

Technical Appendix D: Hydrology and Hydraulics Methodology

- 1. FHWA Pilot Project: Skagit River Basin Severe Weather Adaptation Strategies**
- 2. Bridges**
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FHWA Pilot Project: Skagit River Basin Severe Weather Adaptation Strategies

1.0 Introduction

The Washington State Department of Transportation (WSDOT) recognizes that floods may significantly impact the operations and maintenance of the state highway system. We anticipate that climate change will lead to not only an increase in the frequency and intensity of extreme weather events, but also in changes to patterns of precipitation, such as snow and the timing of the subsequent melting of that snow in the mountainous regions of Washington (Lee and Hamlet, 2011). The highway system may be damaged by the flow of water over the highway or simply by inundation.

Flow over the highway may cause scouring of the road surface, undermining of the pavement, scouring of embankments, washout of guardrails, accumulation of sediment on the highway surface and adjacent drainage facilities, accumulation of debris in hydraulic structures, and washing out of hydraulic structures (bridges, culverts, and stormwater facilities).

The Federal Highway Administration (FHWA) developed a methodology for estimating embankment damage to flood overtopping as well as evaluating protective measures (Chen and Anderson, 1987). Once floodwater overtops an embankment, erosion will occur when locally high velocities create erosion forces that exceed the strength of the embankment. Embankment failure begins with erosion of the downstream shoulder and slope. [Figure 1](#) shows the typical progression of erosion over time from free flow over the embankment and a submerged flow over the embankment. With a low tailwater condition, the water accelerates over the top of the embankment and passes through critical depth and then forms an undulating hydraulic jump near the toe of the embankment. As the toe erodes, the material above becomes unstable and more erodible. As the tailwater depth increases, a hydraulic jump with standing waves forms just downstream of the grade break between the embankment top and slope.

Inundation may also be very damaging, although not readily apparent. Floodwater may alter the load-bearing characteristics of the roadway fill and underlying soil materials. Consequently, there may need to be a wait time until the road can be inspected and traffic can safely use the road.

Although it is beyond the scope of this analysis to conclusively define all the risks to the state highway system, in the balance of this section, we describe an approach to identifying segments of the state highway system that are vulnerable to flooding and bridges that may impact or be impacted by floodplain functions.

1.1 Goals

We have three primary goals in the provision of this analysis:

- Develop processes or procedures to identify segments or features of the state highway system that are susceptible to severe weather events and flooding under existing and future conditions.
- Develop processes or procedures to identify potential constraints that may be encountered when planning future projects, to reduce the risk of damage to the highway system.
- Develop processes or procedures to identify these features that can be applied statewide or even nationwide.

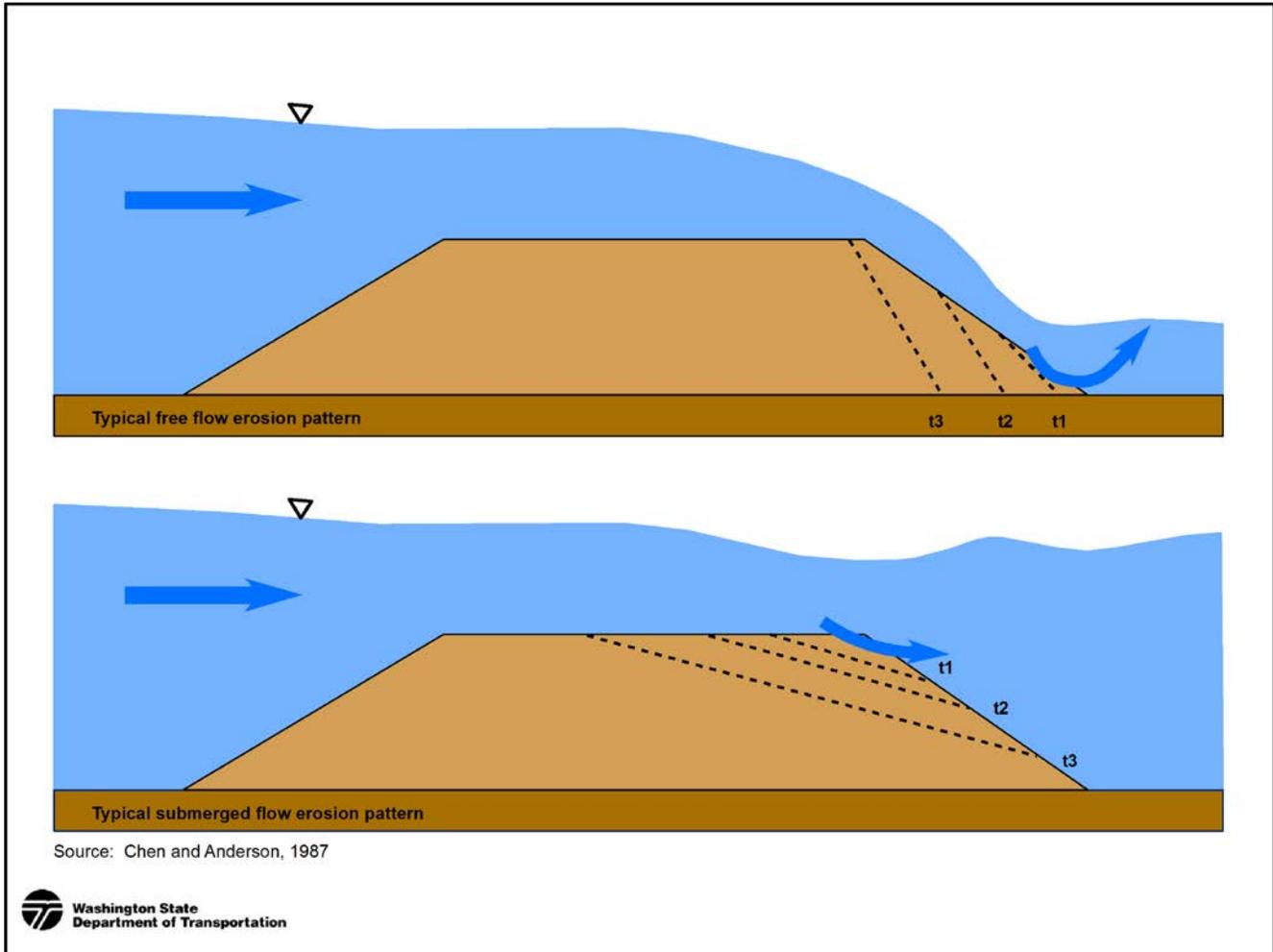


Figure 1 – Typical embankment overflow erosion progression

1.2 Objectives

Our objectives for the project are to develop processes and procedures to identify segments or features of the state highway system that are susceptible to extreme weather events by leveraging existing WSDOT data, along with data from other state or federal agencies and local governments. Specifically, we intend to:

- Develop processes and procedures using ArcView to process and store data to the maximum extent practicable.
- Collect and use existing data with a minimum amount of manipulation.
- Test processes and procedures.
- Identify weaknesses or problems with the processes and procedures.
- Revise processes and procedures.
- Identify and discuss lessons learned.

1.3 Processes and Procedures

We selected the Skagit River basin in Skagit County as the area to develop and test screening processes and procedures. The US Army Corps of Engineers (Corps) recently completed a General Investigation (GI) and draft Environmental Impact Statement (EIS) for flood hazard reduction on the lower Skagit River. This meant we would have access to an abundance of up-to-date topographic and land use data available, as well as a sophisticated two-dimensional hydraulic model that simulated overland flow in the floodplain.

Early in the process, we conducted a preliminary screening to identify WSDOT facilities that were subject to flooding, to define the study area and to identify segments of the highway system that may be susceptible to changes in the precipitation/runoff response due to climate change. In addition, local stakeholders such as diking districts, city and county public works, and WSDOT maintenance staff met to identify their areas of concern regarding flood hazards. These activities are summarized in the body of this report, and the detailed results are included in the Appendix A.

In the balance of this section, we focus on the development of processes and procedures to identify flood hazards that effect state highway facilities using the best available data, representing the conditions on the ground and the output from the hydraulic model developed by the Corps. In Appendix B we discuss the development of processes and procedures to identify constraints to future projects, such as critical facilities (hospitals), wetlands, endangered species, cultural resources, etc.

We further divided the flood hazard analysis into two parts—highways and bridges—as bridges themselves are rarely inundated but may be affected by scour and floodplain processes such as channel migration. Consequently, we developed separate methodologies and tests for highways and bridges. Each of those sections describes our development of preliminary processes and procedures, the data, problems encountered with the data or processes, revisions, results, and lessons learned.

2.0 Highways

Flow over the highway may cause scouring of the road surface, undermining of the pavement, scouring of embankments, washout of guardrails, accumulation of sediment on the highway surface and adjacent drainage facilities, and accumulation of debris in hydraulic structures, and washing out of hydraulic structures (bridges, culverts, and stormwater facilities.)

Inundation may also be very damaging, although not readily apparent. To the lay person, the obvious impact is that water on the roadway prevents traffic flow, and once the water drains away, the roads will be ready for travel. However, water alters the load-bearing characteristics of the roadway fill and underlying soil materials. Consequently, there may need to be a wait time (depending on the depth and duration of flooding, as well as the underlying soil materials) as the water drains from the fill materials, until the roadway can be inspected to determine if traffic can safely use the road. State highway engineers may need to evaluate the tradeoff between the user costs of road closure versus the costs of potentially increased road damage.

2.1 Preliminary Process and Procedures

As identified previously, the Corps recently completed a GI/EIS to reduce flood hazard in the lower Skagit River basin. As part of that project, the Corps created a high-resolution digital elevation model (DEM) of the land surface of the lower Skagit River floodplain, west of SR 9, using various LiDAR (light detection and ranging) and

other topographic sources. The Corps then used this DEM as input to a two-dimensional hydraulic model (FLO-2D) to simulate the overland flow under numerous flood scenarios that represent the existing conditions. FLO-2D output is available as grid data of maximum water surface elevations, maximum depths, maximum velocities, direction of maximum velocities, duration of flooding to specified depth, and tabular data.

WSDOT intended to rapidly identify at-risk sections of the state highway system using ArcView to intersect the highway with the depth grids to identify what sections of road would flood and how deep. We intended to use velocity data to segregate flooded road segments into areas of “flow over the highway” or “inundation” to further refine the vulnerability to damage. The following steps outline this procedure:

- Use ArcView’s 3D Analyst tool “Profile Stacker” to intersect WSDOT’s road centerline coverage with the output grid data from FLO-2D and get tabular information of where the highway intersects the surface defined by each of the grid cell data sets.

2.2 Data

Skagit County, the Corps’ cooperating partner for the GI/EIS, provided output data from the FLO-2D model. During the course of this pilot, only water surface elevation and depth grids were available for each model scenario; no other output data was made available by the Corps. They also provided the high-resolution DEM.

- **HIGHWAY DATA** – WSDOT has transportation facilities GIS coverage for the entire state.
- **DEM** – The Corps developed a DEM for the Skagit River GI that was used as the basis of their hydraulic analyses of various flood scenarios. This DEM was made available to WSDOT.
- **FLOOD GRID DATA** – The Corps’ models were run for 21 flood scenarios. The scenarios included various return interval floods as well as alternative levee breach failures for most of the return interval floods.

2.3 Problems and Revised Procedures

When we examined the Corps’ gridded output data, we found that output data was represented with a grid cell size of 400 feet X 400 feet and not the DEM cell size of 6 feet X 6 feet. The grid data for maximum velocities, direction of maximum velocity, and duration of specified depths was not provided during our pilot. We hope this data will be available at a later time. The FLO-2D model has the option to provide these outputs. We do not know if these data are available within the model or if the model would need to be run again with specific commands to get those output grids.

We also do not know how the FLO-2D model was developed. Was the output simplified, or was the 400-foot grid cell used in the computations? If the data had been simplified for presentation, it may have been possible to get the raw data. We reviewed the FLO-2D user’s manual, which quickly settled the issue. The manual presented information regarding computational time based on the number of grid cells: a simulation with 50,000 cells would take about an hour to complete, and a simulation with 1,000,000 cells would take about a day to complete. Since the model output provided had approximately 55,000 cells and the DEM had 128 million cells, it became obvious that running the model on the DEM grid was not practical.

After a closer examination of the provided FLO-2D model output and the FLO-2D user’s manual, we determined that the depth grids and the velocity grids, if they had been available, could not be used as planned. [Figure 2](#) shows a diagram of the basic FLO-2D input/output data. Briefly, the DEM was aggregated

and represented as the average elevation of the 400-foot x 400-foot model grid cell (green bars on the figure). You can see that at some locations in the floodplain, the average elevation reasonably represents the land surface found in the DEM (brown line on the figure). At other locations such as at highway embankments, the average elevation masks features such as the highway embankment and roadside ditches. The highway embankments and other linear features that may obstruct flow, however, are included in the model as “levee cards” that modify the hydraulic properties of the grid cell boundary (orange box on the figure).

