INTERIM REVIEW OF
US ARMY CORPS OF ENGINEERS
LOWER SKAGIT RIVER FLO-2D MODEL

REVIEWED BY:

NORTHWEST HYDRAULIC CONSULTANTS INC

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Skagit River Flo2D Model Review

Skagit County has requested that **nhc** review the Flo-2D model used in the draft Skagit River Flood Insurance Study (FIS) as one part of its overall review of the study. Concerns with the hydrology portion of the study are being separately addressed and will not be reiterated here. Ultimately, it is the base flood elevations determined from the Flo-2D model that are at issue as these will be used to evaluate development potential and determine flood insurance premiums.

The purpose of this report is to evaluate the Flo-2D model and determine how sensitive lower Skagit River flood elevations are to varying estimates of peak flows and hydrograph volumes. If it turns out that flood elevations do not vary much regardless of variations in peak flow or volume there may be little reason to pursue further detailed hydrologic investigations, at least with respect to the determination of flood elevations. Conversely, a high sensitivity would justify further work to obtain the best possible flow estimates.

This is an interim report. Several of the issues raised in this report are under continuing investigation by Skagit County, **nhc**, and the Corps of Engineers.

1 Methods

nhc obtained all the Flo-2D model runs from the Corps of Engineers. These provided the basis for our model review. Our initial work was with a May 2007 release of Flo-2D v2006.01. However, we were unable to reproduce the Corps results until we obtained an earlier April 2006 version of the program executable file from the Corps. The Corps is taking the lead in working with Dr. Jim O'Brien, the author of Flo-2D, to identify and resolve the version differences that are occurring. All results presented in this report were generated using the April 2006 version of Flo-2D in order to ensure consistency with the Corps work.

A key prerequisite for the review of model geometry is a high resolution topographic dataset. Due to concerns with the available lidar data, the level of effort needed to process it, and desiring to focus our analysis on the areas of greatest interest to Skagit County, we have limited our review to the Burlington and Mt. Vernon areas. The methods used can be extended to the entire floodplain, but extensive processing of the lidar data would need to be completed first.

2 Model Geometry Review

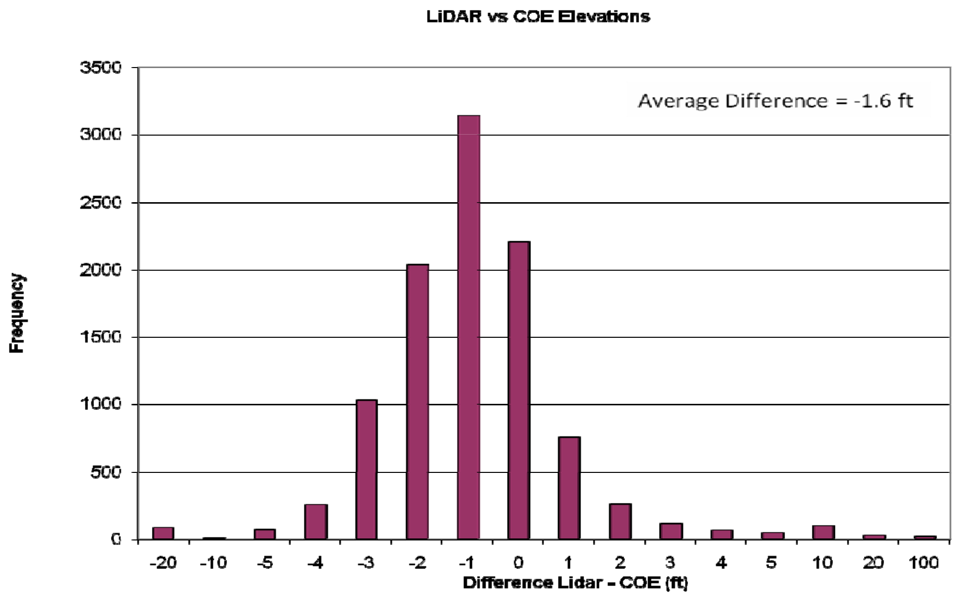
Accurate hydraulic modeling depends most fundamentally on having a correct representation of the topography of the floodplain and river channel. We compared the Flo-2D model topography against the original photogrammetric survey used to develop the model and a recently acquired lidar dataset in key areas.

nhc has a preliminary lidar data set of Skagit County in raw form without metadata or other quality assurance information available. The data was acquired under a USGS contract. According to USGS staff contacted, the initial data did not meet quality specifications. We are attempting to contact Ralph Haugerud of the USGS, who evidently has or plans to further process it in order to improve the quality.

Due to the preliminary nature of the data and the information from the USGS concerning the data quality, we performed a series of checks on the lidar. We compared the lidar data against the topographic data set based on aerial photogrammetry flown under Corps of Engineers contract in the 1990s. This flight was specifically for initial development of the Flo-2D model. The data is certified to meet ASRPS standards, with spot elevations accurate to +/- 0.67 ft. The spot elevations were obtained at 100 meter spacing through the floodplain, with additional points along key features such as tops of levees and elevated roadways. Horizontal accuracy was visually checked by ensuring prominent features such as roadways correctly lined up with each other and the underlying orthophotography.

The lidar data averages 1.6 ft lower than the COE dataset for the 10,216 points we compared. There was no apparent geographic distribution to the differences, which are shown below.

Figure 1: Preliminary USGS Lidar DEM vs. COE Photogrammetric Spot Elevations



For this review we did not consider elevation differences between the model and lidar of less than 2 feet to be significant. We conducted our review using the lidar and aerial survey data, but clearly further quality checks of the lidar data are warranted.

2.1 Geometry Review

2.1.1 Levee Crests/Top of Banks

The elevations of levees and the riverbanks are the most critical elevations in the model, as these determine how much overbank flow can leave the channel. Under the FEMA levee policy, the river is modeled with various combinations of levees left in place and removed in order to determine the worst case condition for each area. The levee removed condition is modeled by assuming the levee does not exist, i.e. overflows are controlled by the natural bank elevation. Like many rivers, the Skagit has natural high ground immediately adjacent to the main channel, further reinforcing the need for accurate bank elevations.

We checked the Flo-2D levee and bank elevations against the lidar data for left and right banks in the focus area. Lines were digitized along the top of levee and to the landward side of the levee toe. The lidar elevations were extracted at regular intervals along each line, as were the corresponding Flo-2D bank grid cell and levee crest elevations. The results are shown in the following Figures 2 and 3.

