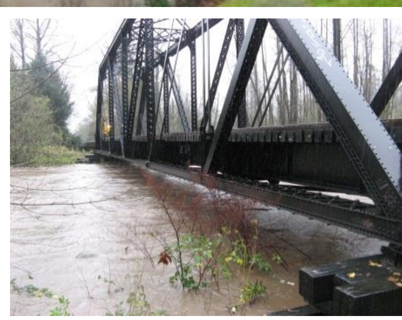
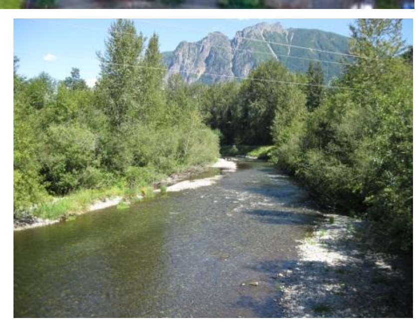
South Fork Snoqualmie River
Levee Repair and Reconstruction Plan

South Fork Snoqualmie River Levee Characterization Report

River Mile 2.0 – 5.9

June 2014





King County
Department of Natural Resources and Parks
Water and Land Resources Division

SOUTH FORK SNOQUALMIE RIVER
LEVEE REPAIR AND RECONSTRUCTION PLAN

SOUTH FORK SNOQUALMIE RIVER LEVEE CHARACTERIZATION REPORT

RIVER MILE 2.0 – 5.9

JUNE 2014

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King County

Department of Natural Resources and Parks
Water and Land Resources Division

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South Fork Snoqualmie River Levee Characterization Report
River Mile 2.0 – 5.9

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PROJECT TERMINOLOGY

Alternative—A set of projects or management actions. In hydraulic modeling, an alternative is a model simulation representing a set of projects.

Alluvium—Loose, unconsolidated soil material, deposited in a riverine environment.

Aquifer—Layer of water-bearing permeable rock or soil, typically gravels and sands.

Atmospheric River—Relatively narrow regions in the atmosphere responsible for horizontal transport of water vapor outside the tropics (NOAA, 2014). See also Pineapple Express.

Backwater—Elevated flow depth usually resulting from an instream obstruction such as a bridge or culvert, channel narrowing, sediment deposition, or a large meander bend.

Basin—A geographic area that contains and drains to a stream named and noted on common maps, or a geographic area that drains to a non-flowing water body, such as a lake or marine area, named and noted on common maps.

Calibration—Process of adjusting model variables so that model-predicted values match observed values within a pre-defined tolerance.

Capacity—Magnitude of flow that can be safely conveyed without flooding. Capacity is defined at the top of the bank or levee and may include freeboard.

Concept Design—A planning-level description of a project, including physical extent, feasibility, work items (e.g. permitting and property acquisition), construction quantities, schedule, and cost estimate to a 10-percent level.

Conveyance—Ability to transport stream flow through a reach.

Culvert—Pipe installed through a levee or roadway embankment to convey stream flow from upstream to downstream of the embankment.

Deleterious Material—Stumps, large woody debris and other non-structural fill material found in a levee prism.

Design Flood Event—Synthetic flood events associated with an annual probability of occurrence and used to describe conditions in the study area. Design flood events are based on the annual probability of occurrence in the South Fork Snoqualmie River and include stream flow conditions in the river and its tributary streams.

Development—Any man-made change to improved or unimproved real estate, including, but not limited to, buildings and other structures, mining, dredging, filling, grading, paving, extraction or drilling operations, farming, or storage of equipment or materials.

Erosion—Wearing away of ground surface as the result of the movement of wind, water or ice.

Existing Conditions—Land use, South Fork Snoqualmie River and tributary stream channel, and topographic conditions present in the study area in 2009 and 2010.

Factor of Safety—Ratio of the design strength of a system to the design load. A factor of safety less than 1 indicates failure. A factor of safety greater than 1 indicates a stable structure.

Federal Emergency Management Agency (FEMA)—An agency created in 1978 to provide a single point of accountability for all federal activities related to disaster mitigation and emergency preparedness, response and recovery (now part of the Department of Homeland Security).

FEMA Floodway—The channel of a stream and the portion of the adjoining floodplain that is necessary to contain and discharge the base flood flow without increasing the base flood elevation more than 1 foot.

Fill—Native or non-native earth material used to construct levees and other embankments.

FLO-2D—A two-dimensional hydraulic computer model used to predict hydraulic characteristics in a stream channel and overbank floodplain.

Flood or Flooding—A general and temporary condition of partial or complete inundation of normally dry land areas from the overflow of inland or tidal waters or the unusual and rapid accumulation of surface water runoff from any source.

Floodplain—The total area subject to inundation during a flood event.

Freeboard—Vertical height of a bank, levee or other containing structure above a given water surface elevation. A factor of safety usually expressed in feet above a flood level for purposes of floodplain management.

Future Aggradation Scenario—Assumed channel condition with up to 3 feet of gravel deposition in the South Fork Snoqualmie River between River Mile 2.74 and River Mile 4.58, with a localized scour section near River Mile 4.0. Deposition assumptions are based on a single estimate of aggradation based on available data and extrapolated into the future with no consideration of other factors, such as gravel removal, levee setback, gravel storage areas, or instream hydraulic conditions.

Geotechnical—Behavior of earth materials and soil mechanics used to determine subsurface conditions relating to slope stability, liquefaction and seismic conditions.

Ground Penetrating Radar (GPR)—A geophysical method that uses electromagnetic radiation in the microwave band of the radium spectrum to image subsurface conditions.

HEC-RAS—One-dimensional hydraulic computer model used to predict hydraulic characteristics in a stream channel.

Headwaters—Land area found in the upper elevations of a watershed near the watershed divide.

Hydraulics—General term for flow characteristics (e.g. velocity, depth, shear) of a stream channel or hydraulic structure.

Hydraulic Structure—Instream structure, usually man-made, having hydraulic characteristics significantly different from those of the adjacent stream channel. Bridges and culverts are examples of hydraulic structures.

Hydrology—The analysis of waters of the earth. For example, a flood discharge estimate is developed by conducting a hydrologic study.

Hydrogeology—Distribution and movement of water in the subsurface geology.

Landward—On the land side of a levee; opposite of riverward.

Left Bank—Left-side South Fork Snoqualmie River channel edge looking in the downstream direction.

Incorporated Areas—Areas within a city. King County contains 39 whole incorporated cities and parts of two others.

Large Woody Debris—Large pieces of wood in or partially in stream channels, including logs, pieces of logs, root wads of trees, and other large chunks of wood. Large woody debris provides streambed and bank stability and habitat complexity. It is also referred to as coarse woody debris. Either term usually refers to pieces at least 20 inches in diameter.

Levee—A manmade structure, usually an earthen embankment, designed and constructed to contain, control, or divert the flow of water so as to provide protection from temporary flooding.

Overbank—Floodplain area outside the South Fork Snoqualmie River channel.

Overtopping—River flow over the top of a levee during a flood condition when the depth of flow in the channel exceeds the levee crest elevation.

Piping-Seepage flow carrying sediment particles resulting in erosion of the levee foundation.

Pineapple Express—Extended period of heavy rainfall accompanying a flow of warm, moist air originating in the tropic and sub-tropical latitudes. Also see Atmospheric River.

Probability of Occurrence—The statistical likelihood of the occurrence of a peak flood event of a given magnitude in any year. Probability of occurrence is expressed as the percent-annual-chance flood event.

Problem—A discrete hydraulic or geotechnical deficiency in design, condition or construction materials of a levee or flow conveyance structure (e.g. a low spot in levee crest elevation, an undersized culvert along a tributary, a known area of piping, or levee toe erosion).

Problem Area—Area that includes one or more hydraulic or geotechnical problems that could be addressed by a construction project or management actions (e.g. the left bank from River Mile 5.2 to River Mile 4.8).

Project—A construction solution or management action that addresses a problem or problem area to the level of the overall project goal and to the extent feasible. An example project could be a left-bank setback levee from River Mile 3.5 to River Mile 2.7 or a reconstructed levee with seepage blanket from River Mile 2.5 to River Mile 2.3.

Repair—To fix or restore to sound condition after damage. Repair does not include replacement of structures or systems.

Revetment—A facing of stone, broken rock, or other material placed on a streambank or slope to minimize erosion by moving water.

Riparian Area—The area adjacent to flowing water bodies—such as rivers, perennial or intermittent streams, seeps or springs—that contains elements of both aquatic and terrestrial ecosystems, which mutually influence each other.

Riprap—Large rock material used to protect stream banks from scour and erosion.

Right Bank—Right-side South Fork Snoqualmie River channel edge looking in the downstream direction.

River Mile—Measurement along the river thalweg from downstream to upstream, according to datum and river thalweg determined by 2005 FEMA floodplain study. River miles shown on figures in this report are an approximation of the FEMA river mileage.

Riverward—On the river side of a levee; opposite of landward.

Seepage—Discharge of river water through a levee through seeps and springs during flood events.

Shear—Force of moving water along the channel bed or streambank.

Slope Stability—Ability of the levee face to maintain design structure configuration over a variety of flow conditions. Analysis of slope stability is expressed as a factor of safety in terms of resistance forces over driving forces.

Structure—Permanent fixture constructed in or on the ground, or over the water; excluding fences 6 feet or less in height, decks less than 18 inches above grade, paved areas, and structural or non-structural fill.

Surcharge—Pressurized flow condition at a road crossing structure where the water surface elevation is at or above the top of a culvert pipe. Surcharging occurs at bridge structures when the water surface elevation is at or above the low-chord of the structure.

Thalweg—The line along a river channel’s length defined by the lowest elevation point at every channel cross-section.

Tributary—A smaller stream that flows into a larger stream. Clough Creek, Ribary Creek and Gardiner Creek are tributary streams to the South Fork Snoqualmie River.

Watershed—An area of land that drains into a single outlet and is separated from other drainage basins by a divide.

WSDOT—Washington State Department of Transportation. Government agency responsible for management of the state highway system in Washington state.

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- Erik Peters, Project Manager
- Todd Hurley, Lead Geotechnical Engineer
- Clint Loper, South Fork Snoqualmie River Basin Manager
- Phyllis Meyers, Lead Ecologist
- Richelle Rose, Stakeholder Involvement Lead
- Mark Ruebel, Lead Hydraulic Engineer

The following consultant team members participated in this study:

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- Jay Smith/Tetra Tech, Lead Hydraulic Modeler
- James Templeton/Tetra Tech, Engineering Support
- Deb Overbay/GeoEngineers, Lead Geotechnical Engineer
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- Brad Thiel/NWEC, Lead Ecologist
- Matt Stevenson/Core GIS, GIS Graphics

EXECUTIVE SUMMARY

ES.1 INTRODUCTION

The South Fork Snoqualmie River Levee Characterization Report presents a comprehensive evaluation of hydraulic, geotechnical, and ecological conditions of the South Fork Snoqualmie River and its floodplain. It includes an evaluation of existing conditions and proposes a prioritized program for improvement and maintenance of the levee system. The hydraulic evaluation employed a two-dimensional hydraulic model to evaluate existing conditions and a future aggradation scenario. The geotechnical evaluation included geophysical testing of over 9,000 feet of levee and geotechnical and hydrogeologic stability was analyzed at critical sections of the levee system. The ecological evaluation qualitatively assessed habitat conditions associated with streambank velocity refuge, floodplain connectivity, riparian condition, and instream natural habitat functions.