The FLO-2D model is run by applying the flood flow boundary conditions to the model grid. The water surface elevation is then calculated based on the calculated grid cell ground elevation, assumed roughness, and any special grid cell boundary conditions. The maximum water surface elevation for each run is recorded (blue bars on the figure). The maximum depths are calculated by subtracting the calculated ground elevation from the maximum grid water surface elevation from the calculated ground elevation. The maximum velocities are then calculated by dividing the flow through the grid by the product of the grid cell width and the average depth. As described by Chen and Anderson, the maximum velocity occurs just downstream of the grade break on the embankment; the precise location is dependent on the tailwater elevation, which is variable through a flood event. Consequently, as shown on [Figure 2](#), the maximum depth and velocity grids, if available, could not be directly used to evaluate the risk to affected highway segments, as they oversimplify the complex ground elevations and hydraulic conditions found where flood flows overflow the highway embankment ([Figure 1](#)).

We revised the screening process to subtract the road surface elevation from the water surface elevation grids to determine depth of flooding. We accomplished this by using the ArcView’s 3-D Analyst tools with WSDOT’s road centerline data, the DEM, and the water surface elevation grids to determine depth of flooding. Following is the process we used:

- Intersect highway centerlines with the DEM and water surface elevation grid data using the ArcMap 3-D Analyst Stack Profile tool to identify the ground surface and water surface elevations along the highway centerlines.
- Use column math to subtract the ground surface elevation from the water surface elevation to determine the depth of flooding within ArcView for each flood or alternatively export the data to Excel for processing.

The results of the process would be a table of approximately 6-foot-long road segments with the ground elevations, water surface elevations, and water depths for each flood scenario that could be manipulated within ArcView or with an outside application like Excel.

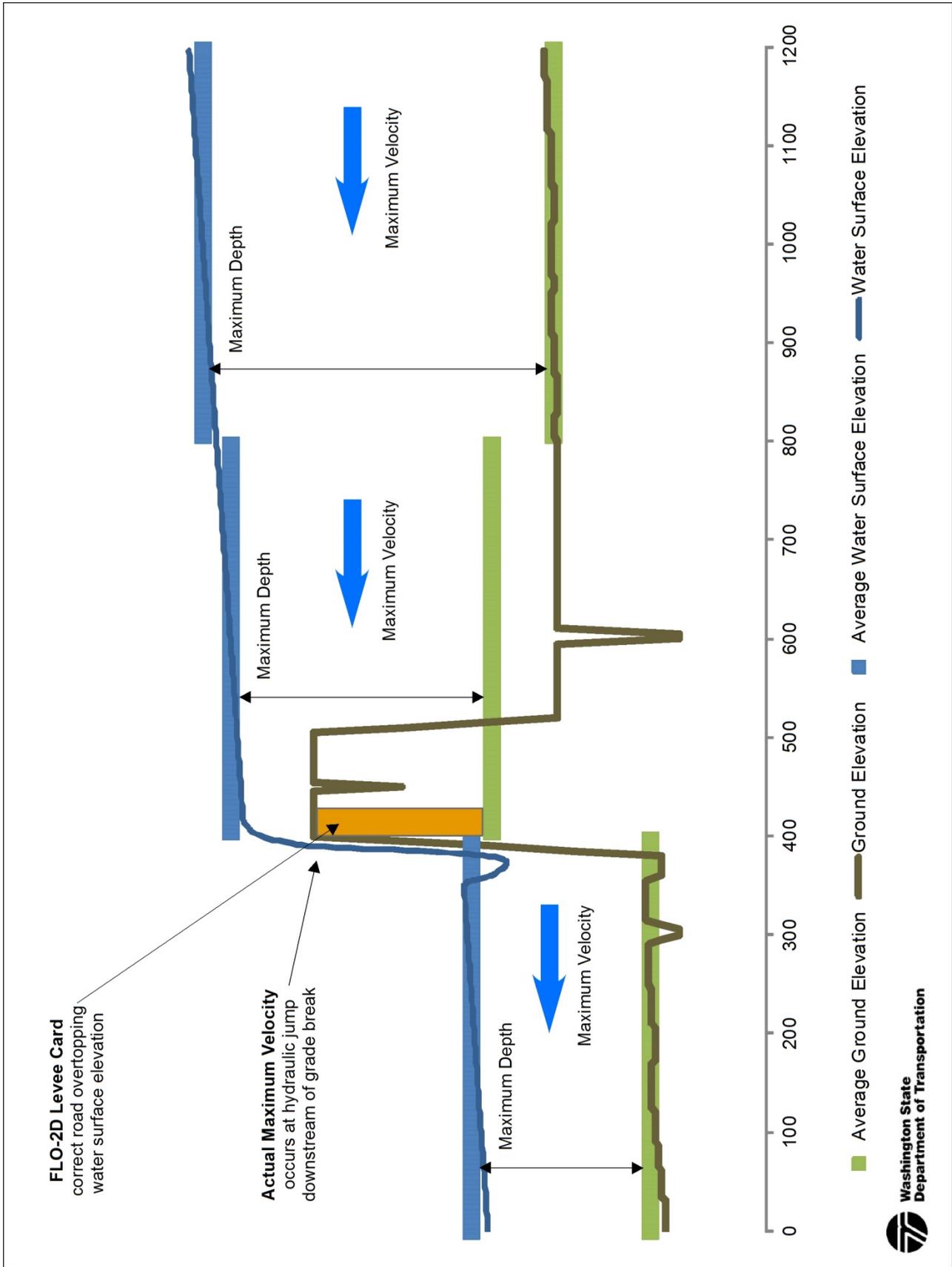


Figure 2 – FLO-2D Model Output Grids

After we attempted to use the Stack Profile tool several times unsuccessfully, we needed an alternative process to identify highway segments vulnerable to flooding.

After some consideration, we determined that we would need to manually delineate the flood-susceptible highway segments. To minimize the manual efforts, we created a worst-case floodwater surface for each return interval flood. For planning purposes, rather than individually analyzing all 21 scenarios, we thought that a worst-case analysis would adequately identify highway features susceptible to flooding. Following is the process we used:

- Create new worst-case water surface rasters by using the “Raster Mosaic” tool to overlay and select the highest value for each grid cell.¹
- Create new high-resolution worst-case depth rasters by using the “Raster Math” tool to subtract the DEM from the worst-case water surfaces created previously, and set the output raster grid size to the same as the DEM (6 feet X 6 feet).
- Display the worst-case depth rasters on screen and manually delineate the highway segments that would be inundated for each return interval by tracing over the highway centerlines.

To identify the maximum depth of water over each highway segment:

- Convert the delineated highway segments to 3D features using 3D Analyst “Features to 3D” tool using each of the worst-case depth rasters to define the surface to be intersected.
- Use the 3D Analyst “View Profile” tool to examine the profile and use the advanced options tab to identify the maximum depth in the profile.

We found during this manual process, where ArcView still did the heavy lifting, that we had to expend significant effort to carefully ground truth potential inundation areas, especially in areas near levees or berms that would prevent inundation. In many cases, the original water surface elevation grids spanned one or both banks of the Skagit River or other major drainage courses. In those situations, the average water surface is shown on both sides of the levees or berms above the ground surface, although these areas would not actually be flooded. Alternatively, in locations where there is significant dry area (e.g., where the model cells intersect hills) within the grid cell, the cell may have been discarded by the FLO-2D model, leaving a hole in the data set. While delineating the inundation highway segments manually, we found that it was relatively easy to work through these problem areas by switching on and off the DEM and seeing if the highway continued at a similar elevation or if there was a hump in the road.

Although it may have been simpler to generate a table of inundated road sections using the Stack Profile tool as initially intended, a possibly more difficult effort would have been needed to ground truth the results, as they would not necessarily have been easy to display on screen. It would have been hard to visibly discern and resolve problems as well, as some additional preprocessing would have been needed to fill the missing grids with an appropriate water surface elevation.

¹ The [Puget Sound Partnership Report: Near-Term Action WSDOT Floodplain Impacts Methodology for Bridges](#) describes how the levee breach scenario that resulted in the highest water surface elevation was added to the grid data. This was not used in identifying the highway segments susceptible to flooding, but provided additional information to support evaluations of potential adaptations to the highway system described in Appendix B.

The maximum depth values also required some close examination. Although now represented on a 6-foot grid, we noticed when examining profiles that sometimes cross ditches were represented in the topographic surface representing the area occupied by the highway. These problems occurred where the highway had been widened after the LiDAR data had been collected or where there was adequate LiDAR scatter around a bridge structure, so that when the data was processed, the channel banks and water surfaces were the lowest elevation returns rather than the bridge deck.

As an added benefit, we used the resulting maximum depth grids to look at other features in the project area for sensitivity to flooding that could not be accessed with the Corps-provided grids. Also, by examining the depth grids, we were able to roughly delineate flow paths and identify, at least coarsely, where the floodwaters would flow over the highway.

We found that in some locations, the DEM was well aged and did not incorporate projects (e.g., SR20/SR536 Indian Slough) that had been implemented since the topographic data was collected. Although there may be some false positives (areas that are indicated to flood but do not) or areas where the depths of flooding is overestimated, the DEM is still adequate as an element of a screening tool, as we would fully investigate individual sites early in the design process of any adaptation.

2.4 Results

Table 1 presents the summary length of state highway flooded under the worst-case condition for each return interval flood. Interestingly, a large segment on I-5 and SR 234 is flooded under the 25-year event and the 100-year event, but not the 50-year event; it appears that this occurs because of levee break scenarios. During the 10-year event, there is levee overtopping or failure in the downtown area of Mount Vernon; under the 50-year event, there is an upstream failure that diverts a portion of the flow and relieves the pressure on the downtown area levee system; and under the 100-year event, although the upstream failure still diverts floodwater, it is not enough to relieve the pressure on the downtown area levee and it is overtopped. Table 2 provides a more detailed description of at risk segments of highway.

Table 1 – Summary of Length of the State Highway System Inundated Under the Worst-Case Flood Scenarios for Each Annual Chance of Exceedance.

State Route	Annual Chance of Exceedance									
	10 Percent		4 Percent		2 Percent		1 Percent		0.2 Percent	
	feet	miles	feet	miles	feet	miles	feet	miles	feet	miles
5	--	--	35,680	6.76	17,056	3.23	47,247	8.85	52,614	9.96
9	3,071	0.58	7,432	1.41	10,799	2.05	13,897	2.63	20,283	3.84
11	--	--	11,411	2.16	3,844	0.73	14,931	2.83	47,087	8.92
20	730	0.14	47,555	9.01	44,928	8.51	62,026	11.75	70,692	13.39
534	--	--	2,170	0.41	--	--	2,211	0.42	3,313	0.63
536	--	--	8,440	1.60	10,119	1.92	19,136	3.62	2,938	5.63
538	--	--	882	0.17	6,761	1.28	7,135	1.35	7,847	1.49
Total	3,801	0.72	113,570	21.52	16,880	3.20	166,583	31.53	204,774	43.86