Bank elevations in the Flo-2D model generally agreed with the lidar data in the upper portions of both levees. Further down the river there are numerous locations where the modeled bank elevations appear to vary between the natural bank elevations and the levee crest elevations. The modeled levee crest elevations vary from good agreement with the lidar data to up to 3 feet above it. Also plotted are the levee crest elevations from the Corps topographic survey.

The consequences of inaccurate bank and/or levee crest elevations are complex and may include both under and over predicting water surface elevations. Where the model has bank elevations that are erroneously set at the levee elevations, removing the levee to follow the FEMA policy will have no effect. In locations where the levee profiles are too high, the volume of overbank flow from levee overtopping will be underestimated. This could cause higher flood levels on the opposite overbank under the FEMA levee removal policy simulations.

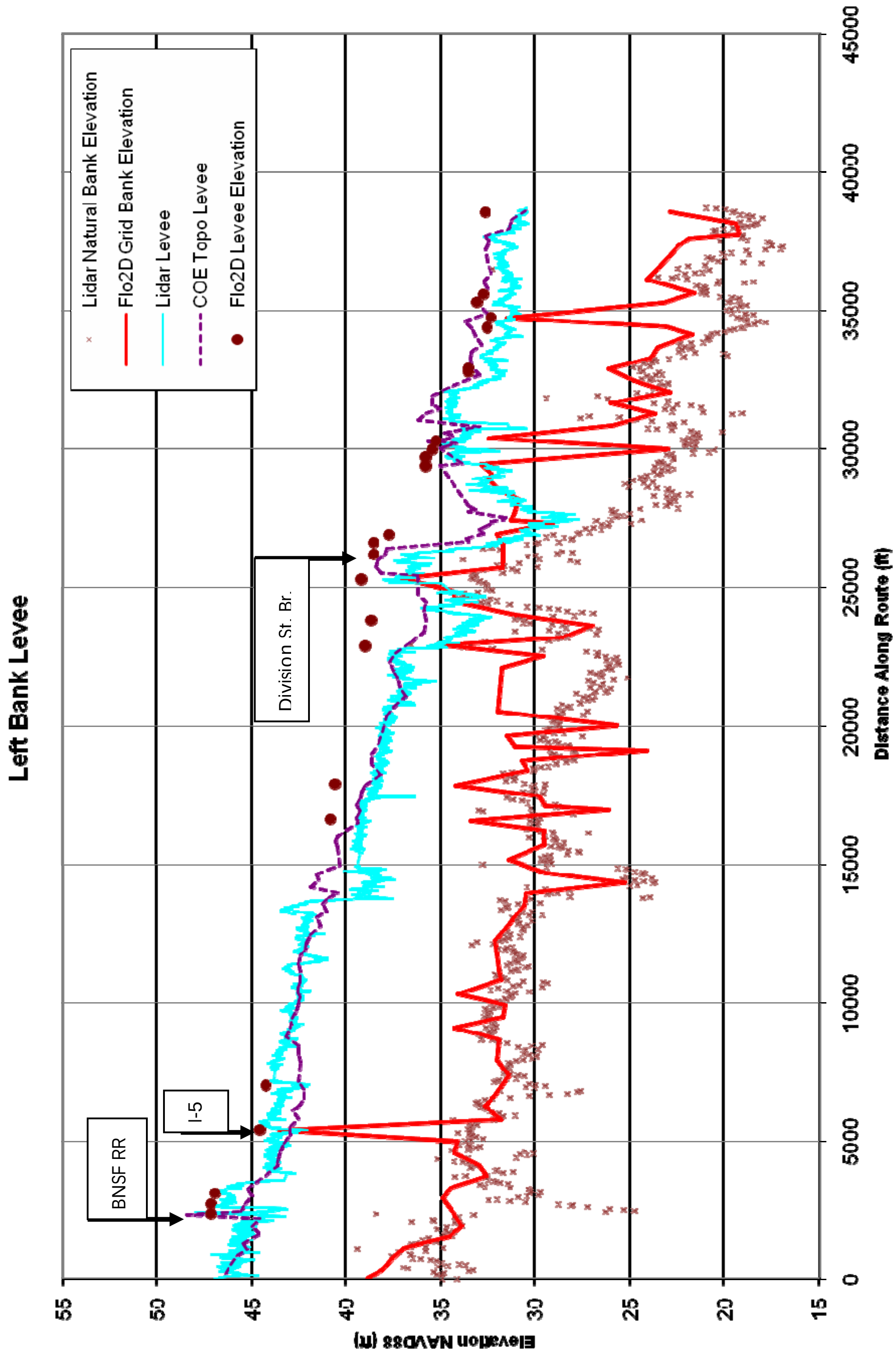


Figure 2: Left Bank Levee and Bank Elevation Profile

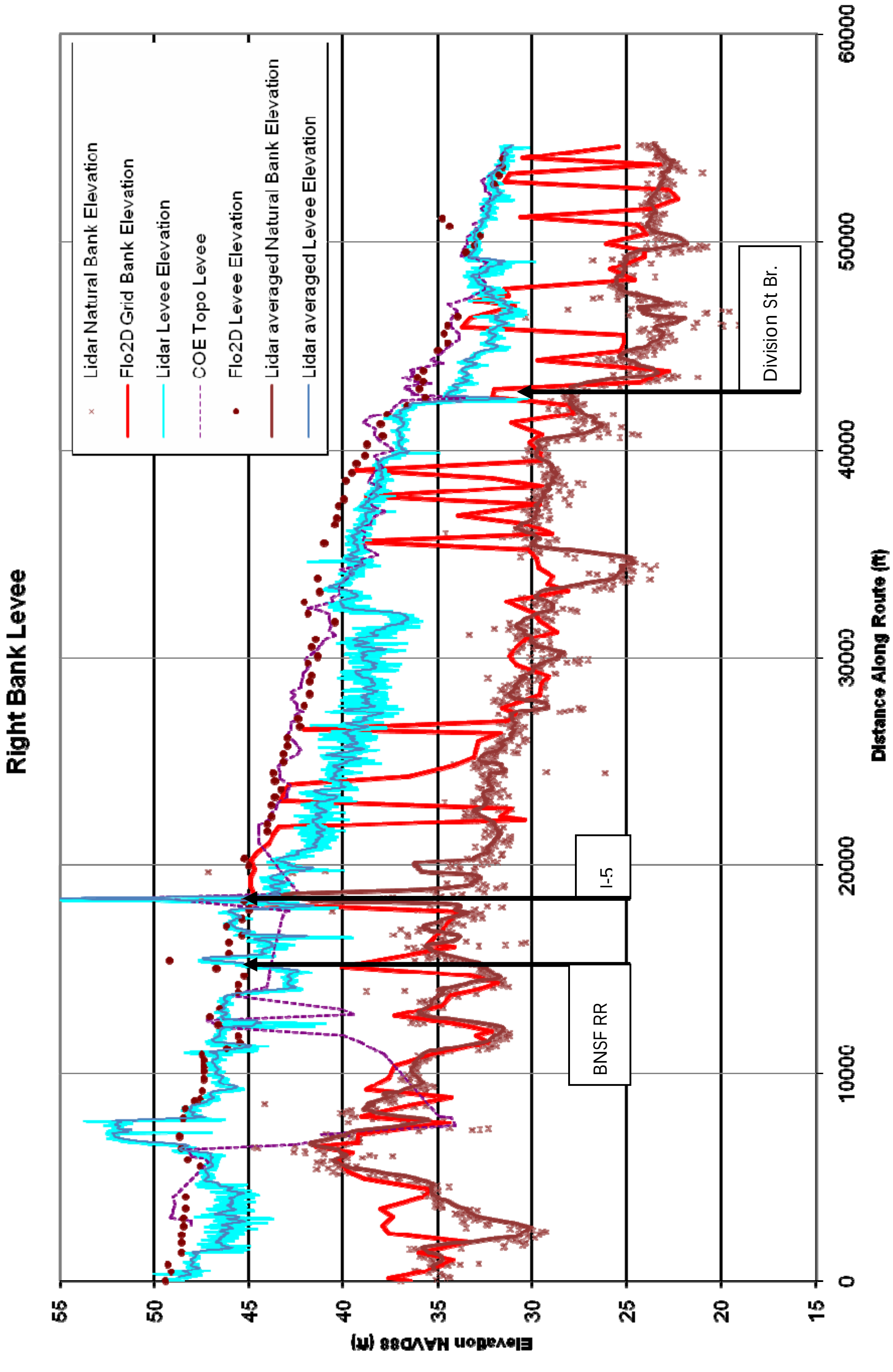


Figure 3: Right Bank Levee and Bank Elevation Profile

2.1.2 Burlington Issues: I-5, Railroad and Gages Slough