ES.1.1 Study Objectives

The overall goal of the planning process is to lay the groundwork for informed decision making for evaluation of potential project actions to successfully realize the three goals of the flood plan. To meet this goal, the objectives for the levee characterization report are as follows:

- Characterize the existing conditions in the study area.
- Evaluate the performance of the levee system during extreme flood events.
- Define the existing level of service.
- Identify hydraulic and geotechnical problems.
- Evaluate the levee system against the 1964 design basis of accommodating flows up to 13,000 cubic feet per second (cfs) while maintaining a minimum of 1 foot of freeboard.
- Qualitatively asses ecological function.

ES.1.2 Study Area

The study area for this project extends along the South Fork Snoqualmie River from River Mile (RM) 2.0 to RM 5.9 (see Figure ES-1). The study area on the west (left) side of the river extends to the toe of the valley edge, including Interstate 90 and Gardiner Creek. The study area on the east (right) side of the river extends about a mile landward from the right bank, through the City of North Bend. The hydraulic analysis assessed conditions of the South Fork Snoqualmie River channel, the levees and the overbank floodplain area. The left overbank floodplain area was analyzed in greater detail because it experiences more frequent overtopping and flooding from the South Fork Snoqualmie River. Geotechnical analysis was performed at discrete locations on both banks of the river.

The South Fork Snoqualmie River upstream of RM 2.0 drains an area of about 84 square miles (U.S. Geological Survey, 2013). Within the North Bend city limits, the river is confined by levees on both sides. Six bridges cross the South Fork Snoqualmie River within the study area. Several smaller streams contribute flow to the South Fork Snoqualmie River. These streams have headwaters along the east flank of Rattlesnake Mountain and descend to flatter areas near Interstate 90 as they enter and cross the South Fork Snoqualmie River's large floodplain. The smaller streams combine into three main tributaries within the study area: Gardiner Creek, Ribary Creek and Clough Creek (see Figure ES-1).

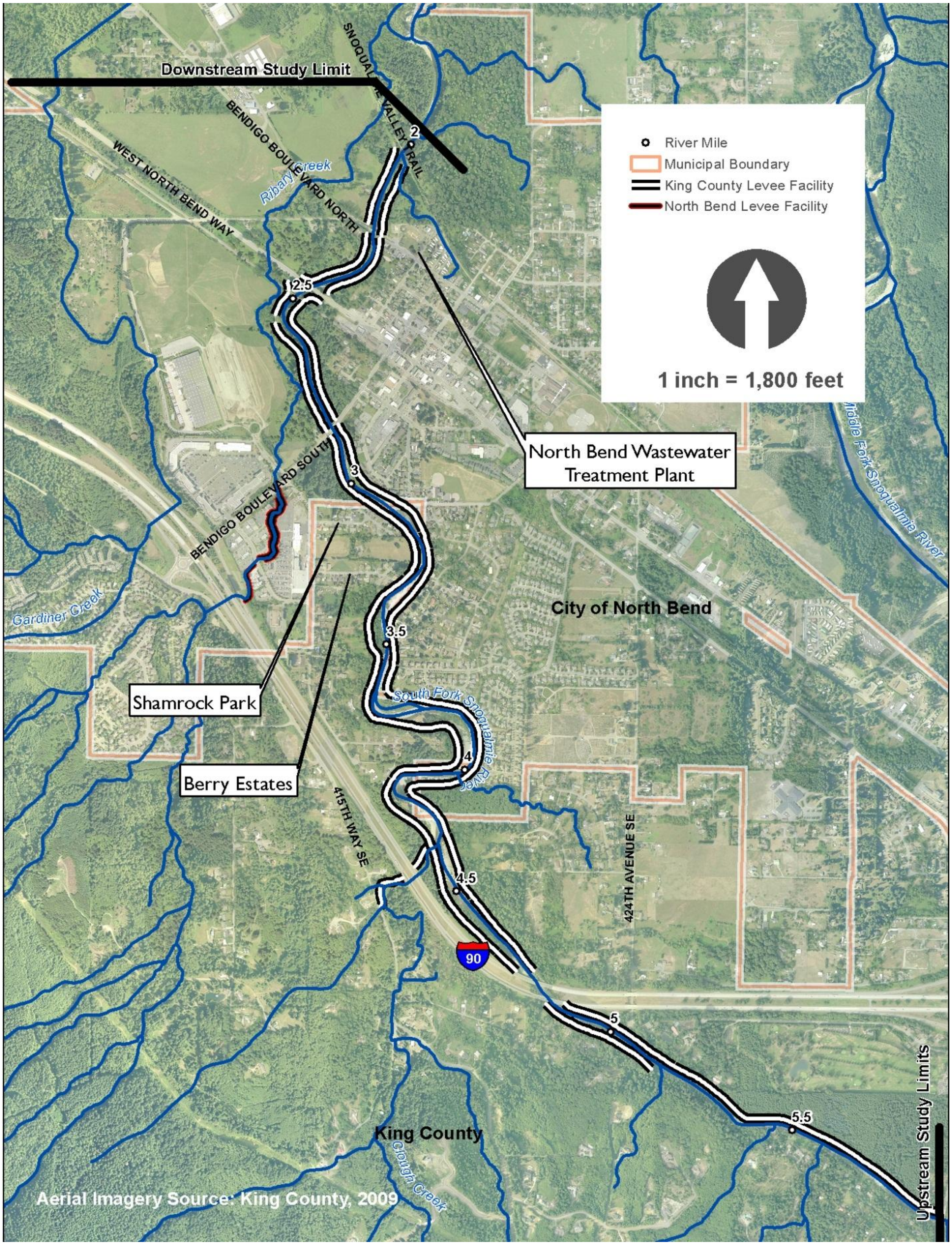


Figure ES-1. Study Area

ES.1.3 Levee System

There are nine King County levees along the banks of the South Fork Snoqualmie River. In 1964, King County raised and strengthened the levees in the study area (Kato and Warren 2000) to accommodate a design flow of 13,000 cfs. Figure ES-1 shows the location of the levees in the study area.

Levees evaluated for this study between RM 2 and RM 5.9 range in height from about 2 feet to 10 feet as measured from the landside toe. More than half of the levees are less than 5 feet in height. Portions of the levees are lined with revetment or slope up to high ground. In addition to the South Fork Snoqualmie River levees, King County maintains the levee on the left bank of Clough Creek that ties into the Reif Road levee and extends upstream to 415th Way SE. The City of North Bend maintains the levee along both banks of Ribary Creek from Bendigo Boulevard South to Interstate 90. The South Fork Snoqualmie River levees in the study area are not accredited by the U.S. Army Corps of Engineers or by the Federal Emergency Management Agency (FEMA) and therefore are not recognized by FEMA as flood control levees.

ES.1.4 Flooding in the South Fork Snoqualmie River

South Fork Snoqualmie River levee overtopping allows flood flows to spread across the floodplain along uncertain flow paths that may be dispersed or concentrated. In the floodplain, river flow overtops low watershed divides and significantly increases flow in tributary streams. Flows from tributary streams may in turn contribute to the flooding. Man-made structures, such as road crossings, restrict flow, causing upstream diversions and exacerbating backwater flooding. The magnitude of flooding in the study area is largely determined by the capacity of the South Fork Snoqualmie River levee system and the hydraulic restrictions caused by the bridges.

All major floods in the Pacific Northwest are caused by events generated by atmospheric rivers. These events are characterized by warm, moist air originating in the tropics and subtropics, and bringing an extended period of rainfall. In the past 10 years, three South Fork Snoqualmie River flood events have occurred with peak flows at or above the 10-percent-annual-chance flood frequency: in November 2006, November 2008 and January 2009. The November 2006 flood event was the flood of record at U.S. Geological Survey gages on the South Fork Snoqualmie River at North Bend and Edgewick. These three recent events were used to calibrate and validate the hydraulic model.

ES.1.5 Geology and Geomorphology

The location of the study reach at the downstream end of a drainage basin with ample sediment supply, a steadily decreasing channel gradient, and the widening of the valley bottom relative to the upstream areas all favor sediment deposition (King County 2011). The South Fork Snoqualmie River has a steep gradient of 1 to 3 percent in the mountainous headwaters east of the study area, and an average channel gradient of 0.3 to 0.4 percent within the study area. The drop in gradient has resulted in a coarse alluvium depositional fan that underlies the North Bend area. Alluvium, typically consisting of gravel and sand with variable silt content, is found throughout the study area.

Channel mobility is constrained by the levee system constructed in the 1960s (Bethel, 2004). The levees have effectively prevented channel migration upstream of Snoqualmie Valley Trail. Furthermore, the bridge at Snoqualmie Valley Trail and five other road crossings located in the study reach have also impeded channel migration (Perkins, 1996).

The North Bend aquifer is a substantial body of groundwater contained within the alluvium. Under normal river flow conditions (neither flood nor drought, with no significant inflow from surface runoff), the river level typically drops gradually over time. Groundwater usually drains from the aquifer,

sustaining long-term base flow to the river and the entire system draining the valley. Under flood conditions, groundwater rises rapidly in a direct response to the flood wave.

ES.2 LEVEE HYDRAULIC CONDITION ASSESSMENT

ES.2.1 Hydraulic Model Development

The two-dimensional modeling software FLO-2D was selected to assess existing conditions in the study area and the effects of future potential gravel accumulation. The model domain extended from RM 1.1 to RM 5.9 and includes the river channel and associated floodplain areas. The focus of the study was the capacity of the South Fork Snoqualmie River levees and resulting inundation extents in the left bank floodplain area between RM 2.0 and RM 5.9.

The hydraulic model was calibrated using gage data, anecdotal observations, and post-event surveyed water surface elevations from historical flood events. The November 2008 and January 2009 events were used for the calibration, with a calibration criterion of ±0.75 feet. The November 2006 event was used to verify the calibration.

Design flood events were the 5-, 2-, 1-, and 0.2-percent-annual-chance flood events. Design flood event frequencies referred to in this report are flood frequencies for the South Fork Snoqualmie River. Design flood events consist of the inflow hydrographs for the South Fork Snoqualmie River and tributary streams, using the probability of occurrence relationship described in Table ES-1.

TABLE ES-1.
RELATIONSHIP BETWEEN SOUTH FORK SNOQUALMIE RIVER AND TRIBUTARY STREAMS RECURRENCE INTERVALS AND DESIGN INFLOW HYDROGRAPHS

South Fork Snoqualmie River Peak Flows		Tributary Stream Peak Flows			
Design Flood Annual Probability of Occurrence (Return Period)	Peak Flow at Upstream Boundary of FLO-2D Model (RM 5.9)	Design Flood Annual Probability of Occurrence (Return Period)	Peak Flow Clough Creek	Peak Flow Ribary Creek	Peak Flow Gardiner Creek
5 (20-year)	12,190 cfs	40 (2.5-year)	180 cfs	130 cfs	110 cfs
2 (50-year)	14,160 cfs	25 (4-year)	220 cfs	160 cfs	140 cfs
1 (100-year)	15,650 cfs	16.7 (6-year)	250 cfs	180 cfs	160 cfs
0.2 (500-year)	19,120 cfs	7.1 (14-year)	330 cfs	240 cfs	210 cfs

Modeling was performed for existing conditions and for a scenario representing future sediment aggradation in the South Fork Snoqualmie River in the study area if no improvements are implemented. This scenario assumes that channel changes and sediment trends observed over the past 14 to 17 years will continue at a similar rate over a future 30-year period. This future aggradation scenario assumed gravel deposition up to 3 feet between RM 2.74 and RM 4.58, with a localized scour section near RM 4.0.

