Appendix A: Hydraulic Model

Skagit River Flood Risk Modeling

Hydraulic Model Development Report

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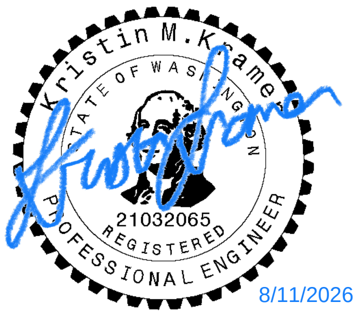

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- Vaughn Collins — Technical Advisor and Reviewer
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- USACE — Model data
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- WDFW — Surface data
- DIDC — High water mark data, prior studies

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ABBREVIATIONS

Acronym / Abbreviation	Definition
1D	one-dimensional
2D	two-dimensional
AdH	Adaptive Hydraulics
City Light	Seattle City Light
CWMS	Corps Water Management System
DIDC	Skagit Drainage and Irrigation Districts Consortium
FEMA	Federal Emergency Management Agency
HEC-HMS	Hydraulic Engineering Center Hydrologic Modeling System
HEC-RAS	Hydraulic Engineering Center River Analysis System
HWM	high-water mark
LiDAR	light detecting and ranging
MAE	mean average error
MHHW	mean higher high water
NAIP	National Agriculture Imagery Program
NAVD88	North American Vertical Datum of 1988
NF	North Fork
NHC	Northwest Hydraulic Consultants, Inc.
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
PL 84-99	Public Law 84-99, Emergency Response to Natural Disasters
RCP	representative concentration pathway
RM	river mile
SC2	Skagit Climate Science Consortium
SF	South Fork
SITC	Swinomish Indian Tribal Community
Skagit GI	Skagit River Flood Risk Management General Investigation

Acronym / Abbreviation	Definition
SLR	sea level rise
SRSC	Skagit River System Cooperative
SWE-ELM	Shallow Water Equations with a Eulerian-Lagrangian Method
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UW CIG	University of Washington Climate Impact Group
WDFW	Washington Department of Fish and Wildlife
WSE	water surface elevation
ECY	Washington State Department of Ecology
WSDOT	Washington State Department of Transportation

1 INTRODUCTION

The Skagit River Hydraulic Model Development Report has been prepared as part of the Skagit River Flood Resilience Project (Project) on behalf of the Swinomish Indian Tribal Community (SITC), as identified in Resolution No. 2024-09-179. The Project partners include Skagit River System Cooperative (SRSC), Skagit Climate Science Consortium (SC2), and University of Washington Climate Impacts Group (UW CIG). Northwest Hydraulic Consultants (NHC) was contracted by SITC to develop and calibrate a new, reach-wide two-dimensional (2D) hydraulic model of the Skagit River (Project model).

This technical report documents the model development and has been prepared as an appendix to the *Understanding Current and Future Skagit Flood Risk Through New Modeling Capabilities report* (SITC et al., 2026, hereafter referred to as the Project Report). The Project Report summarizes the study objectives and watershed context, with mapping products included, while this report documents development of the Project model, including data collection, model assumptions, and limitations.

1.1 Purpose and Background

The goal of the Project is to increase understanding of riverine and coastal flood risk to communities and habitats in the Skagit River watershed using the best available tools and latest data. This has been completed by developing a fully two-dimensional (2D) hydraulic model of the Skagit River from Marblemount to the Puget Sound. Similar efforts to develop updated, reach-wide modeling tools have been undertaken in other western Washington rivers, including along the Nooksack River, the Stillaguamish River, the Puyallup River, and the Skykomish-Snoqualmie-Snohomish river system. These large-scale models help support flood planning and emergency management, and, in the case of the Nooksack model, are actively updated as new data are collected.

A hydraulic model is a computer-based tool that simulates water moving through rivers, floodplains, and coastal areas. Previous reach-wide studies of the Skagit River used partial one-dimensional (1D) models along the main channel as well as floodplain areas upstream of Burlington. A 1D hydraulic model simulates flow in a single, streamwise direction. In contrast, a 2D hydraulic model can simulate flow in both streamwise and lateral directions, allowing the model to better represent complex flow patterns across floodplains, through side channels, and around islands and structures. In addition, a 2D hydraulic model can provide detailed visualization of flow patterns, water surface elevations, flood extents, and various other products which can support flood planning, emergency management, and habitat restoration.

To support the goal of improving floodplain mapping, the Project model was developed with the following objectives:

- Develop a fully 2D hydraulic model of the Skagit River from Marblemount to the Puget Sound, including the entire delta and lower Samish River, to provide detailed flood results mapping within the entire study area;
- Apply the best available topobathymetric and hydraulic structure data from newly available sources and previously developed models and calibrate the model to the November 2021 event; and
- Evaluate riverine and coastal flooding under historic[1] and future climate conditions for three primary areas of interest: flood risk, habitat, and agriculture.

The model builds upon previously developed hydraulic models of the Skagit River and involved extensive data collection to obtain prior hydraulic models, recent calibration data, and the latest available topobathymetry. This study assesses present-day built conditions and does not include evaluation of future flood risk management scenarios. The model has been used to develop mapping products, provided in Appendix B of the Project Report. As part of the Project, the model and results will be available for use and adaptation by others.

1.2 Study Area

The study area covers approximately 85 miles of the Skagit River, primarily within Skagit County, Washington, from seven miles upstream of Marblemount extending downstream into Skagit, Padilla, and Samish bays as shown in Figure 1.1. The hydraulic model includes floodplain mapping for short reaches of major tributaries to the Skagit River, including the Baker, Cascade, and Sauk rivers, as well as the lower ten miles of the Samish River. Flows from these major tributaries are fully incorporated into the model. The study area includes portions of the coastline of the Swinomish Indian Tribal Community reservation, the cities of Burlington, Mount Vernon, Sedro-Woolley, and Stanwood, the towns of Marblemount, La Conner, Concrete, Hamilton, and Lyman, and several other unincorporated communities.

Along the lower Skagit River, a system of approximately 50 miles of dikes and 40 miles of coastal dikes is overseen by diking districts, with some dike facilities co-managed with the U.S. Army Corps of Engineers (USACE) in the PL 84-99 program. Previous studies often refer to facilities along the Skagit River as “levees”; however, “dikes” is the term more commonly used in the local community and will be used throughout this report. The dike systems along the Skagit River generally have the capacity to contain an approximately 20-year return period flood. The coastal dike systems provide protection against coastal events, but can prolong landward flooding

[1] The term “historic” refers to flood model simulations using hydrology from the Skagit River GI (USACE, 2014).

within the Skagit lowlands. More information on historic flooding and watershed characteristics for the Skagit River is included in the Project Report.

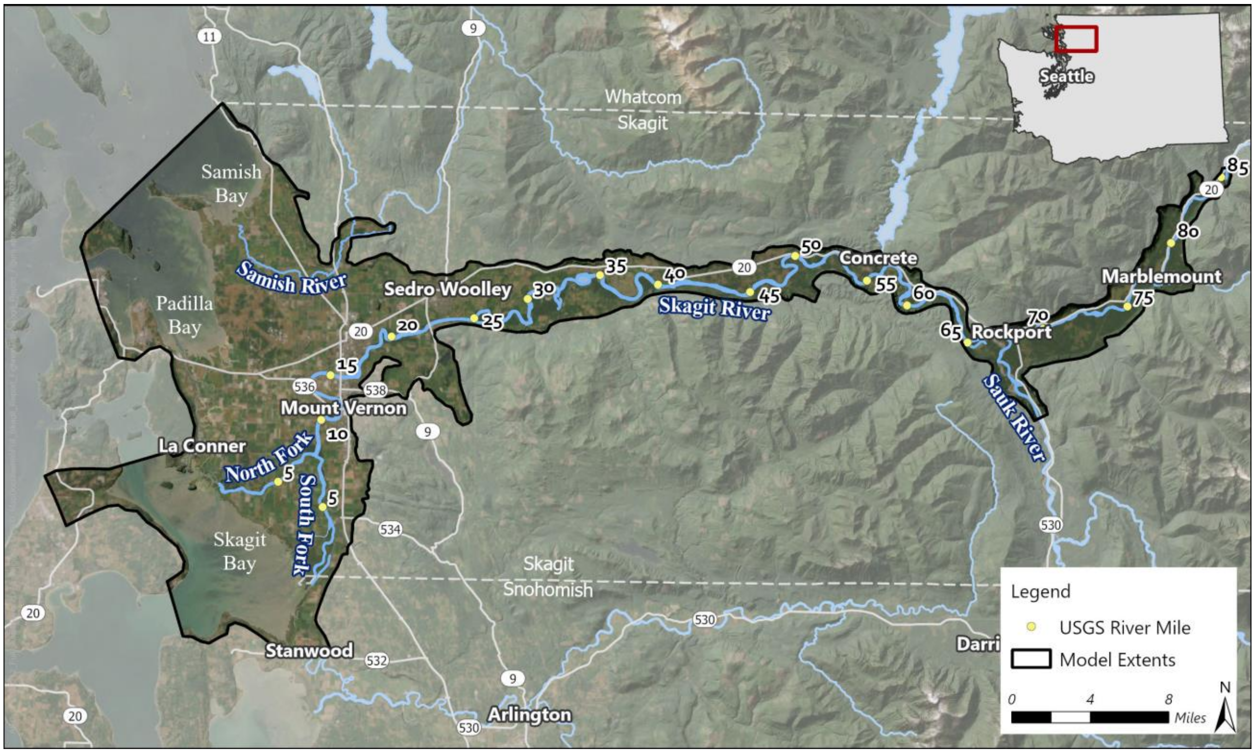


Figure 1.1 Skagit River hydraulic model study area

2 PREVIOUS STUDIES AND DATA COLLECTION

Multiple significant studies and planning efforts have been conducted within the Skagit River watershed. To support development of the Project model, NHC reviewed several studies for applicability and collected relevant data and models as needed, as summarized in Table 2.1. This process included coordination with USACE and Seattle City Light to obtain previously developed models. Hydrology used in the Project model is based on the Skagit GI (USACE, 2014). For model development, the USACE's CWMS model (2022) was primarily used as the starting point because it used the same model software, had a similar domain, and had been recently updated and calibrated to the November 2021 event. However, the Delta model (NHC, 2023) was primarily used to obtain culvert and tide gate data, given the project completed an inventory of significant drainage infrastructure in the lowlands, downstream of Burlington.

The additional studies reviewed, along with data incorporated into the Project model, are provided in Table 2.1. Data collected for development of the topobathymetric surface and calibration process are not detailed in this section but are described in sections 6.1.1 and 6.4, respectively.

Table 2.1 Previously developed hydraulic models and technical studies

Title	Source	Model Type	Data Used
Skagit River General Investigation (Skagit GI)[1]	(USACE, 2014)	Separate 1D HEC-RAS and Flo-2D models[2]	Hydrology, dike failure locations and parameters
Skagit River Corps Water Management System (CWMS) RAS model	(USACE, 2022)	Combined 1D/2D HEC-RAS model[4]	Breaklines, initial roughness, bridge geometry, culvert and tide gate data (secondary)
Skagit River Delta Flood Drainage Project (Delta model)	(NHC, 2023)	Three separate 2D HEC-RAS models[3]	Culvert and tide gate data (primary), bathymetry, Samish River roughness
Upper Skagit Instream Flow model	(Seattle City Light, 2023)	2D HEC-RAS model[5]	Breaklines, initial roughness
Maddox Creek Big Ditch Alternatives Evaluation	(NHC, 2020)	2D HEC-RAS model[6]	Culvert data, breaklines[6]
Old Highway 99 at Thomas Creek Bridge Replacement	(NHC, 2025)	2D HEC-RAS model[7]	Bridge and breakline data near Thomas Creek and Samish River[7]
McGlinn Island Jetty Project	(USACE, 2021)	AdH model[8]	Report reviewed, bathymetry used[8]
Skagit Hydrodynamic Model (SHDM) Project	(Whiting et al., 2017)	FV-COM model	Report reviewed, no model data used

Notes:
1. Included review of several reports initiated by USACE and Skagit County dating back to the early 2000s.
2. The 1D HEC-RAS model captures the main channel and floodplain areas upstream of Burlington; the separate Flo-2D model represents floodplain areas within the Skagit delta.
3. Three model domains covered overbank flooding areas downstream of Sedro-Woolley, including Fir Island but not Mount Vernon; the models do not include the mainstem Skagit, North Fork, or South Fork. Samish River was calibrated to the February 2018 flood event.
4. Model recently updated and calibrated to the November 2021 event. Model uses 1D cross sections to represent the main channel as well as floodplain areas upstream of Burlington. The combined 2D areas represent the Skagit delta. Channel bathymetry was applied from the FEMA study, dating back to 1975, and floodplain areas were updated with more recent LiDAR from 2017 and 2019.
5. The model domain extends from Rockport to Newhalem and uses a very fine mesh resolution to support detailed analysis of instream flows and aquatic habitat.
6. The model domain extends from Mount Vernon to Stanwood and does not include the mainstem Skagit or South Fork. Culvert data mainly limited to key infrastructure along I-5.
7. Model developed from the Delta model (NHC, 2023). Used existing conditions geometry and added bridge geometry and breakline resolution added near Samish River and Thomas Creek at Old Highway 99.
8. Bathymetry was obtained using elevations from the AdH model mesh. In 2014, a large channel avulsion occurred on the North Fork. As part of the project, 2019 and 2022 bathymetric data were collected along the recent avulsion, lower North Fork, Swinomish Channel, Skagit Bay, and Padilla Bay.

3 MODEL ASSUMPTIONS AND CAPABILITIES

The Project model has been developed to simulate riverine and coastal flooding along the Skagit River to evaluate flood risk to communities and habitats. The following sections describe the key improvements relative to previously developed models, the current capabilities of the model, and additional capabilities that could be supported with further development. In addition, this section describes limitations of the model software.

3.1 Key Improvements Compared to Previous Models

The Project model incorporates several key improvements compared to previously developed hydraulic models. For comparison purposes, the following improvements are listed relative to the CWMS model (USACE, 2022), which was primarily used for model development, including:

- Develop a fully 2D model domain of the Skagit River mainstem from Marblemount to the Puget Sound, including floodplain areas upstream of Burlington.
- Expand the model domain into Skagit, Samish, and Padilla bays to allow for modeling of a full tidal range, and the addition of the lower ten miles of the Samish River to simulate floodplain interaction between the Skagit and Samish rivers.
- Model projected flows under climate change conditions. In addition, simulate moderate to major flood events within a fully 2D domain to better understand floodplain activation and routing in addition to facility overtopping.
- Use the latest available bathymetric data sources, from 2012 to 2024, compared to 1975 data.
- Apply a more refined 2D mesh resolution in the mainstem and floodplain areas to provide more accurate routing of flood flows.
- Incorporate additional drainage infrastructure from the Delta model (NHC, 2023) within the Skagit lowlands, downstream of Burlington.

3.2 Key Capabilities, Assumptions and Limitations of the Model

The Project model includes the following capabilities and components:

- The model is capable of accurately simulating flood flows, depths, elevations and velocities in the main channel and floodplain. In addition, the model can simulate flood durations for the historic 100-year riverine flood.
- The model can simulate flows through bridges and culverts and over the crests of dikes and coastal dikes.
- The model can simulate the interaction of riverine flows and tides.
- The model mesh resolution is designed for the accurate routing of flood flows. The resolution is not fine enough to evaluate in-channel habitat or other microscale features, but it is appropriate to identify activation of side channels.

- Representation of the Mount Vernon Flood Wall is included in the model, but other temporary flood fighting techniques are not included, such as construction of temporary sand bag walls and activation of pump stations.
- The model only includes significant culverts and tide gates from the Delta model (NHC, 2023) and CWMS model (USACE, 2022), which are limited to key infrastructure in the delta downstream of Burlington. In addition, limited culvert data is included in the area south of Mount Vernon to Conway as obtained from the Maddox Big Ditch project (NHC, 2020), and no drainage infrastructure was modeled along Gages Slough near Burlington.
- No debris blockage at bridges is simulated.
- Buildings are not discretely represented in the model.
- Hydrologic inputs for the Skagit and Samish rivers are applied from the Skagit GI (USACE, 2014). Inflows to the Skagit River and Baker River are based on reservoir operating policies at Ross Dam and Upper Baker Dam during the time the Skagit GI was developed in 2012. The regulated inflow hydrographs used in this study do not account for recent and/or forthcoming (2026) flood operating policies at Ross and Upper Baker reservoirs.
- The model does not show flood risk related to smaller tributaries.
- The model is a fixed bed model with no sediment transport, bed aggradation or scour simulated.
- The HEC-RAS software used to develop the Project model does not have capability to represent the following processes or conditions:
  - Lateral migration and channel avulsions.
  - Saltwater intrusion or other groundwater dynamics.

3.3 Additional Capabilities with Further Development

With additional development and analysis, the model could also evaluate the following:

- Calibration to the recent December 2025 flood, which best represents current channel characteristics along the North Fork, South Fork, and mainstem through Burlington.
- Proposed flood risk management scenarios.
- Additional hazard mapping products, such as additional flood duration maps (currently only produced for historic 100-year riverine event) and velocity maps with flow vectors.
- Future land use changes that could impact flows such as development related to forest conversion or impervious surface increases.
- Coastal dike failure scenarios.
- Incorporation of soil infiltration rates into the model geometry to simulate losses in the floodplain.

- Model events using spatial precipitation data (rain-on-grid).
- Incorporation of pipe network data into the model geometry.
- Future flood risk with projected channel aggradation and/or widening.

4 MODEL SCENARIOS

A suite of model scenarios was simulated, selected to span the range of meaningful riverine and tidal flood risk now and in the future. The scenarios include the following:

- Riverine and coastal flooding under historic, mid-century (2040s), and late-century (2080s) scenarios for the 10-, 25-, and 100-year flood events. The historic record shows that riverine and coastal floods almost never occur at the same time, therefore riverine floods were paired with normal tides, and coastal floods were paired with mean winter river flows.
- For riverine flooding, the 10-year event was selected to represent a moderate flood event with flows contained within the lower Skagit River dike system. The 25-year event represents conditions where dike overtopping begins to occur, and the historic 100-year event represents a large, damaging event and matches the regulatory flood used by FEMA. These were paired with normal tides with high tides reaching mean higher high water (MHHW).
- For coastal flooding, the same 10-, 25- and 100-year probability events were used, paired with mean winter flows on the Skagit and Samish rivers.
- An “extended” version of the historic conditions 100-year riverine flood was simulated for over a month in order to evaluate the duration of flooding affecting residences, infrastructure, and agriculture. All other simulations were run for shorter periods spanning only the flood event itself.
- Six dike failure scenarios were simulated along the Skagit River under the historic conditions 100-year event, using locations and failure parameters from the Skagit GI (USACE, 2014). These runs were used to evaluate the implications for flood risk downstream of Sedro-Woolley.
- Calibration and validation plans were developed for four significant flood events observed over the past three decades, as further described in Section 6.4.
- Initial conditions plans were developed to establish mean winter flows at the beginning of all simulations, as described in Section 6.3. A separate initial conditions file was created for the December 2025 flood, using observed inflow data, to better establish initial conditions at the Nookachamps area.

A summary of all the simulations is presented below in Table 4.1. Details on the river flow and tidal boundary conditions used for each run are described in the next section.