The flood profiles in the draft hydraulic report prepared by the Corps of Engineers for the flood insurance study show that the I-5 roadway, and to a lesser extent the BNSF Railroad, exert strong hydraulic control over flood elevations in the City of Burlington. The results indicate that these features act as dams, causing water levels upstream to be elevated above what could be expected under natural conditions. We examined how the model represents these features in detail due to their importance.

The same method as was used for the levee crest review was used. We extracted points along the top of the roadways from the lidar data and compared them to the elevations in the model. Results are shown below for I-5.

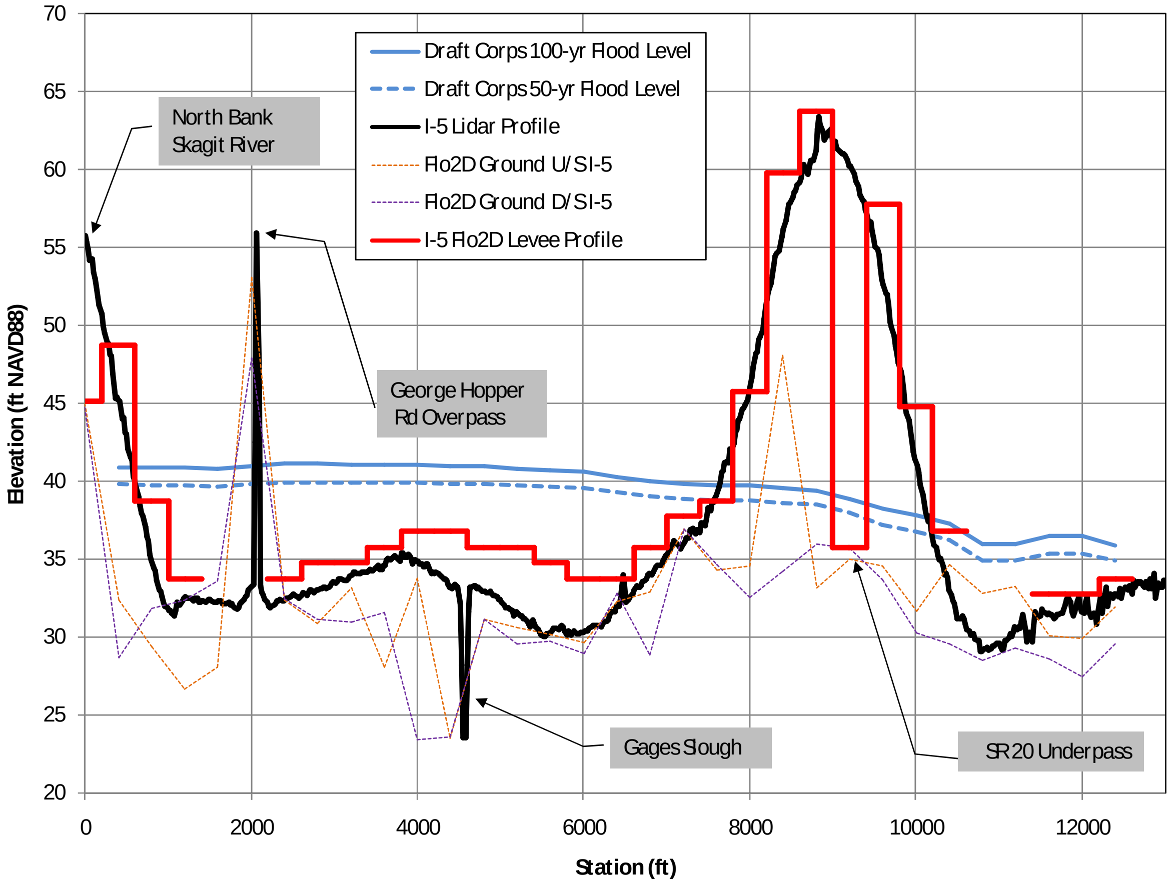


Figure 4: I-5 Roadway Profile and Water Surface Elevations

It appears that the model may not accurately represent the I-5 roadway crest elevations in the area beginning south of Gages Slough and extending north to where the roadway rises to cross over Highway 20. The lidar shows the roadway is 3-5 ft lower over nearly 3000 ft in this area. Weir flow increases exponentially with depth, so if the lidar is correct the model could be underestimating the flow capacity across I-5 by a substantial margin, an important factor governing upstream water levels through the core of Burlington.