Table 2 – Highway Segments At Risk by Flood Scenario

State Route	Annual Chance of Exceedance Percent	Highway Segment		Length		Maximum Depth	Highway Segment at Risk from Each Breach Scenario													
		Milepost Start Miles	Milepost End Miles				Annual Chance of Exceedance (%) and Breach Location (River Mile)													
				10% ACE				4% ACE				2% ACE				1% ACE				
		--	4.64	12.39	13.79	21.59	16.79	17.89	4.65	8.28	12.39	13.79	16.78	17.89	21.59					
5	4	224.69	219.95	25,070	4.75	10.6	--	--	X	--	--	--	--	--	--	X	--	X	--	--
5	4	228.85	228.66	1,023	0.19	4.6	--	--	--	--	X	X	X	X	X	X	X	X	X	X
5	4	228.89	228.98	499	0.09	4.9	--	--	--	--	X	X	X	X	X	X	X	X	X	X
5	4	229.30	229.27	148	0.03	3.3	--	--	--	--	X	X	X	X	X	X	X	X	X	X
5	4	229.40	229.39	73	0.01	1.7	--	--	--	--	X	X	X	X	X	X	X	X	X	X
5	4	229.45	229.41	209	0.04	0.9	--	--	--	--	X	--	X	X	X	X	X	X	X	X
5	4	229.58	229.52	296	0.06	3.6	--	--	--	--	X	--	X	X	X	X	X	X	X	X
5	4	230.41	230.82	2,137	0.40	5.2	--	--	--	--	X	--	X	X	X	X	X	X	X	X
5	4	232.10	231.06	5,495	1.04	5.1	--	--	--	--	X	--	--	X	X	X	X	X	X	X
5	4	233.00	232.86	730	0.14	2.3	--	--	--	--	X	X	--	X	X	X	X	X	X	X
5	2	227.32	227.64	1,676	0.32	9.6	--	--	--	--	--	X	--	--	--	--	--	X	--	--
5	2	227.84	228.06	1,189	0.23	10.8	--	--	--	--	--	X	--	--	--	--	--	X	--	--
5	2	228.85	228.66	979	0.19	6.1	--	--	--	--	X	X	X	X	X	X	X	X	X	X
5	2	229.70	229.38	1,642	0.31	5.4	--	--	--	--	X	--	X	X	X	X	X	X	X	X
5	2	230.62	230.41	1,100	0.21	4.6	--	--	--	--	X	--	X	X	X	X	X	X	X	X
5	2	233.02	232.82	1,051	0.20	1.5	--	--	--	--	X	X	--	X	X	X	X	X	X	X
5	1	219.90	225.03	27,129	5.14	13.8	--	--	X	--	--	--	--	--	--	X	--	X	--	--
5	1	227.26	227.64	2,019	0.38	9.3	--	--	--	--	--	X	--	--	--	--	--	X	--	--
5	1	227.84	228.17	1,737	0.33	11.2	--	--	--	--	--	X	--	--	--	--	--	X	--	--
5	1	228.63	229.79	6,106	1.16	7.0	--	--	--	--	--	X	X	X	X	X	X	X	X	X
5	1	230.41	232.36	10,256	1.94	8.0	--	--	--	--	--	X	--	X	X	X	X	X	X	X
9	10	52.03	51.86	919	0.17	1.6	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	10	53.42	53.22	1,073	0.20	3.6	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	10	53.92	54.12	1,079	0.20	7.6	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	4	52.05	51.74	1,641	0.31	6.9	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	4	52.53	52.37	841	0.16	1.3	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	4	53.06	53.65	3,167	0.60	6.5	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	4	53.89	54.23	1,783	0.34	10.5	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	2	51.99	51.88	581	0.11	8.5	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	2	52.37	52.57	1,049	0.20	3.5	--	X	X	X	X	X	X	X	X	X	X	X	X	X
9	2	53.01	53.45	2,302	0.44	8.6	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	2	53.63	54.24	3,261	0.62	12.3	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	2	54.76	55.45	3,606	0.68	2.6	--	--	--	--	--	X	X	X	X	X	X	X	X	X
9	1	51.73	52.06	1,768	0.33	10.1	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	1	52.36	52.59	1,254	0.24	5.0	--	X	X	X	X	X	X	X	X	X	X	X	X	X
9	1	52.74	53.46	3,811	0.72	9.7	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	1	53.65	54.26	3,245	0.61	13.0	X	X	X	X	X	X	X	X	X	X	X	X	X	X

State Route	Annual Chance of Exceedance	Highway Segment		Length	Maximum Depth	Highway Segment at Risk from Each Breach Scenario															
		Milepost Start	Milepost End			Annual Chance of Exceedance (%) and Breach Location (River Mile)															
						10% ACE	4% ACE				2% ACE		1% ACE								
							Percent	Miles	Miles	Feet	Miles	Feet	4.64	12.39	13.79	21.59	16.79	17.89	4.65	8.28	12.39
9	1	54.71	55.44	3,819	0.72	3.4	--	--	--	--	--	X	X	X	X	X	X	X	X	X	X
11	4	0.14	1.92	9,559	1.81	5.2	--	--	--	--	X	X	X	X	X	X	X	X	X	X	X
11	4	2.55	2.90	1,852	0.35	6.0	--	--	--	--	X	--	--	X	X	X	X	X	X	X	X
11	2	0.14	1.80	8,941	1.69	3.9	--	--	--	--	X	X	X	X	X	X	X	X	X	X	X
11	1	0.14	2.96	14,931	2.83	6.8	--	--	--	--	X	X	X	X	X	X	X	X	X	X	X
20	10	62.70	62.57	730	0.14	1.7	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
20	4	58.64	52.70	31,433	5.95	10.3	--	--	--	X	X	X	X	X	X	X	X	X	X	X	X
20	4	59.68	59.42	1,370	0.26	2.0	--	--	--	--	X	--	X	X	X	X	X	X	X	X	X
20	4	59.91	59.80	573	0.11	1.2	--	--	--	--	X	--	--	X	X	X	X	X	X	X	X
20	4	59.97	59.94	171	0.03	1.2	--	--	--	--	X	--	--	X	X	X	X	X	X	X	X
20	4	60.75	60.22	2,853	0.54	3.5	--	--	--	--	X	--	--	X	X	X	X	X	X	X	X
20	4	63.03	60.91	11,155	2.11	7.9	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
20	2	58.95	52.70	33,081	6.27	10.5	--	--	--	X	X	X	X	X	X	X	X	X	X	X	X
20	2	59.68	59.42	1,411	0.27	2.7	--	--	--	--	X	--	X	X	X	X	X	X	X	X	X
20	2	63.14	61.16	10,436	1.98	6.3	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
20	1	58.98	51.54	39,325	7.45	12.0	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
20	1	63.21	59.31	20,665	3.91	9.5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
20	1	64.13	63.75	2,036	0.39	1.0	--	--	--	--	--	--	--	X	X	X	X	X	X	X	X
534	4	0.08	0.50	2,170	0.41	12.1	--	--	X	--	--	--	--	--	--	X	--	X	--	--	--
534	1	0.07	0.49	2,211	0.42	14.2	--	--	X	--	--	--	--	--	--	X	X	X	--	--	--
536	4	0.21	0.00	2,101	0.40	3.0	--	--	--	--	X	X	X	X	X	X	X	X	X	X	X
536	4	1.19	0.00	6,339	1.20	4.0	--	--	--	--	X	X	X	X	X	X	X	X	X	X	X
536	2	0.21	0.00	2,101	0.40	4.0	--	--	--	--	X	X	X	X	X	X	X	X	X	X	X
536	2	1.51	0.00	8,018	1.52	5.0	--	--	--	--	X	X	X	X	X	X	X	X	X	X	X
536	1	0.21	0.00	2,107	0.40	4.0	--	--	--	--	X	X	X	X	X	X	X	X	X	X	X
536	1	1.89	0.00	10,023	1.90	4.6	--	--	--	--	X	X	X	X	X	X	X	X	X	X	X
536	1	4.70	3.37	7,005	1.33	8.9	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--
538	4	2.57	2.73	882	0.17	1.6	--	X	X	X	X	X	X	X	X	X	X	X	X	X	X
538	2	0.00	0.99	5,456	1.03	14.9	--	--	--	--	--	X	--	--	--	--	--	X	--	--	--
538	2	2.51	2.75	1,305	0.25	3.5	--	X	X	X	X	X	X	X	X	X	X	X	X	X	X
538	1	0.00	1.00	5,491	1.04	15.3	--	--	--	--	--	X	--	--	--	--	--	X	--	--	--
538	1	2.46	2.77	1,644	0.31	4.9	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Based on the screening data, it appears that there are two locations, one on SR 20 and one on SR 9, where floodwater would flow over the highway during a 10 percent Annual Chance of Exceedance (ACE) flood event, and these areas should be highlighted as areas of concern. Several other locations along SR 9 and SR 538 appear to be inundated under the 10 percent ACE flood event by backwater on the Skagit River causing overflow and accumulation of floodwaters in the Nookachamps basin.

Figure 3 shows the previously identified areas of concern, the affected highway segments, and an index of areas covered by Figures 4 through 9. Figures 4 through 9 provide a more detailed interpretation of the flood hazard conditions; depicting the flood flow paths and noting the maximum depths under the 4 percent and 1 percent worst-case flood conditions.