ES.2.2 Hydraulic Performance Results

Water surface profiles for the modeled existing-conditions and future-aggradation scenarios are shown in Figures ES-2 and ES-3, respectively. Figures ES-4 and ES-5 show modeled areas of inundation for the 1-percent-annual-chance flood event for the two scenarios. Table ES-2 summarizes key results of the modeling of the two scenarios.

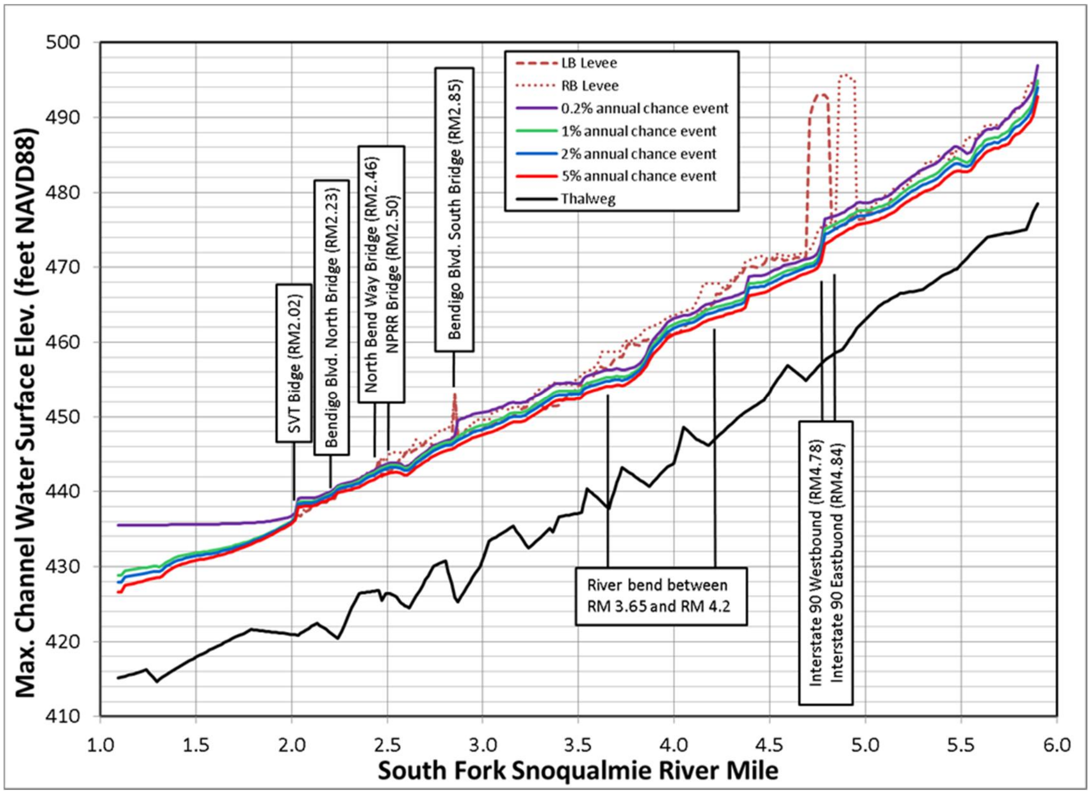


Figure ES-2. Maximum Channel Water Surface Profiles for Existing Conditions

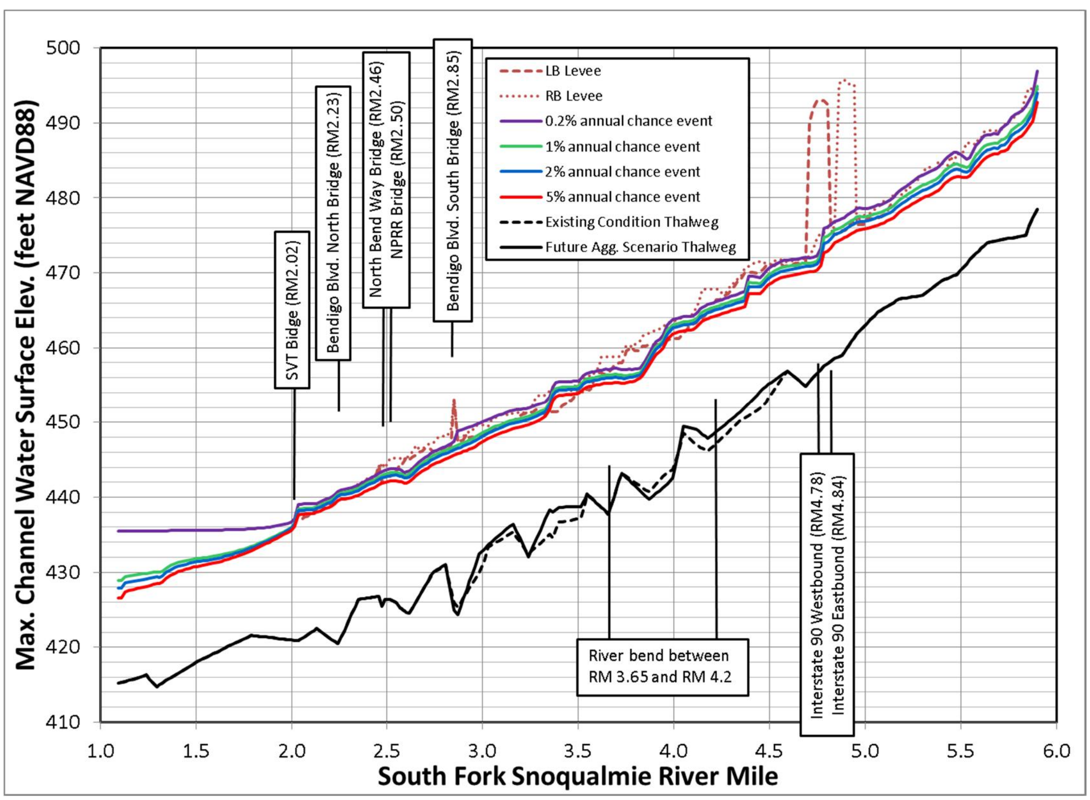


Figure ES-3. Maximum Channel Water Surface Profiles for Future Aggradation Scenario

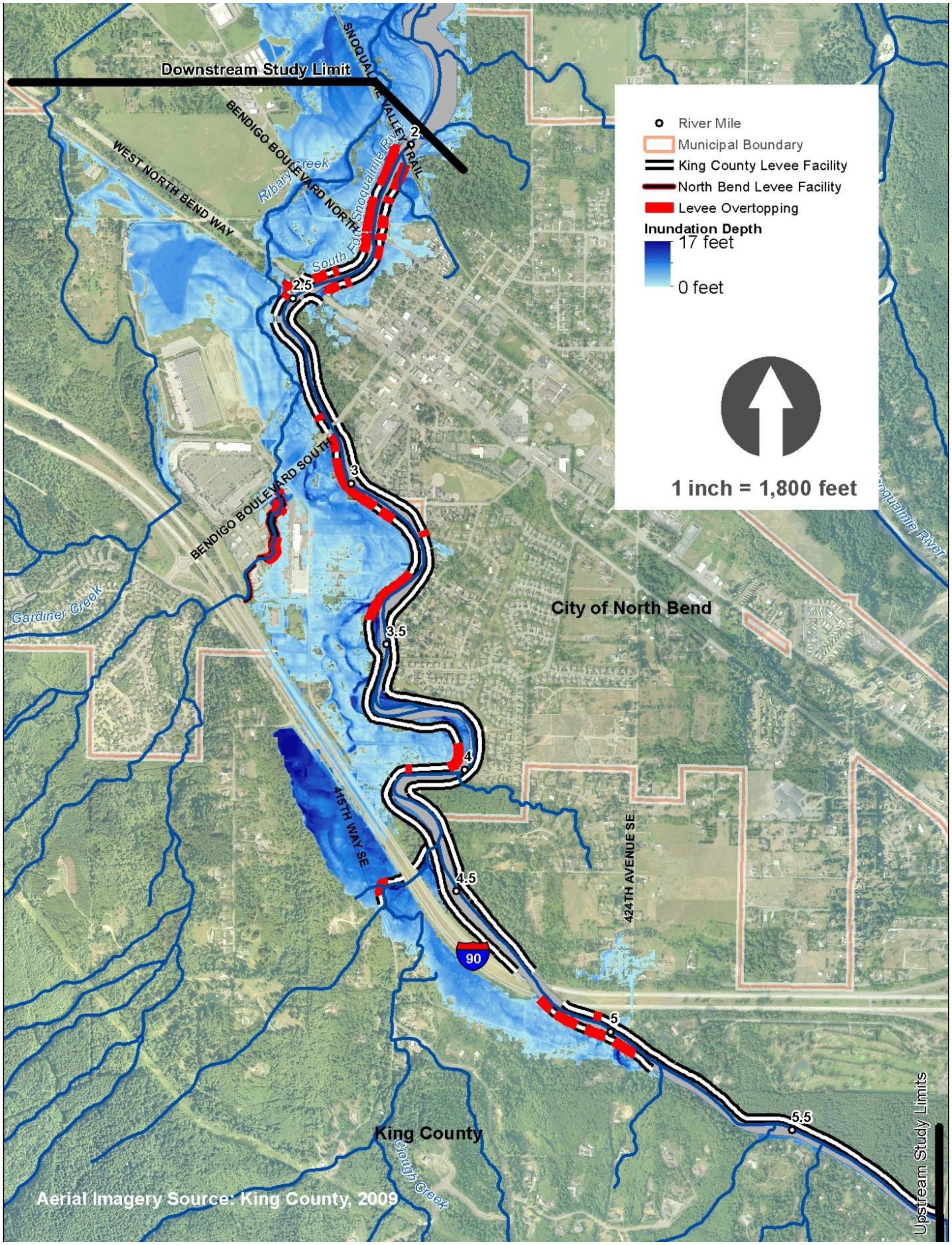


Figure ES-4. Existing Conditions Inundated Area for 1-Percent-Annual-Chance Flood Event