Another area of concern is the representation of Gages Slough. The slough is heavily vegetated, and the majority of its width blocked by the I-5 fill prism, both factors that significantly reduce its conveyance capacity. However, there is a bridge opening on I-5, and the low elevations of the slough will help it serve as a conveyance channel despite the vegetation. The Flo-2D model does not represent the I-5 bridge opening at all, rather it assumes that the roadway fill extends across and completely blocks the slough. Finally, the model resolution may be too coarse to represent the slough well. The model uses 400x400 ft square grid cells to route flows over the floodplain. Most of Gages Slough is less than 400 ft wide, so selecting an elevation that neither under nor over represents the conveyance capacity of the channel is difficult.

3 Numerical Sensitivity

The in-channel portion of the Flo-2D model has been calibrated to data from the 1995 and 2003 floods. There have been no recent floods that overtopped the levee system that would allow a floodplain calibration to be performed and provide greater confidence in the overbank area model results. The importance of correct model geometry and parameters is even more important in this case, where there is no comparison to real floods available. The sensitivity of a model can be investigated as a partial substitute for calibration data. The sensitivity of the output (water levels) to variation of key model input parameters across the range of physically realistic values can give guidance as to which are the controlling factors driving flood levels and lead to greater confidence in the results. We conducted a partial sensitivity analysis of the Skagit River model, looking at the numerical sensitivity/stability and the peak flow and volume sensitivity.

We performed two validation runs to investigate the numerical sensitivity and stability of the model when minor changes were made to model inputs. A limiting factor on the ability to evaluate the model has been the long run time each simulation takes. Typical run times using the Corps model were around 27 hours. Many completed runs obtained from the Corps took 50 to 80 hours, with one run exceeding 220 hours (9 days). Examination of the Corps models revealed that two of the 24,295 grid cells, both containing channel elements, were consistently causing the majority of the long run time problems. Minor changes to model parameters for these two elements and changing the numerical tolerance and stability parameters resulted in much faster simulations, typically on the order of 6-8 hours. The effects of these changes to model geometry were checked by re-running a Corps scenario and comparing outputs. Ideally such minor changes would cause negligible differences in model outputs. In the Skagit River model, outputs in the focus area of Burlington-Mt Vernon varied only slightly with the modified model input. There were several areas that showed greater sensitivity to variation in model inputs – primarily along the Burlington-Samish Bay flow path and the Nookachamps area. However, these areas also showed greater sensitivity to variation in flow inputs as well, which indicates that this appears to be a natural condition, not an artifact of the model itself. If these areas are naturally sensitive then the model grid and levee elevations in the area should be the focus of more extensive quality review.

Another issue of concern is overestimation of weir flow by the Flo-2D program. The Skagit River model contains extensive lengths of levees and elevated roadways that are represented in the model as levees. The model uses the weir flow equation to calculate the flow over these structures. However, for a straight levee segment, Flo-2D uses weir lengths 20% greater than the true length, which results in overestimation of flow rates by 20%. The methods available in Flo-2D to correct this overstatement of weir length are not implemented in the Skagit River model and to do so would involve extensive manual file editing. For the I-5 roadway discussed previously, this error would tend to counterbalance errors that would occur if the roadway elevation is overestimated, but to what degree is not known.

4 Peak Flow and Volume Sensitivity

We used existing outputs from two Corps of Engineers runs and performed 4 additional sensitivity runs to investigate the effects variation in peak flow and volume have on flood levels. For all runs we used the Corps scenario "Right Bank Levee removed except South Fork". This scenario provides the worst case flood levels for Burlington, west Mt. Vernon and the area north of the Skagit mainstem. The scenario follows the FEMA levee removal policy for non-certified levees, and results in modeling the floodplain as if the approximately 75,000 ft of right bank levee downstream of Sedro Woolley does not exist.

The following table and figure show the run variations and inflow hydrographs used. We selected a series of alternatives that bracket the approximate range of proposed 100-yr flows and volumes from various sources. Run "Q50-42%" was developed by digitizing a hydrograph attributed to Pacific International Engineering (PIE) contained within a September 5, 2007 PowerPoint presentation by Chal Martin, Public Works Director for the City of Burlington, that was obtained from the web site www.skagitriverhistory.com. PIE labels this hydrograph with a peak of 196,000 cfs as the 100-yr event. However, the peak flow in this event is only 2% greater than the Corps 50-yr event. We scaled the hydrograph to match the Corps 50-yr peak and present the change in flood volume and results relative to the Corps 50-yr event.

For runs 4, 5, and 6, Nookachamps Creek inflow hydrographs were scaled in the same proportion as the Skagit River inflow. For Run 7 where no information on Nookachamps Creek flows was available, the base Corps 50 yr inflow was used. The Corps one-day coincident flows on Nookachamps Creek are 7720 and 8920 cfs for the 50-yr and 100-yr events respectively. We do not believe that variations in Nookachamps Creek inflow make a significant difference in Skagit River water surface elevations.

Table 1: Peak Flows and Volumes

Run Name	Run Code	Flood Event	Peak Flow (cfs)	% Change in Volume from Corps Run	Flow Volume above 100,000 cfs (ac-ft)
Corps 100yr	Corps Q100	100-year	235,000	0%	547,000
Run 4	Q100 -25%	100-year	235,000	-25%	410,000
Corps 50yr	Corps Q50	50 year	192,000	0%	297,000
Run5	Q50 +50%	50 year	192,000	+50%	445,000
Run6	Q50 +25%	50 year	192,000	+25%	371,000
Run 7	Q50 – 42%	50 year	192,000	-42%	172,000