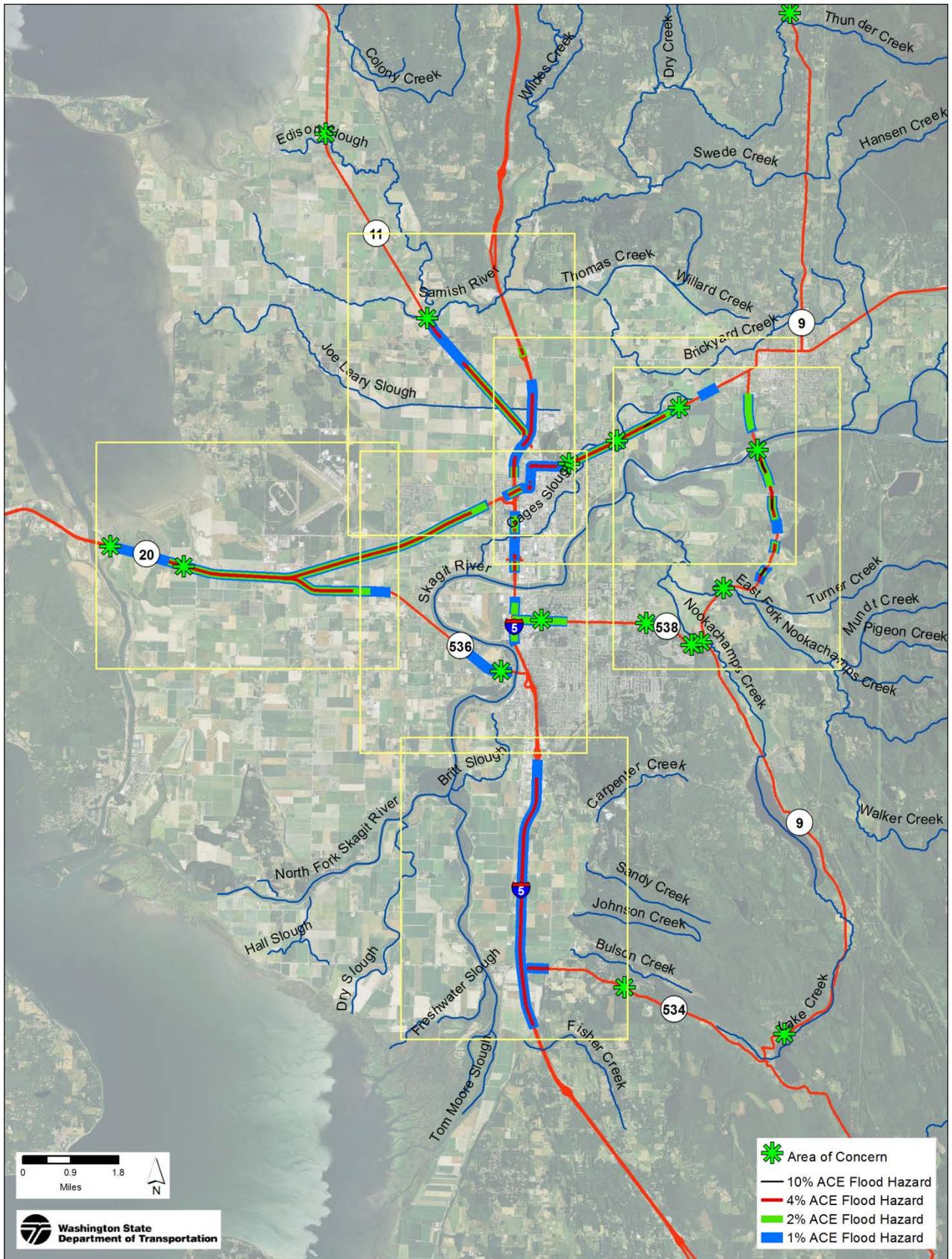


Figure 3 Highway Segments and Areas of Concern

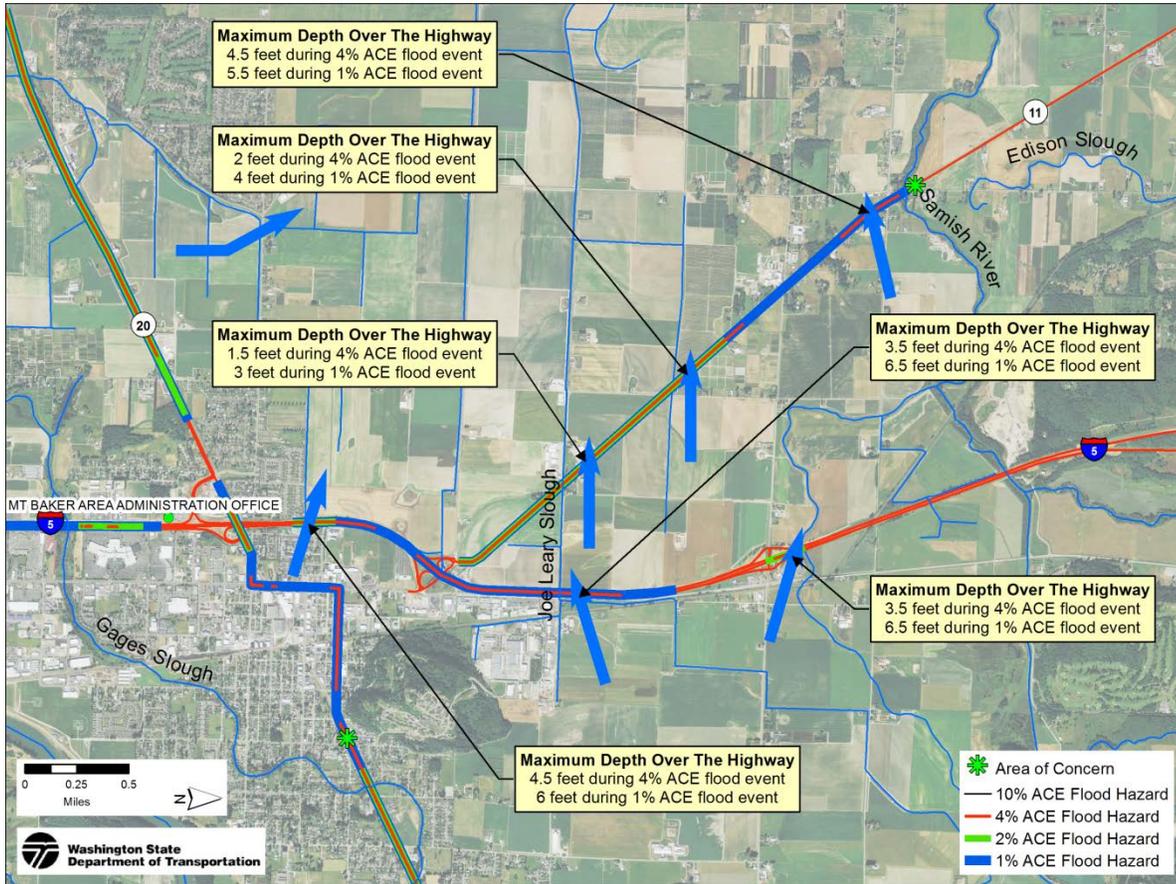


Figure 4 I-5 North

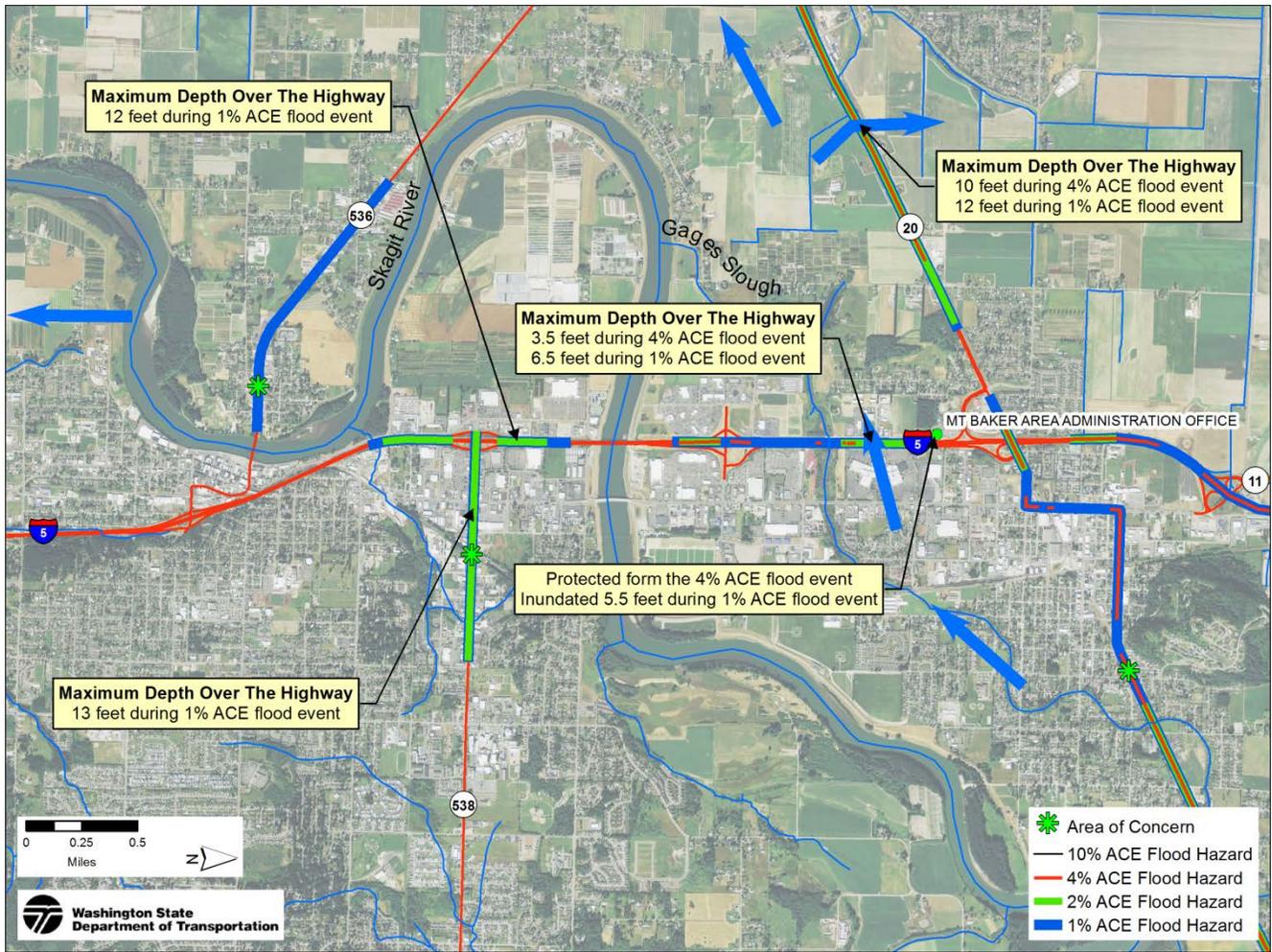


Figure 5 I-5 Central

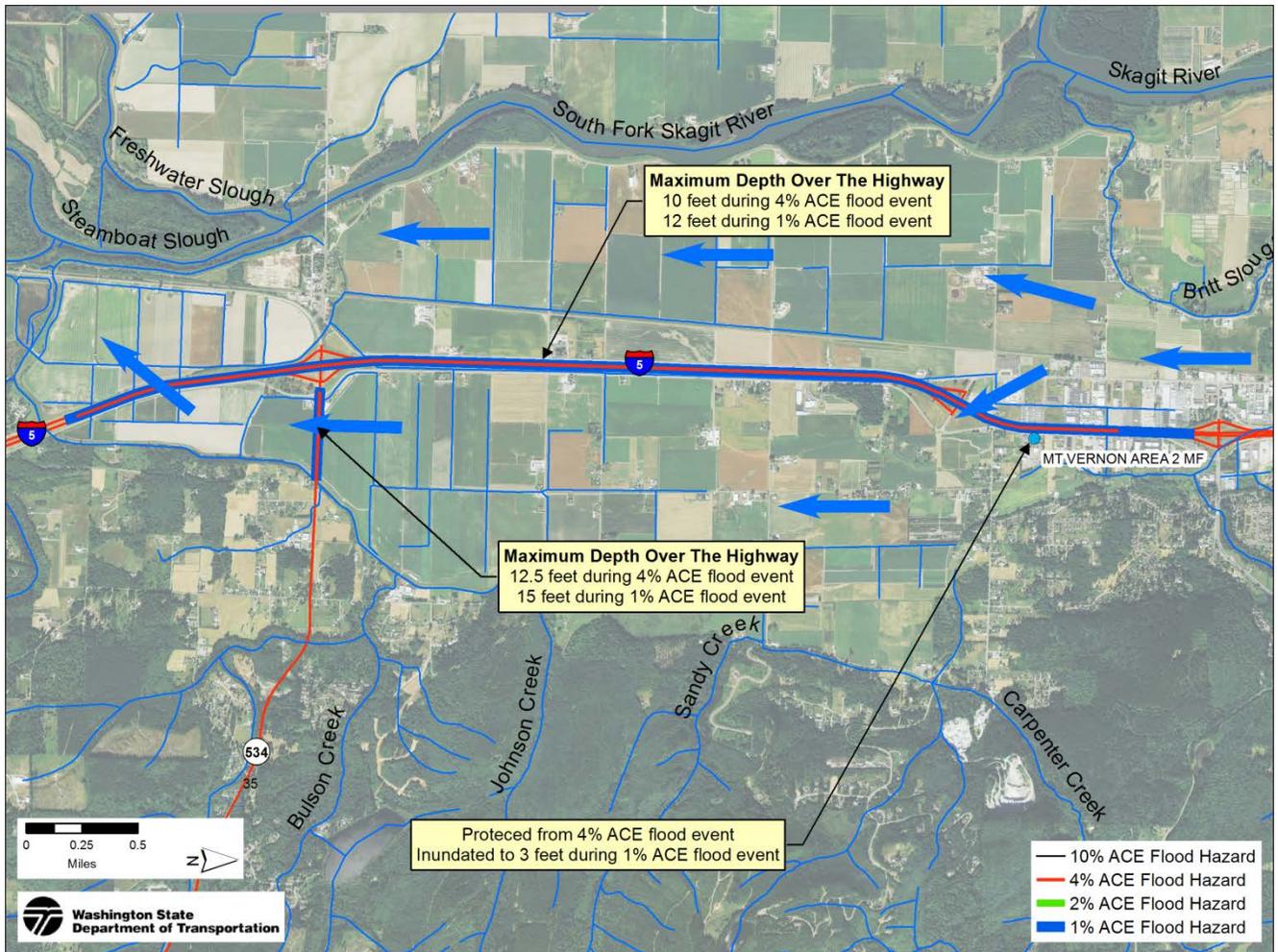


Figure 6 I-5 South

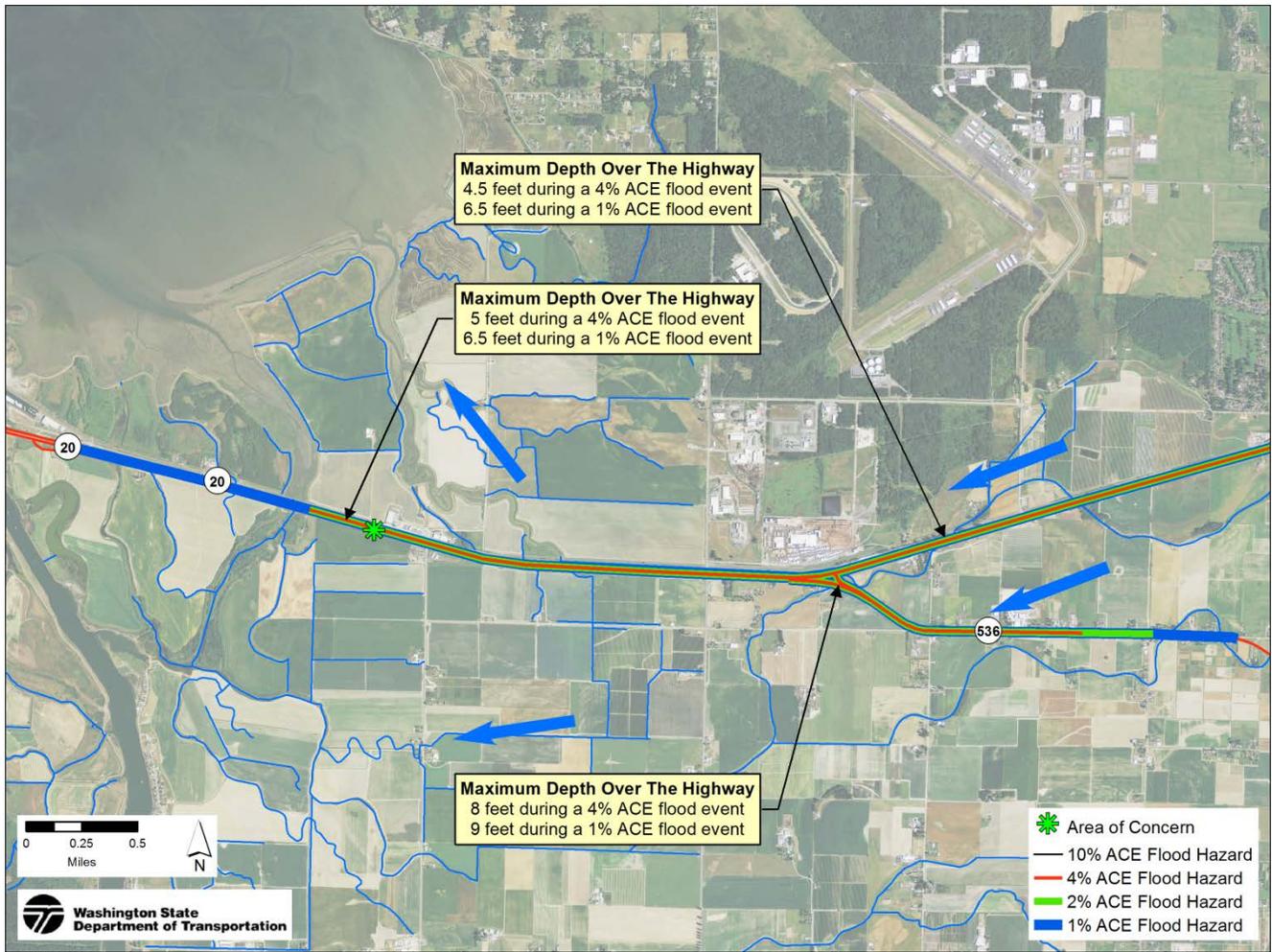


Figure 7 SR 20 West

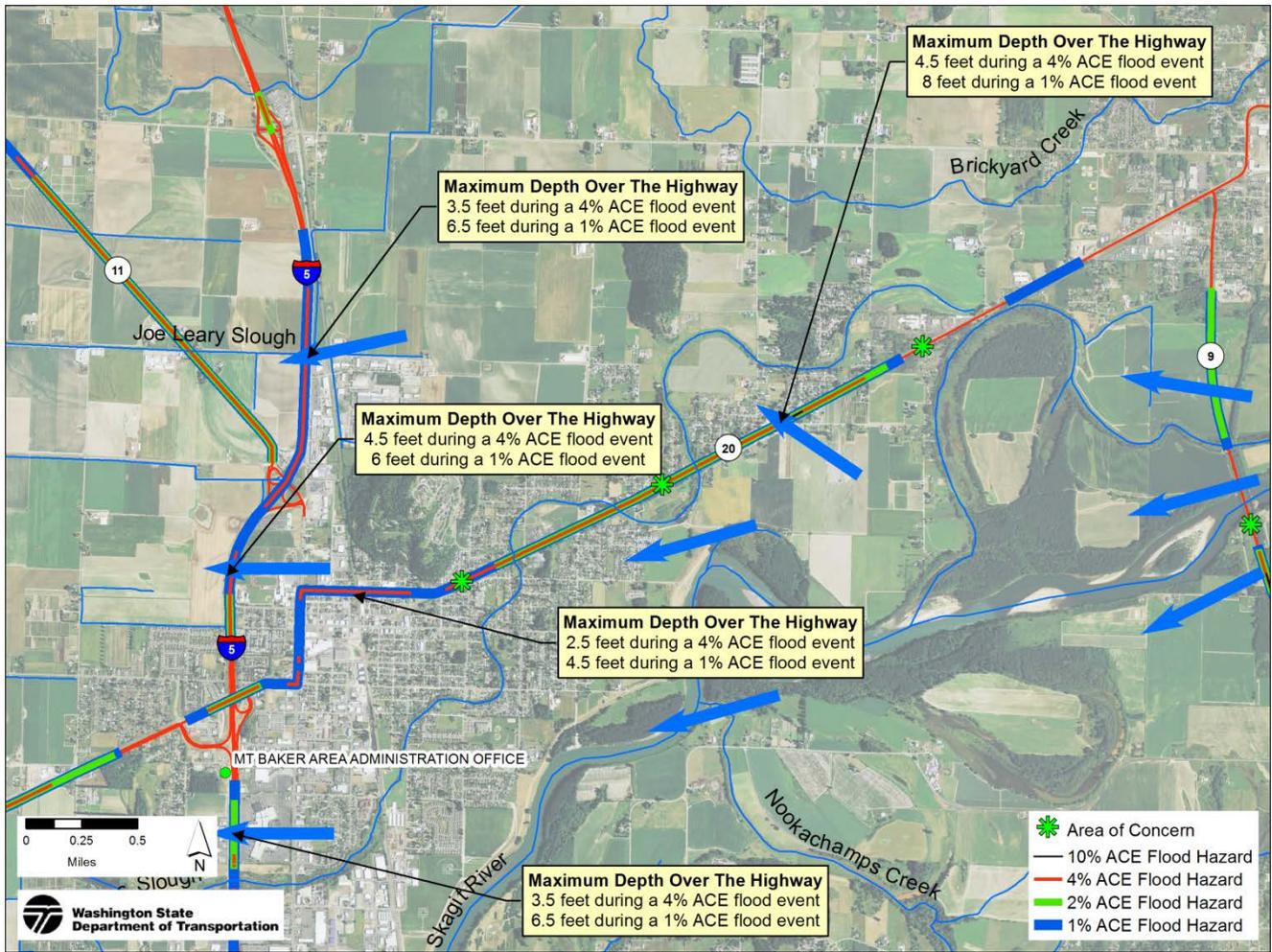


Figure 8 SR 20 East

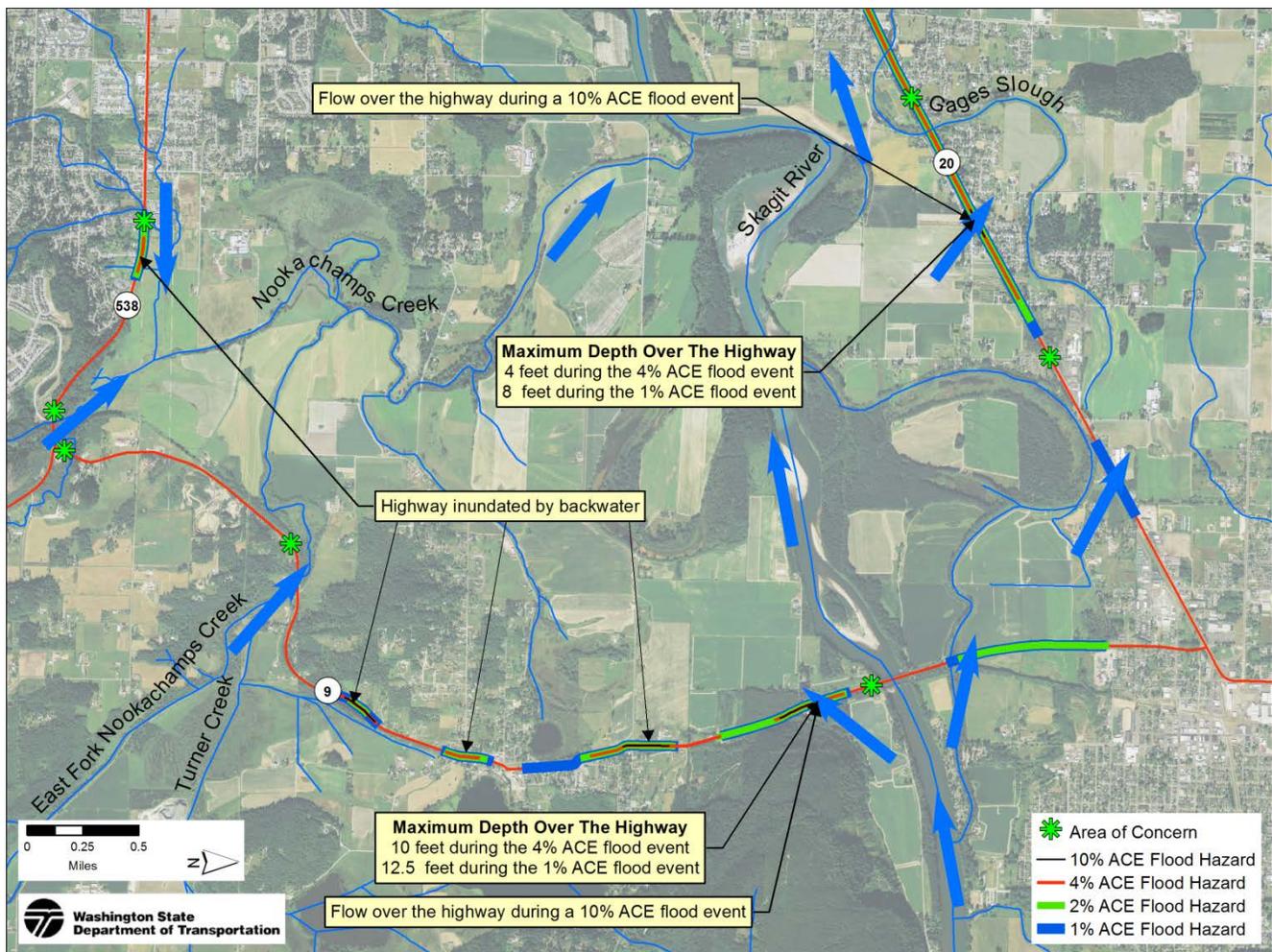


Figure 9 SR 9

2.5 Lessons Learned

We learned several lessons during the process, some of which were related to problems using the ArcView tools, but also others that were critical to the process.

1. **Coordinate Early** – Coordinate and partner with cooperating agencies early in the process to ensure special data or model outputs are selected without having to backtrack, redo, or rerun models to get appropriate data.
2. **Know Your Data** – Review and understand the data before developing analysis processes and procedures. Developing a process without the data in hand may cause problems, as you may not be able to conduct the analyses and provide the answers that were desired and anticipated by other members or partners of the project team. In this case, what we thought was a very easy ArcView process of intersecting lines with grid data, evolved into a much more labor-intensive manual process. It was not possible for us to identify the severity of hazards related to the velocity of floodwaters over the highway, because, as shown in [Figure 2](#), the FLO-2D model did not provide that output.