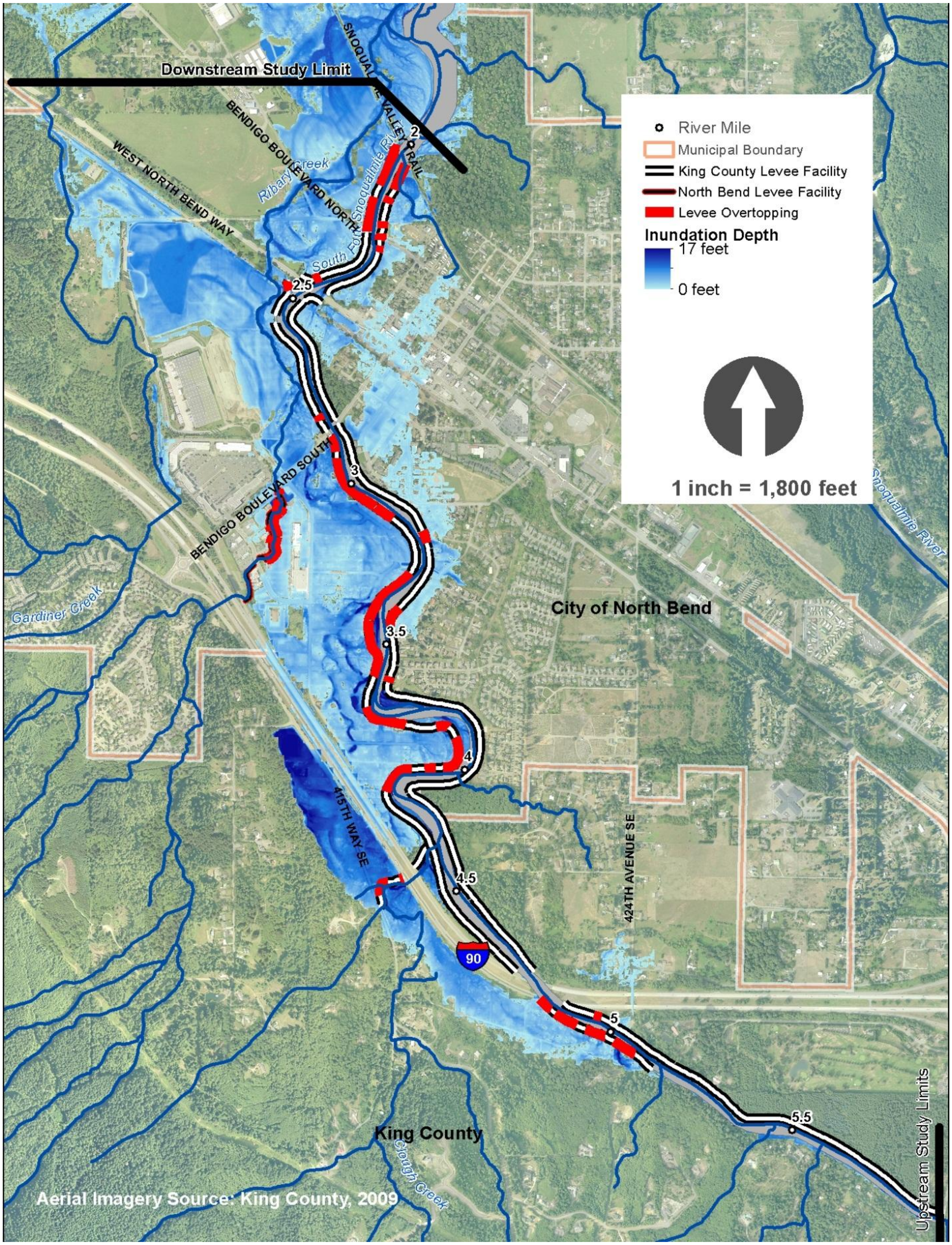


Figure ES-5. Future Aggradation Scenario Inundated Area for 1-Percent-Annual-Chance Flood Event

TABLE ES-2.
SUMMARY OF HYDRAULIC ANALYSIS RESULTS

	Predicted Flooding from Hydraulic Modeling	
	Existing Conditions	Future Aggradation Scenario
In-Channel Water Surface (see Figures ES-2 and ES-3)	• Most significant head loss (drop in water surface elevation) at the Snoqualmie Valley Trail Bridge and at the Interstate 90 Bridges for all events. • Significant head loss at Bendigo Boulevard South Bridge for the 0.2-percent-annual-chance event. • Significant head loss between RM 3.75 and RM 4.00 due to channel sinuosity.	• Water surface elevations increase for all flood events upstream of RM 3.40. Smallest increase is for 0.2-percent-annual-chance event because flow escapes the river channel upstream. • Downstream of RM 3.40, the water surface elevations are less than for existing conditions because of more flow overtopping the levees upstream, reducing downstream water surface elevations in the channel.
Levee Overtopping Length	• Overtopping along 1,300 feet levees for 5-percent-annual-chance event, increasing to 17,000 feet for the 0.2-percent-annual-chance event. • For the 5 percent-annual-chance through 1 percent-annual-chance events, the overtopping length is significantly greater for the left bank than for the right bank, because the left bank levees are lower.	• Increased total length of overtopping compared to existing conditions. • Length of levee overtopping increases by 770 feet for the 5-percent-annual-chance event and 1,630 feet for the 1-percent-annual-chance event. • Some overtopping where none is predicted for existing conditions, generally in the aggradation reach between RM 2.8 and RM 4.2.
Structure Flooding and Area Inundation (see Figures ES-4 and ES-5)	• Greater on left overbank than right overbank for all flood events except the 0.2-percent-annual-chance event. • Right-bank residential area adjacent to the river and downtown commercial area affected by the 0.2-percent-annual-chance event. • Entire Shamrock Park area is inundated for the 2-percent-annual-chance flood event. • Berry Estates area is inundated during the 1 percent-annual-chance flood event.	• Greater on left overbank than right overbank for the 5- and 2-percent-annual-chance events. • Many right-bank structures inundated starting with the 1-percent-annual-chance event. • Entire Shamrock Park and Berry Estates area and the commercial district south of Bendigo Boulevard South are completely inundated for the 5 percent-annual-chance flood event.
Roadway Flooding	• 1.4 miles of local street and roads flooded during 5-percent-annual-chance event. • 1 mile of Interstate 90 flooded for the 1-percent-annual-chance event. • Inundated road length more than doubles between the 2- and 1 percent-annual-chance events. • Inundated road length nearly triples between the 1- and 0.2 percent-annual-chance events, due to a large area of inundation in the City of North Bend caused by overtopping of the right bank levee upstream of Interstate 90 and right bank overtopping downstream of RM 3.0. • South Fork Avenue SW, Bendigo Boulevard South, 412th Avenue SE, SE 123rd Street, SE 125th Street, SE 131st Street, and SE 415th Street are all at risk of flooding during the 5-percent-annual-chance flood event. • Roadway inundation at SE 131st Street is due to seepage rather than levee overtopping. • Roadway flooding is not predicted in the right overbank until the occurrence of the 1 percent-annual-chance flood event.	• Length of road flooding is more than double the length for existing conditions for the 5- and 2-percent-annual-chance events, with most of the increase on local roads. • 0.8 miles of flooding is predicted for Interstate 90 for the 2-percent-annual-chance event. • Nearly 60 percent more inundated roadway than existing conditions is predicted for 1-percent-annual-chance event. • Much of the increase in road flooding is on the right overbank in densely developed North Bend residential and commercial areas. • Road flooding for the 0.2-percent-annual-chance event is similar to that for existing conditions. • Road flooding during the 5-percent-annual-chance event is predicted at South Fork Avenue SW, 412th Avenue SE, SE 123rd, SE 125th Street, SE 131st Street, SE 4215th Street, and Bendigo Boulevard South. • Roadway flooding is not predicted in the right overbank until the 1 percent-annual-chance event.

ES.3 GEOTECHNICAL AND HYDROGEOLOGICAL INVESTIGATION

Geotechnical and hydrogeologic investigations were completed to evaluate the current condition of the levees and assess levee stability and seepage characteristics. Investigations included review of levee characteristics and integrity ratings developed during previous studies, additional reconnaissance and subsurface explorations, review of groundwater monitoring data, stability and seepage analyses, and ground penetrating radar testing.

Levees evaluated for this study extend from the Snoqualmie Valley Trail (RM 2.0) to just upstream of 436th Avenue SE (RM 5.9). Levee heights are greatest at the downstream and upstream ends of the study. The height on both the left and right bank ranges from 4 to 10 feet downstream of Bendigo Boulevard South (RM 2.85), 4 feet or less on both sides of the river between Bendigo Boulevard South and RM 4.0, and between 5 and 10 feet upstream of RM 4.0.

The steepest riverside levee slopes are concentrated in the downstream portion of the study area, between Bendigo Boulevard South and the Snoqualmie Valley Trail on the right bank. Riverside slope on the right bank varies from 1.5H:1V (horizontal to vertical) to 2H:1V to steeper than 1.5H:1V in this area. Right bank slope upstream of Bendigo Boulevard are typically 1.5H:1V to flatter than 2H:1V. Slope inclinations on the left bank are typically between 1.5H:1V to 2H:1V to flatter than 2H:1V throughout the study area, with the exception of steeper riverside slopes located within ½ mile downstream of the Interstate 90 crossing (RM 4.36 to 4.85).

ES.3.1 Preliminary Geotechnical Problem Evaluation

A preliminary list of 46 potential geotechnical and hydrogeologic levee problem locations were identified based on the findings from the previous investigations and the additional geologic reconnaissance performed for this study. The preliminary list of problems were divided into higher and lower priority based on a qualitative assessment of the observed presence of potential failure mechanisms (seepage, piping, stability, erosion and subsidence) and considering the adjacent land use.

Higher priority problems were retained for additional evaluation and rated in terms of geotechnical likelihood of failure. High ratings were assigned to areas of observed piping and seepage, moderate to high ratings were assigned to areas of noted erosion and slope instability, moderate ratings were assigned to areas of depressions and toe erosion, and lower ratings were assigned to areas of levee penetrations (pipes or culverts) and areas of outside bends.

Seven of the problem areas were selected as critical sections for detailed stability and seepage analyses and three sections were analyzed for scour and stability. Critical section locations are listed in Table ES-3.

The purpose of the preliminary evaluation was to identify representative problem types and locations. The findings from this evaluation are applied to the larger list of potential problems to determine the geotechnical and hydrogeological problems that warrant full consideration of failure potential.

ES.3.2 Levee Protection

Historic plan documents of the levees show the design riprap protection to consist of a three-foot thickness at the toe of the riverside slope tapering to a two-foot thickness at the crest. However, detailed levee reconnaissance data (Shannon & Wilson 2009) indicates scattered to sparse riprap was observed over more than two-thirds of the riverside slopes. Three excavations with the purpose of evaluating riprap thickness were completed in the riverside slope in areas where reconnaissance data indicated sparse or missing riprap. This investigation showed a three foot layer of riprap at all sites excavated with rock size ranging from 12 to 36 inches, depending on the site. Based on the this data and discussions with King

County, it appears that the rock thickness is in general accordance with the historic plan documents except where repairs or other maintenance have been performed. The riprap apparently is buried by alluvium and obscured by vegetative growth which may have influenced earlier observations of sparse or missing riprap.

TABLE ES-3.
CRITICAL SECTION LOCATIONS

Location ID	River Bank	River Mile
G-1	Right	2.27
G-2	Left	2.51
G-3	Left	2.70
G-5	Left	3.10
G-8	Left	4.18
G-15	Right	2.47
G-23	Left	4.5 to 4.6

ES.3.3 Subsurface Conditions

Subsurface soil and groundwater conditions were evaluated by reviewing previous explorations and drilling six supplemental borings. Subsurface soils are relatively consistent in the borings completed throughout the study area consisting of mostly cohesionless soils with high permeability. The levee fill encountered consists primarily of medium dense to dense gravel with variable silt and sand. Occasional layers of silty sand with gravel were also encountered in the fill. Foundation soils directly beneath the levee are generally more fine-grained (sand with variable silt or silt layers), grading into mostly gravel with sand and silt and occasional sand layers. Both the levee fill and underlying soils encountered in the borings are representative of the native alluvial deposits in the North Bend area containing coarse-grained deposits of moderate to high permeability. Typically, the levee fill soil type is medium dense and has an internal friction angle of 36 degrees or greater and will remain stable at moderate to steep slopes (up to about 1.5H:1V) under static loading conditions. Slope failures are more likely to occur under rapid drawdown and seismic conditions.

Ground-penetrating radar indicates a change in subsurface conditions, which typically indicates extraneous matter. Strong anomalous zones were observed in four general areas, and moderate anomalous zones were observed in more than 40 areas. The most likely extraneous materials are tree stumps and logs; however, the anomalies may represent other items, such as below-grade pipes or structures. Results of the test pit excavation two of the four locations with strong anomalous zones did not find the anomalies identified by the ground penetrating radar nor were large stumps encountered in the test pits.