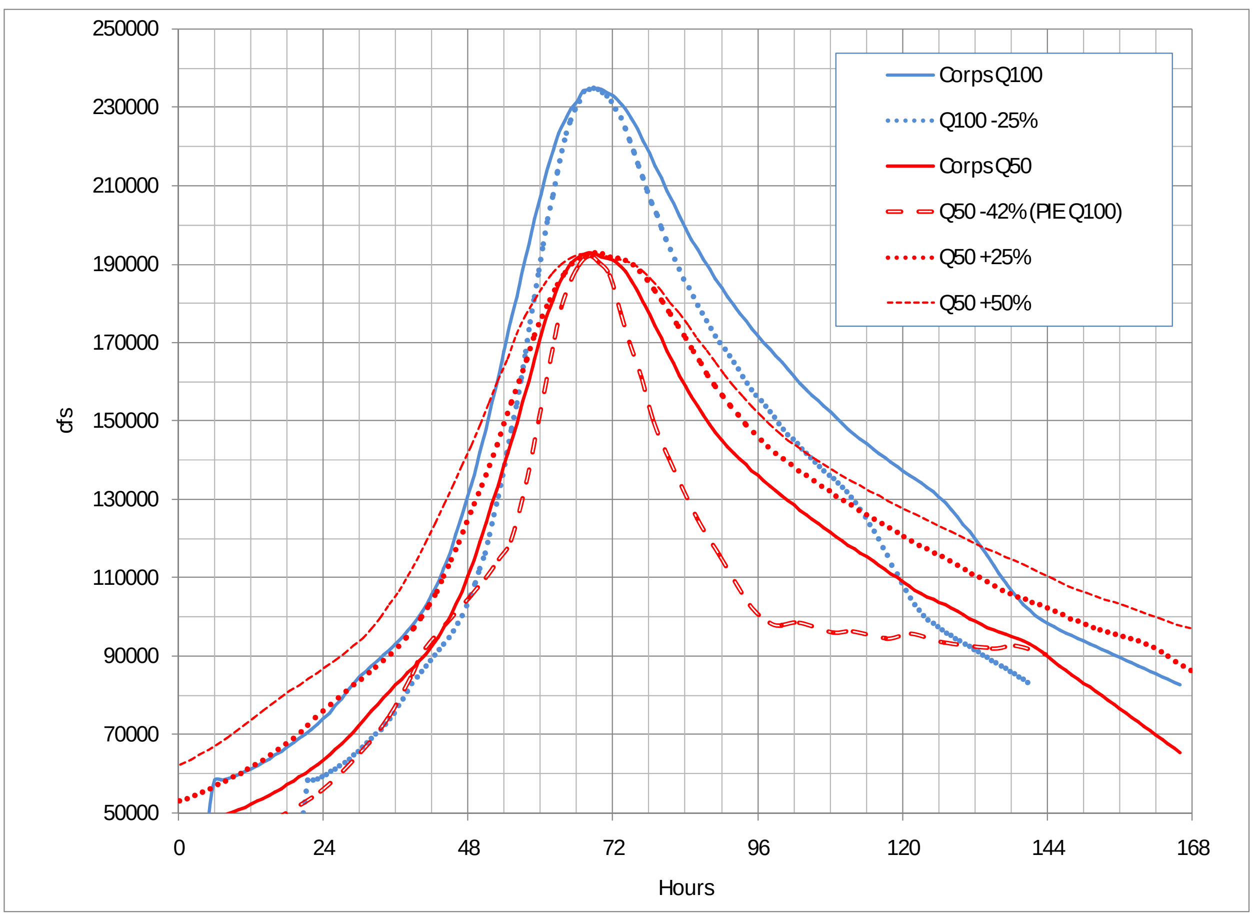


Figure 5: Regulated Flow Hydrographs Skagit River at Sedro Woolley

Results

Results are presented graphically in the following figures. The modeling shows that water surface elevations are insensitive to significant variations in flood volumes at both the 50 and 100-yr flood levels for the Burlington-West Mt. Vernon area, with differences generally less than 0.5 ft (Figure 6 - Figure 8). As of December 2007 the Corps is rerunning the model with slightly reduced 100-yr discharges. This will result in minor lowering of water levels

Figure 9 plots the difference between the Corps 50 and 100 yr flood levels. The 50 yr flood peak is 18% lower and the volume 46% lower than the 100-yr flood. Differences in flood levels are generally between 0.5 and 1.5 feet. Figure 10 compares the Corps 50-yr – 42% (essentially the PIE 100-yr) run with the Corps 100-yr run. Overall, the Nookachamps area shows slightly greater sensitivity, while the greatest changes are consistently seen in the Burlington-Samish Bay flow path. While the term “significant reduction” is subjective, the actual depths of flooding are deep enough in most areas that a reduction of around 1 ft in the regulatory base flood elevation would not make a large difference in how an area could be developed.