Table 4.1 Summary of simulation runs

Flood Type	Climate Scenario	River Inflow	Tidal Boundary Conditions
Riverine	Historic	10-year	MHHW
		25-year	
		100-year	
		100-year (extended)[4]	
	Mid-Century (2040s)	10-year	MHHW + SLR
		25-year	
		100-year	
	Late-Century (2080s)	10-year	
		25-year	
		100-year	
Coastal	Historic	Mean winter flows	10-year tidal stage
			25-year tidal stage
			100-year tidal stage
	Mid-Century (2040s)		10-year tidal stage + SLR
			25-year tidal stage + SLR
			100-year tidal stage + SLR
	Late-Century (2080s)		10-year tidal stage + SLR
			25-year tidal stage + SLR
			100-year tidal stage + SLR
Dike Failure (RM 21.3)	Historic	100-year	MHHW
Dike Failure (RM 18.1)			
Dike Failure (RM 16.8)			
Dike Failure (RM 13.1)			
Dike Failure (RM 11.7)			
Dike Failure (NF RM 8.3)			
November 2021 Flood	Historic	Observed (full domain)	Observed
October 2003 Flood		Observed (domain downstream of Concrete)	
December 2025 Flood			
November 1995 Flood			
Initial Conditions	Historic	Mean winter flows (full domain)	MLLW

Flood Type	Climate Scenario	River Inflow	Tidal Boundary Conditions
Initial Conditions	Historic	Mean winter flows (domain downstream of Concrete)	MLLW
Initial Conditions: December Flood[5]	Historic	Observed (domain downstream of Concrete)[5]	MLLW

Notes:

1. Sea level rise (SLR)
2. Mean higher high water (MHHW)
3. Mean lower low water (MLLW)
4. A separate "extended" version of the historic conditions 100-year riverine flood was simulated for over a month to evaluate the duration of flooding.
5. A separate initial conditions plan was set up for the December 2025 flood to improve initial conditions for the event.

5 FLOOD HYDROLOGY AND TIDES

Hydrologic inputs and tidal stages were developed for both historic and future conditions for use in the hydraulic model. The methodology and data sources used to develop these inputs are described in this section. Section 5.3 provides summary tables and figures of the inflow and tidal data used in the hydraulic model.

5.1 Historic Conditions

The historic conditions hydrology is based on the Skagit GI (USACE, 2014) while tidal stage is developed from observed tidal conditions. A new hydrologic analysis was not completed as part of this Project.

5.1.1 Inflow Hydrographs

For riverine flood events, hydrologic inputs for the historic conditions were applied from the Skagit GI (USACE, 2014). Flood hydrographs for the 10-, 25-, and 100-year events were obtained from locations in the Skagit GI, with 100-year peak flows listed in Table 5.6. Figure 5.1 shows the 100-year inflow hydrographs for the Skagit River and major tributaries. The Skagit GI used hypothetical flood hydrographs developed roughly based on the shape of the observed hydrograph from the October 2003 flood, matching the maximum instantaneous, one-day, and three-day flows for the respective quantiles from the frequency analysis. Hydrograph timing was determined by evaluating the relationship to past events as well as travel time through the system, as further detailed in the Skagit GI. The historic hydrographs are based on reservoir operating policies at both Ross Dam and Upper Baker Dam at the time the Skagit GI was developed in 2012. The inflow hydrographs used do not account for recent and/or forthcoming (2026) operating policies at Ross and Upper Baker reservoirs, nor potential changes related to the Skagit dams relicensing agreement.

For coastal flood events, mean winter river flows from December to January were determined at the inflow boundary locations used in the hydraulic model, with resulting flows shown in Table 5.6. Mean winter flows were developed using USGS gage data post 1977 when flood control facilities on both Ross Dam and Upper Baker Dam were in operation.

5.1.2 Tidal Stage Hydrographs

NHC developed tidal stage hydrographs at the boundary condition locations described in Section 6.2 with observed NOAA tide data from stations at Seattle and Port Townsend as the basis. Tidal stage hydrographs were scaled to the closest tide prediction (subordinate) station and converted to NAVD88 datum for use in the hydraulic model (Table 5.1). The conversion for the Crescent Harbor station was applied based on published station datum information. NAVD88 conversion data were not available for the Anacortes and Ala Spit Stations; therefore, NOAA's vertical datum transformation tool (2025) was used to determine the datum conversions.

For riverine flood events, tidal stage hydrographs were developed using a period with high tides near the MHHW stage (November 7-12, 2022). The MHHW elevations at each boundary condition are reported in Table 5.7. An example of the tidal stage hydrographs used in the riverine flood event at the Skagit Bay (North) boundary condition is shown in Figure 5.2.

Extreme flood tides were based on observed data from a recent event on December 27, 2022. This event, like other coastal flood events examined, consisted of a single high tide reaching levels substantially higher than those before and after it. Exceedance probability stages for the 10-, 25-, and 100-year events were calculated using exceedance probabilities at the reference stations developed as part of the Washington State Coastal Resilience Project (Miller et al., 2019) (Table 5.2). These stages were transformed to the model boundaries using the same methods as for normal tides as described above. The observed stage hydrograph for the December 27, 2022 coastal flood event was then shifted so that the peak high tide matched the calculated exceedance probability stage. Table 5.8 reports the peak tidal stage at each boundary condition location. An example of the tidal stage hydrographs in the coastal flood event at the Skagit Bay (North) boundary condition is shown in Figure 5.3.

Table 5.1 Tidal boundary conditions

Boundary Condition Location	NOAA Subordinate Station (Tide Predictions)	NOAA Reference Station (Tide Observations)
Samish Bay and Padilla Bay	Anacortes, Fidalgo Island WA	Port Townsend WA (9444900)
Skagit Bay (north)	Ala Spit, Whidbey Island WA	Seattle WA (9447130)
Skagit Bay (south)	Crescent Harbor, Whidbey Island WA	Seattle WA (9447130)

Table 5.2 Tides plus storm surge (feet)

Recurrence Interval	NOAA Seattle Station (1950-2024)		NOAA Port Townsend Station (1980-2024)	
	Rel. to MHHW	Rel. to NAVD88	Rel. to MHHW	Rel. to NAVD88
10-year	2.9	11.9	2.7	10.4
25-year	3.1	12.1	2.9	10.6
100-year	3.4	12.4	3.0	10.7

5.2 Future Conditions

NHC collaborated with the UW CIG to develop future conditions hydrologic and tidal inputs for mid-century (2040s) and late-century (2080s) scenarios, considering climate projections, sea level rise, and storm surge. The following sections summarize the scalars developed by UW CIG for use in the hydraulic model.

5.2.1 Inflow Hydrographs

For riverine flood events, future inflow hydrographs were developed by applying median projections for the 1-day duration as scaling factors to the entire historic conditions hydrographs, described in Section 5.1.1. Although there is a range among the projections for each dataset, the median projections were selected for use to provide a middle-of-the-road estimate of future conditions. Future work could explore the implications of higher or lower changes on flood risks. The scaling factors used in the hydraulic model are reported in Table 5.3, as developed by UW CIG. The 100-year peak flows for the future conditions are listed in Table 5.6. Figure 5.2 shows the 100-year inflow hydrographs for the Skagit River and major tributaries.

The Hamlet et al. (2013) dataset was used as input to the reservoir model results provided in the Lee et al. (2016) study – both studies are based on the same hydrologic model simulations. Although older, these studies were prioritized for two reasons: (1) the model calibration is superior to the more recent Bandaragoda et al. (2015, 2019) studies, and (2) Lee et al. (2016) is the only available study that provides regulated flow projections. The Bandaragoda et al. (2015, 2019) results were used for locations that are not included in the Hamlet et al. (2013) or Lee et al. (2016) results.

The Hamlet et al. (2013) and Lee et al. (2016) studies are based on a moderate (A1B) greenhouse gas scenario, whereas the Bandaragoda et al. (2015, 2019) projections only include a low (RCP 4.5) and high (RCP 8.5) greenhouse gas scenario. In order to approximate the moderate greenhouse gas scenario used in the Hamlet et al. (2013) and Lee et al. (2016) projections, UW CIG averaged the results for the low and high greenhouse gas scenario projections from Bandaragoda et al. (2015, 2019).

For coastal flood events, inflow hydrographs were held constant at mean winter flows for the historic conditions, per Section 5.1.1. Future projections were not applied to riverine inflows for the coastal flooding events.

Table 5.3 Future projections scaling factors (1-day duration, median projection) applied to inflow hydrographs in the hydraulic model

Location	10-year		25-year		100-year		Source
	2040s	2080s	2040s	2080s	2040s	2080s	
Gorge[1]	+77%	+130%	+54%	+97%	+25%	+53%	(Lee et al., 2016)
Cascade[2]	+1%	+27%	+2%	+23%	+7%	+18%	(Bandaragoda et al., 2015, 2019)
Sauk	+31%	+59%	+24%	+48%	+13%	+32%	(Lee et al., 2016)
NF Stillaguamish[3]	+18%	+25%	+17%	+24%	+16%	+22%	(Hamlet et al., 2013)
Baker	+9%	+25%	+6%	+24%	+3%	+24%	(Lee et al., 2016)
Nookachamps	-6%	+4%	-6%	+6%	-4%	+13%	(Bandaragoda et al., 2015, 2019)
Samish	+11%	+22%	+11%	+22%	+11%	+23%	(Hamlet et al., 2013)

Notes:
1. Gorge projections were applied to the Regulated Marblemount boundary condition.
2. Cascade projections were applied to the Cascade River and local flows between the Cascade and Sauk rivers.
3. NF Stillaguamish projections were used as a proxy for local inflow between Sedro-Woolley and Rockport due to the similarity with local tributaries in this reach.

5.2.2 Tidal Stage Hydrographs

For riverine flood events, tidal stage hydrographs representing MHHW stage (Section 5.1.2) were shifted to account for sea level rise, using projections developed by UW CIG in Table 5.4. As with riverine changes, the median projections were used for sea level rise, obtained in this case from the Miller et al. (2018) study. Although a newer nationwide study is available (Sweet et al., 2022), it does not provide the same level of detail for Washington's coastline, and the projected changes are similar. To approximate the moderate (A1B) greenhouse gas scenario used in the peak flow projections, UW CIG averaged the results for the low (RCP 4.5) and high (RCP 8.5) scenarios in the sea level rise projections. Future work could explore the implications of higher or lower projections on coastal flood risks. The MHHW elevations at each boundary condition are reported in Table 5.7. An example of the tidal stage hydrographs used in the riverine flood event at the Skagit Bay (North) boundary condition is shown in Figure 5.2.

For coastal flood events, the same tidal stage hydrographs from the historic conditions simulations (Section 5.1.2) were applied, as research suggests that tidal anomalies are not expected to change in the future (Miller et al., 2019). These hydrographs were shifted to account for both sea level rise (Table 5.4) and storm surge (Table 5.2) based on values provided by

UW CIG (Miller et al., 2018, 2019). The combined sea level rise and storm surge values are summarized in Table 5.5. Table 5.8 reports the peak tidal stage at each boundary condition location. An example of the tidal stage hydrographs used in the coastal flood event at the Skagit Bay (North) boundary condition is shown in Figure 5.3.

Table 5.4 Sea level rise

Decade	Rise (feet)[1]
Mid-century (2040s)	0.5
Late-century (2040s)	1.35

Notes:

1. Median projections based on average representative concentration pathway (RCP) 4.5 and 8.5 projections (Miller et al., 2018).

Table 5.5 Combined sea level rise and storm surge (feet, relative to NAVD88)

NOAA Station	MHHW	10-year		25-year		100-year	
		2040	2080	2040	2080	2040	2080
Seattle	9.0	12.4	13.3	12.6	13.5	12.9	13.8
Port Townsend	7.7	10.9	11.7	11.1	11.9	11.2	12.0

5.3 Inflows and Tides used in the Hydraulic Model

The following section summarizes the inflows and tides used in the hydraulic model. Peak inflows for the mean winter and 100-year events are reported in Table 5.6. Select inflow hydrographs for the Skagit River and major tributaries are included in Figure 5.3.

For riverine flood events, peak tidal stage is reported in Table 5.7. An example of tidal stage hydrographs used in the riverine flood event at the Skagit Bay (North) boundary condition is shown in Figure 5.1.

For coastal flood events, peak tidal stage is reported in Table 5.8. An example of tidal stage hydrographs used in the 100-year coastal flood event at the Skagit Bay (North) boundary condition is shown in Figure 5.2.

Table 5.6 Peak inflows used in the hydraulic model

Boundary Condition Location	Mean Winter Flow (cfs)	10-year (cfs)			25-year (cfs)			100-year (cfs)		
		Historic[1]	2040s	2080s	Historic[1]	2040s	2080s	Historic[1]	2040s	2080s
Regulated Marblemount	6,630	40,606	71,873	93,394	53,766	82,800	105,919	70,330	87,913	107,605
Cascade River	900	13,214	13,346	16,782	16,172	16,495	19,892	22,130	23,679	26,113
Local – Cascade to Sauk	0	7,959	8,039	10,108	9,663	9,856	11,885	13,330	14,263	15,729
Sauk River	4,560	70,992	93,000	112,877	95,632	118,584	141,535	121,523	137,321	160,410
Local – Sauk to Baker	0	5,487	6,475	6,859	6,661	7,793	8,260	9,188	10,658	11,209
Regulated Baker	2,970	23,851	25,998	29,814	27,990	29,669	34,708	34,279	35,307	42,506
Local – Baker to Sedro Woolley[2]	3,410	21,848	25,781	27,310	24,080	28,174	29,859	27,944	32,415	34,092
Nookachamps Creek	240	2,087	1,962	2,170	2,709	2,546	2,872	3,780	3,629	4,271
Samish River	480	2,782	3,088	3,394	3,612	4,009	4,407	5,040	5,594	6,199

Notes:

1. The term "historic" refers to flood model simulations using hydrology from the Skagit GI (USACE, 2014).
2. The distribution of local flows between Baker River and Sedro-Woolley are further described in Section 6.2.1.

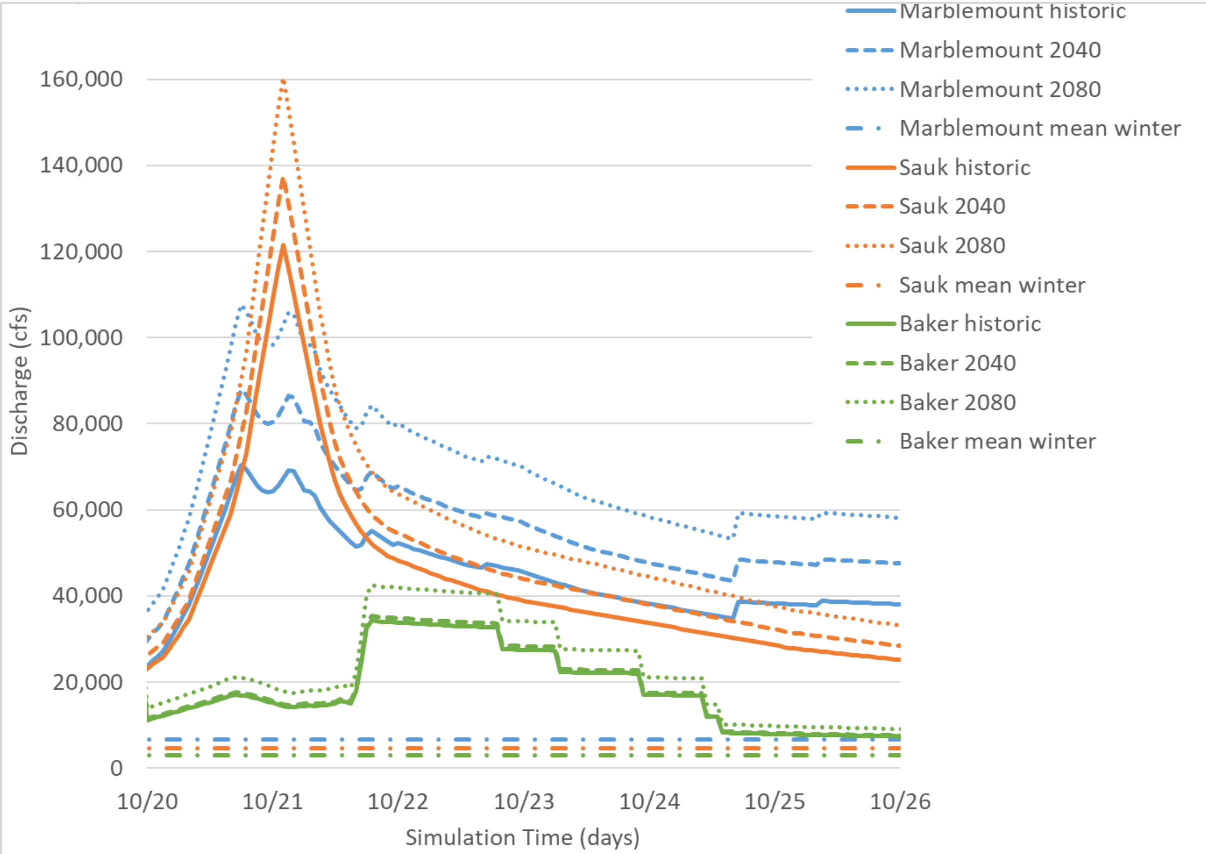


Figure 5.1 Select 100-year inflow hydrographs for historic and future conditions

Table 5.7 Peak tidal stage for riverine flood events (feet, relative to NAVD88)

Boundary Condition	MHHW	MHHW 2040s	MHHW 2080s
Skagit Bay (North)	8.9	9.4	10.2
Skagit Bay (South)	9.5	10.0	10.8
Samish Bay, Padilla Bay	7.7	8.2	9.0

Table 5.8 Peak tidal stage for coastal flood events (feet, relative to NAVD88)

Boundary Condition	10-year			25-year			100-year		
	Historic	2040s	2080s	Historic	2040s	2080s	Historic	2040s	2080s
Skagit Bay (North)	11.6	12.0	12.8	11.7	12.2	13.0	12.0	12.5	13.3
Skagit Bay (South)	12.5	13.0	13.9	12.7	13.2	14.1	13.0	13.5	14.4
Samish Bay, Padilla Bay	10.3	10.8	11.6	10.5	11.0	11.8	10.6	11.1	11.9

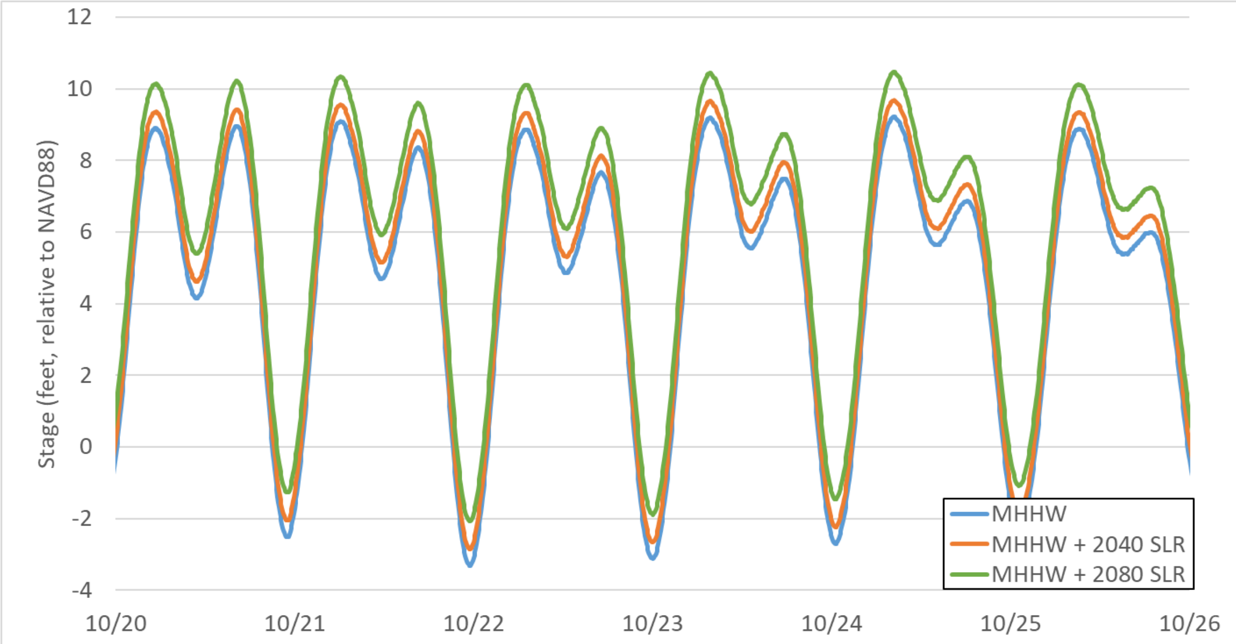


Figure 5.2 Riverine flood event: example of MHHW tidal stage hydrographs for historic and future conditions at the Skagit Bay (North) boundary condition