ES.3.4 Hydrogeologic Conditions

Groundwater levels follow river levels quite closely, indicating that the shallow groundwater system represented in the monitoring wells is hydraulically connected with the South Fork Snoqualmie River. Groundwater recession following flood waves closely follows recession in the river, suggesting that bank storage is discharged back to the river with little time-lag.

The results of seepage analyses completed at the seven critical sections indicate adequate factors of safety against piping. The risk of piping at the seven critical sections was evaluated to be low based on the

guideline that a light/no seepage condition is estimated for exit gradients of < 0.2. However, the seepage analyses assumed uniform conditions extrapolated from the boring data. It is likely that more critical local areas of high permeability layers exist where piping and internal erosion may occur.

Generally seepage below and through the levee soils appears to be widespread. In some locations, rapid seepage occurs via discrete pathways along highly permeable gravel zones that lack a matrix of less-permeable sand or silt. In other locations, these layers result in seeps and springs during flood events. These layers create a risk of seepage forces facilitating piping and internal erosion, which could compromise the stability of the levees. The occurrence of seepage is consistent with the relatively high permeability of the levee materials and subgrade soils, and would represent a significant concern if accompanied by the continued discharge of sand or other fine-grained materials, such as in the form of sand boils or detrital fans adjacent to seepage exit points. The generally broad grain-size distributions for most soils sampled in the borings suggest that they offer some filter resistance to the development of piping, which is more of a problem in relatively uniform soils with low coefficients of uniformity.

ES.3.5 Slope Stability

Table ES-4 summarizes the slope stability analyses of the seven critical sections. Analyses were completed at each critical section for the four defined Corps of Engineers cases assuming an unprotected slope face (no riprap) and a protected slope face (with riprap). The stability analyses found that most cases analyzed at the seven critical sections have adequate factors of safety per Corps of Engineers standards, provided riprap protection is present on the riverside slope face. Exceptions were noted at Problem Areas G-1, G-3, and G-23, where shallow failures with inadequate factors of safety are indicated under seismic conditions, even with the design thickness of riprap. The thickness of riprap on the riverside slope would need to be increased to 5 feet for Problem Area G-1 and 4 feet for Problem Areas G-3 and G-23 to obtain the specified factor of safety under seismic conditions.

ES.3.5 Scour and Stability of the Scour Impacted Section

Three levee sections were selected for scour analysis with the 0.1-percent-annual-chance event. Bend scour was determined to be the primary mode of erosion occurring at all three locations. Although the degree of channel bend in each area was different, the calculated bend scour depth was similar with potential scour depths ranging from 10.5 to 11.5 feet. Based on these results and comparing the scour characteristics of other site areas, scour calculations in other areas are anticipated to be relatively similar. Because the scour analysis indicates a high potential for failure due to scour, additional geomorphic and hydraulic analyses of the potential for the scour to occur in a near vertical configuration should be performed to assess the scour risks along the levee system.

Scour depths analyzed at the three locations were incorporated into the ground surface profile assuming two conditions. Condition 1 assumes the scour depth occurs offset from the toe of the slope and infilling of bed material occurs at the toe. Condition 2 assumes the full scour depth occurs at the toe of the existing riverside slope in a near vertical configuration.

TABLE ES-4.
SUMMARY OF SLOPE STABILITY ANALYSES

				Factor of Safety (FS)			
Analysis Case	Location	River Mile	Bank	Long-Term or Low Stage Condition[b,c] Required FS = 1.3	Steady Seepage at High Stage[b,d] Required FS = 1.4	Rapid Drawdown[b] Required FS = 1.0 to 1.2	Seismic[b,e] Required FS = 1.0
Unprotected Slope (No Riprap)	G-1	2.27	Right	1.20	1.35	1.49	0.88
	G-2	2.51	Left	1.33	1.54	1.09	0.91
	G-3	2.70	Left	1.32	1.16	1.20	0.84
	G-5[h]	3.10	Left	1.17	1.28	0.8 to 1.0	0.81
	G-8	4.18	Left	1.37	1.52	1.19	0.98
	G-15	2.47	Right	1.34	1.62	1.23	0.98
	G-23	4.50	Left	1.24	1.10	1.05	0.90
Protected Slope (Design Thickness of Riprap or Greater)[a]	G-1	2.27	Right	1.33	1.52	>1.49	0.96, 1.03[f]
	G-2	2.51	Left	>1.33	>1.54	>1.09	1.02
	G-3	2.70	Left	>1.32	1.49	>1.20	0.94, 1.07[g]
	G-5[h]	3.10	Left	1.27	1.78	1.20	1.02
	G-8	4.18	Left	>1.37	>1.52	>1.19	1.05
	G-15	2.47	Right	>1.34	>1.62	>1.23	1.07
	G-23	4.50	Left	1.33	1.48	>1.05	0.98, 1.02[g]

a. Design thickness of armor included a 3-foot thickness at the toe tapering to 1 foot at crest. Greater riprap thickness modeled for seismic condition as noted in footnotes f and g.
b. Required factor of safety based on U.S. Army Corps of Engineers Design of Levees.
c. Long-Term or Low Stage Condition based on water level at 2,000 cfs.
d. Steady state water level based on water surface elevation at levee crest or the 1-percent-annual-chance flood event, whichever lower.
e. The design earthquake does not consider the effects of liquefaction or lateral spreading of the alluvial soils below groundwater. Water level assumed as low stage condition at 2,000 cfs.
f. Lower factor of safety shown for design armor, higher factor of safety for 5-foot thickness.
g. Lower factor of safety shown for design armor, higher factor of safety for 4-foot thickness.
h. Stability analysis shown for levee section G-5 represents condition prior to recently completed repairs.

Does Not Meet Factor of Safety Criteria (without riprap)
Does Not Meet Factor of Safety Even with Design Riprap

The results of the stability analyses indicate factors of safety less than the U.S. Army Corps of Engineers standards for both scour conditions described above. For Condition 1, where infilling occurs, the analyses indicates a factor of safety slightly greater than 1.0, and loss of an approximate 3- to 5-foot thick section of the riverside slope that projects roughly to the riverside edge of the levee crest. Condition 2 assumes the full-depth scour occurs at the toe of the riverside slope in a near-vertical configuration. The results of the stability analyses for this condition indicate factors of safety are less than 1.0. Factors of safety as low as 0.5 are indicated that remove approximately the outer 10 feet of the riverside slope, and factors of safety near 1.0 indicate loss of about one-half of the levee crest width.

ES.3.6 Categorization of Geotechnical Problems for Risk Evaluation

After evaluation of the preliminary list of potential geotechnical and hydrogeological problems, The full list of problems were reviewed to determine the problems types that warrant additional consideration of risk and priority during the risk evaluation. Generally, the potential problems associated with active damage failure potential (e.g. observed seepage, piping, depression) were retained for additional analysis. These problems include:

- 5 locations with observed piping and seepage through the levee
- 3 location with depressions or sinkholes in the levee
- 10 locations with erosion at the toe of the levee.

Potential problems identified as culvert penetration, vegetation on the levee, or problems where no active failure mode was observed, were not selected for additional consideration. However, the South Fork Snoqualmie River is a dynamic river system and levee conditions may change during peak flood events. For this reason, the potential problem locations should be included in a monitoring program in case conditions change in the future.

ES.3.7 Key Findings

Key findings of the geotechnical and hydrogeological evaluation are summarized in Table ES-5.

ES.4 ECOLOGICAL ASSESSMENT

ES.4.1 Fish and Wildlife Habitat

The South Fork Snoqualmie River riparian zone provides habitat support for a variety of native wildlife species typical of the area. However, land uses, including agricultural, residential, commercial and transportation uses, have fragmented the riparian areas along the river in many places. Levees along the South Fork Snoqualmie River prevent riparian areas from normal flooding during high flows. Developed land uses and levees have degraded and reduced the scale and overall quality of the instream and riparian habitats along the river corridor, and essentially eliminated floodplain connectivity.

Dominant trees typical of the riparian zone include cottonwood, Douglas fir, western red cedar, big leaf maple and alder. Understory plants include sword fern, salmonberry, red-twig dogwood, and snowberry. In some areas, riparian habitats are degraded by invasive species, such as Himalayan blackberry and English ivy. A program of ivy removal is ongoing in the riparian area near the Bendigo Boulevard South bridge.

A variety of fish and wildlife species use the South Fork Snoqualmie River, its tributaries, and adjacent riparian habitats. The river supports resident populations of cutthroat and rainbow trout, both state priority species, as well as mountain whitefish and sculpin, among others. Tributaries support cutthroat trout and rainbow trout (City of North Bend, 2001; WDFW, 2008).

The North Bend foothills are home to a large herd of resident elk (WSDOT, 2012). Movements of elk occur between the north and south sides of Interstate 90 and like many wildlife species use riparian corridors for migration pathways. Elk have been observed crossing under the Interstate 90 bridge along the left bank of the South Fork Snoqualmie River to move to habitat areas west of North Bend. The space under the Interstate 90 Bridge is not high enough above the streambank to be considered an optimal wildlife crossing for the Interstate 90 corridor.

TABLE ES-5.
SUMMARY OF GEOTECHNICAL AND HYDROGEOLOGICAL EVALUATION

Geotechnical Condition	Key Finding
Levee Condition	• The levees are old and were constructed without material or compaction control. Evidence of organic matter including large tree stumps has been encountered in explorations of the levees. • Based on the rapid response of piezometers on the landward side of the levee to changes in river level, the subsurface soils are concluded to be very permeable. • Based on the limited reported visual observations of slope instability, sand boils and seepage during flood events, the levees appear to be performing satisfactorily; however the character of levees is that they include heterogeneities (presence of organic matter, loose soils, discrete zones of high permeable material, rodent burrowing) that can lead to failures.
Levee Stability	• An adequate thickness of riprap is required to meet the U.S. Army Corps of Engineers factor of safety requirements in areas with steeper river bank slopes. Previous investigations (Shannon and Wilson, 2009) indicated significant areas where riprap is missing, it is possible that the riprap is covered by a layer of silt. A cursory test pit investigation of the presence of the riprap indicated that riprap is present below the silt layer. A more extensive survey of the riprap continuity and thickness would need to be completed to address safety concerns posed by levee breaching due to slope failure. • The risk of piping at the seven critical sections was evaluated to be low. However, there is the possibility of discrete zones of higher permeability that can result in higher exit gradients and the potential for internal erosion. The toe of the levees are inspected during major storm events to check for signs of water seepage through and beneath the levees. • The scour analysis results indicate a relatively deep scour depth that increases the risk of riverside failures. Loss of a portion of the levee crest is possible if the full depth scour occurs in a near-vertical configuration at the location of the existing riverside toe. The failure can occur during both a full flood stage and at a low-water condition where no riprap is present. Geomorphic and hydraulic analyses to evaluate the potential for the scour to occur in a near vertical configuration at the riverside toe is appropriate to assess the scour risks along the levee system.
Levee Problem Evaluation	• Sand boils were observed following the January 2009 flood in the vicinity of RM 2.70. Observations of the levee performance during and after flood events should continue and appropriate repairs should be completed as soon as possible. • Small localized areas of subsidence/depressions were observed in several areas along the levee facility. Depressions may be the result of surface traffic, degradation of subsurface organic matter, or piping. These areas should be monitored over time to observe changes and repairs should be completed as necessary. Excavations to explore the presence of large organic debris should be scheduled based on the monitoring results. • Penetrations through the levee (e.g. pipe culverts) pose a higher risk of piping. These areas should be carefully monitored during annual levee inspections to document changes. Appropriate repairs should be completed as required (excavation and replacement with seepage risk reduction devices). • All the potential geotechnical and hydrogeological problem areas identified as part of this study should be monitored on a regular basis. Remedial repair measures should be developed that address the identified geotechnical and hydrogeological problems where actual damage to the levee was noted (e.g. seepage, erosion, depressions). • Eighteen of the 46 identified potential problems were determined to be actual problems and should be retained for risk priority evaluation and possible remedial action. Generally, the problems associated with active damage failure potential (e.g. observed seepage, piping, depression) were included in the list of problems. • Potential problems identified as culvert penetration, vegetation on the levee, or problems where no active failure mode was observed, were not selected for additional consideration. However, the South Fork Snoqualmie River is a dynamic river system and levee conditions may change during peak flood events. For this reason, the remaining 27 potential problem locations should be included in a monitoring program in case conditions change in the future.

