River (Figure 5-8) where multiple channels are engaged. Negligible change to the flood extent was visible in areas of the Fraser River where the river is confined to the incised channel. In developed areas on the Fraser River, the simplified results bisect developed features that were originally captured in the model. At the high simplification threshold, the extents have been adjusted to include whole properties that were not in the raw results. Such changes can significantly impact the interpretation and application of flood maps.

It should be noted that the simplification algorithm tested does not include any extent cleaning and the process will not remove features. In some locations, this resulted in double counting of area where “noise” was preserved on top of the main flood extent.

5.3 Inclusion of “Protected” Areas (Study Area 2)

Hydraulic models are built with DEMs which typically include areas of raised ground, including berms, roads, or railways acting as informal dike structures. The models do not consider the integrity of these structures unless a breach is explicitly modelled; however, informal dike structures are not recommended to be relied upon for flood plain mapping. As well, disconnected ponded water may not directly be a function of fluvial flooding but instead an artefact of intersecting the DEM with the flood level. However, the low-lying area may still be subject to other types of flooding, such as pluvial.

A pragmatic approach to this challenge is to project the water surface elevation into the low points behind the structures. This approach may be used to identify areas which may require further engineering consideration or modelling assessment (see Section 6 for further discussion). This section illustrates the addition of freeboard (0.6 m) and projection of water surface elevations, as it compares to the 200-year result extents.

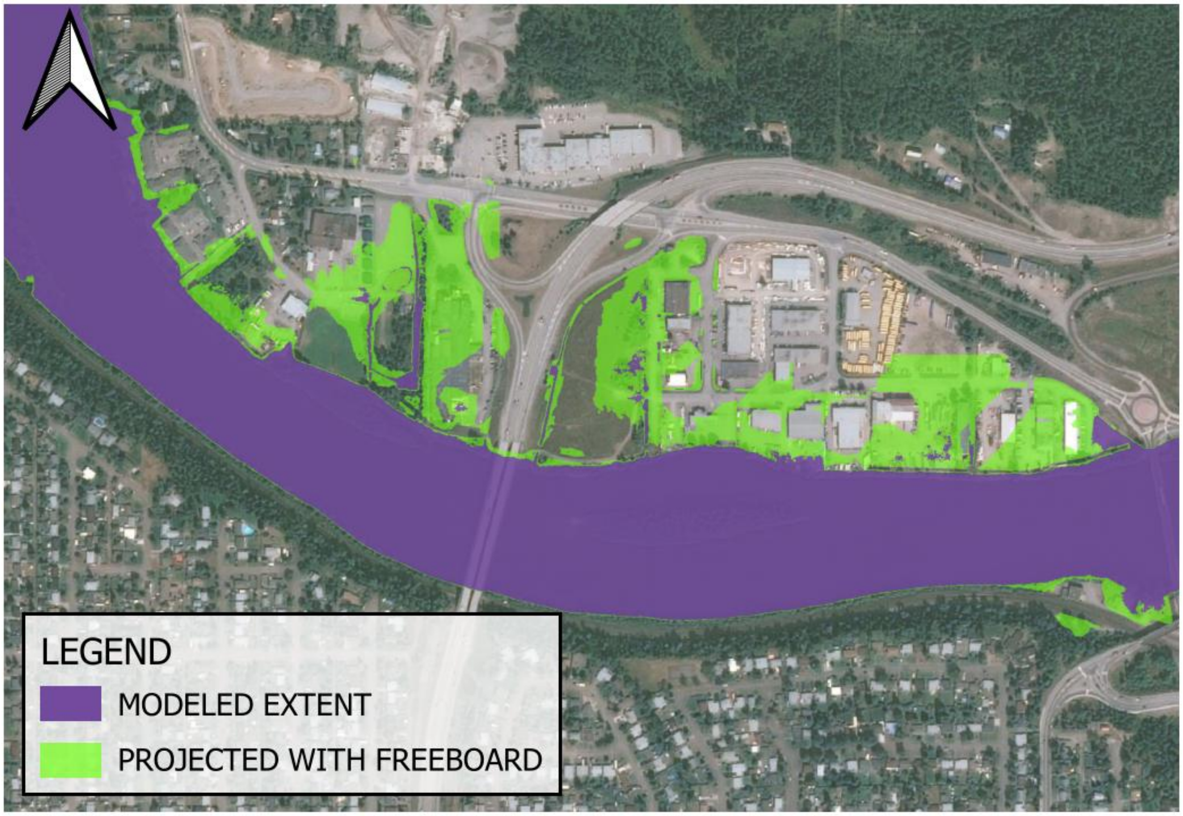

Figure 5-10: Fraser River “protected” areas: projection past berm.

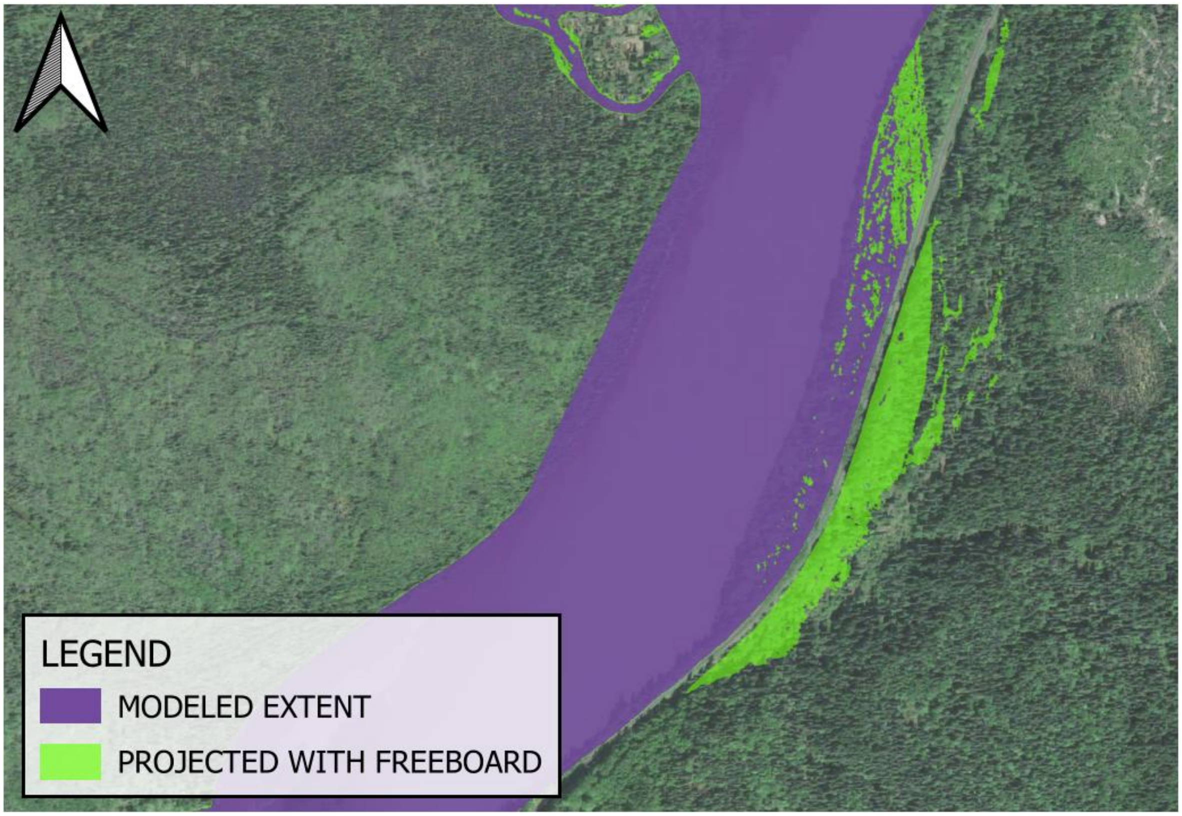

Figure 5-11: Fraser River "protected" areas: projected past railway embankment.

There were no areas on the Salmon River where the projected water surface impacted "protected" areas. This is likely due to the limited infrastructure within the area of interest, and the fact that the Salmon River floodplain was carved by larger historical flows than were estimated for this study.

The Fraser River has numerous berms, roads, and rail lines along its banks that contain flow in the hydraulic model. In some locations, these structures have been constructed in locations that isolate relic channels or portions of the natural flood plain.

Figure 5-10 illustrates the increased extents due to projecting the water surface extent beyond a berm into an industrial area. **Figure 5-11** illustrates where a rail embankment cuts off a portion of the natural flood plain. Whether or not the structures allow for hydraulic connectivity of the isolated areas through either small drainage features or seepage through the embankment material may be out of the scope of a higher level flood mapping exercise. Including projected water surface elevations in "protected" areas may allow the engineer to consider flooding in these areas without requiring detailed assessment and modelling of each structure individually.

5.4 Combination of Multi-Hazard Scenarios (Study Area 2)

In areas with multiple hazards or flood scenarios, such as the confluence of the Salmon River with the Fraser River, flood maps must consider the "worst case scenario". Historically, flood plain maps were developed from 1-D models, and the dominant scenario was selected based on the results in the centre of the channel. For 2D models developed using high-resolution DEMs and detailed mesh in the floodplain, the governing scenario can be determined for each location without the assumption that the water surface profile is the same as in the centre of the channel.