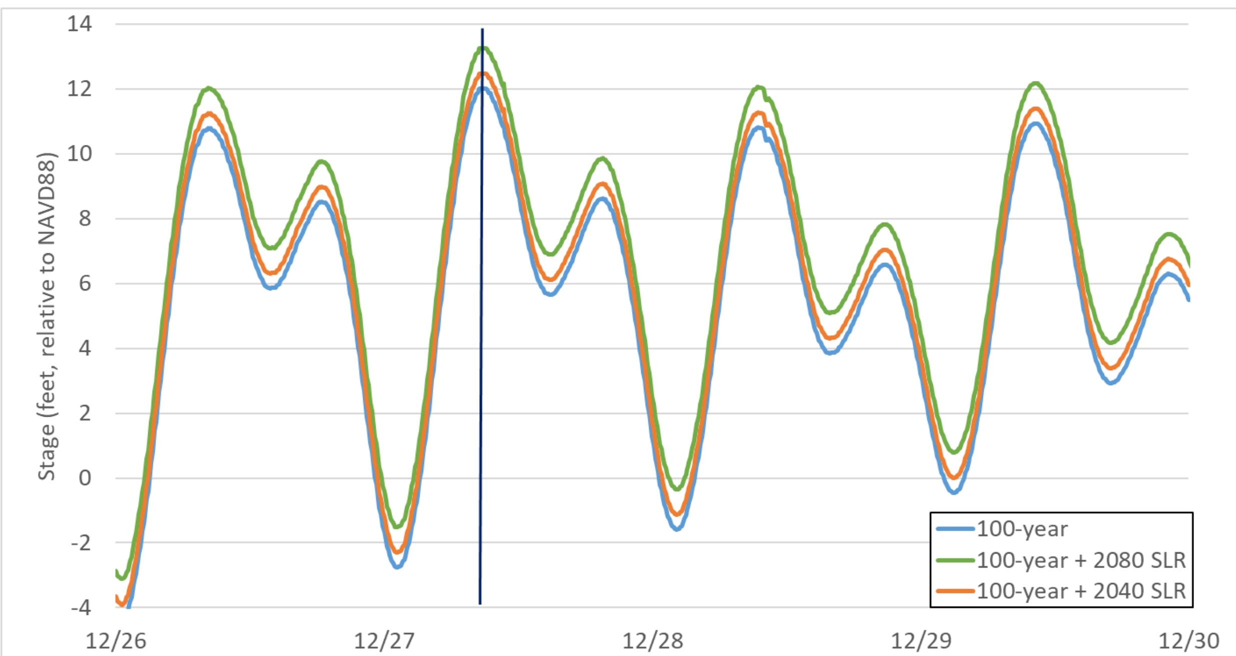


Figure 5.3 Coastal flood event: example of 100-year tidal stage hydrographs for historic and future conditions at the Skagit Bay (North) boundary condition, the vertical line indicates the actual 100-year peak tide

6 FLOOD MODEL DEVELOPMENT

The Project model was developed using 2D capabilities of the USACE's HEC-RAS modeling platform, version 6.6 (USACE, 2024). The 2D HEC-RAS solver computes flow using the full 2D shallow-water equations, allowing for simulation of complex flow patterns in both streamwise and lateral directions. The model is capable of simulating subcritical and supercritical unsteady flows through a full network of open channels and floodplains, including complex terrains with highly non-uniform flows. Development of the hydraulic model components for computer simulations are described in the following sections.

6.1 Model Geometry

The primary components required to develop the 2D model geometry include topobathymetric data, a 2D mesh, infrastructure elements (bridges, culverts, and dikes), and land cover. The following sections describe the collection and preparation of this information.

6.1.1 Topobathymetric Data

NHC compiled the latest available data sources to develop a comprehensive topobathymetric surface for use in the hydraulic model. The data sources used, including limits, are shown in Figure 6.1. In general, bathymetry was developed from boat-based surveys from 2012 to 2024, supplemented with 2022 topobathymetric (green) LiDAR, depicted by the orange areas in Figure 6.1. A more detailed discussion of the data sources and methods used to develop the terrain is in the appended Topobathymetric Mosaic Development Memorandum. In the Project model, some terrain modifications were necessary to correct LiDAR data, including discontinuities along coastal dikes and key drainage segments; these types of corrections are common in LiDAR datasets.

Compared to previously developed models, bathymetry used in the new Project model has been significantly updated. For example, both the current CWMS (USACE, 2022) and Skagit GI (USACE, 2014) models use bathymetry from 1991 downstream of Sedro-Woolley and bathymetry from the 1977 FEMA Flood Insurance Study upstream of Sedro-Woolley. While the CWMS model uses LiDAR sources from 2017 and 2019 in the floodplain areas, the new Project model incorporates more recent LiDAR from 2022 in areas upstream of Sedro-Woolley. Overall, the new Project model will provide a much more accurate representation of current in-channel and floodplain elevations throughout the domain.

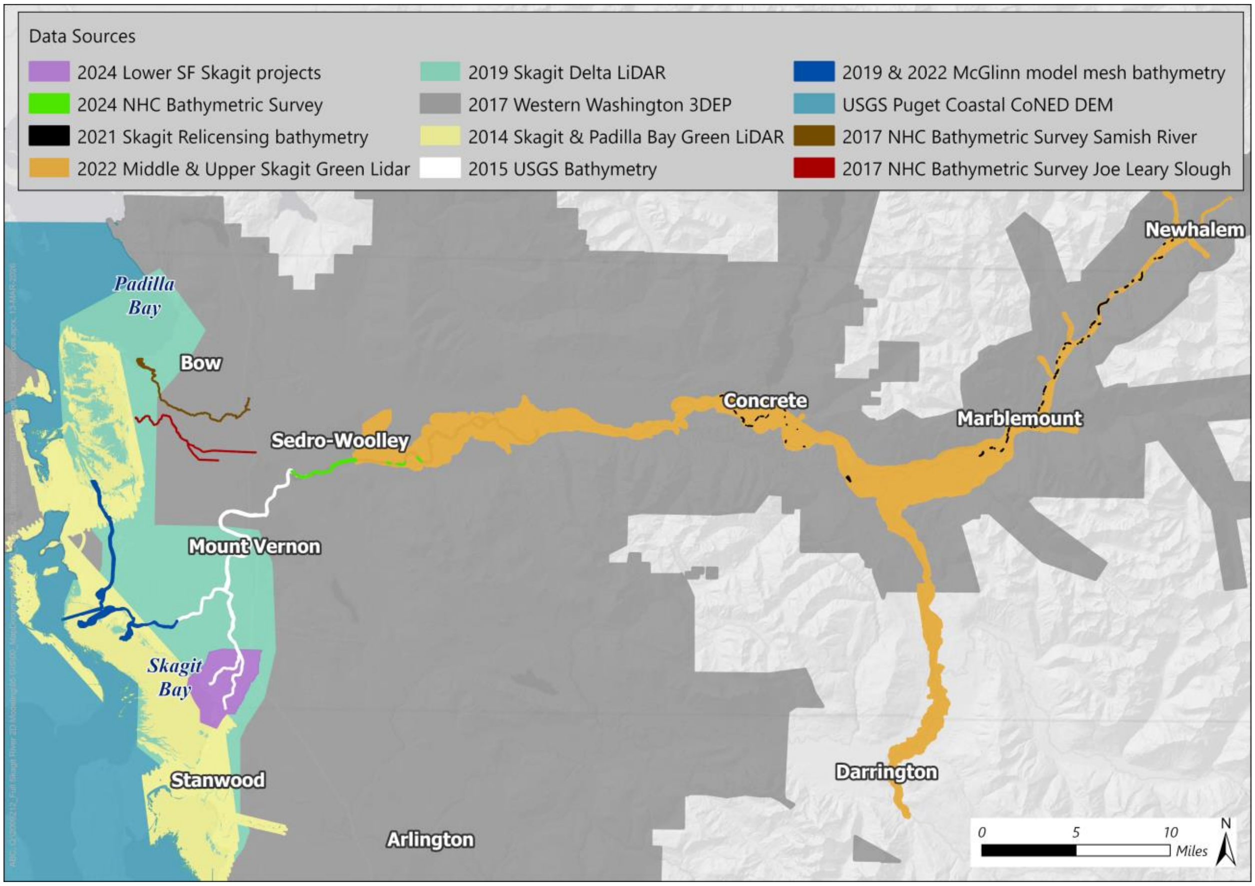


Figure 6.1 Data sources used to develop the topobathymetric surface

6.1.2 Model Domain and Mesh

The 2D model domain includes approximately 85 miles of the Skagit River, from the Puget Sound to the USGS gage above Diobsud Creek near Marblemount, with limits shown in Figure 6.2. The domain includes the Samish River in addition to short reaches of major tributaries to the Skagit, including Baker, Cascade, and Sauk rivers, and Nookachamps Creek. The downstream boundary extends into Skagit, Samish, and Padilla bays to allow for modeling of a full tidal range.

The 2D computational mesh was sized to allow for accurate routing of normal and flood flows while maintaining manageable model run times. The model mesh is comprised of approximately 240,000 cells. Figure 6.3 shows an example of typical cell spacing and breakline definition near the Skagit River mainstem. Within the main channel of the Skagit River and major tributaries, cell size is generally 100 feet. Along the Samish River, the main channel cell size is generally 50 feet. Within the floodplain areas, cell spacing increases to up to 400 feet. Breaklines were added along prominent topographic features to provide refinement and definition to terrain elements such as high points and raised roadways. NHC also applied breaklines to orient main channel cell faces perpendicular to the direction of flow. Floodplain swales, ponds, ditches and waterbodies were represented as captured by the terrain, described in Section 6.1.1, without manual terrain modifications.

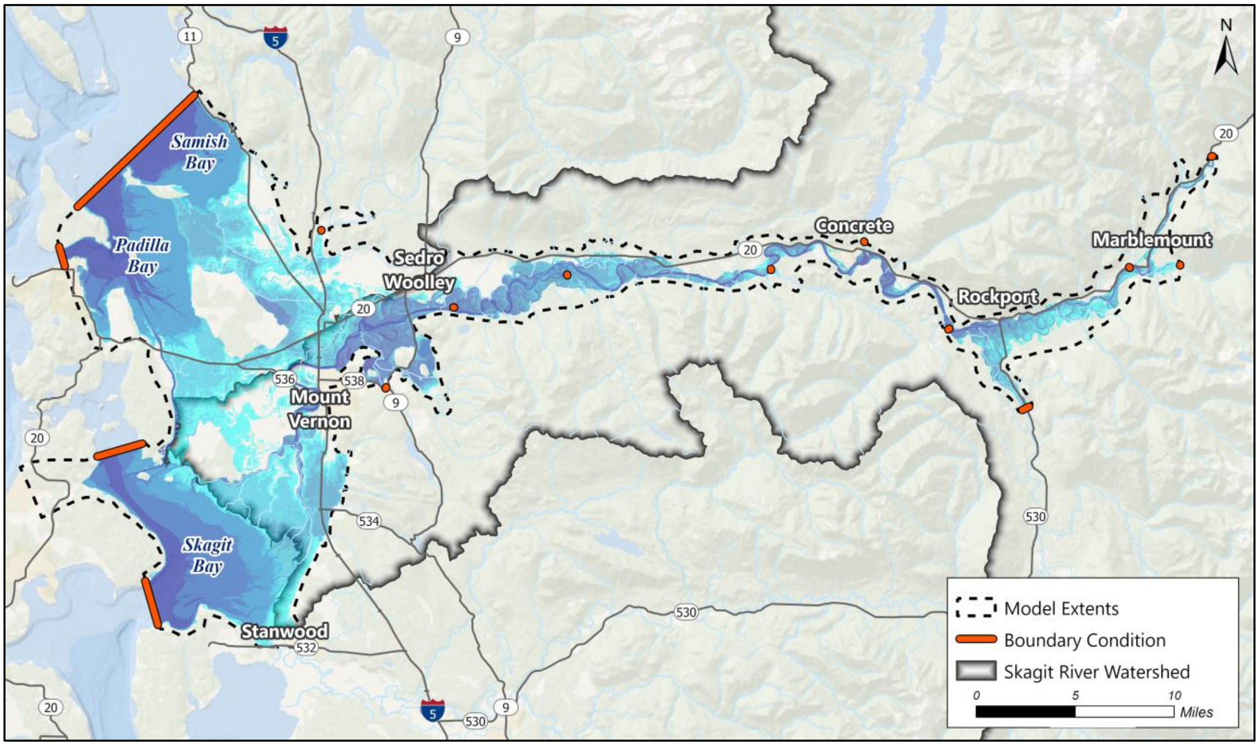


Figure 6.2 Model domain and boundary condition locations

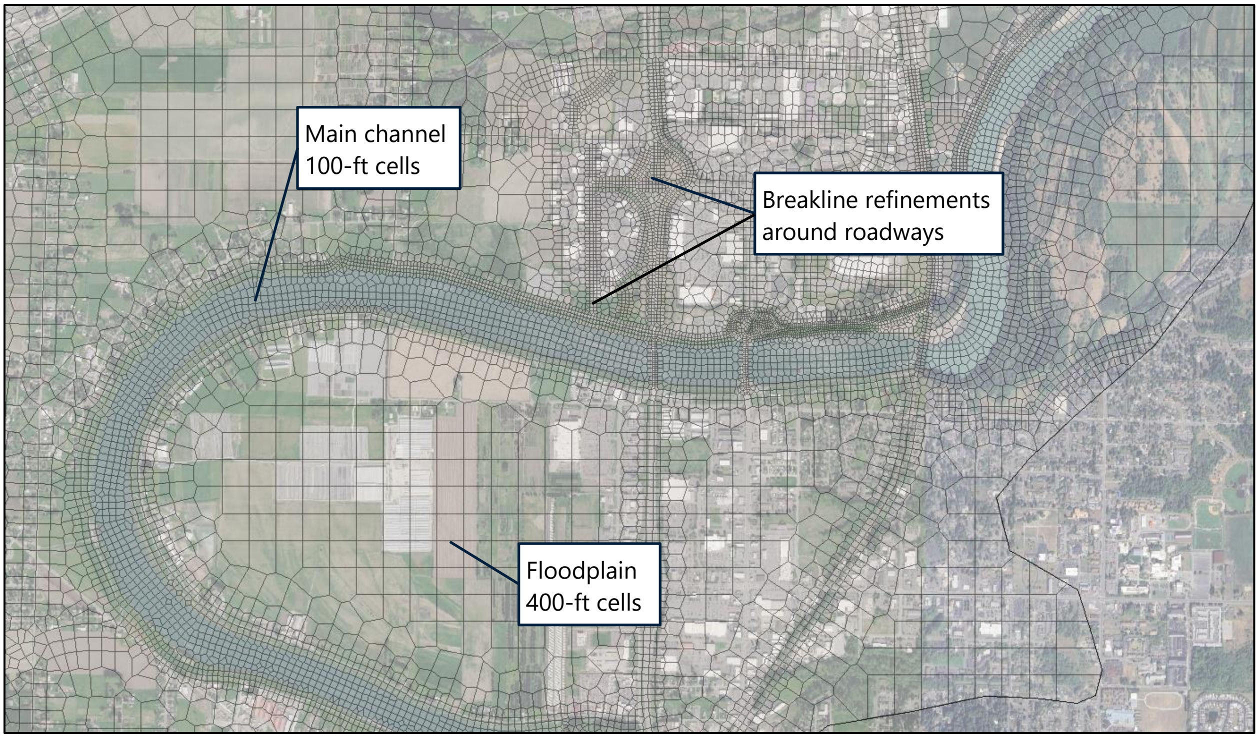


Figure 6.3 Example of 2D model mesh showing typical cell sizes

6.1.3 Hydraulic Structures

Structure representation in the model is limited to main channel bridges, significant relief bridges, dikes, culverts, and tide gates generally downstream of Burlington. The best-available structure data were obtained from prior models, described in Section 2, and used in the new Project model as described in this section. An overview of hydraulic structures applied in the model is shown in Figure 6.4. As part of the Project, NHC did not receive new infrastructure datasets from WSDOT or local governments. In addition, no drainage infrastructure was available or modeled along Gages Slough near Burlington.

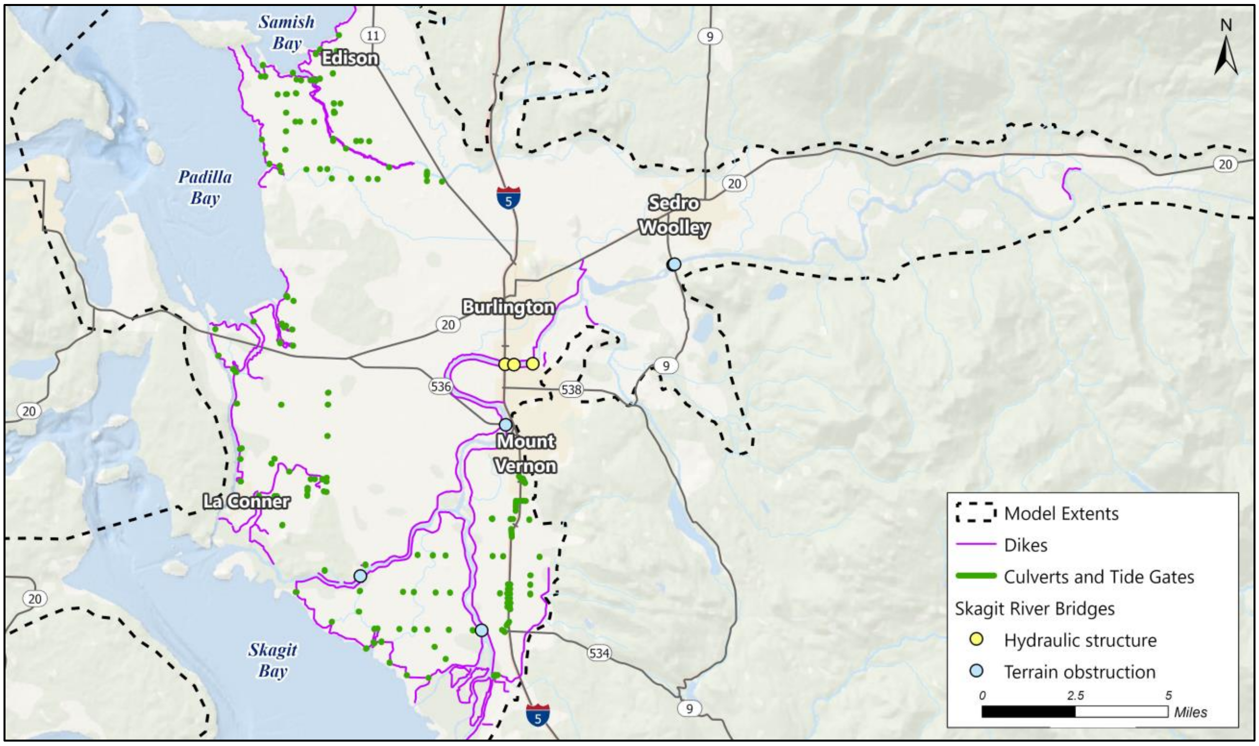


Figure 6.4 Overview of hydraulic structures applied in the Project model

Culverts and tide gates were coded into the Project model based on available data from prior models. Available culvert data were limited to structures greater than 24-inch diameter or span in areas downstream of Burlington, as shown by the green lines in Figure 6.4. Culvert data were primarily obtained from the Skagit Delta model (NHC, 2023) and supplemented with data from the CWMS model (USACE, 2022) and the Maddox Big Ditch project (NHC, 2020), as described in Section 2. The Skagit Delta model was used as the primary source as the study included the most recent inventory of existing drainage features. The structure inventory included a limited field survey; however, in areas where no survey data were available, invert elevations were assumed to match terrain values. The culverts were coded into the model as hydraulic structures, with input data including inlet configuration, pipe length, and invert elevations. Tide gates were modeled as culverts with flap gates (set to no positive flow flaps) preventing saltwater inflow to the interior areas during high tide.