The South Fork Snoqualmie River study area was divided into three reaches generally aligned with study reaches used in the hydraulic condition assessment:

- The lower reach (RM 2.0 to RM 2.85) contains a forested riparian area for much of the reach, generally ranging from 100 to 300 feet in width, although a few areas have been cleared to the levee. Land use adjacent to the river includes single-family homes in with the City of North Bend along the right bank and rural residential and pasture along the left bank. The levee is generally vegetated with shrubs and small trees. Sand and gravel deposits are present along the toe of the levee in the river corridor. The South Fork Snoqualmie River has a few bends in the lower reach, primarily between RM 2.3 and RM 2.6.
- The middle reach (RM 2.85 to 4.85) has greater channel complexity than the upper and lower reaches. Riparian areas are degraded and fragmented with isolated stands of trees. Riparian habitat within the levee footprint (both left and right bank) is also fragmented with isolated patches of shrubs growing over the bank armoring. Land use is primarily a built environment along on the right bank through the City of North Bend. The left overbank is rural residential, with more vegetation coverage. The upper part of the reach has more continuous forested habitat and vegetation between the levee and the river channel. Sinuosity is greater in the middle reach channel than in the upper or lower reaches. Substrates in the middle reach are gravelly with gravel bars alternating from the left bank to the right bank throughout the reach. Several high flow secondary channels are present between the streambank and gravels bars.
- Riparian habitat in the upper reach (RM 4.85 to 5.9) is mostly forested, interspersed with rural residential areas. The levee is vegetated with some sparse trees and shrubs along the right bank. The left bank has stretches with less observed armoring and more mature vegetation in spots. Some properties along the left bank contain landscaped yards down to the water's edge. The upper reach has a higher gradient, as indicated by its coarse gravel and cobble substrate. A few large boulders are present in the river bed. This is the straightest reach in the study area, with a few minor bends in the river.

ES.4.2 Ecological Function Assessment

Habitat conditions along the levees was qualitatively evaluated as follows:

- **Stream bank velocity refuge** is based on the bank condition. Juvenile salmonids occupy low-velocity areas found in edge habitats along banks, bars and backwater areas. Reaches with hydro-modified edges (i.e. armoring) are rated low. Reaches with abundant edge habitat with assumed velocity refuge below 1.5 feet per second, because of vegetation or other refuge with low flows, such as benches and floodplains, were rated high. The habitat assessment rated streambank velocity refuge as low for about 90 percent of the South Fork Snoqualmie River streambank.
- **Connectivity to off-channel habitats**, such as side channels, sloughs, ponds and seasonally flooded wetlands, can provide important refuge areas for juvenile and adult fish during high flows. These areas also can provide important salmonid juvenile rearing habitat. Reaches without floodplain or side channel connections were rated low. Reaches without disconnections to side channels and floodplains were rated high. The habitat assessment rated 100 percent of the South Fork Snoqualmie River as low for connectivity.
- **Riparian condition** is an indicator of habitat conditions and wildlife corridors along a river corridor. Well-developed riparian areas contribute to the health of rivers by providing functions such as temperature regulation, water quality protection, flood conveyance, bank stabilization, wildlife habitat, and large-wood recruitment. Reaches without buffers 150 feet wide and 150 feet tall were rated low. Reaches with 150-foot-wide buffers and 150-foot-tall

trees were rated high. The habitat assessment rated about 39 percent of the South Fork Snoqualmie River as low for riparian function and 61 percent as medium.

- **Instream natural cover** is an important habitat element for salmon recovery and includes submerged and overhanging large wood, log jams, beaver dams, aquatic vegetation, large rocks and boulders, side channels, and undercut banks. Reaches with minimal complexity were rated low. Reaches with a high degree of complexity and cover, such as ample large woody debris, pools and boulders, were rated high. The habitat assessment rated instream natural cover for about 26 percent of the South Fork Snoqualmie River as low 69 percent and 26 percent as high.

Table ES-6 summarizes key results of the ecological assessment.

TABLE ES-6.
SUMMARY OF ECOLOGICAL ASSESSMENT

Ecological Function	Key Finding
Streambank Velocity Refuge	• Ninety percent South Fork Snoqualmie River streambanks have been degraded by armoring and result in low function for velocity refuge. • Low velocity refuge function due to bank armoring is slightly improved over a significant length of streambank where mature shrubs and small trees are growing in the levee.
Floodplain Connectivity	• Connectivity to floodplain habitats (side channels and wetlands) is non-existent throughout the entire study area due to levees blocking off channel refuge and rearing areas for salmonids within the study area.
Riparian Condition	• Areas with low riparian function are primarily associated with residential areas in North Bend and the Berry Estates/ Shamrock Park neighborhood and Interstate 90. • A patchwork of mature riparian areas is present through the study area. These areas lack the average stand height needed to provide ample shading to reduce summer temperatures. • The highest rating assigned to the riparian function was medium due to a gap of about 30 feet between the water's edge and riparian forested areas. This gap further hinders the cooling effect these areas may have and reduces overhanging vegetation in many areas. • Because riparian habitat is setback from the South Fork Snoqualmie River by levees, large wood recruitment is lacking throughout the study area. • Wildlife movement through the area relies on the connectivity of riparian habitat. The riparian habitat is patchy and movement of large animals such as elk are hindered by residential and commercial development in the riparian corridor and Interstate 90.
Instream Natural Cover	• Instream natural cover is generally rated medium for most of the study area. • Low function is found in the lower reach generally due to a lack boulders, wood, and vegetation within the channel. • High function is found in the middle reach where several gravel bars with established willows and other persistent vegetation have collected some large woody debris and many woody debris piles. This area provided the best instream natural cover for the study area. • The relatively straight confined reach downstream and upstream of Interstate 90 was rated low. Above the low rated segment, the upper reach has some large woody debris and large boulders in the channel which improve function to a medium rating. • Suitable spawning areas for salmonids are lacking in the South Fork Snoqualmie River. • Ribary Creek and Clough Creek are the only areas that provide suitable spawning areas and connections to Clough Creek may be hampered by culverts under the levee and Interstate 90. • No barriers to fish movement in the South Fork Snoqualmie River were identified in the project area.

ES.5 PROBLEM IDENTIFICATION AND GROUPING

Hydraulic, geotechnical and ecological problems with the study area levee system were identified based on the findings of the respective technical analyses. Concise problem descriptions were developed along consequences for each problem type. A qualitative risk assessment was applied to the hydraulic and geotechnical problems to identify reaches in the South Fork Snoqualmie river with the most critical problems.

Hydraulic problem areas were identified based on modeling of the existing conditions and flood events, photographs of historical flood events, and anecdotal observations. Geotechnical problem areas were identified based on previous geotechnical analysis, augmented by the new geotechnical investigations. Ecological problems were identified based on reaches with low ecological function for floodplain connectivity, riparian, streambank velocity refuge and instream cover. Sixteen hydraulic problems, 18 geotechnical problems and 12 ecological problems were identified.

Risk scores were developed for the hydraulic problems based on the likelihood and consequences of failure using the project prioritization criteria developed by the King County Flood Control District (King County, 2008). Risk scores for the geotechnical problems were based on likelihood of failure criteria developed for the initial screening of geotechnical problems. Ecological problem areas were not prioritized but addressing these problems would need to be considered when developing solutions to the hydraulic and geotechnical problems.

The highest risk reaches due to hydraulic issues correspond to reaches where levee overtopping affects critical infrastructure or inundates large residential and commercial areas. Reaches with high hydraulic risk are listed as follows:

- Bendigo Boulevard North to West North Bend Way, right bank (RM 2.25 to 2.45) where levee overtopping inundates the North Bend Wastewater Treatment Plant during the 1-percent-annual-chance flood event.
- Bendigo Boulevard South to RM 3.55, left bank (RM 2.85 to 3.55) where extensive property flooding occurs starting with the 5-percent-annual-chance flood event in the Berry Estates and Shamrock Park area and roadway overtopping at the Bendigo Boulevard South roadway.
- Interstate 90 to 436th Avenue SE where levee overtopping upstream of Interstate 90, combined with high river stage at the Clough Creek confluence, result in overtopping Interstate 90 from Clough Creek between the 5- and 1-percent annual chance flood event.

From a geotechnical standpoint, the highest risk reaches correspond to reaches with observed piping, seepage, and severe toe erosion. Reaches with high geotechnical risk are listed as follows:

- Snoqualmie Valley Trail to Bendigo Boulevard North, left bank (RM 2.0 – 2.25) where severe toe erosion has occurred and also seepage through the levee near the Bendigo Boulevard North bridge.
- West North Bend Way to Bendigo Boulevard South, left bank (RM 2.45 – 2.85) where piping with a depression was observed in this reach during the 2009 flood event. Also in this reach, seepage with a depression was observed during the same flood event.
- RM 3.55 to Interstate 90, left bank (RM 3.55 to 4.85) where toe erosion and an unstable levee slope has occurred downstream of Interstate 90. Seepage was also reported near SE 131st Street in this reach.

The geotechnical analysis documented two potential system-wide problems regarding the absence of riprap and bed scour which are not addressed in the problem evaluation.

Previous analyses indicated sparse or missing riprap in the levee system. A limited field investigation performed for this study however showed riprap to be present at locations previously noted as missing, but obscured by a layer of alluvium and vegetation suggesting riprap is present in the system. At this time, it is assumed that riprap is present in the levee system and is therefore not considered to be a system-wide problem. However, a more thorough investigation of riprap should be performed to confirm the presence of riprap throughout the system.

A scour analysis performed for this study showed that scour depths of 10 feet or more are possible resulting in a potential loss of a significant portion of the levee. However, the scour analysis was limited in scope so there is uncertainty in the conclusions drawn from this analysis. A more rigorous analysis of scour potential would need to be performed to reduce the uncertainty and improve the understanding of scour potential in the river channel especially at outside bends and significant channel constrictions.

CHAPTER 1.
INTRODUCTION

1.1 BACKGROUND AND REPORT ORGANIZATION

The South Fork Snoqualmie River basin in central King County, Washington drains an area of the western slopes of the Cascade Mountains from Snoqualmie Pass to North Bend. The basin's meteorological and topographic characteristics can lead to significant flood events. Large storm events from the Pacific Ocean can generate flow rates in the river that overwhelm the channel and overflow to the floodplain at the river's low-gradient alluvial reaches near North Bend.