This section compares the multi-hazard results using:

- 1D method (dominant hazard selected based on the centre of the channel).
- 2D method (dominant hazard selected based on 2D results at each location).

Table 5-4 compares the difference in flood extent and elevations between the 1D and the 2D multi-hazard merge methods. The different extents are shown in **Figure 5-12**.

Table 5-4: Impacts of Extent Simplification on Flooded Area

Multi-Hazard Merge Method	Flooded Area			Water Surface Elevation Difference	
	Total Area (ha)	Change from 1-D (ha)	Change from 1-D (%)	Maximum Change from 1-D (m)	Mean Change from 1-D (m)
1-D Method	393	-	-	-	-
2-D Method	394	+ 1	+ 0.3 %	+ 0.42	+0.01

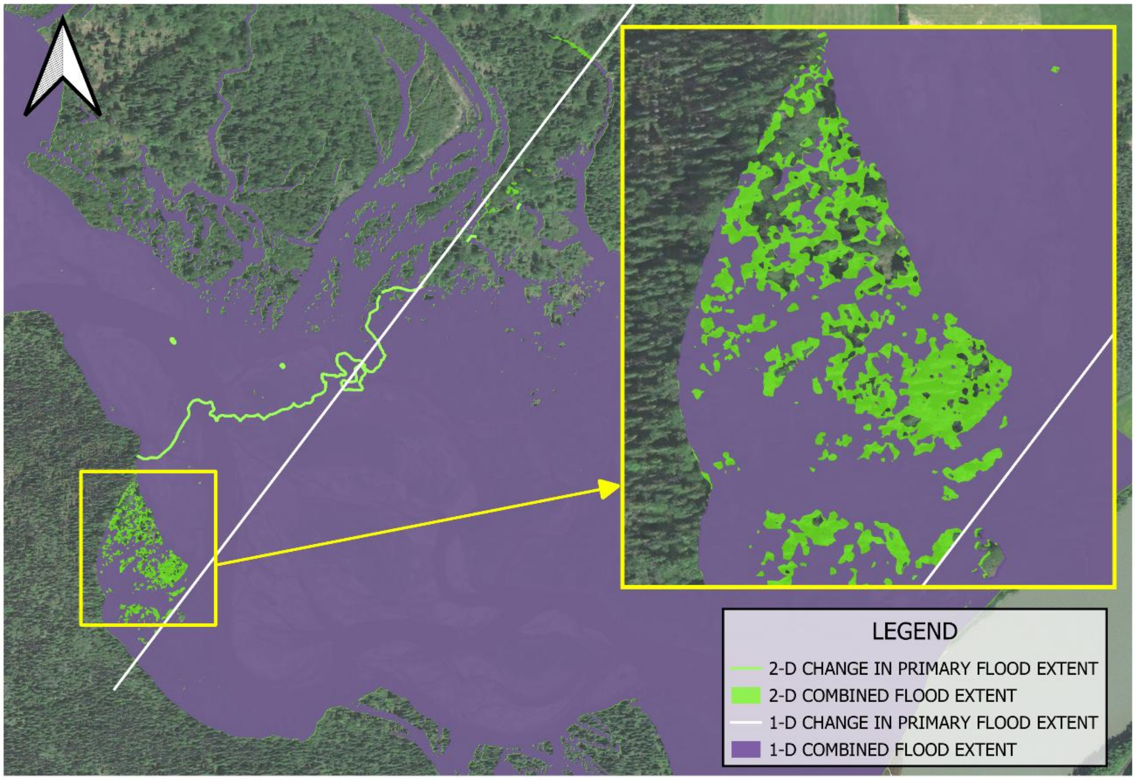

Figure 5-12: Multi-Hazard Flood Scenario Combination at Salmon River Confluence with the Fraser River.

It is understood that 2D models provide improved results compare to 1D models when provided with adequate data. Similarly, the 2D post-processing method should be favoured over the 1D method where sufficient data exists. This comparison is intended to illustrate the scale of change that could be expected when comparing 1D modelling and processing methods to 2-D methods in multi-hazard zones.

5.5 Isoline Generation and Smoothing (Study Area 2)

In flood mapping, water surface elevation isoline generation is used to generate Flood Construction Level lines; these lines may also include an engineering freeboard. Flood Construction Level lines may be used by municipal governments and the general public to inform land development and planning processes and must therefore require minimal interpretation by the user. Hydraulic models developed with high-resolution DEMs often preserve a high-resolution and high-precision of results, which leads to overly detailed or complex isolines.

This section compares the generation and simplification of isolines using the following methods:

- No smoothing. Raw data contour.
- Smoothed results surface.
- Simplified lines.
- Reviewed and refined for readability (herein referred to as "reviewed"); i.e. the simplification of results from the very high granularity of 1 m DEM model results to final mapping which is developed for use by the general public (see figure examples below).

Where the isolines meet the flood extent is particularly important for interpretation and application to development. **Table 5-5** compares the various generation methods to both the raw data and the reviewed data.

Figure 5-13 and **Figure 5-14** show the isolines at areas of interest along the Salmon and Fraser Rivers.

Table 5-5: Impacts of Isoline Generation Method on Relative Position

Isoline Type	River	Entire Line[1]		End Points2	
		% Similarity to Raw Data	% Similarity to Reviewed Data	Avg. Dist. From Raw (m)	Avg. Dist. From Reviewed (m)
Raw	Salmon	100%	60%	0	10
Smoothed Surface		70%	66%	7	12
Simplified Line		60%	55%	8	5
Reviewed		50%	100%	10	0
Raw	Fraser	100%	52%	0	70
Smoothed Surface		46%	41%	30	10
Simplified Line		71%	60%	10	60
Reviewed		45%	100%	60	0

[1] A similarity parameter was developed to facilitate comparison of methods. This parameter reflects the percentage of overlapping area of a 10 m buffer of each line.

[2] Values have been rounded to reflect the scale of the rivers on which they are calculated. Values on the Salmon River are rounded to the nearest 1 m. Values on the Fraser River are rounded to the nearest 10 m.

For comparison, note that isolines on the Salmon River are on average 164 m apart, and isolines on the Fraser River are on average 860 m apart. On both rivers, the average variation of the end points was less than 10% of the spacing between isolines.

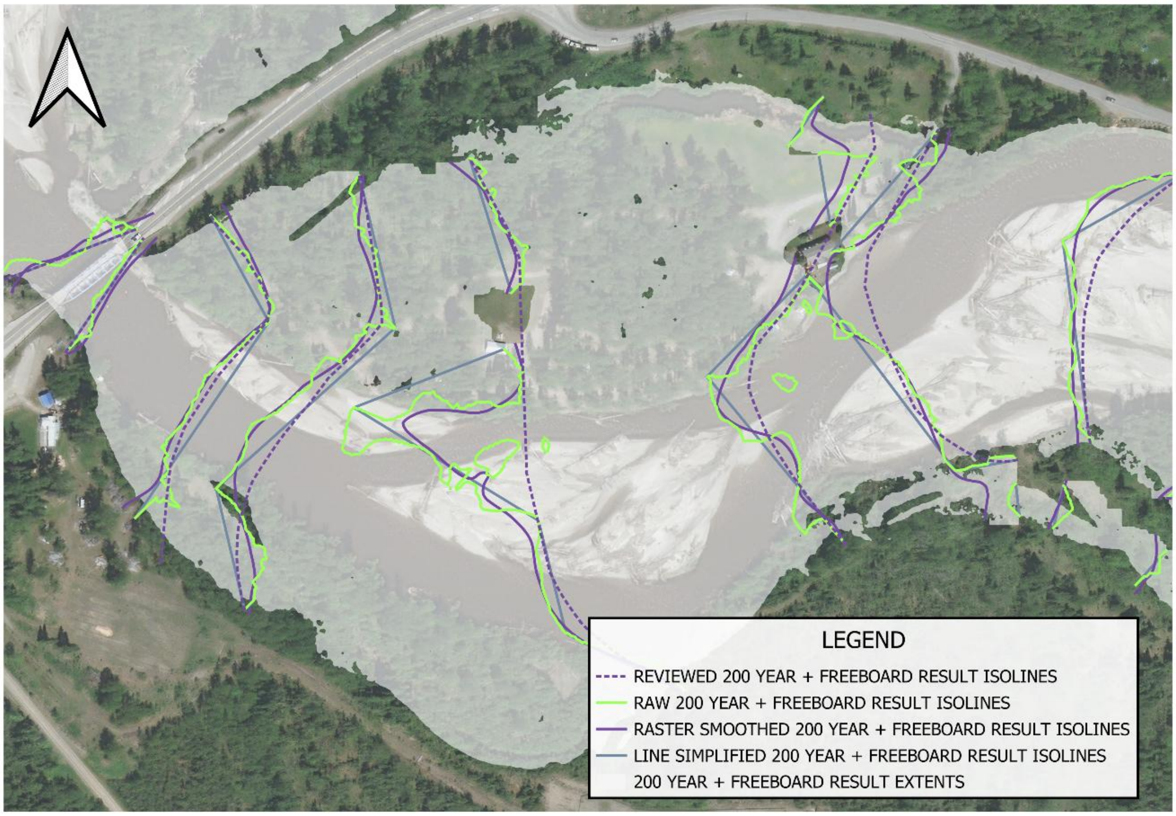

Figure 5-13: Salmon River isoline generation methods.