3. **Use Staff with Resource-Specific Understanding** – Although the processes we developed appear simple and ripe for fully exploiting the capabilities of ArcView to identify highway segments susceptible to flooding, we found that the data available was not useable in its original form. Understanding the local flood conditions allowed us to confidently use the water surface elevation data to create more detailed floodwater depth maps. While manually delineating susceptible highway segments, it was possible for us to work through gaps in the data, discontinuities caused by edges on the water surface grids, and discontinuities caused by the limitations of the DEM. Without an operator that had at least a basic understanding of how the model data was created, the data gaps or discontinuities may have underestimated potential flood hazards, provided false positives, and overestimated the depth of flooding.

Bridges

In response to the Puget Sound Partnership Action Agenda, Near Term Actions (NTA), WSDOT previously developed a screening methodology to identify bridges located within floodplains and prioritize them based on floodplain impacts. Figure 10 shows the FEMA Q3 floodplain and state highway transportation features, including the bridges.

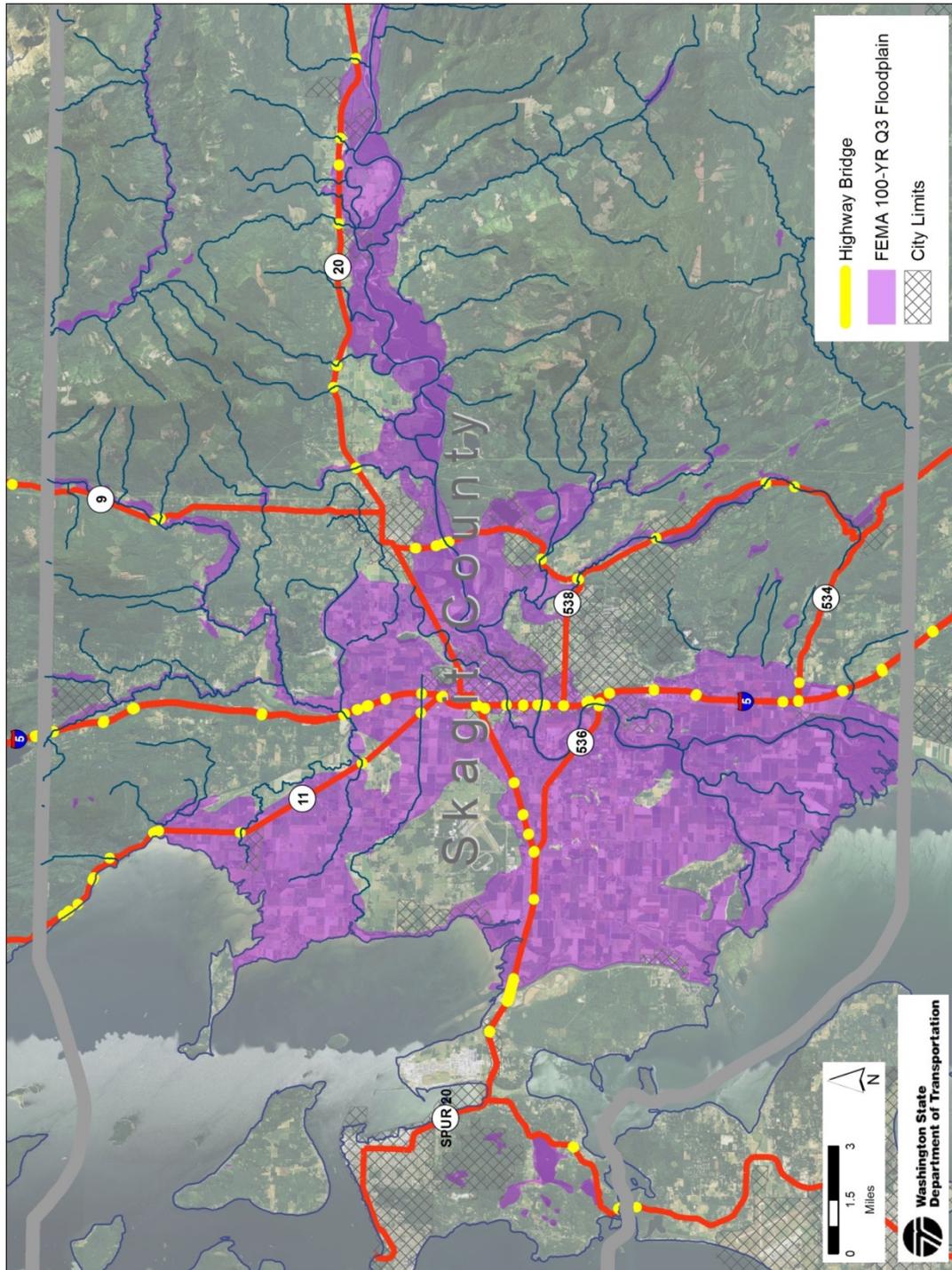


Figure 11 – FEMA Q3 Floodplain and State Highway Bridges in Skagit County

This pilot project provided us an opportunity to apply and test those methods with the Skagit Valley. Because this analysis was not dependent of the Corps GI/EIS, we applied it county wide. As described in the PSP Action Agenda memo outlining the methodology, bridges that confine the active river channel have the potential to dramatically impact the floodplain. This is due to the fact that the size of a bridge relative to the floodplain crossing affects every floodplain process and function, including channel migration; formation of side channels and other aquatic, wetland, or riparian habitats; floodplain storage; sediment transport; large woody material (LWM) recruitment and transport; and flood flow conveyance.