The South Fork Snoqualmie River has a long history of flooding. As the valley developed to agricultural and urban land uses, levees were constructed in an attempt to contain flood flows in a narrow river corridor, preventing overtopping onto the surrounding floodplain. Levees in the study area were constructed over many years using unknown design criteria, levee materials and construction methods (Kato and Warren 2000). None of the levees in the study area are certified by the U.S. Army Corps of Engineers or accredited by the Federal Emergency Management Agency (FEMA). Several bridges over the river encroach on the river channel and may exacerbate flooding. Numerous studies have been conducted in the recent past of flood conditions, flood elevations, geomorphology, geotechnical condition of the levees, and hydraulic conditions at bridges. These studies focused on specific solutions (e.g. gravel removal) or on a relatively small area (e.g. the State Route (SR) 202 bridge) and do not present a comprehensive evaluation of problems in the system.

This report presents a comprehensive and integrated evaluation of hydraulic, geotechnical, and ecological conditions of the South Fork Snoqualmie River and its floodplain. It includes an evaluation of existing conditions and proposes a prioritized program for improvement and maintenance of the levee system. The hydraulic evaluation employed a sophisticated two-dimensional hydraulic model to evaluate existing conditions and proposed alternatives, integrating recent flow gage data and observations of conditions during recent flood events. The geotechnical evaluation included geophysical testing over 9,000 feet of levee. Geotechnical and hydrogeologic stability was analyzed at critical sections of the levee system. The ecological evaluation qualitatively assessed habitat conditions associated with streambank velocity refuge, floodplain connectivity, riparian condition, and instream natural habitat functions.

As a component of the overall South Fork Snoqualmie River Levee Repair and Reconstruction Plan, this levee characterization report presents a summary of the hydraulic, geotechnical and ecological conditions of the South Fork Snoqualmie River levee system. It includes analysis of existing conditions, future gravel aggradation, and an assessment of flooding and stability problems with the existing levee system. Details of the analyses are provided in appendices.

1.2 STUDY OBJECTIVES

The overall goal of the planning process is to lay the groundwork for informed decision making for evaluation of potential project actions to most successfully realize the three goals of the flood plan. To meet this goal, the objectives for the levee characterization report are as follows:

- Characterize the existing conditions in the study area.
- Evaluate the performance of the levee system during extreme flood events.
- Define the existing level of service.

- Identify hydraulic and geotechnical problems.
- Evaluate the levee system against the 1964 design basis of accommodating flows up to 13,000 cubic feet per second (cfs) while maintaining a minimum of 1 foot of freeboard.
- Qualitatively assess ecological function

1.3 DESCRIPTION OF STUDY AREA

The study area for this project extends along the South Fork Snoqualmie River from River Mile (RM) 2.0 to RM 5.9 (see Figure 1-1). The study area on the west (left) side of the river extends to the toe of the valley edge, including Interstate 90 and Gardiner Creek. The study area on the east (right) side of the river extends about a mile landward from the right bank, through the City of North Bend. The hydraulic model of the river and floodplain extends farther downstream, to RM 1.1, in order to account for potential tailwater conditions. The hydraulic analysis assessed conditions of the South Fork Snoqualmie River channel, the levees and the overbank floodplain area. The left overbank floodplain area was analyzed in greater detail because it experiences more frequent overtopping and flooding from the South Fork Snoqualmie River. Geotechnical analysis was performed at discrete locations on both banks of the river.

1.3.1 South Fork Snoqualmie River

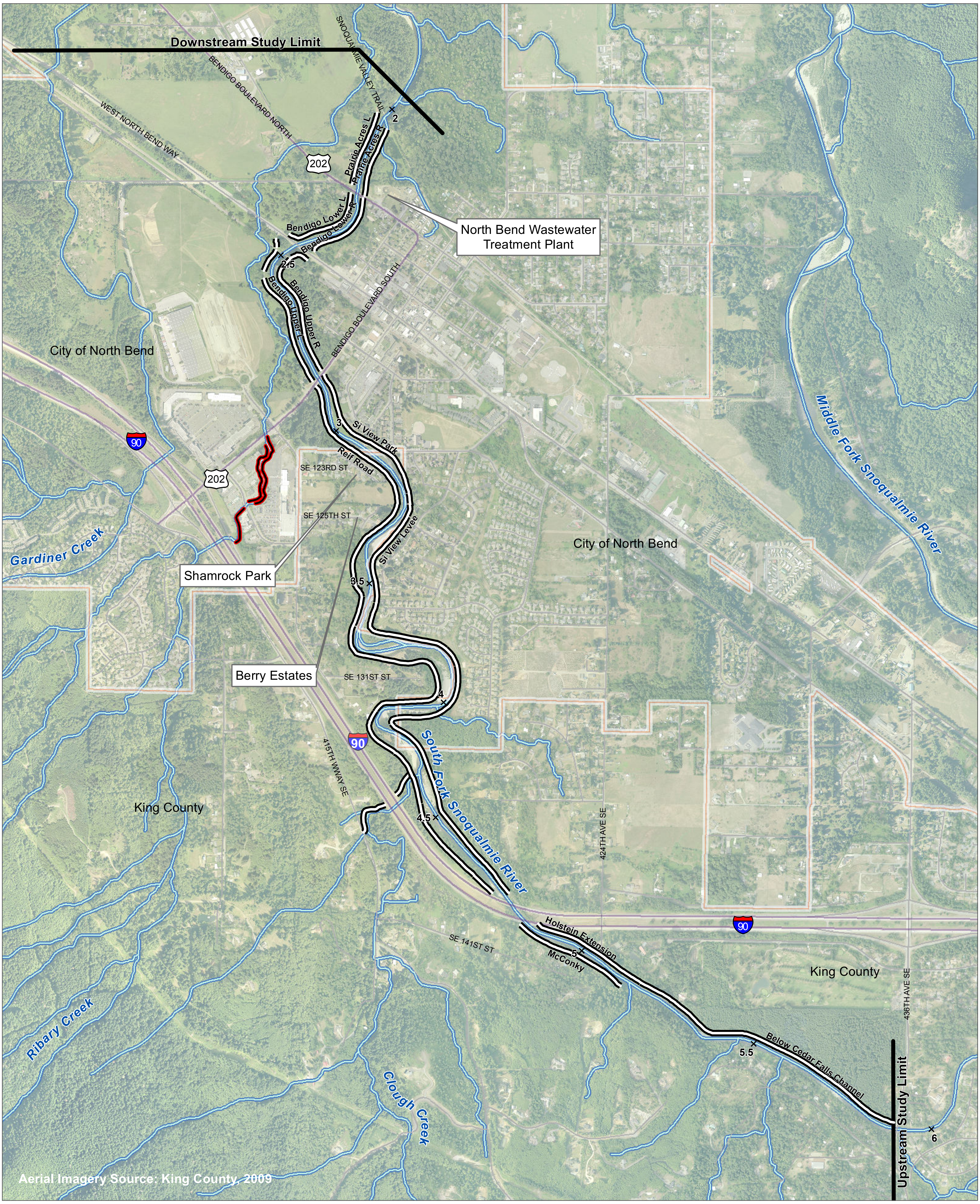
The South Fork Snoqualmie River upstream of RM 2.0 drains an area of about 84 square miles (USGS, 2013). Within the North Bend city limits, the river is confined by levees on both sides. The South Fork Snoqualmie River has no significant diversions or regulation. The U.S. Geological Survey (USGS) maintains and operates two long-term stream flow gages on the South Fork Snoqualmie River near the study area (see Figure 1-1):

- South Fork Snoqualmie River at North Bend, USGS Gage #12144000, is on the right bank on the upstream side of the Bendigo Boulevard South river crossing at North Bend, at RM 2.84. The South Fork Snoqualmie River watershed area tributary to this gage is 81.7 square miles. This gage has 74 years of records, missing the 1950s and most of the 1970s. The gage record at this location is affected by overtopping of the upstream levee system.
- South Fork Snoqualmie River at Edgewick, USGS Gage #12143600, is upstream of the study area at RM 8.8, upstream of the confluence with Boxley Creek. The South Fork Snoqualmie River watershed area tributary to this gage is 65.9 square miles. This gage has been in operation continuously since 1983 and operated intermittently in the 1960s. Data from this gage after 2004 showed irregularities in peak flows. After review and consultation with USGS staff, it was determined that the data for this period are not reliable. The data were adjusted for this project as described in Appendix A.

Table 1-1 shows flood-frequencies for the two gages, based on peak annual flow data from the records.

1.3.2 Local Tributaries

Several smaller streams originating outside the study area contribute flow to the South Fork Snoqualmie River. These streams have steep headwater reaches along the east flank of Rattlesnake Mountain that descend into flatter areas near Interstate 90 as they enter and cross the South Fork Snoqualmie River's large floodplain. The smaller streams combine into three main tributaries within the study area: Gardiner Creek, Ribary Creek and Clough Creek (see Figure 1-1). Stream reaches of the three tributaries within the study area are included in the hydraulic analysis. A fourth tributary, Boxley Creek, flows into the South Fork Snoqualmie River between the USGS Edgewick gage and the upstream study area limits.



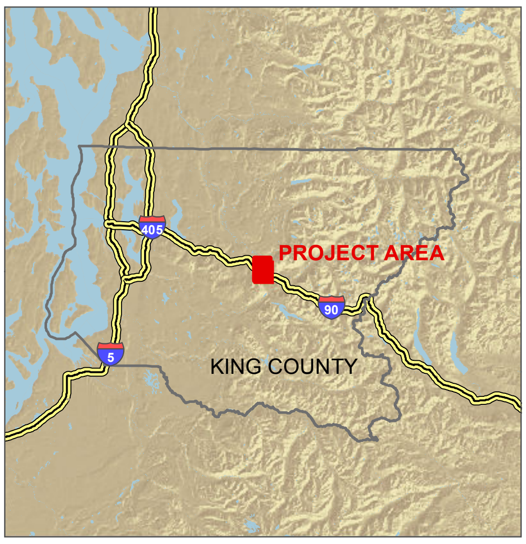


Figure 1-1. Study Area

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9

TABLE 1-1.
PEAK FLOWS AT SOUTH FORK SNOQUALMIE RIVER USGS STREAM FLOW GAGES

Annual Probability of Occurrence	Return Period	Corresponding Peak Flow (cfs)	
		USGS 12144000 South Fork Snoqualmie River at North Bend, WA[a]	USGS 12143600 South Fork Snoqualmie River at Edgewick, WA[b]
50 percent	2-year	5,184	6,477
10 percent	10-year	9,600	10,478
5 percent	20-year	11,302	11,984
2 percent	50-year	13,502	13,927
1 percent	100-year	15,150	15,384
0.2 percent	500-year	18,968	18,790

a. Period of record 1909 – present (74 years with peak flow data)
b. Period of record 1985 – present plus 1964 and 1965 (data after 2004 were adjusted for this project)

Table 1-2 shows the drainage areas of these tributaries. In the study area, Gardiner Creek is about 25 feet wide and 6 feet deep, Ribary Creek about 12 feet wide and 6 feet deep, and Clough Creek is 28 feet wide and 5 feet deep. These channel characteristics are approximate sizes for the tributary stream upstream of the South Fork Snoqualmie River Floodplain.

TABLE 1-2.
TRIBUTARY STREAM DRAINAGE AREAS

	Location of Confluence with South Fork Snoqualmie River	Basin Area (square miles)
Gardiner Creek[a]	South Fork Snoqualmie River RM 1.15	1.73
Ribary Creek[a]	South Fork Snoqualmie River RM 1.60	1.89
Clough Creek[a]	South Fork Snoqualmie River RM 4.38	2.68
Boxley Creek,[b]	South Fork Snoqualmie River RM 8.8	5.89

a. King County Geodatabase
b Estimated by USGS StreamStats website

Tributary flooding has been cited in past reports (NHC, 2001a, 2001b and 2001c) and was documented in photographs during a 2009 flood event. Causes of tributary flooding include the following:

- Reduced conveyance capacity resulting from backwater in the South Fork Snoqualmie River
- River flows overtopping levees and flowing into the tributary basins
- Conveyance restrictions caused by road crossings and sediment deposition in the tributaries.