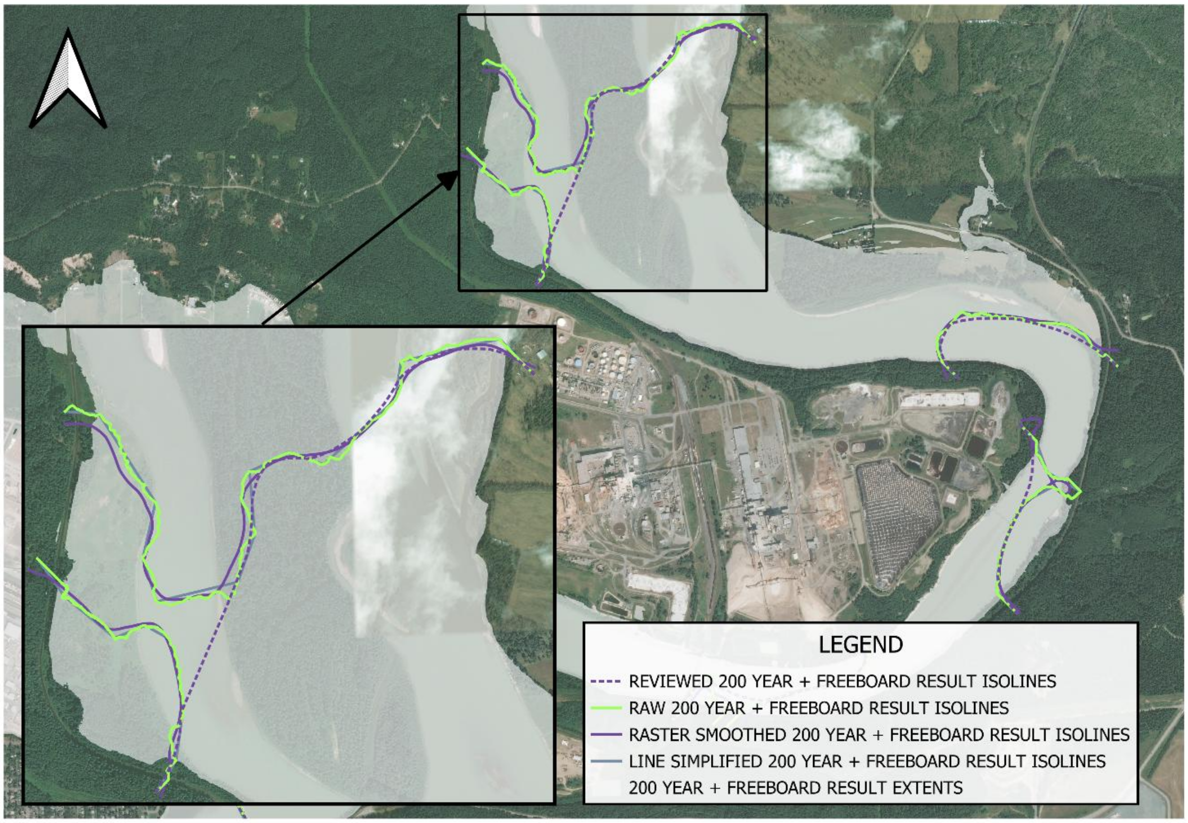

Figure 5-14: Fraser River isoline generation methods.

In general, the simplified line method maintains extreme points that are captured in the raw data better than the smoothed raster method despite its inorganic shape, although it does not maintain all extreme features. The smoothed raster method follows the general shape of the raw data, with some blunting of the features.

The automated smoothing methods create a useful approximation of the reviewed isolines, but do not replace the need for engineering review and interpretation. A smoothed version of the simplified line method was used as the base upon which engineering judgement was applied for the reviewed and refined isolines used in this comparison. The automated methods that were tested are unable to preferentially select conservative placement (**Figure 5-13**) or simplify and group isolines representing phenomenon such as superelevation (**Figure 5-14**), as done in the reviewed isolines.

5.6 Comparison of WSEL and EGL (Study Area 1)

In some cases, the Energy Grade Line (EGL) can be a safer parameter to use for flood mapping compared to the Water Surface Elevation (WSEL), since it represents the total energy of the water, or the water level that would be reached if the water were to stop moving. A detailed comparison can be conducted between the EGL and WSEL results, with particular emphasis on the regions surrounding built structures. In these areas, substantial disparities can emerge between the EGL and WSEL (which equal the velocity head, or $v^2/2g$). As illustrated in the figure below, **Figure 5-16** showing difference between EGL and WSEL, the EGL and WSEL profiles can diverge significantly around a structural element within a hydraulic model, highlighting the importance of understanding these differences for an informed hydraulic analysis and design. The cross-section view in **Figure 5-16** shows the difference between EGL and WSEL but when mapped as shown in **Figure 5-15** the extents are the same as water velocity was too low to generate a noticeable change in head. This is a result of the fact that the EGL and WSEL show the largest difference where the velocity is highest, which is through the bridge constriction, where the walls are vertical, resulting in no change in flood extents under the bridge. In the upstream and downstream vicinity of the bridge, the velocity is highly reduced, meaning the EGL and WSEL are closer in elevation, to the point that their respective flood extents are indistinguishable.

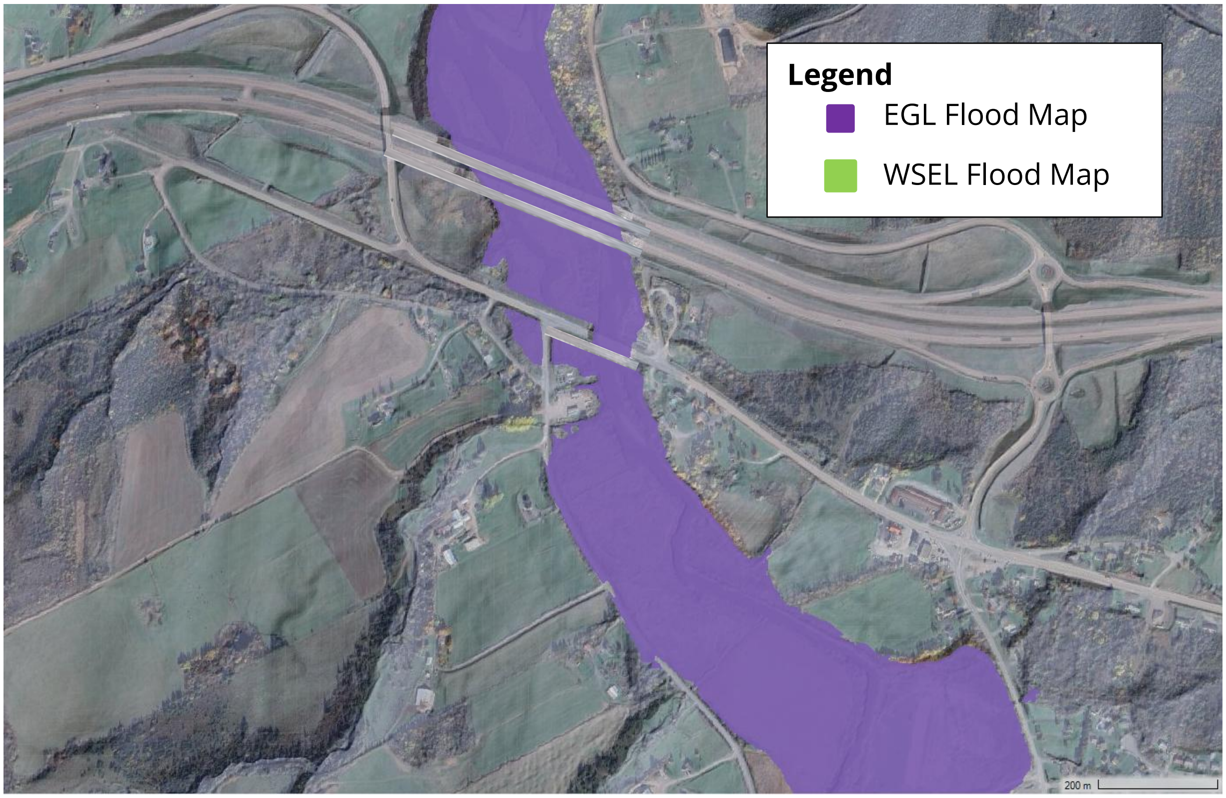

Figure 5-15: EGL and WSEL flood map extents.