NHC assessed the representation of bridges within the 2D model domain. Data for the bridge geometries were obtained from the CWMS model (USACE, 2022), which simulated bridges in a 1D reach. Two approaches were used to represent bridges within the Project model domain. In the first approach, bridge low chords that are above the maximum simulated discharge (2080 100-year) were modeled using terrain modifications to represent piers and abutments. In the second approach, where bridge decks were anticipated to be in contact with floods (pressurized flow condition), bridges were coded as hydraulic structures with dimensions as defined in the

CWMS model geometry. A summary of the bridges included in the model domain is included in Table 6.1. No debris blockage was modeled at the bridge structures for this project.

Similar to the CWMS model, the bridges at Highway 530 (RM 67.8) and Cascade River Road (RM 78.2) are not included in the model domain, though these features could be added in the future. Based on the calibration results in Section 6.4.2, HWMs near both of these bridge crossings are considered a good match.

Table 6.1 Summary of bridges represented in the model domain

Bridge Name	River	RM	Modeling Method
Best Road	North Fork	4.1	Terrain obstruction
Fir Island Road	South Fork	4.5	Terrain obstruction
Division Street (SR 536)	Skagit	11.5	Terrain obstruction
I-5	Skagit	15.6	Hydraulic structure
S Burlington Blvd	Skagit	15.9	Hydraulic structure
BNSF Railway	Skagit	16.3	Hydraulic structure
Highway 9	Skagit	22.5	Terrain obstruction
Great Northern Railway	Skagit	22.6	Terrain obstruction
Concrete Sauk Valley	Skagit	54.2	Hydraulic structure

Dikes and coastal dikes were coded into the model as hydraulic structures. The types of facilities were divided into segments to allow more discretization in parameters and calculation methods. Discretization of the dike segments within the model will allow for dike failure scenarios to be performed with more flexibility in future applications. Dikes were modeled using the 2D flow equations to maintain model stability. Crest elevations were applied from LiDAR based on the topobathymetric surface described in Section 6.1.1, with exception to the Mount Vernon Flood Wall, which used elevations from the CWMS model (USACE, 2022).

6.1.4 Land Cover and Roughness

Land cover for the floodplain was assigned based on NLCD 2021 data (USGS, 2025) and classified into 13 categories as shown in Table 6.2. Roughness values for each land cover type were determined by literature review and consideration of the calibrated CWMS model (USACE, 2022) and City Light model (2023). Floodplain roughness values were then refined through the model calibration process.

River and major tributaries were delineated separately using NAIP aerial imagery (USDA, 2023) and LiDAR data to define the main channel limits. The Skagit River mainstem values were split into discrete reaches during the calibration process. Main channel roughness values were initially assigned based on review of previously developed models and then refined through the calibration process. Section 6.4 includes a detailed discussion on the calibration processes. The Samish River values were applied from the Skagit Delta model (NHC, 2023), calibrated to the February 2018 flood event. The final calibrated roughness values for main channel reaches are reported in Table 6.3.

In the future conditions scenarios, no consideration was given for land use changes that could impact flows such as development related to forest conversion or impervious surface increases.

Table 6.2 Final floodplain land cover areas and roughness values

Land Cover	Final Manning's Roughness Coefficients
Open water	0.0275
Developed, open space	0.03
Developed, low intensity	0.05
Developed, medium intensity	0.055
Developed, high intensity	0.06
Barren land	0.03
Forest (deciduous, evergreen, mixed)	0.1[1]
Shrub-scrub	0.05
Herbaceous	0.055
Pasture-hay	0.05
Cultivated crops	0.055
Woody wetlands	0.08
Emergent herbaceous wetlands	0.07

Notes:
1. Roughness values for the forest zones were refined through the calibration process.

Table 6.3 Final main channel reaches and calibrated roughness values

Reach[1]	RM	Final Manning's Roughness Coefficients
North Fork Skagit River	1-7	0.022
South Fork Skagit River	1-8	0.022
Skagit River from Forks to Burlington	8-17	0.026
Skagit River from Burlington to Hamilton	17-42	0.034-0.036
Skagit River from Hamilton to Rockport	42-66	0.02-0.024
Skagit River from Rockport to Marblemount	66-79	0.032

Reach[1]	RM	Final Manning's Roughness Coefficients
Skagit River upstream of Marblemount	79-86	0.02
Skagit River major tributaries (Nookachamps, Baker, Sauk, and Cascade)[2]	N/A	0.03
Samish River[3]	N/A	0.025-0.06

Notes:
1. Roughness coefficients for all reaches were calibrated unless noted in this table.
2. Roughness coefficients for the Skagit River major tributaries were not calibrated as part of the project.
3. Calibrated roughness coefficients for the Samish River were applied from the Skagit Delta model (NHC, 2023).

6.2 Boundary Conditions

Boundary conditions used in the Project model consist of the primary Skagit River inflows, major tributary inflows, Samish River inflows, and four downstream stage boundaries. Locations of the boundary conditions are shown in Figure 6.5. Boundary condition inputs were developed for two flood hazard types: riverine and coastal flooding. This section summarizes the hydrologic and tidal inputs applied to the hydraulic model for these two hazard types, while Section 5 details development of the inputs.

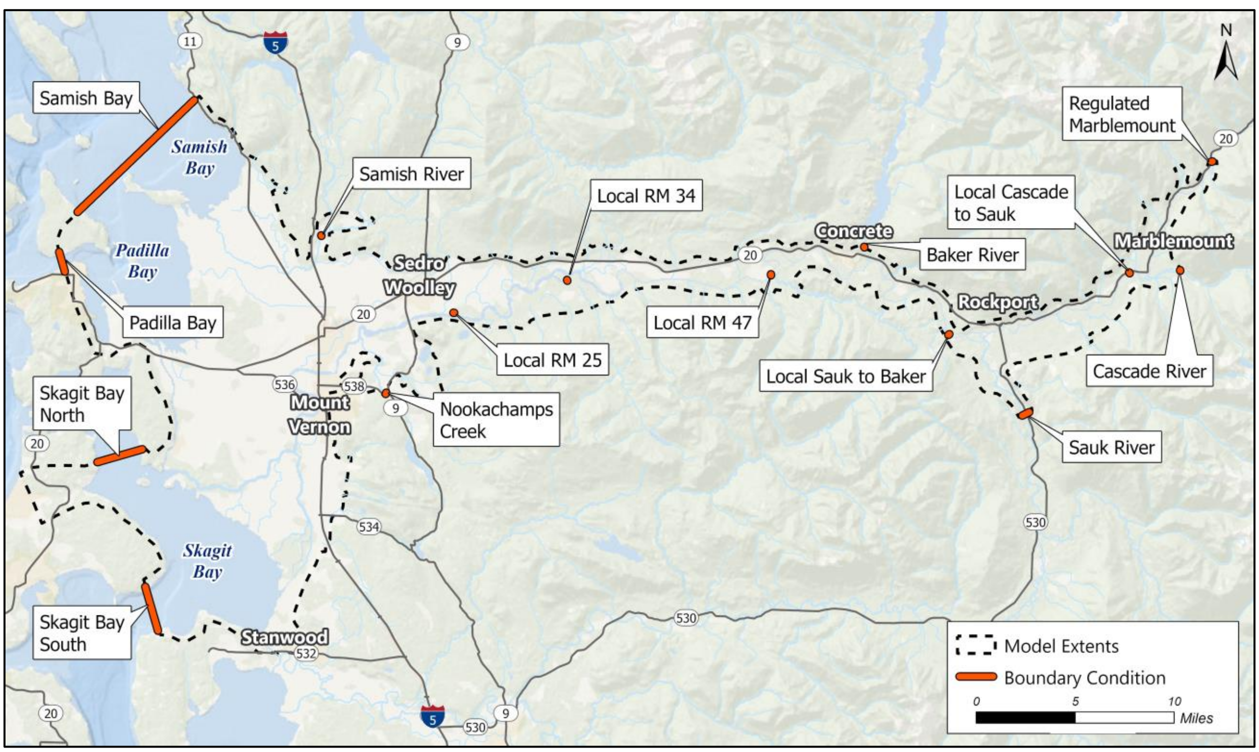


Figure 6.5 Boundary condition locations

6.2.1 Riverine

In historic conditions scenarios, riverine inflows for the 10-year, 25-year, and 100-year flood events were applied using hydrographs from the Skagit GI (USACE, 2014), with peak flows shown in Table 5.6 in Section 5.3. The Skagit GI grouped local inflows from Baker to Sedro-Woolley into a single hydrograph which was distributed evenly along 1D sections in that reach. Because HEC-RAS 2D cannot evenly distribute inflows along a reach the same way as a 1D model, these local inflows were instead applied at three locations in Figure 6.5, labeled “Local RM 25,” “Local RM 34,” and “Local RM 47.” Scaling factors were applied to the Skagit GI hydrographs based on the proportional basin area at each local inflow location. For riverine flood events, tidal boundary conditions are defined as stage hydrographs with high tides near the MHHW stage, as reported in Table 5.7.

In future conditions scenarios, hydrologic inputs were modified by applying climate projection multipliers to the inputs, with peak flows listed in Table 5.6. The downstream tidal boundaries were shifted to account for sea level rise, with peak tidal stage listed in Table 5.8.

6.2.2 Coastal

In historic conditions scenarios, coastal flood boundary conditions were developed for the 10-year, 25-year, and 100-year coastal storm tides, coupled with average winter inflows.

In future conditions scenarios, tidal stage hydrographs representing the MHHW stage were shifted to account for both sea level rise and storm surge. Average winter inflows remained unchanged from the historic conditions scenarios.

6.3 Run Control Parameters

Model computation parameters were selected from a series of preliminary test runs to accurately simulate flood-scale hydraulics in the 2D domain while producing reasonable run times. The full momentum equations set (Shallow Water Equations with a Eulerian-Lagrangian Method, or SWE-ELM) were used with no turbulence model applied. The computational time step was set to a fixed time step of five seconds. Default Theta, tolerances, and solver iteration options were specified for all simulations.

A restart file was used to establish initial conditions at mean winter flows at the beginning of all simulations. The riverine flood events were generally run for an eight-day simulation period to span the inflow hydrographs and routing through the system. To evaluate riverine flood duration for the 100-year event, a separate run was developed with a one-month simulation period to capture interior drainage post peak. The coastal flood events were run for a four-day simulation to span the tidal events.

6.4 Calibration and Validation

The hydraulic model calibration and validation were performed for four significant flood events over the past three decades, as summarized in Table 6.4. Model calibration primarily focused on the November 2021 flood, which best represents the most current channel characteristics. Secondary consideration was given to the October 2003 flood, which was the only dataset that included observed data downstream of I-5, along the North Fork and South Fork. In December 2025, after model development phase was completed for the Project, historic flooding occurred within Skagit County, resulting in the stage of record at Mount Vernon (USGS 12200500) and a stage just below the 1995 event at Concrete (USGS 12194000), as shown in Table 6.4. As a result, the 2025 event was primarily used to validate the model calibration, and the 1995 event was used for secondary validation. While the flood in November 2006 was also a large event, it was not used in this Project because the peaks were slightly lower than 1995 and HWMs collected from this event were mainly limited to the reach between Mount Vernon and Sedro-Woolley.

The goal of model calibration was to replicate the hydrograph shape, peak stage, and peak discharge at the Mount Vernon gage (USGS 12200500), while matching peak stage at other USGS gages within 0.5 feet. In addition, the calibration focused on matching a widespread set of high-water marks (HWMs) within one foot. Matching USGS peak stage within 0.5 feet and HWMs within one foot is considered good for calibration performance, given measurement uncertainty. To achieve this, the Skagit River mainstem was divided into longitudinal reaches and roughness values were assigned to each reach to best match observed data. The 2025 and 1995 events were then used to validate the model's calibration, with focus placed on the more recent 2025 event. Data available for model calibration and validation generally includes USGS gages and HWM datasets collected by various sources. The final calibrated roughness values and longitudinal reaches are shown in Table 6.3 in Section 6.1.4. Model calibration and validation assume no bridge debris.

Table 6.4 Reported USGS gage peak stage and discharge for events used in model calibration and validation

Flood Event	Type	Concrete Gage		Mount Vernon Gage	
		Stage (ft, gage datum)	Peak Flow (cfs)	Stage (ft, gage datum)	Peak Flow (cfs)
November 2021	Calibration	38.93	134,000	36.99	127,000
October 2003[2]	Calibration	42.21	166,000	36.19	135,000
December 2025[3,4]	Validation[4]	41.13[4]	152,000[4]	37.73[4]	133,000[4]
November 1995	Validation	41.57	160,000	37.34	141,000

Notes:
1. Highlighted rows indicate the focus of model calibration and validation.
2. The 2025 and 2003 floods were the only events where HWMs were collected downstream of I-5, along the North Fork and South Fork.

3. The December 2025 flood occurred after the model development phase was completed for the Project. As a result, the model was not calibrated to this event but was used for model validation to evaluate the model performance to a more recent event.
4. Provisional data subject to revision by USGS.

6.4.1 Model Input

The calibration and validation runs required the development of event-specific boundary conditions. For all modeled events, the downstream boundary conditions were applied as tidal stage hydrographs using observed NOAA tidal statistics at stations described in Section 5.1.2. In three of the four runs described below the model was truncated at the USGS Concrete gage. The purpose is doing this was to significantly reduce uncertainty in lower river flows due to cumulative routing errors building up. Combined with tributary scaling, this allowed accurate routing of flows to the delta, as measured by comparing with observed flow at the USGS Mount Vernon gage (USGS 12200500). With more accurate flows there was greater confidence in calibrating roughness values to match observed HWMs and stage at gages. Inflow boundary conditions and model domain limits for the model calibration and validation runs varied by event and available data, as summarized below:

- For the 2021 event, the full model domain was used and USGS gaged flows were applied as inflows on the Skagit River, Samish River and major tributaries to the Skagit, as available. Local inflows (Cascade to Sauk, Sauk to Baker, and Baker to Sedro-Woolley, and Nookachamps) were applied by combining basins from the CWMS HEC-HMS model (USACE, 2022). Scaling factors were then applied to the local inflow hydrographs to best match the observed discharge and stage hydrographs at Mount Vernon (USGS 12200500).
- For the 2003 and 1995 events, the upstream limit of the model domain was truncated at Concrete (USGS 12194000) to match the extents in the Skagit GI (USACE, 2014). Local inflows along the Skagit River were applied from the Skagit GI. USGS gaged flows were applied as inflows on the Skagit River at Concrete and the Samish River. However, the Samish River USGS gage was not online during the 1995 event and was therefore not included in the 1995 validation run.
- For the 2025 event, the upstream limit of the model domain was truncated at Concrete (USGS 12194000) as the validation effort focused on where HWMs were collected, downstream of Sedro-Woolley. Local inflows from Baker River to Sedro-Woolley were applied using the 2003 hydrograph from the Skagit GI and then adjusted using scaling factors to best match the observed discharge at Mount Vernon (USGS 12200500). Local inflows for Nookachamps Creek were applied using the Washington State Department of Ecology (ECY) gage (03G100) located along East Fork Nookachamps Creek at Beaver Lake Road. The ECY gage was then scaled to the mouth of Nookachamps Creek based on regression estimates.

6.4.2 Calibration: November 2021 Event

Calibration data available from the November 2021 event includes USGS gages, surveyed HWMs, and SRSC gage peak stages, with the number of observations summarized in Table 6.5. The calibration data span Mount Vernon to Marblemount, with no data available downstream of I-5.

The simulated WSEs were evaluated longitudinally along the Skagit River mainstem. Figure 6.6 depicts the difference in simulated minus observed WSEs for HWMs and USGS gages for the 2021 event, as shown by orange and green points. Additionally, summary statistics for the errors are summarized in Table 6.5 and Figure 6.7 presents the distribution. Refer to the appended tables for a comparison of all observed points and simulated WSEs. In addition, Figure 6.8 shows a comparison of time series results at the Mount Vernon gage.

Simulated WSEs at the USGS gages generally indicate a good match with less than a 0.5-foot difference, except at Sedro-Woolley and Rockport gages. The model shows no systematic bias with mean errors near zero and no large outliers, as shown in the mean absolute error (MAE) of 0.4 feet and standard deviation of 0.5 feet. As shown in Figure 6.8, there is a very good match at the Mount Vernon gage, within 0.3 feet of stage and 0.1 percent discharge. At the Mount Vernon gage, the simulated peak discharge occurs about 3 hours before the observed peak, as shown in Figure 6.8. At the Concrete gage, shown in Figure 6.9, there is a good match of about 0.5 feet, but the model does tend to oversimulate stage and discharge slightly. However, the timing of the simulated peak discharge matches.

HWMs along the mainstem show mean error near zero and MAE of 0.6 feet indicating a good match. The distribution in Figure 6.7 shows that the model tends to oversimulate WSEs by about 0.5 feet. HWMs in the floodplain tend to show a broader distribution, with floodplain HWMs and SRSC gages having MAEs of 0.9 feet.

Table 6.5 Summary of error statistics for the November 2021 calibration event

Dataset	No. of Points	Mean Error (ft)	Mean Absolute Error (ft)	Standard Deviation (ft)	Max Error (ft)	Min Error (ft)
USGS gages (mainstem)	8	-0.2	0.4	0.5	0.5	-1.0
HWMs (mainstem)	35	0.2	0.6	0.8	2.4	-2.0
HWMs (floodplain)	34	0.3	0.9	1.1	3.0	-1.8
SRSC loggers (floodplain)	9	-0.0	0.9	1.0	1.5	-1.6

Notes:
1. See the appended tables for a detailed comparison of all observed points and simulated WSEs.