One of the key problems with bridges is that they force all flows through single openings. Although those openings may provide adequate cross-sectional area to convey the flows, the configuration of the openings do not mimic natural channel/floodplain configurations. Consequently, bridges locally cause increased depths and velocities of floodwaters, which in turn may cause scour of the bridge piers and abutments. The local effects of bridges may also cause a disruption of the sediment transport continuity, causing channel degradation or aggradation in the reaches above or below the bridge. This may affect channel migration processes as well as associated aquatic and riparian habitats.

Consequently, the screening methodology uses the ratio of bridge opening to floodplain width (S/FW) as the primary driver of floodplain impact and then modifies that value by considering the number of traffic lanes (PW), a land use development modifier (PD), a presence of estuary modifier (ES), and a climate change vulnerability modifier (CV):

$$S/FW-PW+PD-ES-CV$$

Where:

- S/FW = primary driver of floodplain impact
- PW = number of traffic lanes
- PD = land use development
- ES = presence of an estuary
- CV = climate change vulnerability

The following describes our efforts to gather the required data to apply the screening methodology and identify areas where data acquisition or interpretation was more complicated than we anticipated.

3.1 Methods

We extracted a list of bridges for Skagit County from WSDOT's transportation facilities GIS database. We then refined the list to eliminate grade separations and other bridges that are not associated with 4th order or higher streams or rivers. We further reduced the resulting list of 60 bridges to 49 water crossings, as 11 bridges were parallel structures created by separate bridges for each direction of traffic on divided highway segments of I-5 and SR 20.

Most of the modifier information can be quickly collected for each bridge, number of lanes, and land use development by using aerial photography, either within the agency's GIS database or simply using Bing or Google Maps available on the Internet. Climate change vulnerability had been previously assessed (cite the CIVA report).

The bridge span opening information was a bit more time-consuming to gather, as we had to query the WSDOT Bridge Engineering Information System for each bridge, and we had to examine the layout plans to determine the width. We took care to review all the layout sheets, because in some cases the bridges had

been modified or replaced over time. (Note: Although WSDOT has a GIS layer containing bridges, the lengths in this database do not necessarily match the lengths shown on the layout sheets; presumably, the lengths in this GIS coverage were based on photo interpretation and may have been adequate for this level of screening).

Applying the estuary modifier was not clear cut. The Skagit and Samish Rivers provide freshwater inputs to Skagit, Padilla, and Samish Bays. The methodology specifically called out estuaries such as the Duwamish, Puyallup, and Deschutes to *not* receive an estuary modifier because the Ports of Seattle, Tacoma, and Olympia, respectively, have extensively developed these estuaries. The Skagit and Samish deltas have largely been reclaimed from their associated estuaries with dikes and ditches for mostly agricultural uses. Though these are recognized as agricultural areas of “statewide importance,” there is pressure to restore estuary functions as part of the Puget Sound Nearshore Estuary Restoration Project (PSNERP) by removing tide gates and dikes and restoring some tidal channels. Although the Skagit River is tidal above the I-5 crossings, the I-5 corridor is largely developed and constrained by a levee system. This makes it unlikely that there would be significant estuary functions that could be altered by changing the configuration of the WSDOT bridges. As a result, we identified only the SR 11 crossing Colony Creek/McElroy Slough as having had potential for improved estuary functions.

The floodplain width is the most difficult feature to measure and interpret. Assigning the floodway width brought up three significant issues:

1. The Skagit River floodplain extends from wall to wall of the valley and across the entire delta. Along the I-5 corridor, the floodplain is approximately 7 miles wide. Along with state highways, there are numerous county roads, railroads, levees, and urban centers that impact and prevent restoration of floodplain functions. These conditions led us to several questions:
 - Should the floodplain width be segmented and applied to each crossing?
 - How should the floodplain be segmented?
 - What about other bridge structures, such as grade separations, that do not cross active water courses but would act as conveyance features during extreme flood events?

Along the I-5 corridor, we decided to attribute the floodplain width only to the area that the active channels could move or would be allowed to move (effective floodplain width). The effective floodplain width was assumed to be the distance between the levees for the Skagit and Samish Rivers, between the topographic channel banks for poorly defined ditches, or the top of the banks for maintained drainage facilities.

2. As is common in rural communities, only major rivers like the Skagit, Samish, and Sauk have detailed Special Flood Hazard Area (SFHA) studies and maps. Minor streams are not analyzed, although there may be a flood hazard and a significant investment in road crossings and associated infrastructure. We found that where minor streams were crossed by state highways and a SFHA is mapped, the SFHA is likely a result of a backwater condition or floodplain inundation related to one of the major rivers; it doesn’t necessarily reflect the floodplain or any analysis of that minor stream. It was also found that some crossings had no floodplains mapped.

In these situations, some professional judgment is needed to select a floodplain width. We used the NRCS County Soils map and DNR Geology maps to identify areas of hydric soils and river wash materials, respectively, that were likely subject to frequent flooding. We used aerial photographs, scour reports, and

photos of the bridges in the WSDOT Bridge Engineering Information System to refine or estimate the widths of the floodplains at these crossings.

3. The Corps' Skagit River GI is investigating flood hazard reduction measures for the Skagit Valley, including bypass channels that parallel SR 20 and Joe Leary Slough that could result in improved conveyance channels intersected by SR 20 and SR 11 west of I-5. The Corps' GI is also investigating setback and improved levees around the urban centers that could impact WSDOT's bridges along the I-5 corridor. Should we consider actions planned by other entities when determining the effective floodplain width? Although, in the long-term, we may implement projects that may cause WSDOT to reevaluate the function of bridges in the Skagit River floodplain, at this time we determined it was speculative to assign higher priority or sensitivity to bridges in these study areas in evaluating needs for a NTA.

3.2 Additional Modifiers

When looking at a SFHA map, it is not possible to identify the depth and velocity of water in the floodplain. Although susceptible to inundation and providing floodplain storage, much of the floodplain may not be contributing to channel migration functions; formation of side channels and other aquatic, wetland, or riparian habitats; sediment transport; or LWM recruitment and transport.

Along major rivers, where we have completed detailed floodplain analyses, there are several other metrics that could be included to better identify facilities that have floodplain impacts. The FEMA flood profiles identify the low and high cords of bridge structures as well as plotting the water surface elevations for several return interval floods. From this data, we can see where a bridge may not have adequate freeboard to pass debris during a flood or could be overtopped, and where the bridge and its approaches are constricting the flood flows, increasing the water surface elevation immediately upstream of the bridge.

We added the following metrics to assist with prioritization:

1. **Detailed Study (DS)** – Yes: no adjustment; No: add 0.5. Without a detailed study of the particular bridge crossing, there is a substantial level of uncertainty about the adequacy of the crossing and its potential to impact floodplain functions. This is especially true where a SFHA is mapped as a result of backwater conditions from another water course. Adding to the score decreases its priority.
2. **Freeboard (FB)** – Yes: no adjustment; No: subtract 0.02 if there is less than 3 feet of freeboard (F) above the 100-year profile; subtract 0.10 if there would be a pressure flow (P) condition for the 100-year profile; or subtract 0.20 if the bridge would be overtopped (O) by the 100-year profile. Bridges without adequate freeboard may be considered deficient, and planning may be already underway for a replacement. Subtracting from the score increases the priority. It is desirable to have floodplain functions fully evaluated if a bridge replacement project is in the planning stages.
3. **Head Loss (HS)** – No: no adjustment; Yes: subtract 0.06 if observable on 10-year (10%) profile (10); 0.04 if observable on 50-year (2%) profile (50); or 0.02 if observable on 100-year profile (100). Subtracting from the score increases the priority. The rationale for increasing correction for increasing return interval is that many ecologically important functions occur in the active channel and on the floodplain at less than the 100-year (1%) return interval flood.

3.3 Results

Table 3 provides a summary of the bridge identification and the scoring conducted according to the initial screening methodology and a revised scoring with the additional metrics. Interestingly, the results gave the highest initial ranking to a drainage ditch along I-5 (BN 5/719E) that appears to convey agricultural drainage from a relatively small area and provide flood conveyance when the Skagit and or Samish Rivers overflow during significant flood events. Even with the revised scoring metrics, it still ranks highly, as topographically, the overflow pathway appears to be large compared to the bridge opening. The original methodology did not highly prioritize the SR 9 (BN 9/223) bridge over the Samish River because the floodplain is locally narrow. However, the flood profile (Panel 11P) shows that the bridge would be overtopped in a 100-year flood event. It also shows that, even during more frequent flood events, there is head loss through the bridge. This indicates that flows may be constricted by the bridge, possibly making the bridge and abutments susceptible to scour as well as causing channel formation effects up- and downstream of the bridge. The revised scoring method brings the ranking of BN9/223 up 16 places.

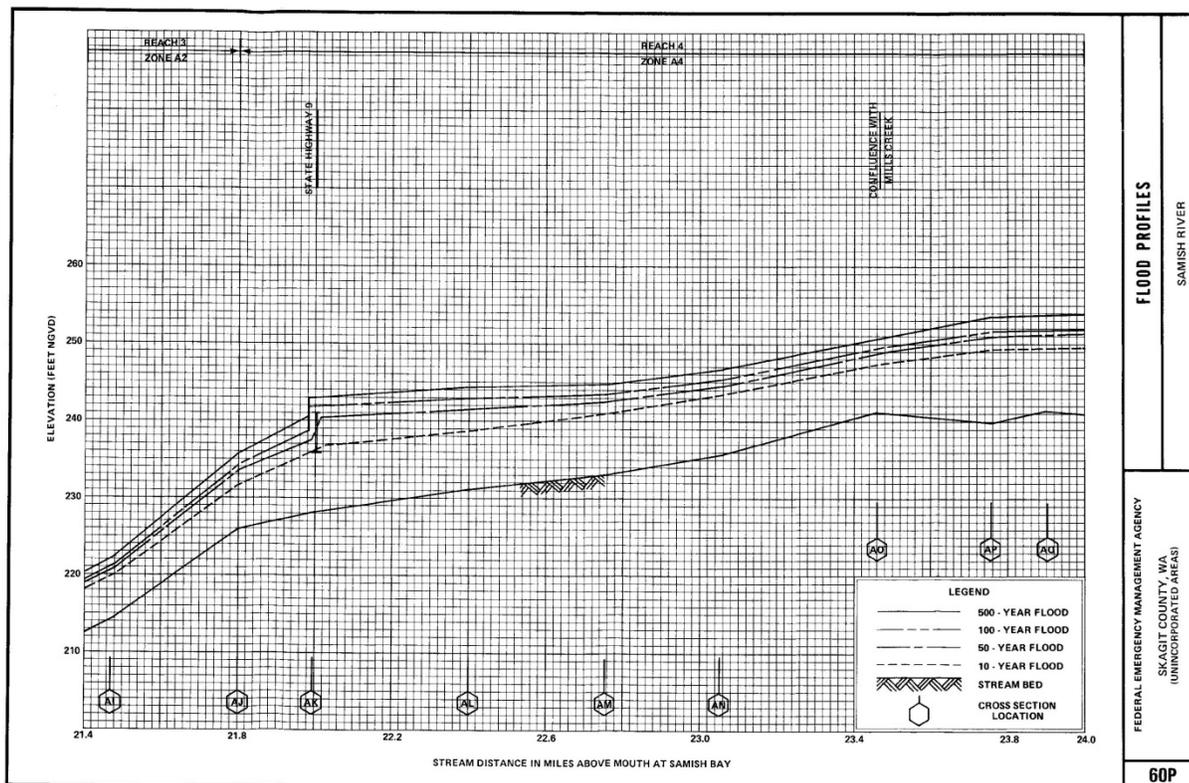


Figure 12 Profile Panel 60P

3.4 Lessons Learned

We learned several lessons during the process, some of which were related to problems with using the ArcView tools; however, others were critical to the process.