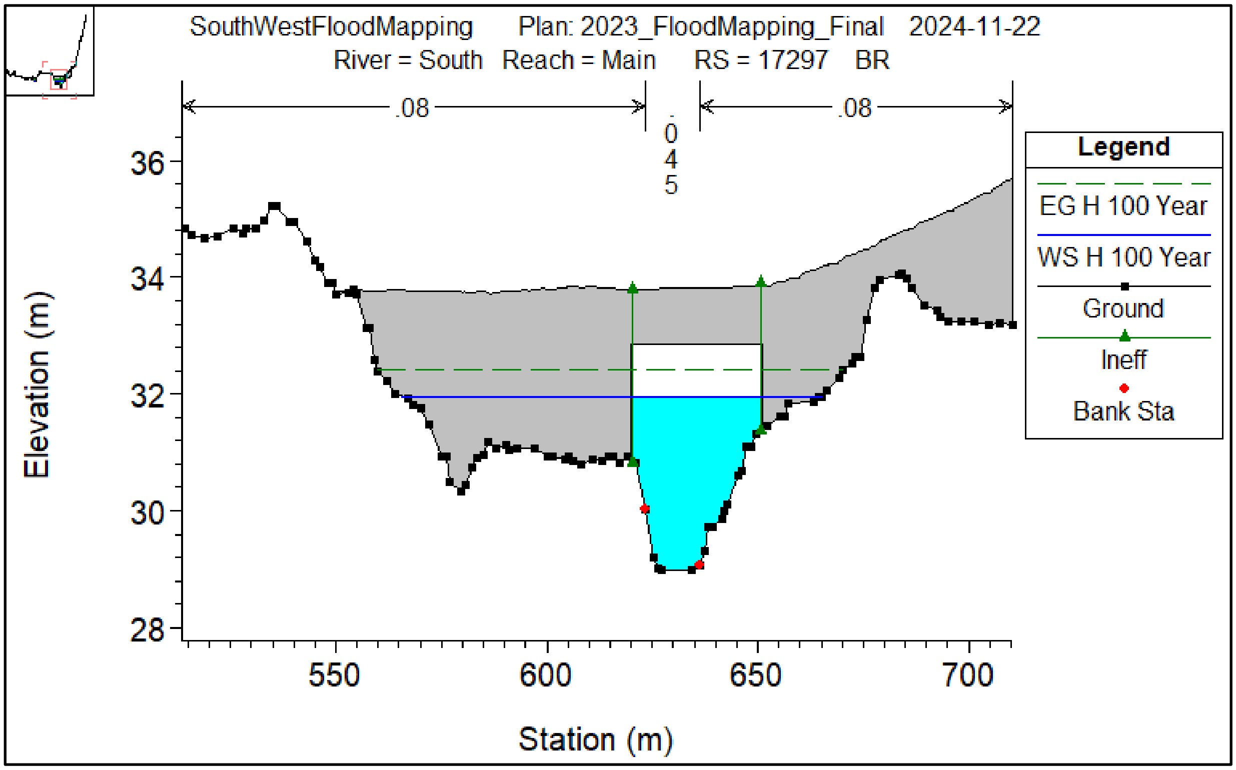

Figure 5-16: Cross-Section Plot showing difference between EGL and WSEL.

6 Conclusions and Recommendations

6.1 General Conclusions and Recommendations

This pilot study conducted a systematized sensitivity analysis on the three primary aspects of flood hazard mapping: hydrologic analysis, hydraulic modelling and GIS post-processing. This sensitivity analysis explored the impacts of a number of different parameters and approaches within each of the three aspects as well as observation of how the three aspects interact and influence one another.

Relative uncertainty and resulting impacts to flood maps vary depending on hydrologic and hydraulic mechanisms of the study area, local topography, available data sources and quality and a number of other site-specific parameters. It is therefore not possible to prescribe exactly how a practitioner conducts an uncertainty assessment nor is it possible to prioritise any of the three primary aspects of flood hazard mapping above one another. However, it is possible to use each of these aspects (hydrologic analysis, hydraulic modelling and GIS post-processing) and engineering check points to identify study area-specific points of higher uncertainty.

It is recommended that the practitioner use a sequence similar to the one shown in Figure 6-1. The practitioner may also use this approach to identify other engineering check points throughout the course of their study which are not discussed below. Using this approach, flood mapping methodology becomes a balance of the practical limitations informed by each aspect of the flood hazard mapping process, instead of a linear path from hydrologic analysis through hydraulic modelling to GIS post-processing.

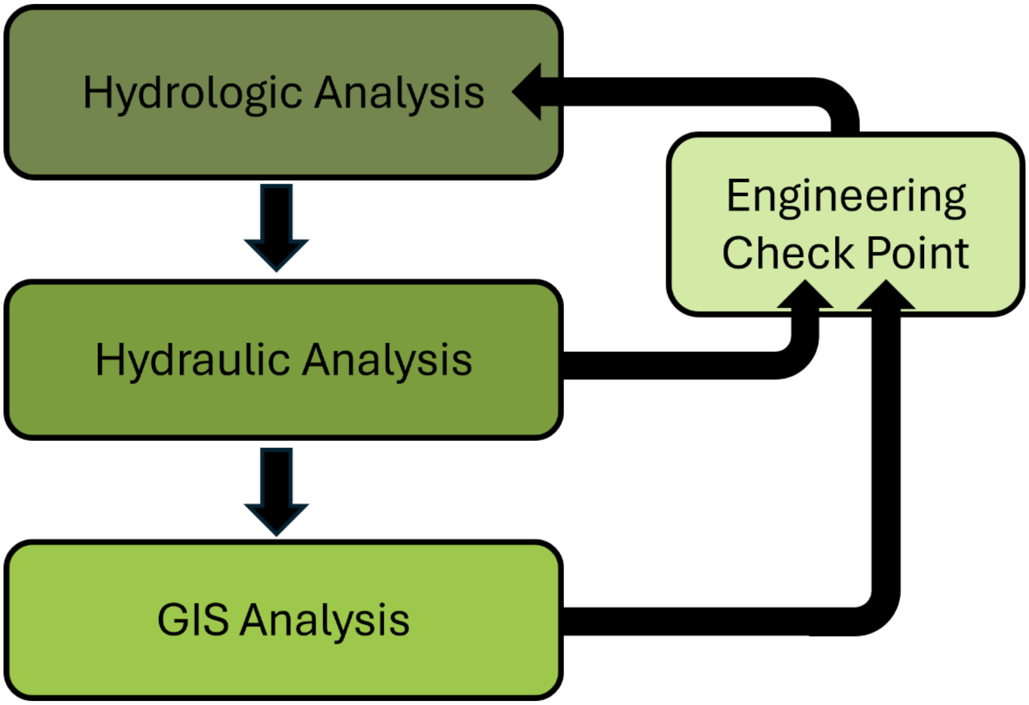

Figure 6-1: Identifying Study-Specific Levels of Uncertainty using the Three Primary Aspects of Flood Hazard Mapping and Engineering Check Points

Engineering Check Point 1 – Impact of Hydrology and Design Flows on Flood Mapping
The flood mapping's sensitivity to uncertainty in the hydrologic inputs may be assessed by running the design flows, or a range of possible design flows, through the hydraulic model. This can be used to determine whether the possible variation in the design flow is in a range which substantially impacts the resulting flood extents. Examples of higher sensitivity to flow variation would include flow variation within a range over which water depths may reach a threshold that overtops a river bank, berm, dike or other natural or man-made obstruction. Should the flood extents prove to be highly sensitive to the range of hydrologic flows, practitioners may consider an uncertainty assessment to inform decision making.

Engineering Check Point 2 – Impact of Hydraulic Modelling Extents on Flood Mapping
GIS processes may be used to support an engineering check to review the results of hydraulic modelling and analyse results. Specifically, GIS post-processing can be used to identify possible at-risk "protected areas" by taking the maximum water surface elevation results from the hydraulic modelling and extending them as a plane across the DEM / available topographic data. This process will highlight low-lying areas currently identified as "protected" from the hydraulic flooding. It is up to the practitioner, or the practitioner in cooperation with their client, to determine whether these areas are in fact at risk of flooding and whether further modelling assessment is appropriate. The practitioner may also choose to add a nominal freeboard to the calculated water surface elevations prior to this GIS processing exercise.

Within each of these three primary aspects, there are opportunities for parameter and process optimization to minimize uncertainty. Each of these three aspects of flood hazard mapping is discussed in greater detail in a sub-section below. As with the larger aspects, the sensitivity of flood mapping to the various aspect methodologies and parameters is highly dependent on the study area.

6.2 Hydrologic Analysis

Testing was conducted on the most typical approaches to obtaining peak flows to support flood studies, namely hydrologic modelling and Flood Frequency Analysis. The sensitivity of a range of key parameters in the two approaches was investigated to better understand their potential impacts on the resulting flows, flood levels and extents. The two approaches were tested in each study area individually, and compared between each other, through the magnitude of peak flow sensitivity.

Regardless of flow estimation approach, practitioners should be aware that increases in flow are not proportional to increases in flood extents. The relationship between changes in flow and changes in flooded areas is highly dependent on topography and infrastructure, especially features which confine or constrict the river channel. For instance, if a river channel is heavily confined, flood extents may be relatively insensitive to increases in flow until water surface elevations exceed the bank or dike elevations. **Table 6-1** summarizes the numerical results of the hydrological parameter sensitivity testing in terms of impacts to peak flows, peak water levels and change in flood extents.