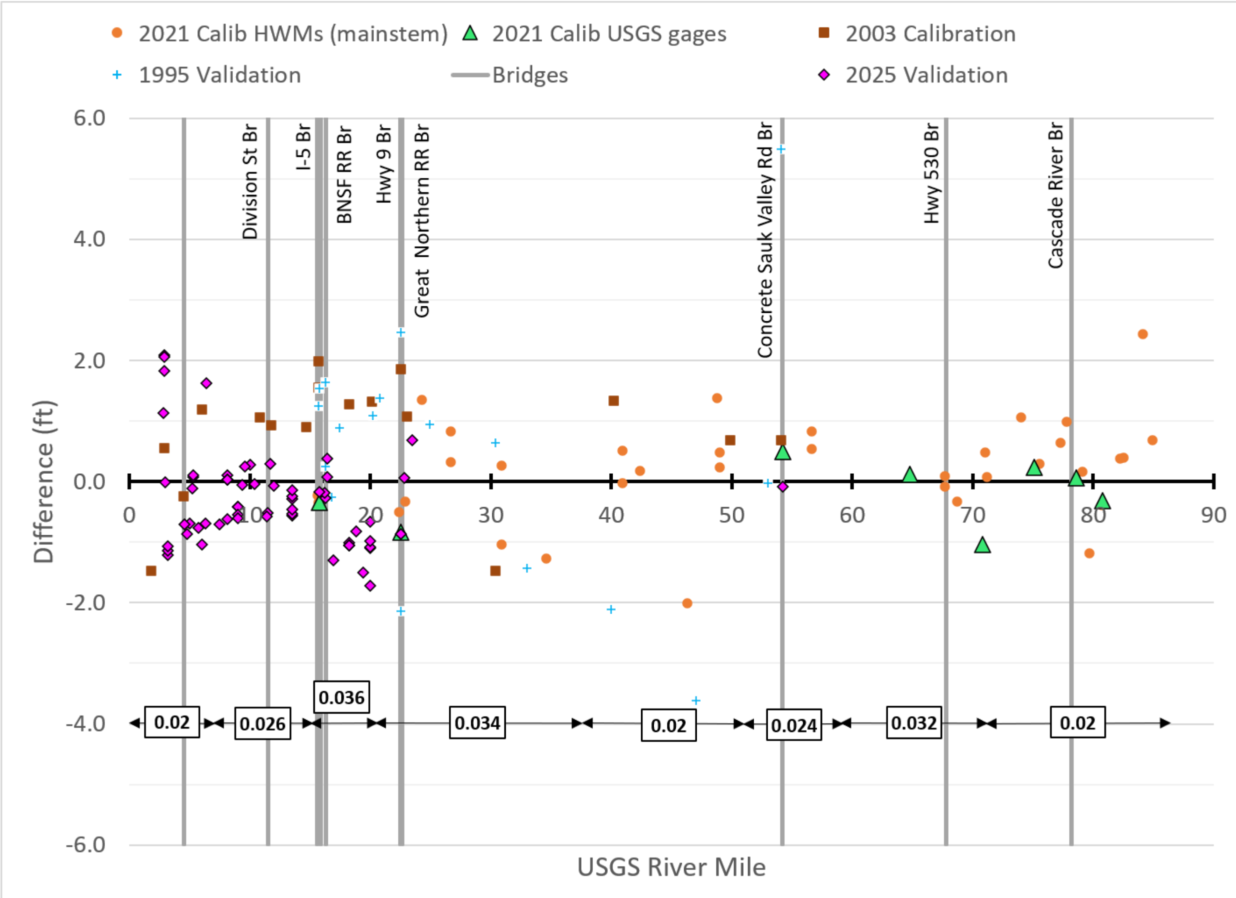
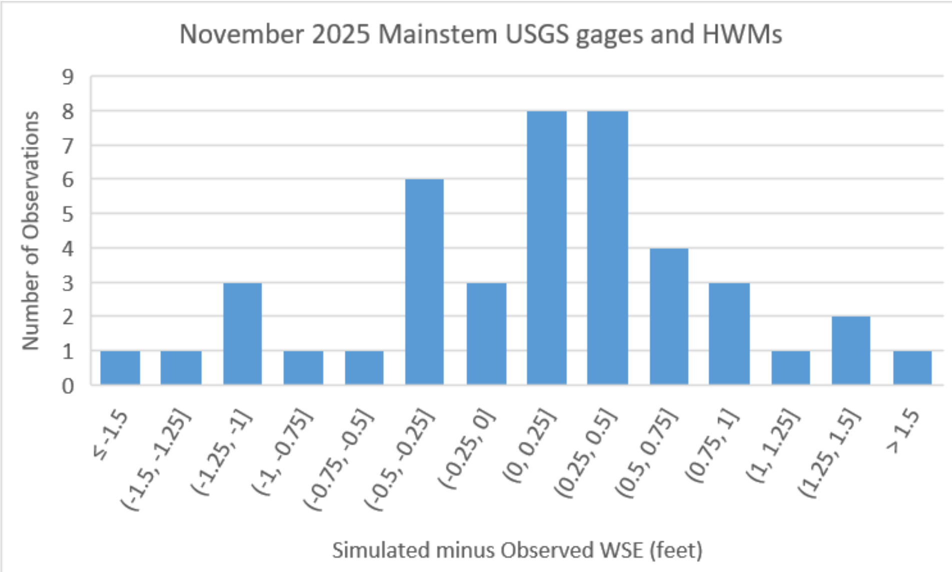


Figure 6.6 Difference in simulated minus observed WSEs along the Skagit River mainstem for all events



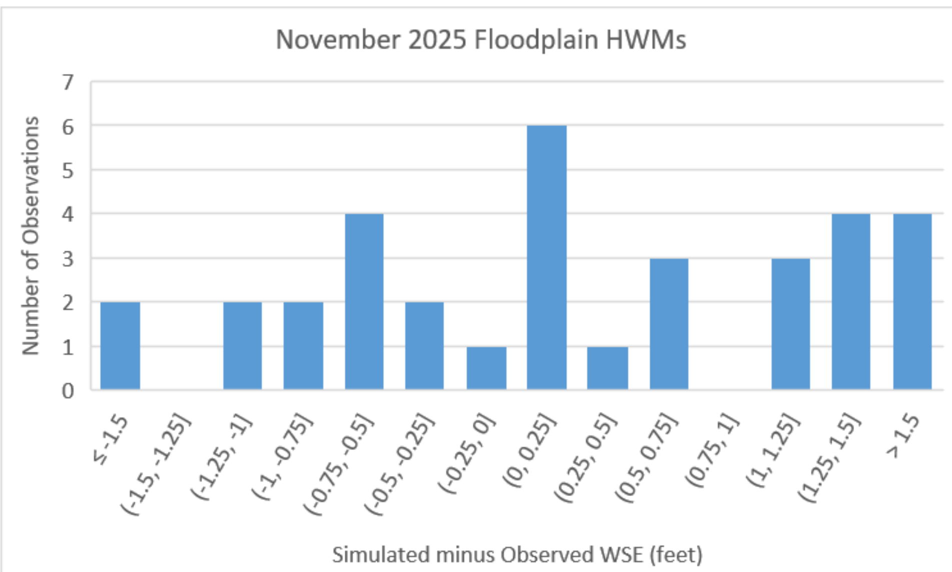


Figure 6.7 November 2021 peak WSE residual distribution for mainstem HWMs and USGS gages (top) and floodplain HWMs (bottom)

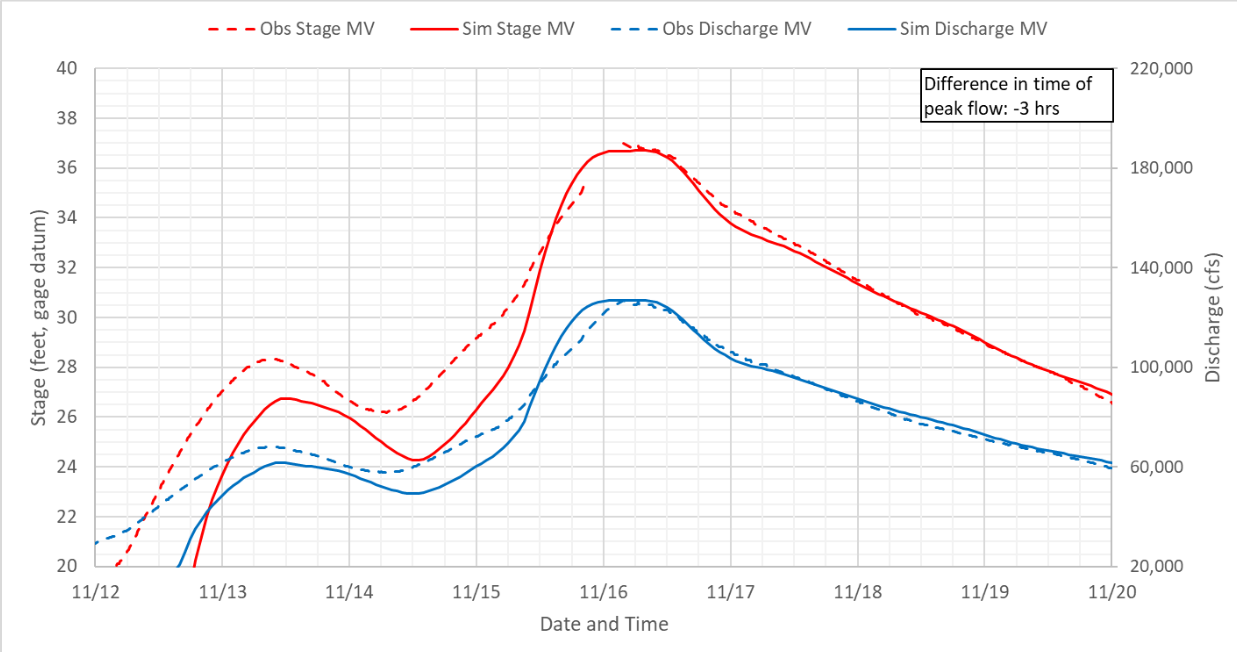


Figure 6.8 Comparison of simulated and observed stage and discharge at Mount Vernon USGS gage for the 2021 event

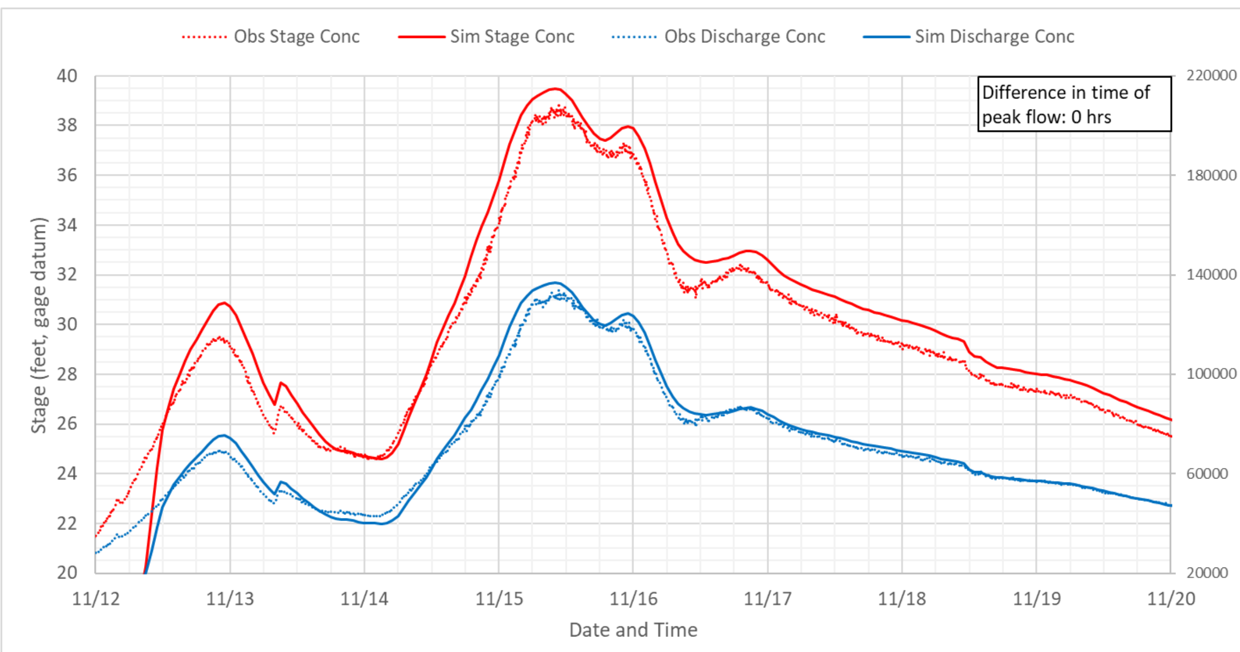


Figure 6.9 Comparison of simulated and observed stage and discharge at Concrete USGS gage for the 2021 event

6.4.3 Calibration: October 2003 Event

Calibration data available from the October 2003 event includes USGS gages and surveyed HWMs from the Skagit GI (USACE, 2014) from Skagit Bay to Concrete. The 2003 event was the only calibration dataset that included HWMs downstream of I-5, along the North Fork and South Fork. However, in 2014, a large avulsion formed on the North Fork which is represented in the Project model. The avulsion has significantly grown since that time, changing bathymetry and hydraulics through the reach, so consideration should be taken when comparing 2003 observed data with simulated results.

Along the profile in Figure 6.6, the 2003 simulated WSEs are consistently higher, by about one foot, as compared with observed data. This is also apparent in the error statistics, with a mean error of 0.8 feet, per Table 6.6. The calibration oversimulation generally implies a loss of channel capacity or conveyance between 2003 and 2015 (the date of the delta main channel bathymetric survey). The calibration process attempted to better match HWMs downstream of I-5, by selecting a lower Manning's roughness coefficient of 0.02 along both the North Fork and South Fork, per Table 6.3 in Section 6.1.4. However, there wasn't justification to lower it further based on observed bed conditions and to best match the 2021 observed stage at the Mount Vernon gage. For the 2003 event, the model oversimulates WSE at the Mount Vernon gage by 1.7 feet, as shown in Figure 6.10. Due to a gage failure during the flood, no timing comparisons are possible. Where there was both 2003 and 2021 observed data, the 2021 flood was given more weight in calibration due to recency, closer time to the main channel survey date, and higher number of HWMs.

Table 6.6 Summary of error statistics for the October 2003 event

Dataset	No. of Points	Mean Error (ft)	Mean Absolute Error (ft)	Standard Deviation (ft)	Max Error (ft)	Min Error (ft)
HWMs and USGS gages	17	0.8	1.2	1.0	2.0	-1.5

Notes:
1. See the appended tables for a detailed comparison of all observed points and simulated WSEs.

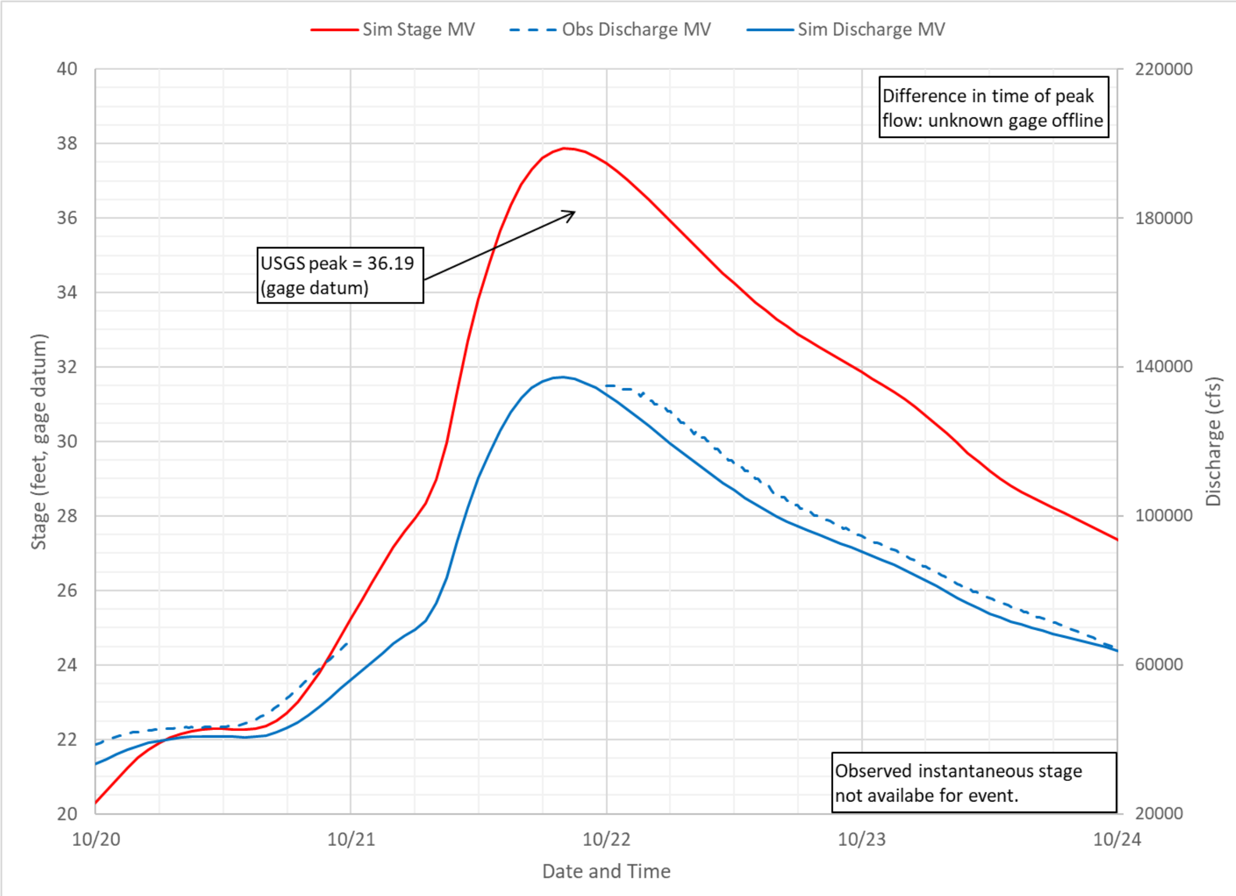


Figure 6.10 Comparison of simulated and observed stage and discharge at Mount Vernon USGS gage for the 2003 event

6.4.4 Validation: December 2025 Event

Observed data available for the December 2025 event includes USGS gages, NHC loggers, and surveyed HWMs, as summarized in Table 6.7. Prior to the event, NHC installed three level-loggers along the North Fork and South Forks to measure stage during the event. During the flood, Skagit Drainage and Irrigation Districts Consortium (DIDC) and NHC staff were deployed to stake and collect HWMs along the Skagit River between Sedro-Woolley and Skagit Bay. NHC met with DIDC staff to gather information and survey HWMs. The HWMs included debris lines, seed lines, and mud lines. Each HWM was evaluated for how precisely it defined the peak stage using the USGS high-water mark uncertainty rating for comparison to the simulated water surface profiles during validation. In addition, NHC reviewed photos and videos from several sources to collect additional HWMs. Refer to the appended tables for all observed data obtained.

As previously mentioned, the 2025 flood occurred after model development phase was completed for the Project. Therefore, the 2025 data were only used to validate the model and to provide insight into future calibration efforts. This Project does not include calibration to the 2025 event.

Along the profile in Figure 6.6, the 2025 simulated WSEs are generally near zero or lower, indicating a trend to generally match or undersimulate WSEs. This is also apparent in the distribution in Figure 6.12 and error statistics in Table 6.7, with a mean error of -0.3 feet and MAE of 0.6 feet. At the Mount Vernon gage, simulated stage and discharge show a very good match with stage within 0.2 feet and discharge within one percent, as shown in Figure 6.13. Similar to the 2021 event, the timing at the gage occurs about 3 hours early. Based on detailed results in the appended table, the undersimulation is most apparent in the Nookachamps area, where WSEs are typically one foot below observations. This could indicate BNSF bridge debris having an impact on simulated WSEs; though further investigation would need to be done to confirm.

Figure 6.11 depicts WSE differences along the North Fork and South Fork, to provide additional detail from the profile plot which superimposes data. Along the South Fork, the model consistently undersimulates WSEs similar to the reach upstream of the split. However, along the lower North Fork, the model oversimulates WSEs by generally one to two feet near Fish Town. The oversimulation in this area could be attributed to poor quality bathymetric survey at Blakes Marina, as described in the appended Topobathymetric Mosaic Development Memorandum. The model also shows very high velocities here, which could indicate that significant scour occurs during floods not captured in the fixed bed model.