1. **Know Your Data** – Review and understand the data before developing analysis processes and procedures. Developing a process without the data in hand may cause problems, as you may not be able to conduct the analyses and provide the answers that were desired and anticipated by others. In this case, what we

thought was a very easy process of measuring the lengths of lines across the special flood hazard zone shown on the FEMA Q3 data, evolved into a much more labor-intensive process that relied on user interpretation of the data.

2. **Use Staff with Resource-Specific Understanding** – Although the processes developed appear simple to implement, they required some level of interpretation by an operator familiar with the floodplain mapping process. Without some professional judgment, we would rank bridges that appear to span wide developed floodplains higher than bridges that are in danger of being washed out during significant flood events.

Lee, Se-Yeun, A.F. Hamlet, 2011. Skagit River Basin Climate Science Report. Prepared for Skagit County and the Envision Skagit Project. Prepared by the University of Washington Department of Civil and Environmental Engineering and The Climate Impacts Group.

Chen, Y. H. and B. A. Anderson. Development of a methodology for estimating embankment damage to flood overtopping. (FHWA/RD-86/126) Prepared for FHWA – Office of Engineering and Highway Operations, McLean, VA. Prepared by Simons, Li & Associates, Fort Collins, CO.

Table 3 – Summary of Bridge Screening for Skagit County

BRIDGE IDENTIFICATION				BRIDGE SCREENING METHODOLOGY							REVISED BRIDGE SCREENING METHODOLOGY								
County	Route	Crossing Name	Bridge No.	S/FW	PW	PD	ES	CV	Total Score	Rank	Detailed Study	Freeboard	Head Loss	DS	FB	HL	Revised Total Score	Revised Rank	Change
Skagit County	5	SAMISH R	5/720E	0.22	0.02	0	0	0.02	0.18	3	Y	Y	N	0	0	0	0.18	1	2
Skagit County	530	SAUK RIVER BRIDGE	530/207	0.41	0.01	0	0	0.03	0.37	12	Y	Y	N	0	0	0	0.37	2	10
Skagit County	9	SAMISH RIVER	9/223	0.42	0.01	0.25	0	0.02	0.64	19	Y	O	10	0	-0.2	-0.06	0.38	3	16
Skagit County	5	DRAINAGE DITCH	5/719E	0.11	0.02	0	0	0.02	0.07	1	N	Y	N	0.5	0	0	0.57	4	-3
Skagit County	20	HANSEN CREEK	20/229	0.16	0.01	0	0	0.03	0.12	2	N	Y	N	0.5	0	0	0.62	5	-3
Skagit County	20	E FK RED CABIN CR	20/241	0.25	0.01	0	0	0.03	0.21	4	N	Y	N	0.5	0	0	0.71	7	-3
Skagit County	20	BACON CR	20/280	0.26	0.01	0	0	0.03	0.22	5	N	Y	N	0.5	0	0	0.72	8	-3
Skagit County	20	SR 20 OVER DAMNATION CR	20/283	0.31	0.01	0	0	0.03	0.27	6	N	Y	N	0.5	0	0	0.77	9	-3
Skagit County	20	HIGGINS SLOUGH	20/220N	0.33	0.02	0	0	0.03	0.28	7	N	Y	N	0.5	0	0	0.78	10	-3
Skagit County	9	BATEY SL	9/217	0.08	0.01	0.25	0	0.02	0.30	8	N	Y	N	0.5	0	0	0.80	11	-3
Skagit County	20	DRAINAGE DITCH	20/213.5 A	0.36	0.01	0	0	0.03	0.32	9	N	Y	N	0.5	0	0	0.82	12	-3
Skagit County	20	JONES CR	20/238	0.15	0.01	0.25	0	0.03	0.36	10	N	Y	N	0.5	0	0	0.86	13	-3
Skagit County	9	W FK NOOKACHAMPS CREEK	9/208	0.15	0.01	0.25	0	0.02	0.37	11	N	Y	N	0.5	0	0	0.87	14	-3

BRIDGE IDENTIFICATION				BRIDGE SCREENING METHODOLOGY							REVISED BRIDGE SCREENING METHODOLOGY								
County	Route	Crossing Name	Bridge No.	S/FW	PW	PD	ES	CV	Total Score	Rank	Detailed Study	Freeboard	Head Loss	DS	FB	HL	Revised Total Score	Revised Rank	Change
Skagit County	5	FRIDAY CREEK	5/726E	0.40	0.02	0	0	0	0.38	13	N	Y	N	0.5	0	0	0.88	15	-2
Skagit County	530	WHITE CREEK BR	530/210	0.54	0.01	0	0	0.03	0.50	14	N	Y	N	0.5	0	0	1.00	16	-2
Skagit County	530	ROCKPORT BRIDGE	530/290	0.05	0.01	0.5	0	0.03	0.51	15	N	Y	N	0.5	0	0	1.01	17	-2
Skagit County	9	SKAGIT RIVER	9/215	0.33	0.01	0.75	0	0.02	1.05	28	Y	Y	N	0	0	0	1.05	18	10
Skagit County	20	ROCKY CR	20/271	0.60	0.01	0	0	0.03	0.56	16	N	Y	N	0.5	0	0	1.06	19	-3
Skagit County	9	HARTS SL	9/216	0.09	0.01	0.5	0	0.02	0.56	17	N	Y	N	0.5	0	0	1.06	20	-3
Skagit County	20	DIOBSUD CREEK	20/277	0.12	0.01	0.5	0	0.03	0.58	18	N	Y	N	0.5	0	0	1.08	21	-3
Skagit County	9	LAKE CR	9/205	0.18	0.01	0.5	0	0.02	0.65	20	N	Y	N	0.5	0	0	1.15	22	-2
Skagit County	5	HILL DITCH	5/702W	0.22	0.03	0.5	0	0	0.69	21	Y	Y	N	0.5	0	0	1.19	6	15
Skagit County	11	SAMISH RIVER	11/4	0.53	0.01	0.75	0	0.03	1.24	35	Y	Y	N	0	0	0	1.24	23	12
Skagit County	20	RED CABIN CREEK	20/238.5	0.30	0.01	0.5	0	0.03	0.76	22	N	Y	N	0.5	0	0	1.26	24	-2
Skagit County	11	OYSTER CR	11/8	0.88	0.01	0	0.06	0	0.81	23	N	Y	N	0.5	0	0	1.31	25	-2
Skagit County	20	SWIFT CREEK	20/268	0.98	0.01	0	0	0.03	0.94	24	N	Y	N	0.5	0	0	1.44	26	-2

BRIDGE IDENTIFICATION				BRIDGE SCREENING METHODOLOGY							REVISED BRIDGE SCREENING METHODOLOGY								
County	Route	Crossing Name	Bridge No.	S/FW	PW	PD	ES	CV	Total Score	Rank	Detailed Study	Freeboard	Head Loss	DS	FB	HL	Revised Total Score	Revised Rank	Change
Skagit County	20	SWINOMISH-D BERENTSON BR	20/211N	0.57	0.02	0.5	0.06	0.03	0.96	25	N	Y	N	0.5	0	0	1.46	27	-2
Skagit County	9	E FK NOOKACHAMPS CR	9/211	0.30	0.01	0.75	0	0.02	1.02	26	N	Y	N	0.5	0	0	1.52	28	-2
Skagit County	20	MEADOW CREEK	20/207.3	1.09	0.01	0	0	0.03	1.05	27	N	Y	N	0.5	0	0	1.55	29	-2
Skagit County	20	HIGGINS SLOUGH	20/214N	0.87	0.02	0.25	0	0.03	1.07	29	N	Y	N	0.5	0	0	1.57	30	-1
Skagit County	20	HIGGINS SLOUGH	20/217N	0.37	0.02	0.75	0	0.03	1.07	30	N	Y	N	0.5	0	0	1.57	31	-1
Skagit County	20	WISEMAN CR	20/235	0.64	0.01	0.5	0	0.03	1.10	31	N	Y	N	0.5	0	0	1.60	32	-1
Skagit County	5	GAGES SLOUGH	5/713E	0.17	0.02	1	0	0.02	1.13	32	N	Y	N	0.5	0	0	1.63	33	-1
Skagit County	20	BAKER R	20/259	0.24	0.01	1	0	0.03	1.20	33	N	Y	N	0.5	0	0	1.70	34	-1
Skagit County	9	THUNDER CREEK	9/222	0.26	0.01	1	0	0.02	1.23	34	N	Y	N	0.5	0	0	1.73	35	-1
Skagit County	9	LAKE CR	9/204	1.35	0.01	0	0	0.02	1.32	36	N	Y	N	0.5	0	0	1.82	36	0
Skagit County	20	GRANDY CR	20/256	0.62	0.01	0.75	0	0.03	1.33	37	N	Y	N	0.5	0	0	1.83	37	0
Skagit County	5	JOE LEARY SLOUGH	5/716E	0.97	0.02	0.5	0	0.02	1.43	38	N	Y	N	0.5	0	0	1.93	38	0
Skagit County	20	HIGGINS SLOUGH	20/223N	0.55	0.02	1	0	0.03	1.50	39	N	Y	N	0.5	0	0	2.00	39	0

BRIDGE IDENTIFICATION				BRIDGE SCREENING METHODOLOGY							REVISED BRIDGE SCREENING METHODOLOGY								
County	Route	Crossing Name	Bridge No.	S/FW	PW	PD	ES	CV	Total Score	Rank	Detailed Study	Freeboard	Head Loss	DS	FB	HL	Revised Total Score	Revised Rank	Change
Skagit County	9	S FK NOOKACHAMPS CR	9/210	0.84	0.01	0.75	0	0.02	1.56	40	N	Y	N	0.5	0	0	2.06	40	0
Skagit County	536	SKAGIT RIVER	536/15	1.15	0.01	1	0	0.03	2.11	43	Y	Y	N	0	0	0	2.11	41	2
Skagit County	20	ALDER CR	20/253	1.17	0.01	0.75	0	0.03	1.88	41	N	Y	N	0.5	0	0	2.38	42	-1
Skagit County	11	SR 11 OVER RR - BLANCHARD	11/7	1.79	0.01	0.25	0.06	0.03	1.94	42	N	Y	N	0.5	0	0	2.44	43	-1
Skagit County	5	TROOPER SEAN M O'CONNELL	5/712	1.22	0.02	1	0	0.02	2.18	44	N	Y	N	0.5	0	0	2.68	44	0
Skagit County	20	JACKMAN CREEK	20/262	2.44	0.01	0	0	0.03	2.40	45	N	Y	N	0.5	0	0	2.90	45	0
Skagit County	20	CANOE PASS	20/207	2.45	0.01	0	0	0.03	2.41	46	N	Y	N	0.5	0	0	2.91	46	0
Skagit County	20	MUDDY CREEK	20/247F	1.78	0.01	1	0	0.03	2.74	47	N	Y	N	0.5	0	0	3.24	47	0
Skagit County	20	MUDDY CR	20/247	2.34	0.01	1	0	0.03	3.30	48	N	Y	N	0.5	0	0	3.80	48	0
Skagit County	530	BOHS SLOUGH	530/289	#DIV/0!	0.01	0	0	0.03	#DIV/0!	49	N	Y	N	0.5	0	0	#DIV/0!	49	0

Puget Sound Partnership Report: Near-Term Action WSDOT Floodplain Impacts Methodology for Bridges ²

The request for development of floodplain priorities based on impact has two central aspects

1. Potential impact of approximately 500 bridges on floodplains draining to Puget Sound.
2. Potential impact of approximately 185 miles of roadway that traverse floodplains draining to Puget Sound.

Although roads and bridges are both components of the transportation infrastructure, they are built and managed very differently. They also affect floodplains in different ways. Because of these differences, evaluating floodplain impacts for bridges must take a different methodological path than evaluating floodplain impacts from roads.

Transportation impacts to floodplains are most dramatically expressed in the form of bridges that confine the active river channel as well as the floodplain. This is due to the fact that the size of a bridge relative to the flood plain crossing affects every floodplain process and function including channel migration, formation of side channels and other habitat, flood storage, sediment transport, and large woody material (LWM) recruitment and transport.

Bridges are both physically and temporally discrete structures. That means they have a discrete project life span that is separate from the roads to which they are attached. When a bridge has reached the end of its structural life, it is removed and replaced with a new structure. At the time of replacement new information related to engineering, highway use, and environmental impacts is brought to bear to improve and update the bridge design. This is the logical phase for making improvements, such as those that would lessen floodplain impacts.