Table 6-1: Summary of Average Absolute Change in Peak Flow, Water Level and Flood Extent in Tested Scenarios

Scenario	Average Change in Peak Flow (%)	Average of Change in Peak Water Level (m)	Average of Flood Extents Change (ha)
Block Hyetograph	-21%	-0.21	17.82
SCS Type III Hyetograph	11%	0.096	-9.88
Northeast Rainfall Source	32%	0.272	-28.99
Western Rainfall Source	-51%	-0.548	82.05
0.1 X Reference Conductivity	10%	0.072	-10.02
10 X Reference Conductivity	-45%	-0.247	75.09
0.01 Initial Deficit	0%	0	0.08
0.8 Initial Deficit	0%	0	-0.13
0.2 X Reference Flow Length	61%	0.449	-49.34
5 X Reference Flow Length	-55%	-0.608	95.58
4 Subcatchments	-26%	-0.425	68.85
52 Subcatchments	-54%	-0.663	141.25
Hurricane Fiona Calibration	-69%	-0.822	151.51
2nd Nov 2021 Model Calibration	0%	-0.006	1.18

6.2.1 Hydrologic Parameter Testing (Study Area 1)

Hydrologic modelling involves assembling a representation of the hydrologic setting of a watershed area, estimating its main hydrologic parameters and calibrating the model to recorded historic extreme flood events. The model can then be used to estimate peak flows of a given frequency by using extreme rainfall hyetographs of the corresponding frequency. The parameters tested included the hyetograph distribution, the rainfall data source, soil hydraulic conductivity, soil initial moisture deficit, maximum overland flow length, subcatchment discretization, model calibration approach and source calibration event.

It was found that the most sensitive parameters that impacted the estimation of peak flows included, in order, the source calibration event, the maximum overland flow parameter, IDF data source, discretization level of subcatchments, soil hydraulic conductivity, and hyetograph distribution. Initial Soil Moisture Deficit did not seem to have any impact on the peak flows, even when varying the timing of the peak flow within the event duration. It is noted that these findings, although likely to be generally applicable to most watersheds with rainfall-dominated runoff responses, are specific to this study area. **Figure 6-2** illustrates these findings.

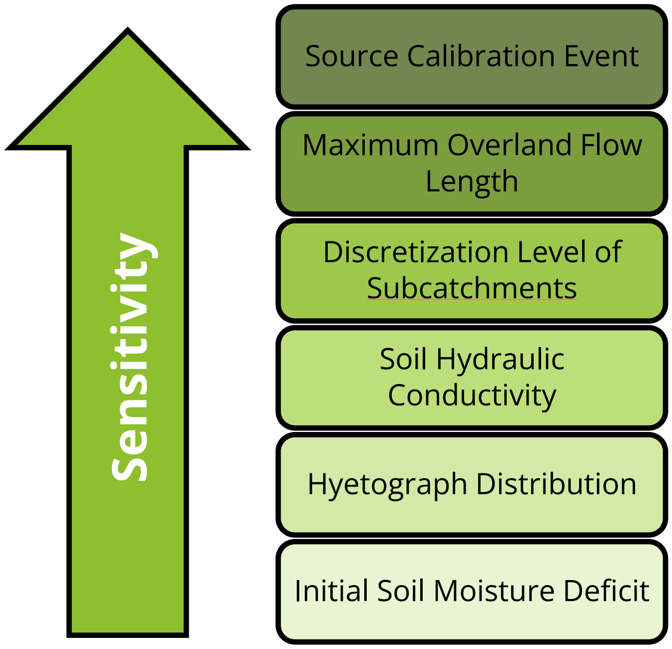

Figure 6-2: Prioritized List of Sensitivity to Hydrologic Modelling Parameters

The conclusion of this hydrologic model testing was that the highest sensitivity of flood extents was not so much in how the calibration parameters were selected, but rather the validity of the calibration data in the first place. Calibration data is considered valid if it is:

- Representative of the extreme rainfall characteristics of a watershed.
- Representative of the extreme flow patterns in a watercourse.
- The rainfall data associated with the extreme flow event used for calibration is representative of the real-world rainfall that occurred on average in that watershed to cause the extreme flow event that was recorded.

Naturally, if the source data used for calibration is not representative in any of the manners listed above, one cannot have confidence in the ability to reproduce the actual flood risks.

Therefore, a major part of the effort in hydrologic modelling should be applied to the identification of a representative flow gauging station, the selection of a suitable flow calibration event, and in turn, the identification of a suitable climate station that recorded the rainfall that generated the peak flow used for calibration, and then the selection of a suitable design rainfall event data source and distribution. These aspects, unfortunately, are very dependent on the availability, quality and suitability of flow gauging and climate station data that are most representative of hydrologic mechanisms in the study area.

The hydrologic practitioner is therefore cautioned to not only conduct the data gathering and selection with great care, but also to bear in mind the associated level of uncertainty (found here to potentially exceed 65%) associated with data availability, quality and suitability. Other model parameters were sometimes found to be highly uncertain (e.g.

maximum overland flow length), but those parameters are adjusted during model calibration, which minimizes the potential uncertainties associated with the initial estimation of those parameters. It was also found that model calibration that is based on an alternative variation of hydrologic parameters results in very little change to the peak flow estimates. These aspects reinforce the fact that the most significant source of uncertainty is the precipitation and flow data that is used for model calibration and design hyetograph generation. It is also noted that the currently existing network of climate and flow gauging stations, while reasonable given industry standards, would provide significant value to the national flood mapping effort upon being expanded.

Recommendations arising from these findings include, beyond judicious review and selection of calibration data, raising awareness of the importance of wide climate and flow gauging station network development.

Regarding the calibration process itself, it is found that advances in hydrologic tools and software are allowing the process to be continuously streamlined and gradually automated, until it may at some point in the reasonable future become fully automated.

Considering the various hydrologic parameters that represent the physical characteristics of a watershed, the parameters that are inherently uncertain are suitable for adjustment during the calibration process. Noting that these findings are specific to this study area, the parameters identified included:

- Soil Hydraulic Conductivity – this parameter is inherently highly uncertain, given the natural variability of soils, as well as the degree of consolidation of the surface layers.
- Flow length – this parameter is also associated with an appreciable amount of uncertainty, given the multiple ways it can be measured.
- Roughness is also naturally a very uncertain parameter given the variability of the ground surface vegetation, with large seasonal changes.

It is noted that some physical understanding of the processes at play should guide the calibration process. For example increasing the roughness and decreasing the flow length would be reasonable in the context of physically based adjustments stemming from knowledge of the watershed. Without this context, however, it would lead to the two changes working counter effectively and potentially cancel each other's effects on flood extents.

An important finding of the calibration testing was that, for a given measured rainfall and gauged flow to calibrate to, using different sets of parameter adjustments in the calibration process had very minor impacts on the flood extents generated, as long as the measured hydrograph was closely represented (notably the peak flow) by the modelled hydrograph.

One of the significant benefits of the hydrologic modelling and calibration process is that it involves making an initial estimation of the various hydrologic characteristics of a watershed, then adjusted through calibration. The process therefore involves engineering judgement in understanding the physical processes at play, followed with some correction through calibration, which further imparts understanding of the hydrologic mechanisms at play. Given the highly uncertain field of hydrology, practice and solidification of engineering judgement in hydrology are valuable traits in an increasingly automated environment that disconnects the engineer from the physical realities that are modelled.

Comparing hydrologic modelling with an FFA approach for pluvial systems with limited hydrometric data, it is accepted that hydrologic modelling is considered more adaptable, comprehensive and representative than the FFA. This is mainly related to the fact that only the flow data (typically from only one station) is used to support the FFA, rather than the hydrologic characteristics of a watershed. Hydrologic modelling can use calibration to adjust the characteristics of a watershed very similar to the gauged watershed, and extend those adjustments to other watersheds, making the process more adaptive to various characteristics. In cases where gauged data exists directly in the study area watercourse, however, the FFA will be more representative than modelling, but only within the vicinity of the flow gauging station, as runoff response may differ widely in other parts of the watershed.

6.2.2 Flood Frequency Analysis (FFA) Testing (Study Area 2)

For large and hydrologically complex watersheds, especially those where flow changes along a river reach are negligible, best design flow estimates will generally be based on FFA of data recorded within the study watershed, especially within the direct vicinity of the flow gauging station. Provided that sufficiently long periods of record and high-quality data is available this is the recommended method as it captures the natural variability of flood events. Where limited or no recorded data is available, a regional analysis, such as the index flood method, or watershed scale hydrologic modeling is recommended as an alternative.

The reliability of FFA-based design flow estimates improves with longer and more recent datasets because they are able to capture hydrologic variability on a large scale and incorporate the influence of recent climate trends.

Use of simple, regional flow equations is not advisable and generally produces flow estimates of questionable reliability.