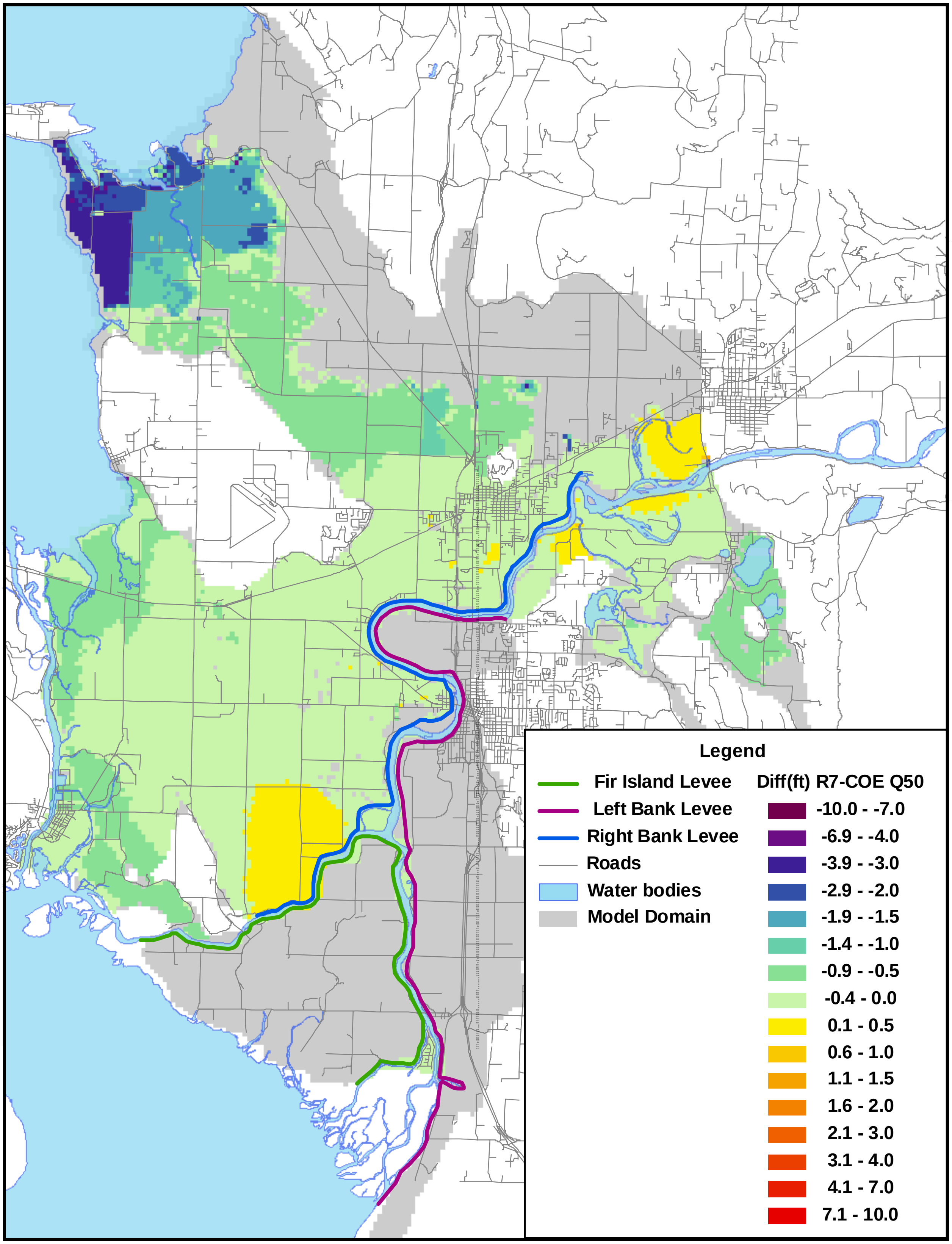


Figure 6: Difference in Flood Elevation – 50-yr Flood, 42% Volume Decrease

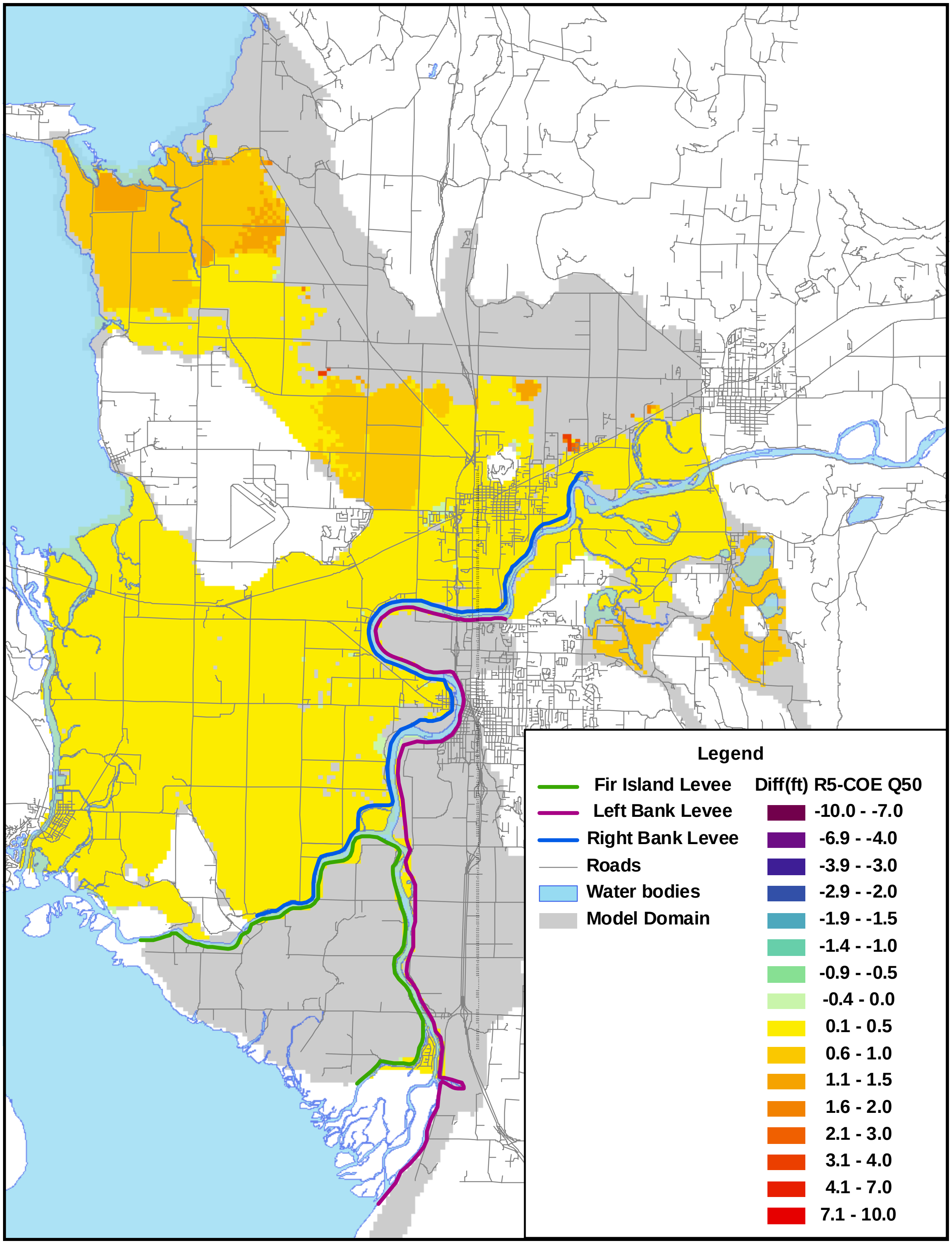


Figure 7: Difference in Flood Elevation – 50-yr Flood, 50% Volume Increase

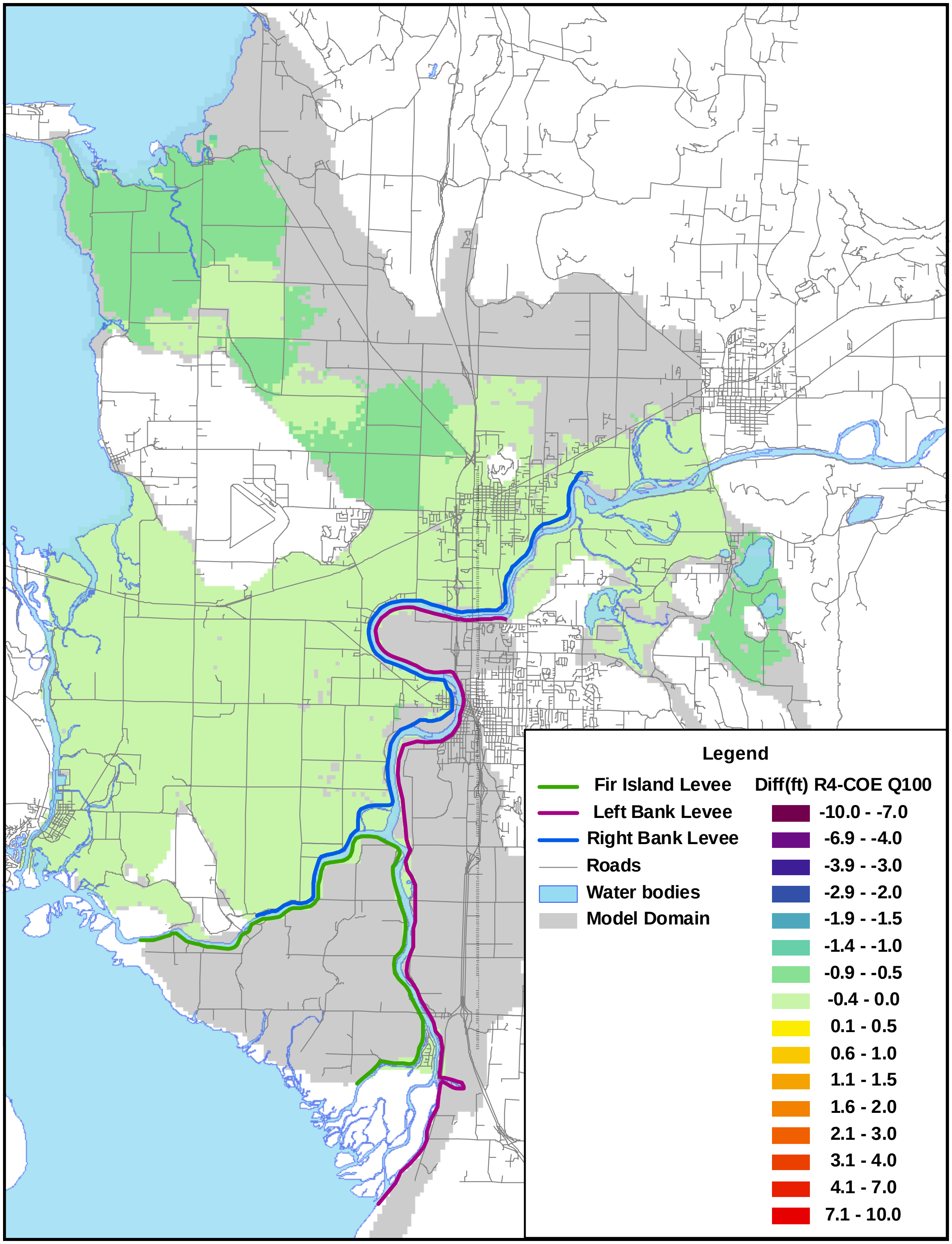


Figure 8: Difference in Flood Elevation – 100-yr Flood, 25% Volume Decrease

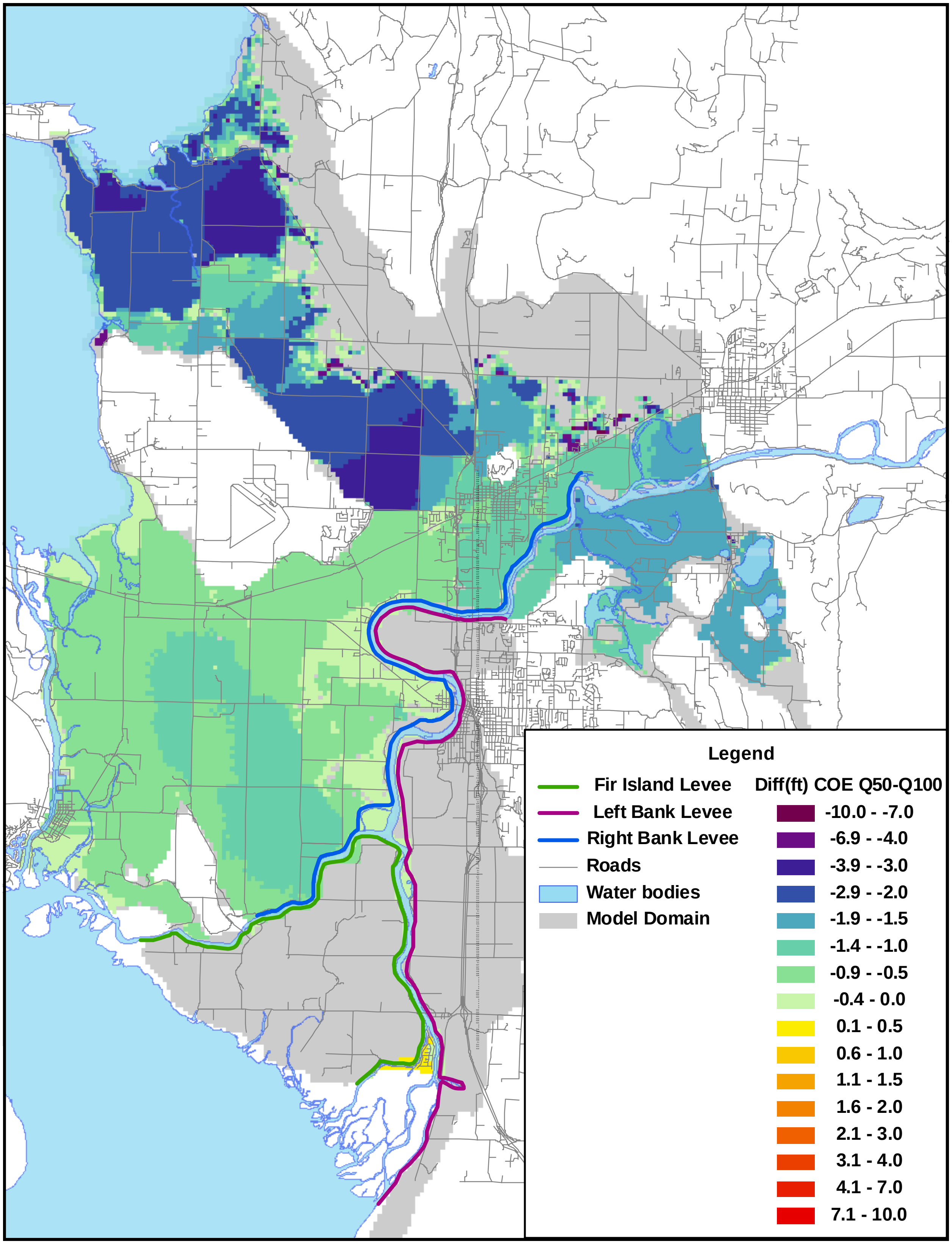


Figure 9: Difference in Flood Elevation: Corps 50-yr – Corps 100-yr Flood

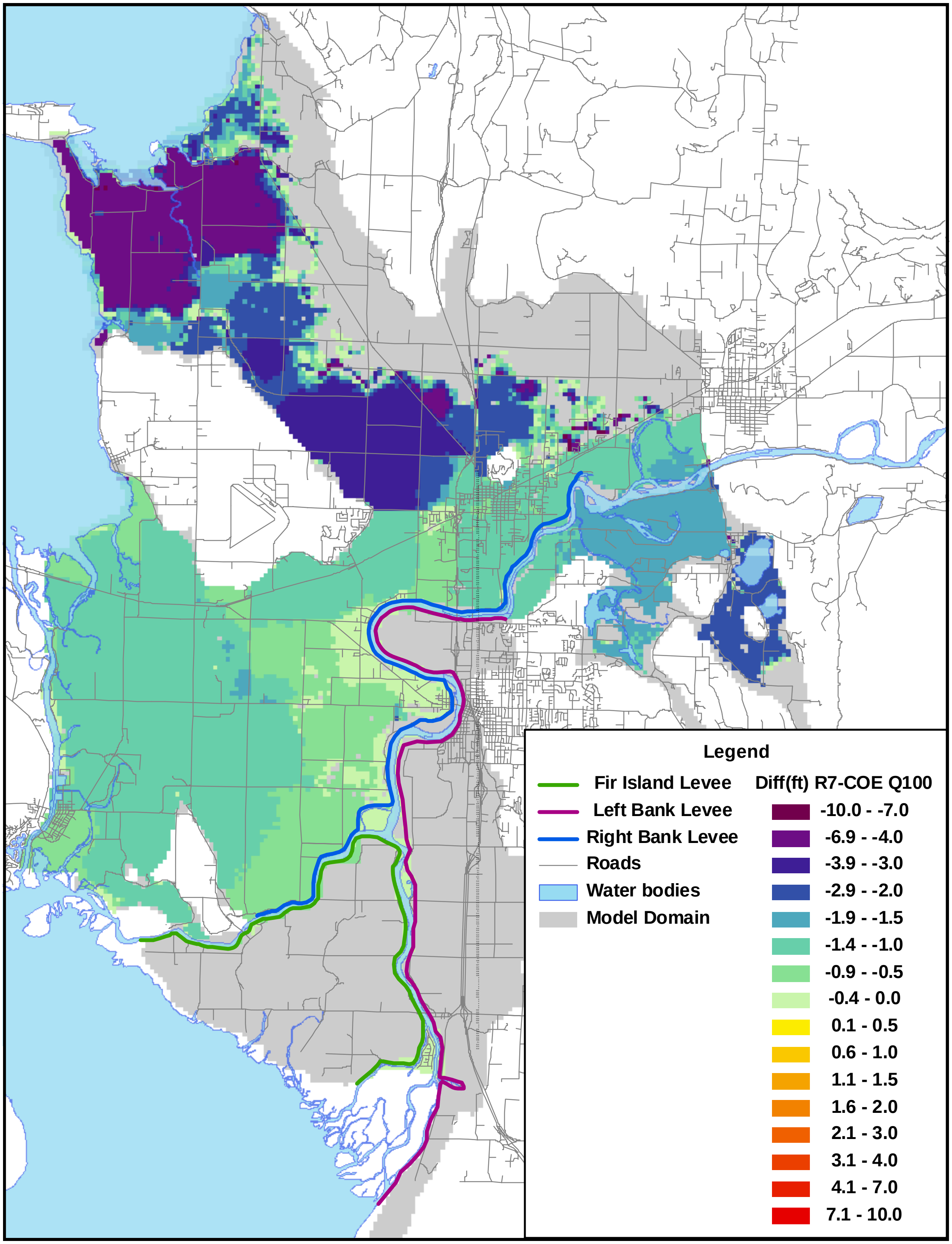


Figure 10: Difference in Flood Elev.: Corps 50yr-42% (PIE 100-yr) – Corps 100-yr Flood

5 Summary

nhc evaluated levee crest, bank and roadway elevations in the model against the original aerial survey used to develop the model and a new lidar dataset. The lidar and aerial survey were compared. The numerical stability and weir flow algorithms of the Flo-2D model were investigated. Four model runs were produced to evaluate the sensitivity of the flood levels to variation in peak flows and volumes.

5.1 Key Findings

5.1.1 Model Geometry

- Generally the model levee crest and top of bank elevations are in agreement with the aerial survey and lidar data. There are sections where the bank grid cells appear to use levee rather than natural bank elevations. There are also levee sections where the model elevations do not match either the aerial survey or lidar data.

- The I-5 roadway in Burlington appears to represented with elevations higher than shown by the lidar. In addition, Gages Slough is modeled as if I-5 completely dams it off. I-5 serves as an important control on water levels in Burlington, and these factors may result in overestimated flood levels in the area.