Table 6.7 Summary of error statistics for the December 2025 event

Dataset	No. of Points	Mean Error (ft)	Mean Absolute Error (ft)	Standard Deviation (ft)	Max Error (ft)	Min Error (ft)
USGS gages & NHC loggers	6	-0.2	0.6	0.7	1.1	-1.0
HWMs	55	-0.3	0.6	0.8	-1.7	2.1

Notes:

1. See the appended tables for a detailed comparison of all observed points and simulated WSEs.

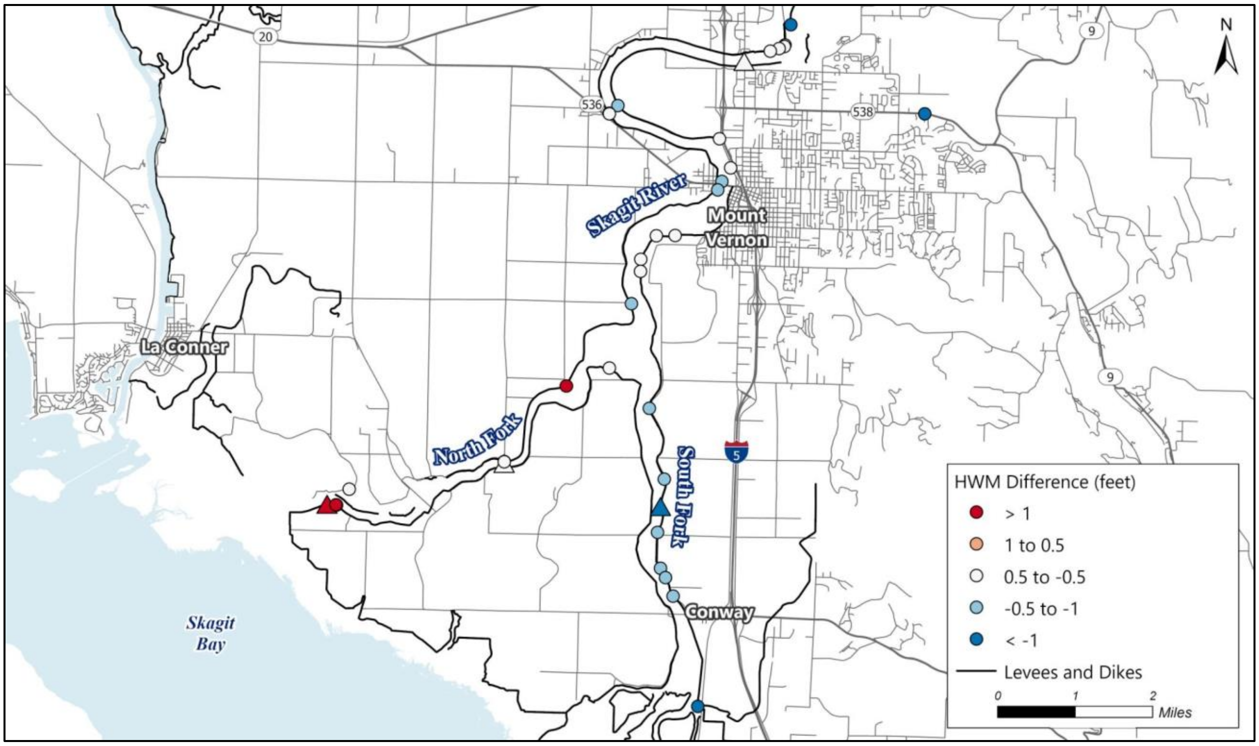


Figure 6.11 HWM differences along the Skagit River downstream of Burlington

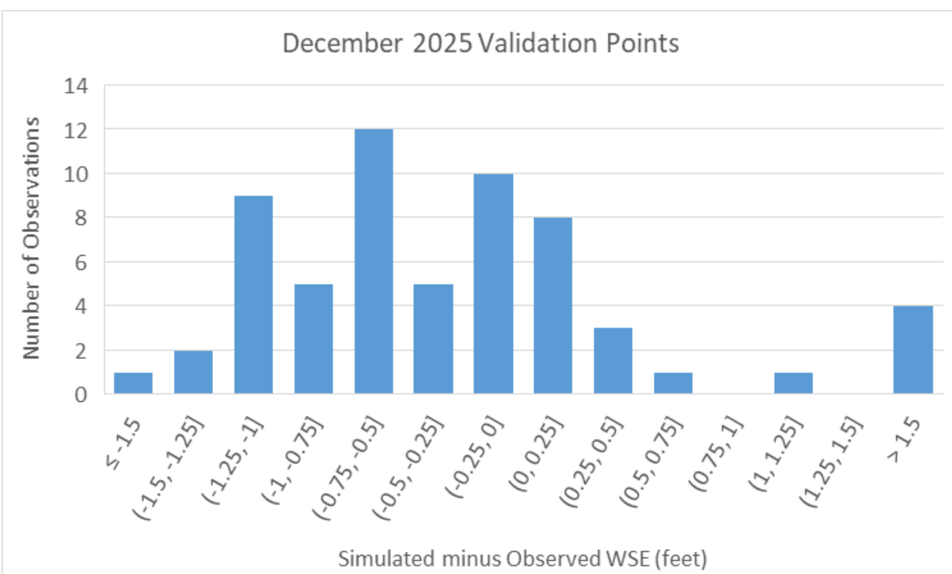


Figure 6.12 December 2025 peak WSE residual distribution for HWMs and gages

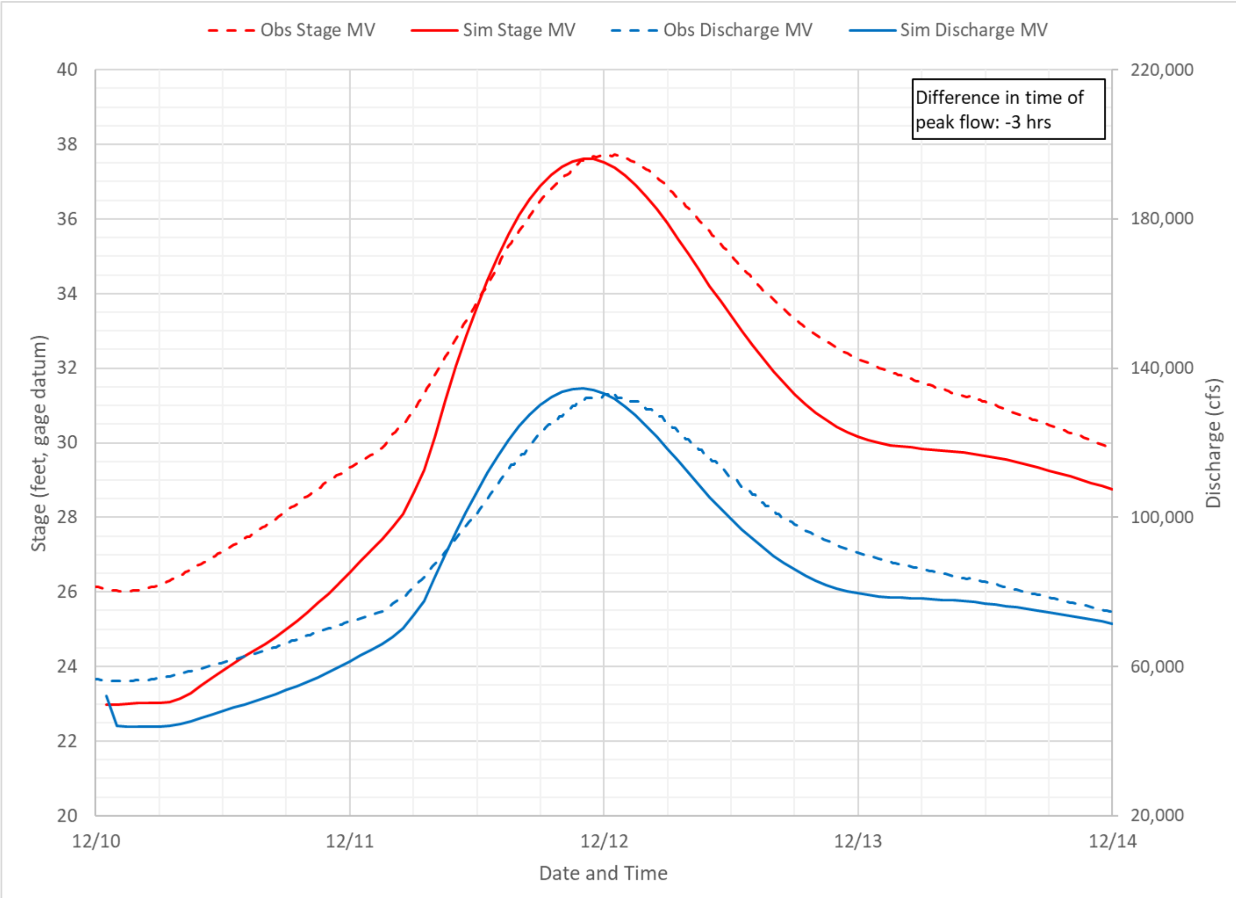


Figure 6.13 Comparison of simulated and observed stage and discharge at Mount Vernon USGS gage for the 2025 event

6.4.5 Validation: November 1995 Event

Observed data available from the November 1995 event includes USGS gages and surveyed HWMs from the Skagit GI (USACE, 2014) from Mount Vernon to Concrete. Similar to the 2003 data, this event occurred prior to the 2014 avulsion, so consideration should be made when comparing 1995 observed data to the Project model.

Along the profile in Figure 6.6, the 1995 simulated WSEs are consistently higher through Mount Vernon and Sedro-Woolley. The 1995 event results in the greatest error, with MAE of 1.6 feet and standard deviation of 2.0 feet, per Table 6.8. The differences are likely attributed to the general aggradational trend of the lower Skagit River between Concrete and Sedro-Woolley. Although, as mentioned in the Skagit GI (USACE, 2014), a few of the USACE HWMs appear to be inconsistent and would require significant variation in roughness to produce a good fit. For the 1995 event, the model oversimulates WSE at the Mount Vernon gage by 1.2 feet, but similar to other events, the simulated peak occurs about three hours early, as shown in Figure 6.14.

Table 6.8 Summary of error statistics for the November 1995 event

Dataset	No. of Points	Mean Error (ft)	Mean Absolute Error (ft)	Standard Deviation (ft)	Max Error (ft)	Min Error (ft)
HWMs and USGS gages	17	0.5	1.6	2.0	5.5	-3.6

Notes:
1. See the appended tables for a detailed comparison of all observed points and simulated WSEs.

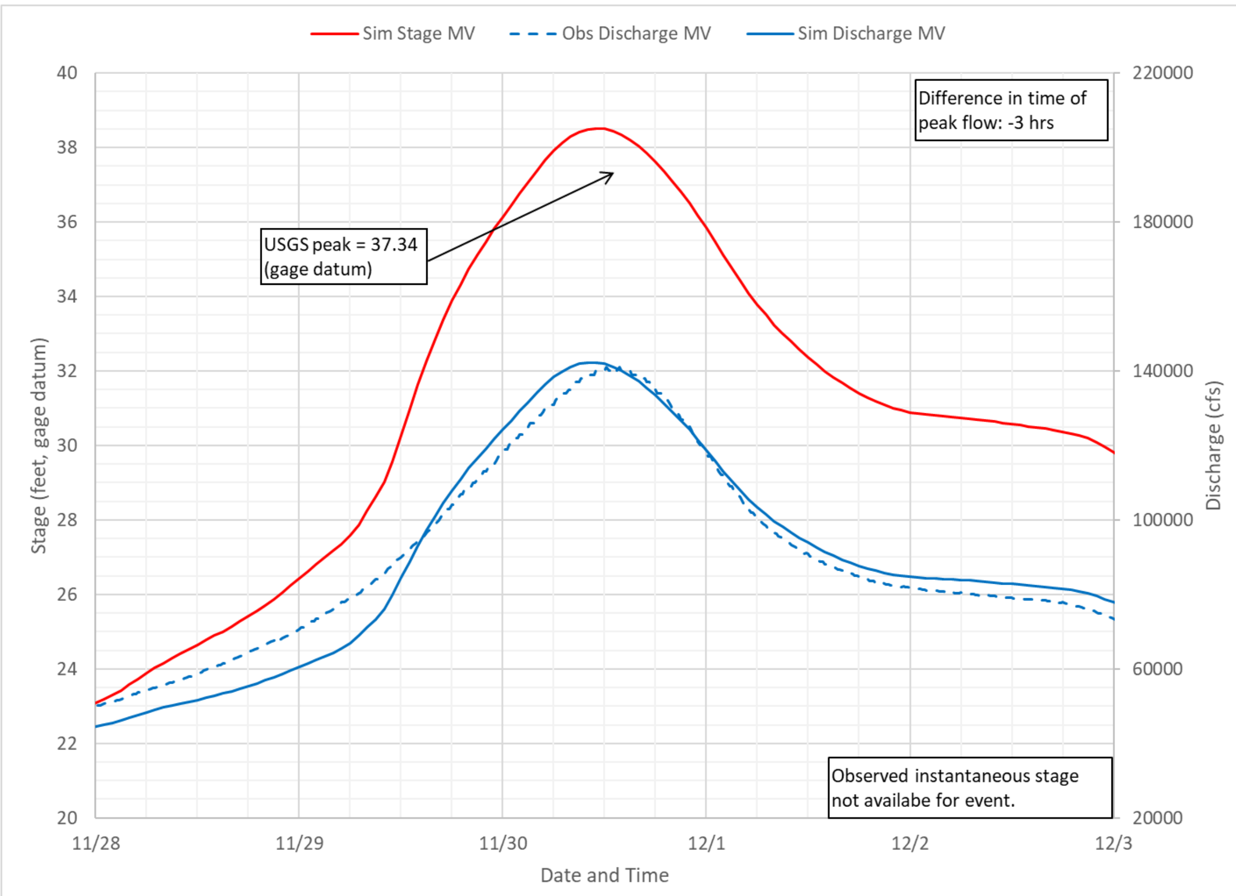


Figure 6.14 Comparison of simulated and observed stage and discharge at Mount Vernon USGS gage for the 1995 event

6.4.6 Summary

The main takeaways from the calibration and validation effort are as follows:

- The 2021 and 2025 events are considered most representative of current channel characteristics represented in the Project model. There are limitations with the calibration and validation for the 2003 and 1995 events due channel bed changes associated with the 2014 avulsion and general aggradational trend of the lower Skagit River system.

- For the 2021 and 2025 events:
  - Calibration to the 2021 event is considered good from I-5 to Concrete, with HWMs generally within one foot of observed data and USGS gages within 0.5 feet, with exception of Sedro-Woolley and Rockport. However, no calibration data were available downstream of I-5, including the North Fork and South Fork.
  - The 2025 event shows the model generally undersimulates WSEs along the South Fork and oversimulates WSEs along the lower North Fork.
  - The 2025 event shows the largest differences directly upstream of the BNSF railroad bridge, extending upstream to Sedro-Woolley.
- For the 2003 and 1995 events, the model consistently oversimulates WSEs by about one foot which could be attributed to changes in the channel bed.
- Calibration to the 2025 event was not included in this Project; however, the model could benefit from calibration to this event using observed data collected and by potentially collecting newer bathymetric data along the forks extending upstream through Burlington. Additionally, conducting future sensitivity testing with bridge debris could improve model performance in the reach upstream of the BNSF railroad bridge.

6.5 Dike Failure Parameters

Dikes along the lower mainstem Skagit River, North Fork, South Fork, and Samish River provide riverine flood risk reduction in the Skagit delta. The Skagit GI (USACE, 2014) identified the potential for the Skagit River dikes to fail during a 100-year flood, and identified locations of primary risk. As part of the Project model development, six separate runs with dike failures were completed. These runs were computed at the 100-year riverine flood event under historic conditions. Dike failure locations selected matched locations in the Skagit GI (USACE, 2014), and preference was given to failure locations resulting in greatest impacts to urban centers. The six selected failure locations are detailed in Table 6.9 and shown spatially in Figure 6.15. No failure runs were completed on coastal dike facilities.

Dike failure parameters and mechanisms were maintained from the Skagit GI (USACE, 2014). The failures are initiated at a selected water surface elevation based on probability of failure elevation identified in the Skagit GI. The fully developed failure width is 400 feet and the failures were assumed to take three hours to reach the fully developed sizes. Only a single failure was assumed to occur in any one flood event to identify the maximum flood inundation that might occur.

Table 6.9 Dike failure locations from Skagit GI

RM[1]	Physical Location
RM 21.3	Skagit River mainstem right bank near Lafayette Road
RM 18.1	Skagit River mainstem right bank upstream of BNSF bridge
RM 16.8	Skagit River mainstem left bank immediately below I-5 bridge
RM 13.1	Skagit River mainstem right bank upstream of Division Street bridge
RM 11.7	Skagit River mainstem left bank downstream of Mount Vernon Flood Wall
North Fork RM 8.3	North Fork Skagit River left bank

Notes:
1. River miles from the Skagit GI (USACE, 2014).

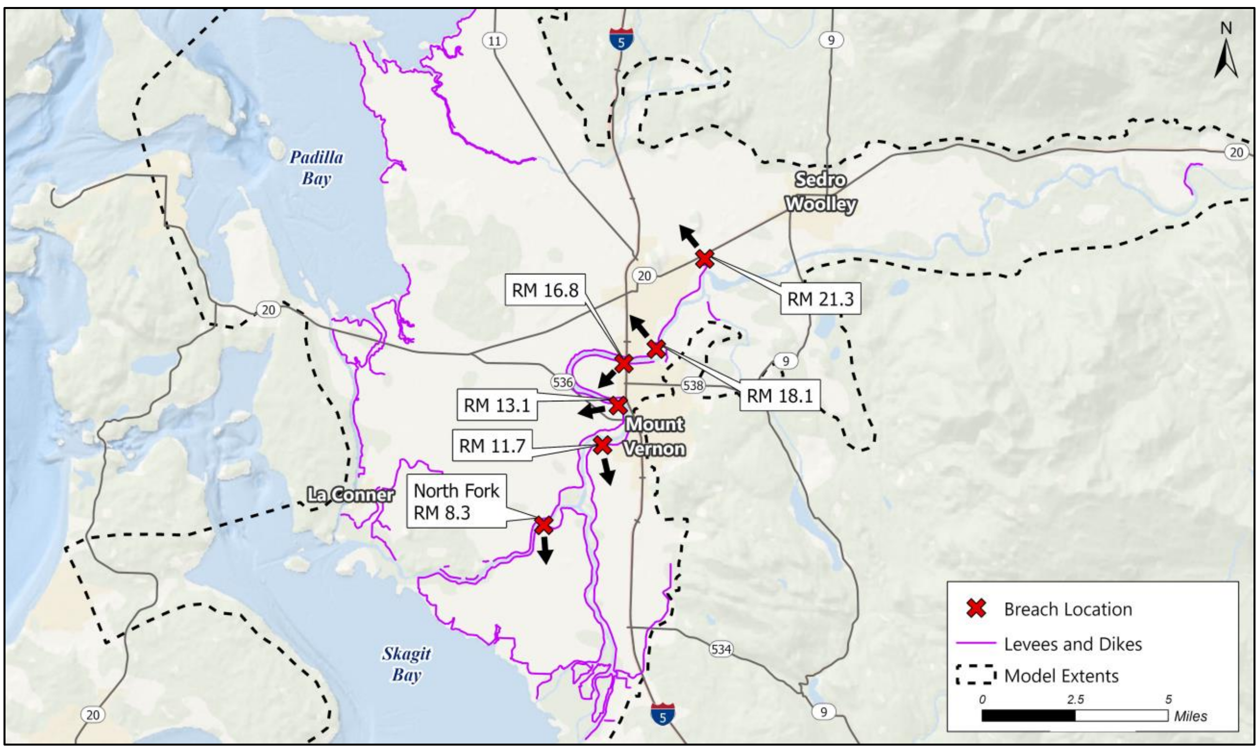


Figure 6.15 Dike failure locations in the 2D model

7 MODEL OUTPUT

This section documents the model output and post-processing methods used to develop the mapping products and animations for the Project. All results are included in Appendix B of the Project Report. Select animation will be available on the Skagit Climate Science Consortium website. Table 7.1 summarizes the output type and the associated post-processing completed. All rasters output from the model have a 3-foot cell resolution.

Table 7.1 Flood model outputs

Output Type	Post-Processing Required
Flood Extent	direct output
Flood Depth	direct output
Flood Velocity[1]	direct output
Water Surface Elevation	direct output
Dike Failure[2]	difference maps post-processed in HEC-RAS (with failure minus historic conditions)
Depth-Velocity Hazard	post-processed in HEC-RAS based on classifications (AIDR, 2017)
Flood Duration[3]	direct output
Animations	direct output and post-processed in video editing software

Notes:

1. Velocity output shows magnitude only and does not depict flow direction.
2. All other mapping products produced for the project assume no dike failure occurs. Dike failure locations described in Section 6.5.
3. Duration map only developed for the 100-year riverine flood in historic conditions.