Record extension based on correlation with nearby gauges can be applied to incorporate additional observed flood years. However, if the study area has a long dataset (e.g., >60 years in the case of this study), record extension may not provide substantial benefit or change. Similarly, for these longer data sets, selecting a different statistical distribution may result only in minor variations in the estimated flows.

The influence of outliers is lesser in longer periods of record, as the statistical weight of a single point is minimized.

The use of existing regional equations developed across large hydrologic zones is not recommended to for developing the final design flows due to their inherit simplifications and uncertainties. However, they may provide a reality check on calculated design flows.

6.3 Hydraulic Analysis

The sensitivity analysis of hydraulic modelling demonstrated appreciable variations in results with changes to each tested parameter. In the hydraulic analysis testing, both study areas were tested with mostly the same changes in parameters, which allows comparisons between the different physiographic regions. Parameters tested included number of flow input locations, potential blockage of bridge openings, steady vs unsteady modelling, timestep variations, adjustment of 2D grid size and changing the water level calibration event.

Hydraulic models are built on available terrain and bathymetry data. While sensitivity of the quality of this data was not part of this study, it should be noted that recent, detailed topographic and bathymetric data provides the best possible foundation for a representative model.

The results of this study indicate that the hydraulic modelling results are sensitive to all of the reviewed parameters. Parameter variations were isolated for the purposes of this study, however, in practice they are highly interdependent. Parameter optimization is recommended in the following sequence to minimize uncertainty propagation and increase confidence in results. This optimization should be completed following establishment of the foundational elements of model construction, including selection of model extents, determination of boundary conditions, development of either cross-sections (1D modelling) or a DEM / terrain surface (2D modelling), and selection of appropriate computational equation sets (see figure on the following page).

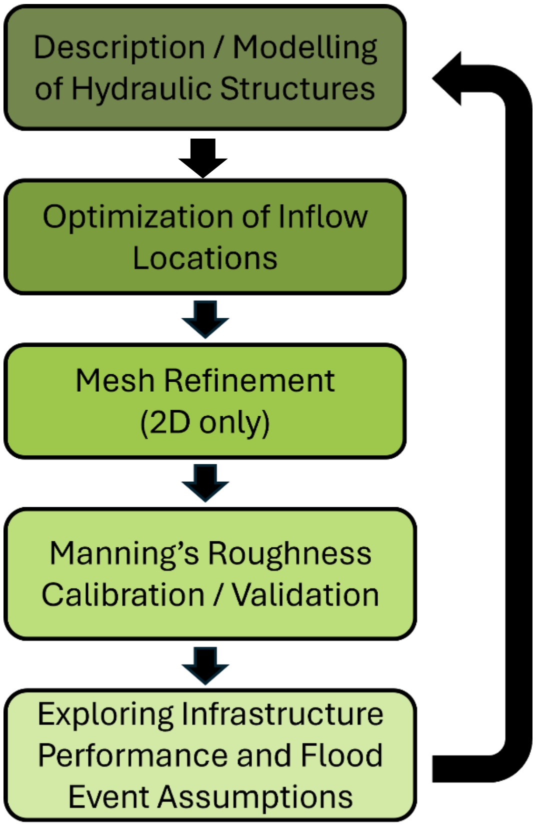

Figure 6-3: Recommended Hydraulic Parameter Optimization.

- It is critical to have updated data on all bridges, dikes and other man-made structures that directly impact the movement of water through a river channel and flood plain. The more closely and directly the structure interacts with flow during flood conditions, the more important it is that the structure be fully and accurately represented within the model. The accuracy of structure information has a disproportionately large impact on hydraulic modelling accuracy and the resulting flood extents. It is also important that river inflows be placed accurately relative to these structures.
- For 1D steady state modelling exercises, of pluvial systems in which a substantial portion of river flow enters along the reach of interest, it is worth additional optimization of the number of flow data input locations to increase the reliability of results. However, beyond a certain point, increasing the number of flow data input locations did not result in significant improvements in model accuracy, suggesting a balance between the number of flow data input locations and the computational cost of the model.
- For 2D models, following the accurate representation of structures and confirmation of inflow locations, the next area of focus should be mesh refinement. The goal is to provide mesh sufficiently detailed to accurately describe infrastructure and topography without being so detailed that the model runs are prohibitively lengthy or unstable. Mesh refinement should focus on describing bridges, dikes and other infrastructure which interacts with flows as well as the river channel and any abrupt changes in topography. For instance, mesh must be fine enough to describe high points and

prevent “leakage” of flow through areas of solid landscape. Mesh through bridges and hydraulic channels should be refined to the point that increasing refinement no longer materially changes water levels.

- Last, Manning’s roughness values may be selected and calibrated to best match observed or anticipated conditions. Manning’s roughness values vary with depth of flow and magnitude of event. It is therefore important to use calibration data of a similar magnitude to the modelled design event, or as similar in magnitude as is available. Care should be taken to review historic changes in river infrastructure and river channel and flood plain topography which may change flood behavior and effect historic data used in the calibration process, making a previous flood event less representative of current conditions. Examples include installation of a dike, replacement of a bridge or a channel avulsion.

Once a model is optimized, the project engineer can explore infrastructure and flood event assumptions, such as partial or complete bridge blockage or dike breaching. Identification of these additional scenarios is subject to project requirements. As these assumptions impact river structures and topography, they are likely to have substantial impacts on resulting flood extents.

Further discussion of each of the reviewed parameters is included in the subsections below.

6.3.1 Input of Design Flow

The number of flow data input locations in a hydraulic model was investigated, since even though it is not typically featured in guidance documents, it was suspected to have non-negligible impact on resulting water levels. An examination of the Flow Change Location parameter used in 1D steady state modelling revealed a clear trend: a higher number of flow input locations generally led to improved results, which was evidenced by both water depth values and the corresponding flood maps. This trend suggests that increasing the number of flow data input locations tends to produce more detailed and accurate flood maps. This is most applicable to river reaches similar to Study Area 1, in which the natural drainage system incorporates a substantial portion of the total river flow in discrete inflow locations along the reach of interest.

For areas similar to Study Area 1, pluvial systems in which a substantial portion of river flow enters along the reach of interest, increasing the number of flow data input locations increased the reliability of results. However, beyond a certain point, increasing the number of flow data input locations did not result in significant improvements in model accuracy. This suggests that there is a balance to be struck between the number of flow data input locations and the computational cost of the model.

For much larger watersheds such as those in Study area 2 (the Salmon River and Fraser River watersheds are 21x and 162x the Study Area 1 watershed, respectively), flow to the river reach of interest is overwhelmingly provided through the upstream boundaries of the river reaches themselves or confluences with other large rivers. Changes to flow along the river reach, with the exception of such a river confluence, are nearly imperceptible. In these cases, design inflow points should be limited to boundary conditions and care should be taken to ensure that model reaches extend a reasonable length up and downstream of any hydraulic infrastructure to allow for the establishment of hydraulic model stability and accuracy before interaction with more complex infrastructure.

Care should be taken when selecting flow input locations, so that they allow for an input to the model that is representative of actual conditions.

6.3.2 Manning's Roughness

Modifications of this parameter, as well as peak flow rates and proper description of hydraulic structures, were found to have one of the largest impact on simulated water depths and flood extents. Increasing Manning's n values led to a decrease in flow velocity and a subsequent rise in water levels and vice-versa. Consequently, meticulous consideration must be given to the selection of appropriate Manning's n values, tailored to the specific characteristics of the local area. Comparing both study areas revealed similar impacts, that are more based on the hydraulic perimeter (flood levels in a wider, flatter floodplain are more sensitive to roughness), as well as the ground slopes along the edges of the floodplain. Indeed, ground slopes along the edges of the floodplain can either confine water levels, resulting in a greater increase in water levels as opposed to flood extents, or be shallow and allow a greater expansion of flood extents with a comparatively low increase in water depth.

6.3.3 Built Infrastructure

The impact of built infrastructure was also investigated. The Clear Span scenario replicated the base flow conditions. The 30% to 50% Extra Opening scenarios, representing scour during a flood event, facilitated increased water flow, although resulting in limited lower water depth values and a slightly reduced flood map footprint. Conversely, the Clogged Structures scenarios, simulating debris accumulation and reduced flow capacity, led to notably higher water depth values and a substantial expansion of the flood map, affecting a larger portion of the modelled area.

Given the magnitude of the potential impacts of clogging of bridge openings, this analysis highlights the value of conducting such analyses where debris accumulation is a potential risk, such that potential impacts can be estimated and managed. Regarding the effect of potential scour on flood levels and extents, the limited impacts exhibited in the modelling indicate that there is limited value in investigating this aspect in further depth.

6.3.4 Numerical Modelling Approaches

Within Study Area 1, a comparative analysis was conducted between the steady and unsteady model simulations. Likely associated with numerical instability issues, the unsteady model yielded higher WSEL values and a larger flood map extent compared to the Steady State analysis.

Within the Study Area 2 2D HEC-RAS models, grid size testing showed major impacts to the water depths and extents. Specifically, increased mesh sizing led to loss of description of important topographic and hydraulic structures causing “leakage” through high points (a common problem in 2D hydraulic models). The larger grid size also created extreme increases in bridge crossing energy losses, creating large backwater effects which impacted upstream water levels.