Highway roadbeds, on the other hand, are not discrete structures with a given (and finite) project life span. Roads may be repaired, repaved, widened, etc., but it is very seldom that entire roads are removed and replaced. Rather, they go through a periodic process of maintenance, repair and occasional upgrade. This makes correcting deficiencies such as floodplain impacts much more difficult. Another way in which roads are not physically discrete is that they are attached to other WSDOT and non-WSDOT infrastructure (on and off ramps, arterials, local roads, rail crossings, driveways, utility lines and corridors, etc. If one desires to raise or move a road, the attached infrastructure must be modified as well. This creates great difficulty, expense and disruption as it now entails moving the entire local transportation network and utility web.

Because of these differences WSDOT recommends that implementing the NTA focus on looking at our bridges with perpendicular crossings over larger (4th and 5th order) streams and rivers. Figures 1 and 2 are schematics depicting and contrasting perpendicular bridge impacts and parallel roadway impacts.

² Strategy A5.4 NTA 1, *The 2012/2013 Action Agenda for Puget Sound*, Puget Sound Partnership

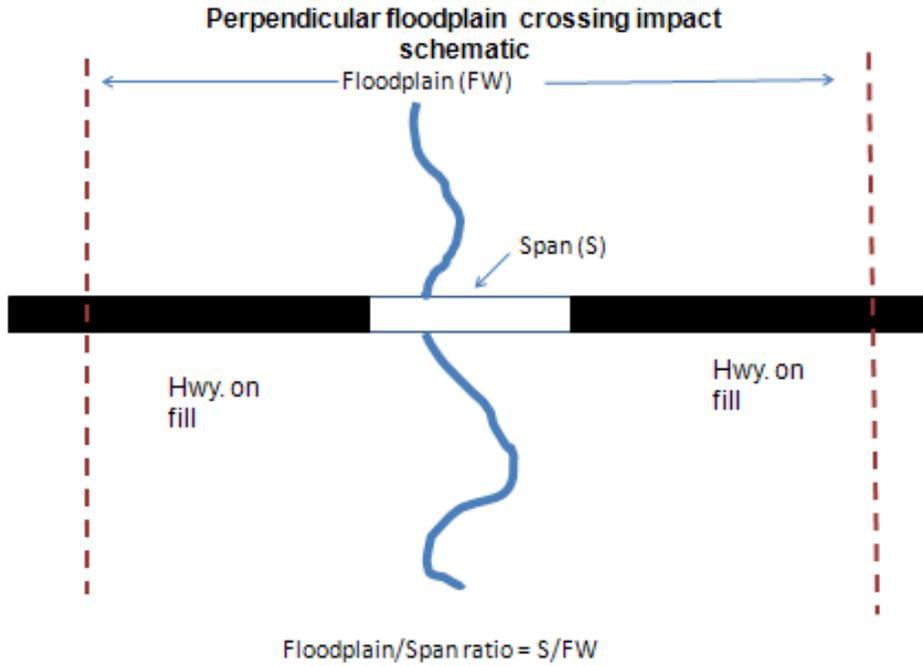


Figure 1. Perpendicular floodplain crossing impact schematic.

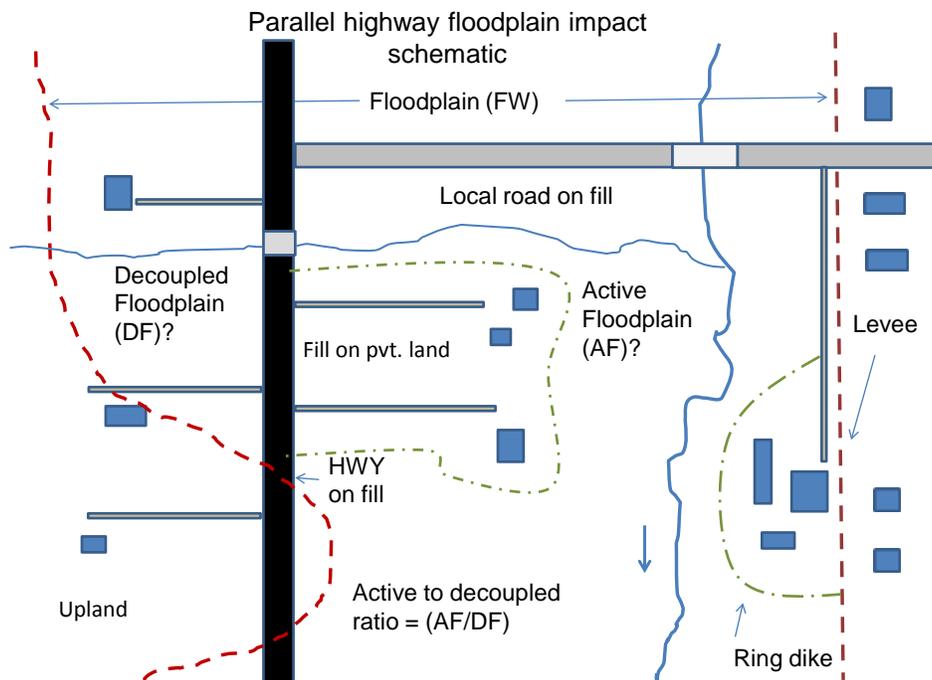


Figure 2. Parallel highway floodplain impact schematic.

Bridges tend to cross the floodplain and river in a more or less perpendicular orientation. This is particularly true of bridges over larger rivers with jurisdictional floodplains. Roadways, on the other hand, tend to parallel rivers with jurisdictional floodplains. Smaller bridges cross tributary streams that may or may not have jurisdictional floodplains. To complicate matters further, some portions of these roads may be within jurisdictional floodplain boundaries, while other segments of the same roads may be outside jurisdictional floodplains, depending on local topography and other factors.

Because of the inherent differences between perpendicular floodplain crossings (bridges) and parallel highways with segments in floodplains, two separate methods must be developed in order to evaluate relative floodplain impacts. This document presents a method for evaluating perpendicular span and fill bridge crossings of floodplains. A method for evaluating parallel road segments in floodplains is under development and will be presented as a separate document.

Prioritizing Perpendicular Floodplain Crossings on Larger Streams and Rivers

When evaluating impacts of transportation infrastructure to floodplain functions, the ratio between bridge span length and total flood-plain crossing is fundamental. This is due to the fact that the size of a bridge relative to the flood plain crossing affects every floodplain process and function including channel migration, formation of side channels and other habitat, flood storage, sediment transport, and LWM recruitment and transport.

The core metric, for evaluating relative floodplain impacts from bridges using the ratio between the bridge span and the total crossing width that is within the jurisdictional floodplain, is shown below:

<p style="text-align: center;">Bridge crossing span to floodplain width ratio</p> <p style="text-align: center;">S/FW</p> <p style="text-align: center;">Where:</p> <p style="text-align: center;">S = span length and</p> <p style="text-align: center;">FW= total floodplain crossing width</p>

For example, bridge “A” crosses the river and floodplain using a 100-foot long bridge, and two 500-foot approach fills. If we divide the 100-foot bridge by the total 1100-foot floodplain crossing we derive a span-to-width ratio of 0.09. Bridge “B” crosses the floodplain using a 200-foot long bridge and two 500-foot approach fills. We derive a span-to-width ratio of 0.16. The smaller the span-to-width ratio, the more impact there is to the floodplain.

The ratios derived correspond to the percentage of the floodplain crossing that is spanned. In this example bridge “A” has more impact to the floodplain.

Prism Width Modifier

The second metric used in the evaluation gages the relative width of floodplain fills. For this we are going to use the number of roadway lanes as an easily identifiable representation of relative fill prism width. The following modifiers will be applied to the span-to-floodplain width ratio to define the relative impacts of the fill prism width (PW), assuming that removing wider fill prisms provides greater benefit for flood storage and other floodplain functions. The equation is expressed as

$$S/FW-PW$$

PW is applied as follows:

- 2 Lanes—subtract 0.01
- 4 Lanes—Subtract 0.02
- 6 Lanes—Subtract 0.03
- 8 or more Lanes—Subtract 0.04

Proportional Development Modifier

Another important factor to consider when evaluating floodplain improvements to WSDOT infrastructure is surrounding development. The environmental lift from a WSDOT improvement project is inherently greater in areas where there is little to no surrounding floodplain development. For example, the environmental benefit of lengthening a bridge over an estuary where there is no adjacent floodplain development (such as the U.S. 101 crossing over the Duckabush River) will be vastly superior to placing larger bridges across a heavily developed floodplain (such as the Puyallup River in Tacoma). In the latter example, the adjacent development effectively cancels the benefits of the longer bridge because floodplain processes cannot be restored. In the Duckabush example however, the replacement with a longer bridge accomplishes complete floodplain process restoration with one discreet project.

For our test cases we used 2011 aerial photos in the WSDOT GIS Workbench to determine the ratings for proportional development (PD). We considered using land use cover data, however we found that that data set has a rather coarse level of precision, is not complete or uniform for the entire Puget Sound basin, and is somewhat dated. Using the 2011 aerial photographs proved to be a simpler, more reliable way of obtain a readily scalable, up-to-date metric. First we divide the floodplain in the vicinity of the bridge crossing into four quadrants. We analyze the development in each quadrant and apply PD as follows:

- No development: Add 0
- Development in 1 quadrant: Add 0.25
- Development in 2 quadrants: Add 0.5
- Development in 3 quadrants: Add 0.75
- Development in 4 quadrants: Add 1.0

In order to evaluate proportional adjacent development the following modifiers will be applied to the span to fill ratio.

The equation thus becomes:

$$S/FW-PW+PD$$

Estuary Modifier

Of all the many habitat types found in Puget Sound basin floodplains, the most rare and valuable are the few remaining estuaries. An **estuary** is geomorphically defined as a partly enclosed coastal body of brackish water with one or more rivers or streams flowing into it, and with a free connection to the open sea.

Estuaries form a transition zone between river and ocean environments and are subject to both marine influences, such as tides, waves, and the influx of saline water; and riverine influences, such as flows of fresh water and sediment. Remaining natural estuaries on Puget Sound typically consist of large alluvial fans bisected with intricate networks of distributary channels. For the purposes of this study, former estuaries that have been heavily developed into port facilities (Olympia (Deschutes River), Tacoma (Puyallup River), Seattle (Duwamish River)) will not be defined as estuaries. With regard to the Port of Everett (Snohomish River), there are considerable restoration efforts under way. Because of this, the Snohomish River estuary will be considered to have estuary restoration potential.

Recent studies indicate that as much as 73% of our estuarine habitat has been lost to development. Among their important functions is the critical role they play as habitat for smoltification of salmonids as they prepare to go to sea. In order to prioritize these critical habitat areas an estuary modifier (ES) has been developed³. If the floodplain crossing being evaluated is also crossing an estuary, this modifier is applied to the span-to-width ratio. This modifier is calculated as “estuary present—Subtract 0.06.”

The equation thus becomes:

$$S/FW-PW+PD-ES$$

Impact Rating, “The Race to the Bottom”

The Impact Rating is derived from applying the various modifiers to the span-to-width ratio. For this we use GIS (for Q3 floodplain data), aerial photographs, a development modifier, fill prism measurements, presence of an estuary (if applicable) and WSDOT’s Bridge Engineering Information System for bridge length and other structural metrics. This method is designed to be simple, quick, and easy to replicate. This is critical as roughly 500 bridges need to be evaluated. It is important to note that because the ratings are based on the span-to-width ratio, the crossings that have the most impacts to floodplains are those crossings that have the **lowest** scores.

³ The data source for the presence of estuaries is the WSDOT GIS Workbench, which is based on WSDOT aerial photography.

Comparison to Climate Vulnerability Modifier

The Near Term Action also requires “consideration of WSDOT’s 2011 Climate Impacts Vulnerability Assessment Report”. The priority list will be modified based on information in this report⁴ to adjust for climate change threats. While the Climate Change Study is based on highway segments rather than specific bridge structures, some bridges that are particularly vulnerable to climate change are described in the study. Most of these, however, are associated with potential sea level rise and thus are not necessarily pertinent to floodplain impacts. There are other highway segments, however, in higher elevations of the Puget Sound basin where impacts are anticipated along rivers that are fed by glaciers. Glaciers are already melting and are carrying large sediment loads from exposed soil. Sediment loads fall out on the journey to the sea and raise the beds of rivers. This causes lateral instability of the river channel, which impacts roadways along those rivers. The assumption, then, is that a longer, higher bridge that accommodates streambed aggradation and lateral migration would have environmental benefits as well as increase the resilience of the highway system.

Each Highway segment was rated “High”, “Moderate” or “Low” (see maps and narrative in the appendix that follows), based upon its location in the ‘sea to mountain’ landscape spectrum. Values developed for applying Climate Vulnerability (CV) are as follows:

High-- Subtract 0.03

Moderate-- Subtract 0,02

Low-- Subtract 0

The equation thus becomes:

$$S/FW-PW+PD-ES-CV$$

⁴ *Climate Impacts Vulnerability Assessment* Report, prepared by the Washington State Department of Transportation for submittal to the Federal Highway Administration, November 2011