The following post-processing was completed on model output:

- Depth difference maps were developed for the dike failure scenarios by calculating the difference between the dike failure minus no-failure scenarios. These layers also highlight newly inundated areas as a result of the dike failure.
- Depth-Velocity hazard maps were developed for this Project based on standard international practice (AIDR, 2017) and classified into six hazard ratings using methodology outlined in Table 7.2, based on limiting depth and velocities. Limitations to the hazard maps include the following:
  - Hazard mapping methodology is based on clearwater riverine hazards.
  - Mapping does not consider secondary hazards such as shoreline and fluvial geomorphic hazards (e.g., erosion, avulsion, debris flows, alluvial fan, etc.).
- Animation videos were created by recording direct output from the hydraulic model that illustrate the timing and progression of flooding during an event. They can help users

visualize the routing of flood waters through the floodplain and as supplemental reference for interpreting model results. Animations are not static maps included in the Project report, but can be generated by technical users familiar with the HEC-RAS modeling software. Animations for select locations can be found at the Skagit Climate Science Consortium website.

Table 7.2 Descriptions for depth-velocity hazard rating mapping (based on (AIDR, 2017))

Rating, color	Description	Classification limit (D*V) (ft^2/s)	Limiting still water depth (D) (ft)	Limiting velocity (V) (ft/s)
H1	Generally safe for vehicles, people, and buildings.	≤3.2	≤1.0	≤6.6
H2	Unsafe for small vehicles.	≤6.5	≤1.6	≤6.6
H3	Unsafe for vehicles, children, and the elderly.	≤6.5	≤3.9	≤6.6
H4	Unsafe for vehicles and people.	≤10.8	≤6.6	≤6.6
H5	Unsafe for vehicles and people. All building types vulnerable to structural damage. Some less robust building types vulnerable to failure.	≤43.1	≤13.1	≤13.1
H6	Unsafe for vehicles and people. All building types considered vulnerable to failure.	>43.1	N/A	N/A

8 TECHNICAL CONCLUSIONS AND RECOMMENDATIONS

This report documents the development of the new hydraulic model to improve floodplain and coastal mapping in the Skagit River watershed. This section summarizes the technical findings, with key primary conclusions listed as follows:

- The fully 2D model provides a robust tool to evaluate riverine and coastal flooding under historic and future climate conditions along both the Skagit and Samish systems. While the tool and mapping products can be used for flood planning, infrastructure design, habitat restoration and emergency management, it will not replace the FEMA effective Base Flood Elevations.
- The model provides good calibration to the 2021 event from I-5 to Concrete; however, no calibration data were available downstream of I-5, including the North Fork and South Fork.
- Validation to the 2025 event showed a trend of oversimulating along the North Fork and undersimulating along the South Fork, in addition to oversimulating in the reach immediately upstream of the BNSF bridge.
- For prior events in 1995 and 2003, the model consistently oversimulates WSEs by about one foot which could be attributed to changes in channel bed of the lower Skagit River.

- The Project model will be available for use and adaptation by technical users proficient with the HEC-RAS modeling software.

Based on the technical findings, there are a few recommendations to improve the Project model capability in the future, including:

- Recalibrating the model to the December 2025 event using observed data to improve model performance along the North Fork, South Fork, and near Sedro-Woolley. The recalibration would benefit by applying newer bathymetry along the forks and mainstem Skagit extending upstream to Burlington. The calibration would also benefit by collecting discharge measurements on the North Fork, South Fork, and above the split. Additionally, conducting sensitivity testing with bridge debris to improve model performance in the reach upstream of the BNSF railroad bridge.
- Improving duration mapping by adding pump stations and additional key culvert and bridge infrastructure, such as along Gages Slough and the area south of Mount Vernon to Conway. Setting up long-term model runs to produce duration maps for events other than the historic 100-year riverine flood (e.g., future 100-year flood, dike failure scenarios, coastal flooding).
- Adding bridge geometry at Highway 530 (RM 67.8) and Cascade River Road (RM 78.2).
- Continuing to update the hydraulic model over time to incorporate the latest available data.
- Conducting sensitivity testing to evaluate bed level variability along the Skagit mainstem.
- Exploring the implications of higher or lower projections on coastal flood risks.

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TABLES

Table 1 November 2021 event: simulated and observed water surface elevations along the Skagit River mainstem

Source	River	Location (RM[1])	Observed (ft, NAVD88)	Simulated (ft, NAVD88)	Difference (ft)
NHC	Mainstem Skagit	84.9	374	374.7	0.7
NHC	Mainstem Skagit	84.1	367.8	370.2	2.4
NHC	Mainstem Skagit	82.5	356.7	357.1	0.4
NHC	Mainstem Skagit	82.2	353.2	353.6	0.4
USGS	Mainstem Skagit	80.8	341.5	341.2	-0.3
NHC	Mainstem Skagit	80.7	341.7	341.3	-0.4
NHC	Mainstem Skagit	79.7	332.1	330.9	-1.2
NHC	Mainstem Skagit	79.1	326.6	326.8	0.2
USGS	Mainstem Skagit	78.6	323.3	323.4	0.1
NHC	Mainstem Skagit	77.8	318.4	319.4	1.0
NHC	Mainstem Skagit	77.3	313.4	314.0	0.6
NHC	Mainstem Skagit	75.5	298.6	298.9	0.3
USGS	Mainstem Skagit	75.1	295.4	295.6	0.2
NHC	Mainstem Skagit	74	282.1	283.2	1.1
NHC	Mainstem Skagit	71.2	256.7	256.8	0.1
NHC	Mainstem Skagit	71	252.7	253.2	0.5
USGS	Mainstem Skagit	70.8	250.5	249.5	-1.0
NHC	Mainstem Skagit	68.7	235.7	235.4	-0.3
NHC	Mainstem Skagit	67.7	232.7	232.6	-0.1
NHC	Mainstem Skagit	67.7	233.4	233.5	0.1
USGS	Mainstem Skagit	64.8	219	219.1	0.1
NHC	Mainstem Skagit	56.6	183.5	184.3	0.8
NHC	Mainstem Skagit	56.6	183.8	184.3	0.5
USGS	Mainstem Skagit	54.2	172.9	173.4	0.5
NHC	Mainstem Skagit	49	146.7	146.9	0.2
NHC	Mainstem Skagit	49	145.9	146.4	0.5
NHC	Mainstem Skagit	48.8	145.6	147.0	1.4
NHC	Mainstem Skagit	46.3	132.7	130.7	-2.0
NHC	Mainstem Skagit	42.4	112.6	112.8	0.2

Source	River	Location (RM[1])	Observed (ft, NAVD88)	Simulated (ft, NAVD88)	Difference (ft)
NHC	Mainstem Skagit	40.9	106.4	106.9	0.5
NHC	Mainstem Skagit	40.9	107	107.0	0.0
NHC	Mainstem Skagit	34.6	80.5	79.2	-1.3
NHC	Mainstem Skagit	30.9	68	67.0	-1.0
NHC	Mainstem Skagit	30.9	66.7	67.0	0.3
NHC	Mainstem Skagit	26.7	57.4	57.7	0.3
NHC	Mainstem Skagit	26.7	56.9	57.7	0.8
NHC	Mainstem Skagit	24.3	51.5	52.8	1.3
NHC	Mainstem Skagit	22.9	48.6	48.3	-0.3
USGS	Mainstem Skagit	22.5	47.3	46.5	-0.8
NHC	Mainstem Skagit	22.4	46.4	45.9	-0.5
USGS	Mainstem Skagit	15.8	40.8	40.5	-0.3
NHC	Mainstem Skagit	15.7	40.8	40.5	-0.3
NHC	Mainstem Skagit	15.6	40.4	40.2	-0.2

Notes:

1. River mile location based on USGS.

Table 2 October 2003 event: simulated and observed water surface elevations

Source	River[1]	Location (RM[2])	Location (RM[3])	HWM (ft, NAVD88)	Skagit GI (USACE, 2014)		2026 Project Model	
					Sim (ft, NAVD88)	Diff (ft)	Sim (ft, NAVD88)	Diff (ft)
USGS Gage	Skagit	54.10	54.1	176.0	172.3	-3.7	176.6	0.7
Skagit County	Skagit	49.75	49.9	153.8	151.6	-2.1	154.5	0.7
Skagit County	Skagit	40.18	40.2	104.4	103.3	-1.1	105.8	1.3
Skagit County	Skagit	29.90	30.4	67.3	65.8	-1.5	65.8	-1.5
Skagit County	Skagit	22.78	23.0	48.9	47.6	-1.3	50.0	1.1
USGS Gage	Skagit	22.30	22.5	45.6	46.0	0.4	47.5	1.9
Skagit County	Skagit	21.60	20.1	44.5	45.0	0.5	45.8	1.3
Skagit County	Skagit	19.48	18.2	43.5	43.5	0.0	44.8	1.3
Skagit County	Skagit	17.07	15.7	40.4	41.3	0.9	42.0	1.6
USGS Gage	Skagit	17.05	15.7	40.0	41.2	1.2	41.9	2.0
Skagit County	Skagit	15.89	14.7	39.0	39.0	0.0	39.9	0.9
Skagit County	Skagit	13.03	11.8	34.0	34.5	0.5	34.9	0.9
Skagit County	Skagit	12.18	10.8	32.0	32.2	0.2	33.0	1.1
Skagit County	NF	8.09	6.0	25.0	24.6	-0.4	26.2	1.2
Skagit County	NF	4.42	2.9	15.5	12.7	-2.8	16.1	0.5
Skagit County	SF	5.80	4.5	19.7	19.7	0.1	19.4	-0.2
Skagit County	SF	3.52	1.8	14.1	11.1	-3.0	12.6	-1.5

Notes:

1. Skagit (Mainstem Skagit), North Fork (NF), South Fork (SF).
2. River mile location based on the Skagit GI (USACE, 2014).
3. River mile location based on current USGS river mile data.

Table 3 December 2025 event: simulated and observed water surface elevations

Source	River	Location (RM[1])	Observed (ft, NAVD88)	Simulated (ft, NAVD88)	Difference (ft)
USGS	Mainstem Skagit	54.2	175.1	175.0	-0.1
NHC Dec23	Mainstem Skagit	23.5	50.6	51.2	0.7
NHC Dec23	Mainstem Skagit	22.8	49.7	49.7	0.1
USGS	Mainstem Skagit	22.5	47.9	47.1	-0.9
NHC Dec23	Mainstem Skagit	20.0	46.4	45.3	-1.1
NHC Dec23	Mainstem Skagit	20.0	46.4	45.3	-1.1
NHC Dec23	Mainstem Skagit	20.0	47.1	45.4	-1.7
Photo	Floodplain	20.0	45.0	44.3	-0.7
Photo	Floodplain	20.0	46.2	45.2	-1.0
NHC Dec15	Mainstem Skagit	19.4	46.8	45.3	-1.5
Photo	Floodplain	18.8	38.5	37.7	-0.8
NHC Dec15	Mainstem Skagit	18.2	45.2	44.2	-1.0
NHC Dec15	Mainstem Skagit	18.2	45.3	44.2	-1.1
NHC Dec15	Mainstem Skagit	18.2	45.3	44.2	-1.1
NHC Dec23	Mainstem Skagit	16.9	44.5	43.2	-1.3
NHC Dec23	Mainstem Skagit	16.4	42.1	42.1	0.1
NHC Dec23	Mainstem Skagit	16.4	41.6	41.9	0.4
NHC Dec23	Mainstem Skagit	16.3	42.1	41.9	-0.3
NHC Dec23	Mainstem Skagit	16.2	41.8	41.6	-0.2
USGS	Mainstem Skagit	15.8	41.5	41.4	-0.2
NHC Dec15	Mainstem Skagit	13.5	37.9	37.3	-0.6
NHC Dec15	Mainstem Skagit	13.5	37.8	37.3	-0.5
NHC Dec15	Mainstem Skagit	13.5	38.2	37.7	-0.5
NHC Dec15	Mainstem Skagit	13.5	38.0	37.7	-0.3
NHC Dec15	Mainstem Skagit	13.5	37.9	37.7	-0.2
NHC Dec15	Mainstem Skagit	13.5	37.8	37.7	-0.1
NHC Dec23	Mainstem Skagit	12.0	35.0	35.0	-0.1
Photo	Mainstem Skagit	11.7	34.0	34.3	0.3
NHC Dec23	Mainstem Skagit	11.5	33.9	33.4	-0.5
NHC Dec23	Mainstem Skagit	11.4	33.8	33.2	-0.6

Source	River	Location (RM[1])	Observed (ft, NAVD88)	Simulated (ft, NAVD88)	Difference (ft)
NHC Dec15	Mainstem Skagit	10.4	32.1	32.0	0.0
NHC Dec15	Mainstem Skagit	10.0	30.8	31.1	0.3
NHC Dec15	Mainstem Skagit	9.6	30.0	30.2	0.2
NHC Dec15	Mainstem Skagit	9.4	29.7	29.6	-0.1
NHC Dec15	Mainstem Skagit	9.0	29.0	28.6	-0.4
NHC Dec15	Mainstem Skagit	9.0	29.0	28.6	-0.4
NHC Dec15	Mainstem Skagit	9.0	29.1	28.6	-0.6
NHC Dec15	Mainstem Skagit	9.0	29.2	28.6	-0.6
NHC Dec15	SF	8.1	28.3	27.7	-0.6
NHC Dec15	SF	8.1	27.6	27.7	0.1
NHC Dec15	SF	8.1	27.6	27.7	0.0
NHC Dec15	SF	8.1	27.6	27.7	0.0
NHC Dec15	SF	7.5	26.0	25.3	-0.7
NHC Dec15	SF	6.3	24.8	24.1	-0.7
NHC Logger	SF	6.0	23.8	22.8	-1.0
NHC Dec15	SF	5.7	23.2	22.4	-0.8
NHC Dec15	SF	5.0	21.5	20.8	-0.7
NHC Dec15	SF	4.8	21.4	20.6	-0.9
NHC Dec15	SF	4.6	20.4	19.7	-0.7
NHC Dec15	SF	3.2	16.7	15.5	-1.2
NHC Dec15	SF	3.2	16.6	15.5	-1.1
NHC Dec15	SF	3.2	16.5	15.5	-1.1
NHC Dec15	NF	6.4	24.5	26.2	1.6
NHC Dec15	NF	5.3	22.1	22.2	0.1
NHC Dec15	NF	5.3	22.1	22.2	0.1
NHC Logger	NF	5.2	22.3	22.2	-0.1
NHC Dec15	NF	3.0	17.2	17.1	0.0
NHC Dec15	NF	2.9	14.4	16.5	2.1
NHC Dec15	NF	2.9	14.7	16.5	1.8
NHC Dec15	NF	2.9	14.5	16.5	2.1
NHC Logger	NF	2.8	14.6	15.7	1.1

Table 4 November 1995 event: simulated and observed water surface elevations

Source	River[1]	Location (RM[2])	Location (RM[3])	HWM (ft, NAVD88)	Skagit GI (USACE, 2014)		2026 Project Model	
					Sim (ft, NAVD88)	Diff (ft)	Sim (ft, NAVD88)	Diff (ft)
USGS Gage	Skagit	54.1	54.1	175.3	171.8	-3.5	180.8	5.5
USACE	Skagit	52.95	53.0	166.6	165.8	-0.8	166.6	0.0
USACE	Skagit	47.55	47.0	142.5	136.2	-6.3	138.9	-3.6
USACE	Skagit	41.1	40.0	107.1	102.5	-4.5	105.0	-2.1
USACE	Skagit	33.3	33.0	75.7	74.4	-1.2	74.2	-1.4
USACE	Skagit	31.45	30.4	65.1	65.7	0.6	65.7	0.6
USACE	Skagit	24.7	24.9	54.6	54.1	-0.5	55.5	0.9
USACE	Skagit	22.4	22.5	50.0	46.2	-3.8	47.8	-2.1
L. Halverson	Skagit	22.3	22.5	45.7	46.2	0.5	48.1	2.5
L. Halverson	Skagit	21.93	20.8	45.1	45.3	0.2	46.4	1.4
L. Halverson	Skagit	21.6	20.2	45.2	45.2	0.0	46.3	1.1
L. Halverson	Skagit	18.57	17.4	43.8	43.3	-0.5	44.7	0.9
L. Halverson	Skagit	17.9	16.8	44.6	42.9	-1.7	44.3	-0.3
C. Bennett Photo	Skagit	17.54	16.3	41.7	42.1	0.4	43.3	1.6
L. Halverson	Skagit	17.53	16.3	43.0	42.1	-0.9	43.2	0.3
L. Halverson	Skagit	17.08	15.8	41.0	41.5	0.5	42.5	1.5
USGS Gage	Skagit	17.04	15.7	41.1	41.3	0.2	42.4	1.2

Notes:

1. Skagit (Mainstem Skagit), North Fork (NF), South Fork (SF).
2. River mile location based on the Skagit GI (USACE, 2014).
3. River mile location based on current USGS river mile data.

SUPPORTING DOCUMENTATION

TOPOBATHYMETRIC MOSAIC DEVELOPMENT MEMORANDUM

MEMO

To:	Heather Spore, Swinomish Indian Tribal Community	**Date:**	August 11, 2026
From:	Kristin Kramer, PE (NHC) Madalyn Ohrt, GISP (NHC) Vaughn Collins, PE (NHC)	**NHC Reference**	2009212
Re:	Development of the Skagit River Topobathymetric Data Mosaic		

1 INTRODUCTION

This memorandum documents the development of the topobathymetric surface mosaic to support the new two-dimensional hydraulic model of the Skagit River for the Skagit River Flood Risk Modeling Project (Project). Northwest Hydraulic Consultants (NHC) was contracted by Swinomish Indian Tribal Community (SITC) to develop and calibrate the new hydraulic model. As part of this work, NHC mosaicked various LiDAR, bathymetric survey, and design datasets to create one comprehensive topobathymetric surface to be used in the hydraulic model. This memorandum describes the data sources used and the methods employed to mosaic the surface.

2 DATA SOURCES

The data sources used to create the comprehensive surface are shown in Figure 1. They comprise of data collected in the form of both topographic and topobathymetric LiDAR, bathymetric data, and design sources. Topographic LiDAR were collected via plane with near-infrared (NIR) laser and, in the case of the 2022 topobathymetric LiDAR collected by NV5 Geospatial (NV5), traditional NIR LiDAR was fully integrated with green wavelength return data in the channel to provide a seamless topobathymetric LiDAR dataset (except for void areas at the time of the flight as discussed in Section 2.1). Bathymetry within the river was compiled from several different data sources, including NHC, USGS, and USACE, as further described in Section 2.2.