Time steps testing was also conducted, and simulations were performed with time steps of various durations depending on the models. Due to severe instabilities, only the 1-second time step simulation was successfully run in Study Area 1. In Study Area 2, impacts to water levels were found to be insignificant with timestep changes, as long as the calculations were stable. This illustrates the importance of balance in time step, that is, detailed enough to describe changing water levels without being so detailed as to cause calculation instability and error, and that care should be taken to ensure checking the results to ensure all calculations were stable during the simulation.

6.3.5 Calibration

The event chosen for calibration can significantly impact the overall water extent results. If the wrong event is chosen that could potentially represent an inaccurate representation of the channel, the results could also be inaccurate. This highlights the importance of choosing the right event for calibration and taking note of major changes to the watercourse over time.

As discussed in the highlighted optimization discussion for hydraulic structures, the “right event” for calibration is one which is representative of current river conditions, a practitioner should review historic changes in river infrastructure, and river channel and flood plain topography, as these may change flood behavior and effect historic data used in the calibration process. Examples of changes which may make a given event no longer applicable include installation of a dike, replacement of a bridge or a channel avulsion.

It is also preferable that a calibration event be of a similar return period to the design event required for flood mapping. This is often unavailable due to limited data availability, and instead it is recommended that the practitioner use the largest flood event on record, provided that it is still representative of current river conditions.

6.4 GIS Process Testing

One of the main steps in the preparation of flood plain maps is the conversion of calculated water levels into flood extents using GIS post processing. There are various approaches to conducting this analysis (including whether 1D or 2D modelling was used), which involve a range of GIS parameters, which are often subjective options, such as the removal of smaller ponding areas. The options tested included the removal of smaller ponding areas, simplification of the flood extent outlines, inclusion of protected areas, combining multi-hazard scenarios, isoline generation and smoothing, and comparing the use of the Water Surface Elevation (WSEL) versus the Energy Grade Line (EGL) for flood mapping. Since the GIS processing of the results does not involve hydrologic or hydraulic mechanisms, the findings can be applicable to any floodplain with similar topographic characteristics.

GIS post processing is heavily dependent on the quality of the raw hydraulic model results, and should be used to simplify, not replace, thorough manual review by the practitioner. **Figure 6-4** summarizes the order in which these GIS post processing practices impacted final flood extents, with the addition of protected areas making the largest impacts and the EGL versus WSEL use for flood mapping having a negligible impact on resulting mapping. This figure does not include the assessment of isoline generation and smoothing approaches, discussed below, as changes to isolines do not directly affect flood extents.

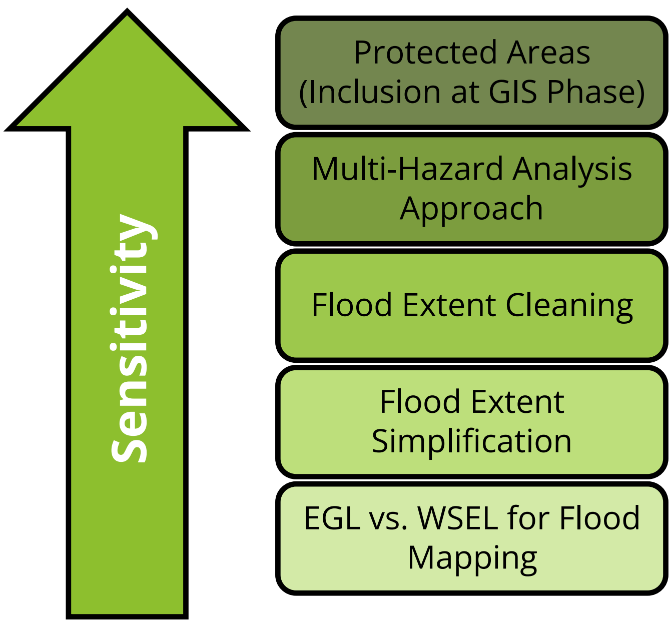

Figure 6-4: Sensitivity of Mapped Extents to GIS Processing

The decision to include protected areas through GIS post processing has the potential to have the largest impact on hydraulic model results, because in some ways, it completely overwrites them. Projecting flood elevations beyond the extents of model results eliminates the impact of well-defined terrain features. The practitioner may consider including protected areas through post processing for a number of reasons, such as the projection of the hydraulic grade line behind a protection structure to highlight flood risk in the case of structure failure.

Including protected areas by implementing a freeboard can assist the practitioner with the identification of safer water levels to use for other purposes such as design. Necessarily, this is a very delicate matter and the selection of a freeboard value should be commensurate with the level of uncertainty in the flood mapping, as well as the importance and vulnerability of the structure to be designed.

In multi-hazard analysis, a 2D post-processing method should be favoured over the 1D method where sufficient data exists as it provides more accurate representation of modelled flood extents.

Selection of a threshold for Flood Extent Cleaning and Flood Extent Simplification requires visual review of the impacts of each threshold to the overall results. Numerical comparison, as used in this study, illustrates that it is possible to “go too far” for flood extent cleaning. At the larger thresholds for both the Salmon and the Fraser River, there is a major increase in the flood extents which is not representative of the hydraulic model results. However, at lower thresholds, the changes are not as well reflected in percent change in flood extents. Selecting a typical ponding area for removal from the flood extents can very much depend on the type of floodplain and its context. The wide floodplain areas of the Salmon River and the unconfined reaches of the Fraser River in Study Area 2 had large ponding areas that may not be directly associated with river flooding, which was more clearly delineated in the more defined floodplains of Study Area 1, in which smaller ponding area thresholds could be identified. It is therefore recommended that the practitioner visually review the modeled flood extents and identify areas they wish to infill or remove based on engineering judgement or assumptions, then select a threshold value based on the standard size of the selected features.

Simplification of floodplain outlines was found to be helpful to reduce file sizes, so it is recommended for use, as long as the floodlines are not altered in any notable manner.

Methods evaluated for generating and smoothing isolines were found to each have advantages and drawbacks, leaving a need for the practitioner to select the most suitable method or a blend of methods on a case by case basis.

The use of the EGL versus the WSEL for flood mapping did not seem to have a visible impact on the flood extents, possibly related to the fact that water velocity is typically low within the floodplain edges. This may not, however, be the case where fast moving water encounters a river constriction, or sharp bends, which can accelerate water and create notable differences between the EGL and the WSEL. Since the difference between the two is the kinetic energy of the water, a large difference will highlight fast moving water, which increases risks to public safety. Flood mapping the EGL may be a safer approach in areas with vulnerable populations and infrastructure, where water is moving fast. It is therefore recommended to review the EGL as well as the WSEL results and discuss the potential value of mapping the EGL.

For all processes, the applicable thresholds cannot be deterministically selected; values depend on the size of the river, how much of the floodplain is being engaged, and other parameters that cannot be quantified. Engineering judgement is therefore a necessary component of the selection of various GIS parameters.

In general, use of any of these processes should prove beneficial to inform engineering review of modelled results for post-processing. A carefully selected threshold may be used as the basis upon which review changes can be made and can greatly reduce the number of manual edits required. None of the processes are recommended to be applied without careful review.

6.5 Limitations and Opportunities for Future Research

6.5.1 Limitations

- This sensitivity analysis involved testing of only select parameters, for select flood mechanisms, in two Study Areas (in 2 Canadian provinces) and 3 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 parameter sensitivity testing in hydrology, hydraulics and GIS.
- Consideration has been given only to freshet (rain on snow) and precipitation driven flood processes and has not reviewed a number of other hydrological processes.
- No discussion has been included regarded the uncertainties which surround the changing Canadian climate.
- This assessment reviewed the PCSWMM and HEC-RAS 1D and 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.
- The sensitivity of changes to a combination of parameters was only just touched upon and did not involve a comprehensive analysis.

6.5.2 Opportunities for Further Research

- Opportunities for future research include analysis of Canadian regions with different topographic, hydraulic and hydrologic flood challenges. 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 comparison of different hydrologic and hydraulic modelling software packages or sensitivity / application of different computational equations within a single software source.
- Recommendations and overall guidance should then be updated to encompass the results of any future research to improve general applicability and practicality of implementation.
- Further research could involve investigating the following:
  - Further the sensitivity of a combination of parameter changes.
  - Various approaches to automated calibration.
  - Uncertainty of additional hyetograph types, including variations such as the timing of the peak intensity.
  - Uncertainty in the source of the IDF data (e.g. between stations within a given range of the study area)
  - Impacts of choosing an interpolation of IDF data vs. no interpolation, or using regional IDF models.
  - Uncertainty in runoff-generating mechanisms such as rainfall-dominated vs. rain on snow vs. spring Freshet dominated vs. rainfall on frozen ground.