5.1.2 Numerical Stability and Model Calculations

- The Flo-2D weir flow algorithm overpredicts flow rates by 20%. Because of the FEMA levee removal policies, the worst case scenarios for each area remove the levees and so this issue may not be important for floodplain mapping work, except in areas where roadways serve as controls on flood levels on the floodplain. I-5 through Burlington is one example.

5.1.3 Peak Flow and Volume Sensitivity

- Simulations for the Corps 50 and 100-year floods show that modeled water levels are relatively insensitive to large variations in flood volumes. Differences are generally within 0.5 ft.

- The difference in water levels between the 50 and 100-year floods is generally between 0.5 and 1.5 feet for most of the north bank floodplain, including the west Mt. Vernon and Burlington areas. These water level differences provide guidance on what the **maximum** expected drop in base flood elevations should be for a wide range of potential revisions to Skagit River hydrology.

5.2 Ongoing Investigations

5.2.1 Representation of I-5

- WSDOT has been asked to determine if there is any high accuracy I-5 roadway elevation information available to help evaluate the preliminary lidar data.

5.2.2 Flo-2D weir flow equation modification

- Dr. Jim O'Brien, the Flo-2D author, has been asked about the feasibility of modifying the model inputs to more accurately simulate weir flow over levees and roadways. Several options are under discussion that may be implemented in future versions of the model.

5.2.3 Flo-2D version differences

- The Corps and Dr O'Brien have identified three key issues that appear to be causing the differences between the April 2006 and May 2007 releases of Flo-2D v2006.01. They are working on resolving these with the intent of having the most current model produce the same results as the April 2006 release. The Corps anticipates documenting the findings on this issue in a report that will distributed to interested parties.

5.3 Recommended Further Work

5.3.1 Model Geometry Modification

- Our review identified areas of bank, roadway and levee elevations that appear to be high based on the lidar data. If the lidar data are found to be accurate, then the model should be modified and rerun to investigate whether more accurate elevations significantly affect flood levels.

5.3.2 Further Sensitivity Analysis

- A sensitivity analysis of the effects of peak flow and volume for the entire floodplain should be performed. This can be done using already completed runs, based on the lack of sensitivity shown in the work done to date for this report.

- The sensitivity of the model to key topographic features should be performed. This would involve modifying elevations of key bank and roadway weir elevations within the accuracy limits of the source data to see the effects on flood levels. Highly sensitive areas may justify acquiring ground based survey information.