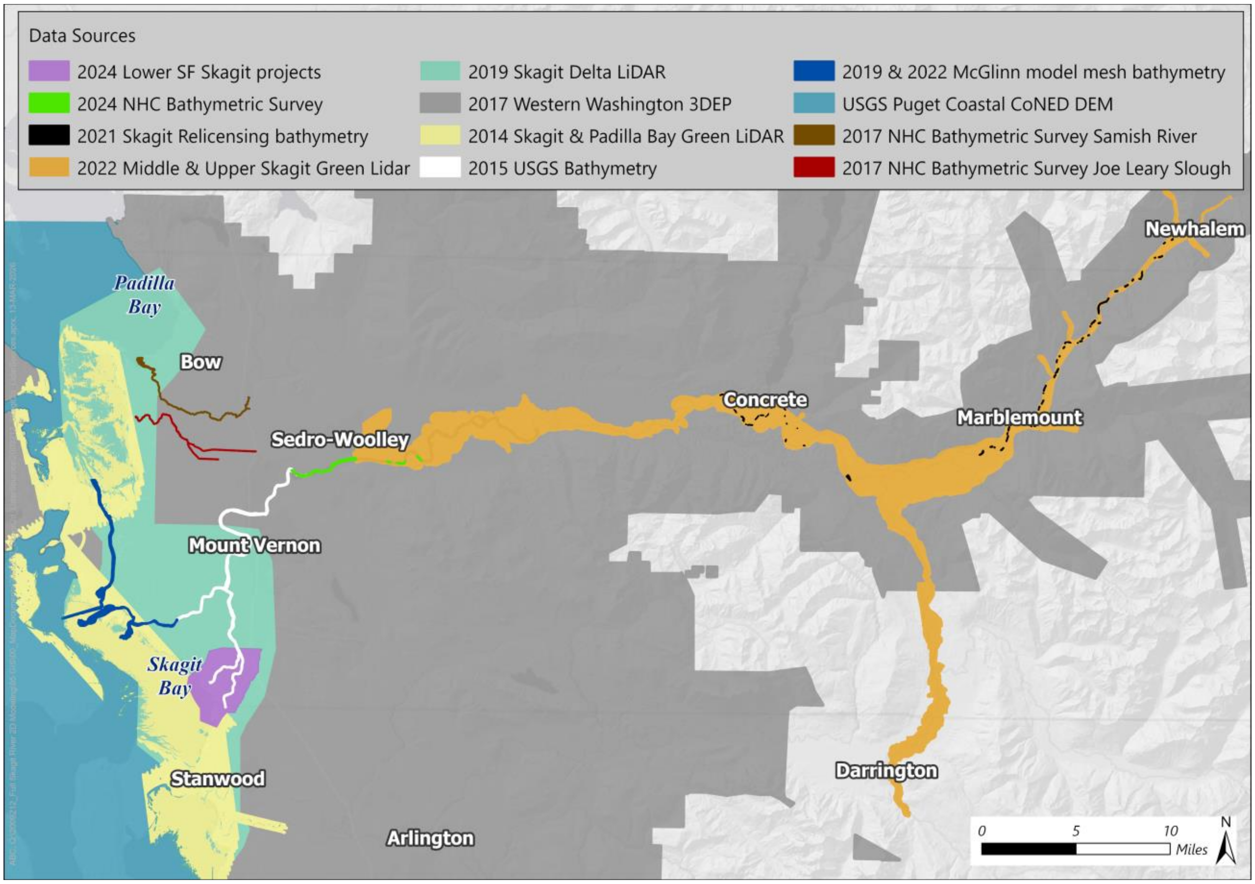

Figure 1 Data sources used to create the mosaicked surface

2.1 Topographic and Topobathymetric LiDAR

Most of the Skagit River floodplain upstream of Sedro-Woolley is covered by topobathymetric LiDAR collected by NV5 in 2022. However, voids exist in the topobathymetric surface because of limitations imposed by water depth, turbulent water, riparian vegetation, and other channel bed conditions. These voids were mapped in a spatial coverage delineating areas void of channel bottom data in the LiDAR sources to better understand the extent of supplemental bathymetric survey to be collected, as discussed in Section 2.1.1.

From Sedro-Woolley to the bay, a majority of topographic LiDAR was applied from 2017 and 2019 sources, with some topobathymetric LiDAR from 2014 providing coverage in Skagit Bay and Padilla Bay. Because a majority of these sources were topographic LiDAR, bathymetric survey was applied to define the riverbed, as discussed in Section 2.2.

2.1.1 Void Filling

Single beam boat surveys conducted by NHC in 2021 and 2024 were used to fill the voids within the NV5 topobathymetric LiDAR. These data were only used to fill void areas within the LiDAR, even if bathymetric data existed beyond the voids. In areas where interpolation occurred between the NHC data and other nearby data points, breaklines were drawn by NHC to produce an adequate merge for use in the hydraulic model. An example of the process is shown in Figure 2. Note that this figure shows two parallel data feeds (black dots in the figure) collected from two different sounders by NHC—one with such tight data spacing that it appears as nearly a solid black line. Not all the void areas in the NV5 topobathymetric data were surveyed by NHC. In these cases, these were smaller void areas which were filled using interpolation between the surrounding LiDAR data.

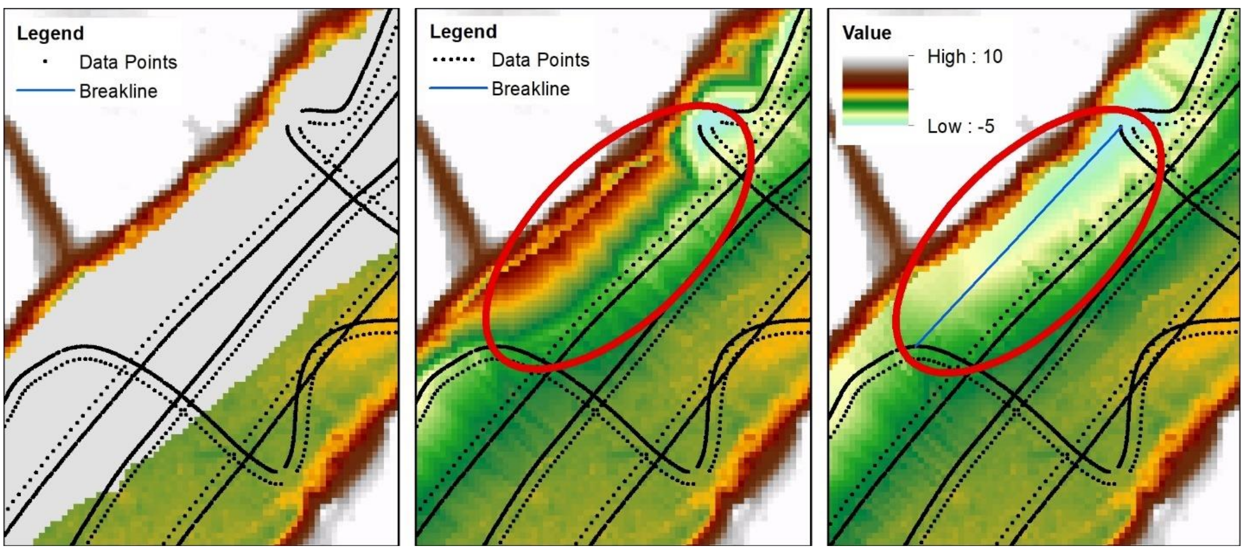

Figure 2 Example void area (left), void area filled with survey data and no breakline (middle), and void area filled with survey data and breakline (right)

2.2 Bathymetric Survey

Bathymetric surveys were initially compiled from available sources from NHC, USGS and USACE from survey dates in 2014, 2015, 2019, and 2022. No recent bathymetry was available near Sedro-Woolley; therefore, during the Project, NHC collected boat-based bathymetric data in 2024 using a single-beam approach to cover this reach, shown in green in Figure 1.

2.3 Design Surfaces

During the Project, NHC obtained data from WDFW covering recently constructed and planned projects along the lower South Fork, including Wiley Slough Dike Raise (constructed), Milltown Island Estuary Restoration (constructed), and Island Unit Estuary Restoration (planned to be constructed in 2027).

3 COMPLETED TOPOBATHYMETRIC MOSAIC PRODUCT AND SOURCE DATA

The completed mosaicked surface has a spatial reference of WA State Plane North HARN feet, a vertical datum of NAVD88 feet and a resolution of three feet. The sources used and described in this memorandum are summarized in Table 2. These data were mosaicked in the order in which they appear in Table 2, with the higher priority dataset overlaying the lower priority datasets in areas where there was overlap.

Table 2 Data sources used to create the topobathymetric surface

Dataset	Year	Contracted by	Source	Type
Lower SF Skagit projects1	2024-2027	WDFW	HDR	Design surfaces[1]
NHC Bathymetric survey	2024	SITC	NHC	Bathymetric survey
Middle Skagit Green LiDAR	2022	SRSC	NV5	Green LiDAR
Upper Skagit Green LiDAR	2022	HDR	NV5	Green LiDAR
Skagit Relicensing bathymetry	2021	HDR	NHC	Bathymetric survey
Joe Leary Slough bathymetry	2017	Skagit County	NHC	Bathymetric survey
Samish River bathymetry	2017	Skagit County	NHC	Bathymetric survey
McGlinn model mesh bathymetry	2019, 2022	USACE	USACE	McGlinn Island Jetty Project ADH model mesh, derived from bathymetric survey
Skagit & Padilla Bay Green LiDAR	2014	USACE	USACE	Green LiDAR
Skagit Delta LiDAR	2019	NOAA	Tetra Tech	Standard LiDAR collected during low tide

Dataset	Year	Contracted by	Source	Type
USGS bathymetry	2015	USGS	USGS	Bathymetric survey
Western Washington 3DEP	2017	USGS	Quantum Spatial	Standard LiDAR
Puget Coastal CoNED DEM	2017	USGS	NOAA	Coastal DEM

Notes:

1. The Lower SF Skagit projects include Wiley Slough Dike Raise (constructed), Milltown Island Estuary Restoration (constructed), and Island Unit Estuary Restoration (planned to be constructed in 2027).

4 LIMITATIONS

This mosaicked surface was developed to be used for watershed scale analysis and hydraulic modeling at the concept level, not for detailed design. More detailed topographic and bathymetric data may be necessary for other purposes. This section provides information on some of the limitations of the completed topobathymetric surface.

4.1 Discrepancies Along Merge Line

The mosaicking process used ensures the more recent dataset takes priority over data from previous years. However, this approach does not always create a smooth transition between datasets, as shown in Figure 3 along the Skagit Bay tidal flats. Though the resulting discrepancies along the tidal flats in this area would not have a significant impact in extreme riverine or coastal flooding simulated by the model. Reasons for the differences may include systematic bias in one of the datasets, construction and grading of the land, better determination of bare earth in densely vegetated areas by one of the LiDAR platforms, or the ability of the new LiDAR to penetrate water and maps features such as flooded fields more accurately.

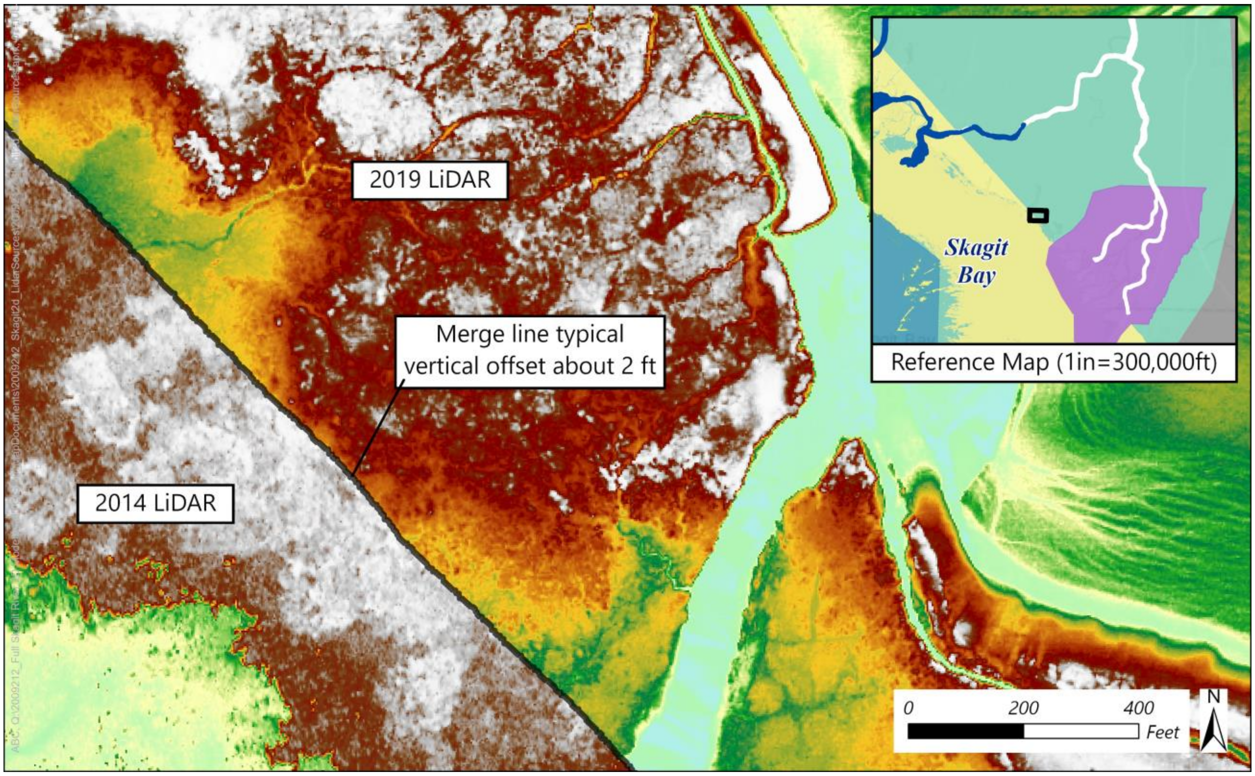

Figure 3 Example of discrepancy between the 2014 Skagit & Padilla Bay Green LiDAR and the 2019 Skagit Delta LiDAR in Skagit Bay

4.2 Discrepancies Within Source Data

Some of the discrepancies are found within the source layers themselves and are not a result of the merging of datasets. As shown in Figure 4, an artifact is found in the 2014 LiDAR south of Skagit Bay in Port Susan. In addition, Figure 5 identifies an area within the ADH Model mesh from the McGlinn Jetty project, derived from 2022 bathymetric survey, where bathymetric data may be missing. However, these issues were determined to not adversely affect hydraulic model results.

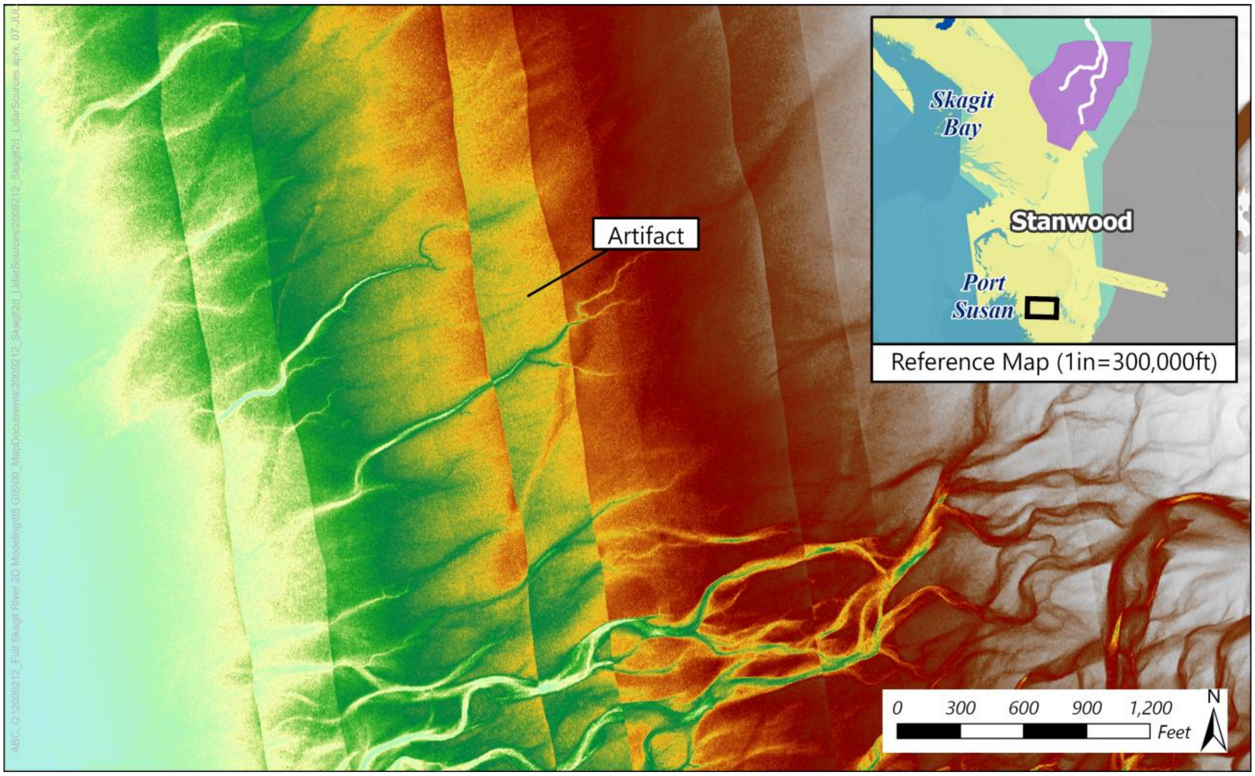

Figure 4 Artifact found in the 2014 Skagit & Padilla Bay Green LiDAR south of Skagit Bay

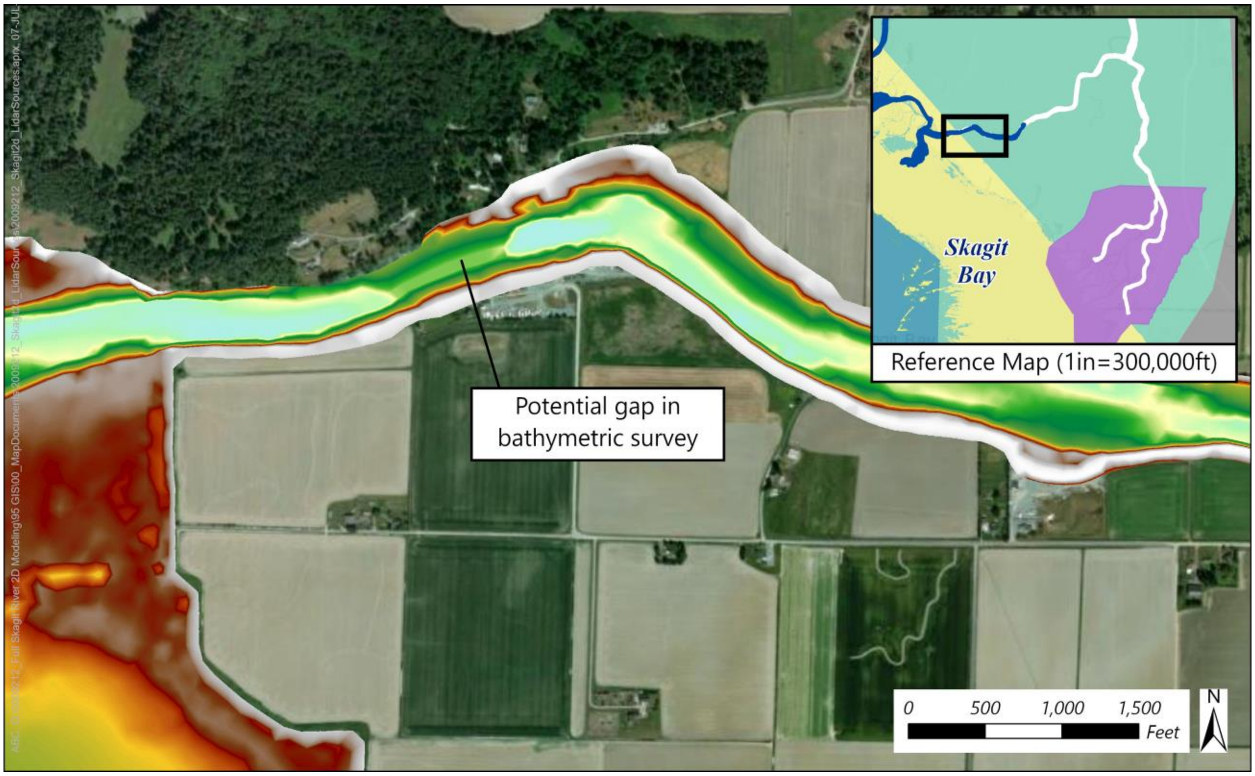

Figure 5 **ADH model mesh along the lower North Fork near Blakes's Marina and Fish Town**

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