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APPENDIX A

Tabulated Results for Testing of Each Parameter – Study Area 1

Max Flow (m^3/s)																	
Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Node	J103	J30639	J27667	J25744	J22791	J20571	J18784	J17346	J14699	J12575	J10963	J9425	J6788	J5179	J3073	J1610	J134
Reference value	25.97	28.44	47.76	48.7	94.98	112.2	112.2	132.3	143.1	172.2	235	256.1	269.5	274.6	296.9	295.8	297.1
0.1 x Conductivity	31.88	34.62	62.26	58.6	102.6	119.8	119.7	140.7	152.2	182.6	248.7	270.9	285.2	290.6	314.2	313.2	314.6
10 x Conductivity	8.663	6.671	10.41	10.23	56.64	69.06	68.46	82.33	89.57	109.8	152.3	166.2	175.7	179	194.2	193.5	194.2
0.01 Initial Deficit	25.97	28.44	47.76	48.7	94.98	112.2	112.2	132.3	143.1	172.2	235	256.1	269.5	274.6	296.9	295.8	297.1
0.8 Initial Deficit	25.97	28.44	47.76	48.7	94.98	112.2	112.2	132.3	143.1	172.2	235	256.1	269.5	274.6	296.9	295.8	297.1
0.2 X Flow Length	64.84	56.79	78.37	76.35	172.8	148.4	186.4	209.2	223.6	255.9	352.7	380.4	395.3	400.6	425.6	424.6	426.1
5 X Flow Length	11.67	12.03	19.78	19.69	43.88	50.47	50.45	58.6	62.86	75.88	102	111.1	121.5	126.3	139.7	139.6	140.9
4 Subcatchments	0	0	0	0	94.9	91.02	85.14	84.29	82.3	79.57	448.4	405.3	301.6	297	287.2	261.9	258.7
52 Subcatchments	11.33	0.315	7.67	3.187	52.81	62.83	62.05	74.04	87.09	91.24	122.3	138.3	145	149.2	157.3	161.9	164.7
Hurricane Fiona Calibration	7.436	5.118	8.351	8.238	29.05	35.58	35.51	42.63	46.24	57.6	79.2	86.27	94.59	98.5	109.4	109.1	110.2
2nd Nov 2021 Calibration	27.01	25.99	45.21	43.72	96.17	112.4	113.5	133.8	144.8	173.8	238.1	259.3	271.9	276.8	298.5	297.4	298.6
ECCC Block Hyetograph	18.41	23.37	42.99	42.63	84.4	92.78	92.69	103.6	110.9	129.8	175.8	190.9	200.9	204.4	221.5	221.1	222.1
ECCC SCSIII Hyetograph	31.91	31.67	48.71	48.72	109.4	127.9	129.2	152	163.8	194.7	263.4	285.3	297	301.4	323.4	321.9	322.7
Reference value	25.97	28.44	47.76	48.7	94.98	112.2	112.2	132.3	143.1	172.2	235	256.1	269.5	274.6	296.9	295.8	297.1
Northeast Rainfall Source	37.27	38.94	66.97	67.2	124.9	144.3	146.5	172.3	186.4	224.1	306.4	333.6	350.5	357.1	386	385	386.7
Western Rainfall Source	12.18	11.31	18.02	17.82	50.54	59.65	58.98	68.91	74.15	88.34	119	128.8	135.2	137.3	147.3	146.8	147.2

Max Water Level (m)																	
Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Node	J103	J30639	J27667	J25744	J22791	J20571	J18784	J17346	J14699	J12575	J10963	J9425	J6788	J5179	J3073	J1610	J134
0.1 x Conductivity	1.752	1.901	1.863	1.319	1.743	1.793	1.94	2.992	1.837	2.566	2.979	2.894	3.906	3.501	3.56	2.852	0.952
10 x Conductivity	1.467	0.83	0.824	0.692	1.426	1.459	1.535	2.428	1.563	2.06	2.51	2.452	3.215	2.928	2.987	2.332	0.761
0.01 Initial Deficit	1.714	1.746	1.713	1.225	1.696	1.75	1.886	2.908	1.795	2.499	2.92	2.829	3.818	3.428	3.488	2.785	0.927
0.8 Initial Deficit	1.714	1.746	1.713	1.225	1.696	1.75	1.886	2.908	1.795	2.499	2.92	2.829	3.818	3.428	3.488	2.785	0.927
0.2 X Flow Length	2.195	2.165	2.119	1.547	2.118	2.212	2.346	3.383	2.144	2.997	3.375	3.412	4.474	3.958	3.972	3.239	1.099
5 X Flow Length	1.329	1.15	1.145	0.881	1.296	1.276	1.35	2.124	1.399	1.769	2.179	2.19	2.76	2.589	2.66	2.041	0.656
4 Subcatchments	0	0	0	0	1.69	1.612	1.67	2.425	1.516	1.794	3.673	3.143	3.981	3.504	3.469	2.557	0.869
52 Subcatchments	0.946	0.185	0.245	0.538	1.384	1.402	1.477	2.284	1.547	1.895	2.327	2.325	2.971	2.745	2.771	2.111	0.705
Hurricane Fiona Calibration	1.262	0.734	0.729	0.641	1.1	1.092	1.163	1.874	1.28	1.59	1.992	2.036	2.473	2.395	2.366	1.845	0.585
2nd Nov 2021 Calibration	1.694	1.663	1.631	1.18	1.704	1.758	1.895	2.924	1.802	2.509	2.934	2.841	3.832	3.438	3.495	2.791	0.929
ECCC Block Hyetograph	1.123	1.595	1.588	1.17	1.629	1.623	1.737	2.643	1.658	2.204	2.638	2.555	3.388	3.07	3.141	2.465	0.81
ECCC SCSIII Hyetograph	1.967	1.69	1.682	1.225	1.784	1.853	2.002	3.07	1.889	2.641	3.04	2.951	3.97	3.549	3.599	2.886	0.964
Northeast Rainfall Source	1.913	2.031	1.981	1.434	1.874	1.957	2.112	3.191	1.994	2.822	3.209	3.184	4.251	3.787	3.838	3.121	1.049
Western Rainfall Source	1.402	1.097	1.092	0.848	1.365	1.371	1.448	2.256	1.468	1.877	2.306	2.276	2.881	2.662	2.709	2.082	0.669

APPENDIX B

Tabulated Results for Testing of Each Parameter – Study Area 2

Max Water Level (m)																	
River Reach	**Salmon River**							**Fraser River**									
Sample Cross-Section	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Baseline – Hydrology FFA	**4.13**	**3.29**	**4.09**	**3.08**	**4.45**	**5.85**	**2.63**	**8.99**	**17.6**	**12.34**	**11.35**	**9.83**	**14.49**	**15.61**	**11.42**	**13.48**	**10.05**
Lower Bound FFA Flow	4.05	3.23	4.03	3.02	4.36	5.77	2.57	8.91	17.51	12.26	11.27	9.74	14.4	15.53	11.38	13.4	9.98
Upper Bound FFA Flow	4.42	3.49	4.32	3.29	4.69	6.06	2.8	9.67	18.29	13.04	12.03	10.63	15.13	16.28	11.83	14.13	10.66
Baseline – Hydraulic Modelling	**4.2**	**3.35**	**4.16**	**3.13**	**4.52**	**5.91**	**2.67**	**9.29**	**17.91**	**12.65**	**11.65**	**10.19**	**14.79**	**15.91**	**11.59**	**13.76**	**10.32**
Inflow Directly Upstream of Bridge	4.22	3.35	4.15	3.13	4.52	5.91	2.67	-	-	-	-	-	-	-	-	-	-
Inflow in Existing Model Location	4.2	3.35	4.16	3.13	4.52	5.91	2.67	-	-	-	-	-	-	-	-	-	-
Low Manning's Roughness	4.13	3.28	4.07	3.03	4.47	5.86	2.61	8.86	17.59	12.3	11.32	9.74	14.33	15.47	11.33	13.3	9.91
High Manning's Roughness	4.28	3.41	4.25	3.25	4.57	5.96	2.74	9.7	18.21	12.98	11.97	10.6	15.18	16.32	11.87	14.2	10.69
Partially Clogged Bridges	6.9	3.36	4.15	3.13	4.52	7.32	2.68	9.53	18.63	14.3	13.88	13.11	18.73	18.16	13.57	15.7	10.22
Fully Clogged Bridges	9.11	5.52	4.15	3.13	4.52	12.52	10.02	-	-	-	-	-	-	-	-	-	-
Smaller Grid Size	4.42	3.35	4.19	3.17	4.52	5.99	2.7	9.31	17.8	12.71	11.71	10.28	14.85	15.99	11.63	13.89	10.26
Larger Grid Size	4.27	3.38	4.25	3.14	4.5	5.94	2.66	9.67	18.08	13.08	12.22	11.54	16.5	17.42	13.05	16.09	10.35
Low Timestep	4.24	3.35	4.15	3.13	4.52	5.91	2.68	9.3	17.91	12.65	11.66	10.2	14.8	15.93	11.6	13.77	10.32
High Timestep	4.19	3.34	4.15	3.13	4.5	5.89	2.67	9.29	17.91	12.64	11.68	10.18	14.78	15.91	11.59	13.76	10.31
Secondary Calibration Parameters	4.63	3.21	3.9	2.89	4.43	5.76	2.5	-	-	-	-	-	-	-	-	-	-

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