The tributary systems are ungaged, so no measured flow data were available for this analysis. The USGS operates a stream flow gage on Boxley Creek (Boxley Creek Near Edgewick, WA #12143900). Boxley Creek is adjacent to the study area and enters the South Fork Snoqualmie River east of the study area at about RM 9. It is reported by the USGS to have significant seepage flows from the adjacent Rattlesnake

and Chester Morse Lakes that increase base flows. The Boxley Creek system is outside the study area but is relevant to this study because it provides information on hydrology of the other local tributaries. Inflow from the Boxley Creek system also needs to be accounted for when developing flow inputs for the hydraulics modeling (see Chapter 2 and Appendix A)

Tributary flooding is not well documented in previous studies of these systems. However, anecdotal observations and findings from previous analyses indicate that when the South Fork Snoqualmie River left bank levee overtops the levee near Berry Estates (SE 125th Street and SE 415th Avenue), overflows from the river cause flooding in the Ribary Creek and Gardiner Creek basins (Kato and Warren 2000, Bean 2011).

Previous analyses and flood events indicate that culverts on Ribary Creek at South Fork Avenue and at Bendigo Boulevard South (SR 202) do not have adequate capacity to convey the 1-percent-annual-chance flood without causing backwater upstream (NHC 2001a). Local topography directs overflows to a low area in Shamrock Park (at SE 123rd Street and 412th Avenue SE). According to anecdotal reports, Shamrock Park was flooded in 1996 when the Reif Road levee near Berry Estates did not overtop (Bean 2011). The cause of this flooding is uncertain, but it may have been Ribary Creek flooding, local drainage, seepage through the levees or some combination of all three sources.

Anecdotal observations indicate that the lower Clough Creek area is subject to flooding at approximately a 10-percent-annual-chance event (Bean 2011). This flooding is due to Clough Creek tributary flows, backwater or reverse flows from the South Fork Snoqualmie River.

1.3.3 Levee System

Description of Levees

There are nine King County levees along the banks of the South Fork Snoqualmie River. In 1964, King County raised and strengthened the levees in the study area (Kato and Warren 2000) to meet a design flow of 13,000 cfs. Design drawings are available but construction materials and methods are not clearly understood although the levees are reported to have been constructed of streambed gravel removed from the river between Bendigo Boulevard North and Interstate 90 (Perkins, 1996). Table 1-3 describes the existing levees. Figure 1-1 shows the location of these levees in the study area. Levees evaluated for this study between RM 2 and RM 5.9 range in height from about 2 feet to 10 feet as measured from the landside toe. More than half of the levee are less than 5 feet in height. Portions of the levee are lined with revetment or slope up to high ground. Additional information is provided on the levee configuration in Chapter 3.

In addition to the levees described in Table 1-3, King County maintains the levee on the left bank of Clough Creek that ties into the Reif Road levee and extends upstream to 415th Way SE. The City of North Bend maintains the levee along both banks of Ribary Creek from Bendigo Boulevard South to Interstate 90.

Accreditation

The South Fork Snoqualmie River levees in the study area are not accredited by the U.S. Army Corps of Engineers or by FEMA and therefore are not recognized by FEMA as flood control levees. For its National Flood Insurance Program, FEMA flood hazard and risk mapping currently recognizes only levee systems that meet and maintain design, operation and maintenance standards consistent with the comprehensive floodplain management criteria in Title 44 of the Code of Federal Regulations (44 CFR) Chapter 1 Section 60.3.

**TABLE 1-3.
KING COUNTY LEVEES ON THE SOUTH FORK SNOQUALMIE RIVER**

Levee Name, Bank	Year Constructed	Approximate Downstream Extent	Approximate Upstream Extent
Prairie Acres, Left & Right Bank	1966	Snoqualmie Valley Trail (RM 2.0)	Bendigo Blvd. North (RM 2.2)
Bendigo Lower, Left & Right Bank	1965	Bendigo Blvd. North (RM 2.22)	West North Bend Way (RM 2.45)
Bendigo Upper, Left & Right Bank		West North Bend Way (RM 2.45	Bendigo Blvd. South (RM 2.85)
Reif Road, Left Bank	1964	Bendigo Blvd. South (RM 2.85)	Interstate 90 (RM 4.85)
Si View Park, Right Bank	1961	Bendigo Blvd. South (RM 2.85)	Riverside Drive (RM 3.28)
Si View Levee, Right Bank, Right Bank	1964	Riverside Drive (RM 3.28)	Interstate 90 (RM 4.85)
Holstein Extension		Interstate 90 (RM 4.85)	RM 5.35
McConky, Left Bank		Interstate 90 (RM 4.85)	RM 5.14
Below Cedar Falls Channel, Right Bank		RM 5.35	436th Avenue SE (RM 5.9)

The levee accreditation standards in 44 CFR Chapter 1 Section 65.10 include criteria related to providing freeboard for the 1-percent-annual-chance flood event, levee embankment protection, levee embankment and foundation stability, settlement, and interior drainage. The certification requirements stipulate that the levee system must tie into natural high ground at the upstream and downstream ends.

The South Fork Snoqualmie River levees were not designed to meet the FEMA levee freeboard requirements, nor do they tie into natural high ground. For these reasons, FEMA levee accreditation for the existing levees is not likely. However, FEMA is developing a new approach for mapping flood hazard areas behind levees that do not fully meet the requirements for levee accreditation, recognizing that such levee systems may still provide a measure of flood risk reduction.

Inspection

King County conducts regular levee inspections during and after significant floods and annually during summer low-flow conditions. Small County construction projects in the last five years have repaired levee damage at RM 3.1 right bank, RM 3.2 left bank, RM 4.1 left bank and RM 6.2 left bank. In 2008 and 2011, King County used ground-penetrating radar (GPR) and surface observations to identify surface depressions, deleterious materials and voids in the levees. Test pits were later excavated at 10 locations: eight selected based on visual observations of surface depressions and two selected based on GPR data. The deleterious material (stumps and large wood debris) and voids were excavated with a backhoe and replaced with appropriate backfill at four of the locations. GPR testing is described further in Section 3.5.

1.3.4 Bridge History

Snoqualmie Valley Trail Bridge

The Snoqualmie Valley Trail bridge is the most downstream structure in the study area. This structure is a truss-type bridge with pier supported approaches originally built for rail traffic when the railroad occupied the current recreational corridor. The structure crosses the South Fork Snoqualmie River at RM 2.0 with a

single 100-foot span over the river. Flood flows are conveyed through the structure through the trestle openings on the floodplain (90 feet on left bank, 66 feet on right bank) with 18-inch-wide piers on approximate 14-foot centers. The depth from the channel thalweg to the low chord of the bridge structure is about 19 feet. This structure is under the jurisdiction of King County Parks and Recreation, which operates the trail system.

Bendigo Boulevard North Bridge

Bendigo Boulevard North (State Route 202) crosses the South Fork Snoqualmie River at RM 2.2. This structure was built in 1936 as a single 100-foot span steel girder with concrete slab bridge (WSDOT, 2011). Flood flows are conveyed under the structure through openings on the floodplain (180 feet on left and right bank) with 14-inch-wide piers on approximate 22-foot centers. The depth from the channel thalweg to the low chord of the bridge structure is about 25 feet. The Bendigo Boulevard North bridge is on a state highway and falls under the jurisdiction of the Washington State Department of Transportation (WSDOT).

West North Bend Way Bridge

West North Bend Way crosses the South Fork Snoqualmie River with a 460-foot-long concrete beam bridge at RM 2.45. The West North Bend Way bridge was constructed in 1941 (Bridgehunter, 2013). The bridge crosses the main channel with two 80-foot spans and one 60-foot span. The bridge extends over the floodplain approximately 240 feet on each side of the river. Six floodplain spans are supported by 30-inch-wide piers. The depth from the channel thalweg to the low chord of the bridge structure is about 19 feet. The West North Bend Way bridge is under the jurisdiction of the City of North Bend.

Historic Railway Bridge

The Historic Railway bridge is on the South Fork Snoqualmie River at RM 2.5. This structure was built in 1891 in Montana and was moved to its current location in 1923 (Bridgehunter, 2013). The bridge no longer carries commercial rail traffic but serves a tourist line from the Railway Museum in the City of Snoqualmie to the City of North Bend. The Historic Railway bridge is a truss-type bridge with timber trestle approaches. Flood flows are conveyed under the structure through the trestle spanning the floodplain. The floodplain span extends 400 feet on the left bank to Ribary Creek and 230 feet on the right bank. Piers 18 inches wide are placed in the floodplain on approximate 12-foot centers. The depth from the channel thalweg to the low chord of the bridge structure is about 19 feet. The Northwest Railway Museum has jurisdiction over this structure.

Bendigo Boulevard South Bridge

Bendigo Boulevard South (State Route 202) crosses the South Fork Snoqualmie River at RM 2.8. The existing Bendigo Boulevard South bridge over the South Fork Snoqualmie River is a single span, 110 feet long. The depth from the channel thalweg to the low chord of the bridge structure is about 23 feet.

According Kato and Warren (2000), the earliest crossing at this location was a 300-foot-long viaduct spanning the channel and floodplain. In 1949, the original structure was replaced with a 150-foot span concrete bridge with earthen approaches that encroached into the floodplain. WSDOT built the current 110-foot span bridge in the mid-1970s to replace the 150-foot-long concrete bridge. During construction of the new bridge, the entire floodplain was filled and no passage for river flow was provided through the bridge approaches (Kato and Warren 2000).

The basis for design of the bridge is not available. Kato and Warren reported that WSDOT estimated the 1-percent-annual-chance peak design flow for the bridge to be 12,000 cfs, which is lower than the 1-percent-annual-chance peak flow of 15,150 cfs estimated for this study; the WSDOT design flow

analysis did not include higher peak flows that have occurred in the intervening years. Comparing the WSDOT estimate to the revised flood frequency presented in Table 1-1 suggests that the bridge design flow assumption for a 1–percent-annual-chance flood event at the Bendigo Boulevard South bridge is now considered to be closer to the 5-percent-annual-chance flood. The area south of the intersection with Bendigo Boulevard South and South Fork Avenue SW was flooded during the January 2009 flood event.

Interstate 90 Bridge

The Interstate 90 bridge was likely built during the mid-1970s, but no information was available regarding construction of this bridge. Interstate 90 runs parallel with the South Fork Snoqualmie River on the left bank from RM 2.6, crosses at RM 4.9 and runs within 1,500 feet of the river on the right bank up to the upstream end of the project. This bridge is 217 feet long with four spans supported by 11-foot-wide piers. The piers are aligned with the roadway rather than the river channel, which increases flow resistance in the South Fork Snoqualmie River. Two spans, 48 and 60 feet long, carry the highway over the South Fork Snoqualmie River channel, and 36-foot segments span both the left and right overbank. The depth from the channel thalweg to the low chord of the bridge structure is about 27 feet. The Interstate 90 bridge falls under the jurisdiction of WSDOT. No flooding from the South Fork Snoqualmie River was reported on Interstate 90 during any recent flood events.

1.3.5 Recent History of River Flooding

The South Fork Snoqualmie River has a long history of flooding. In the past 10 years, three flood events have occurred with peak flows at or above the 10-percent-annual-chance flood frequency—in November 2006, November 2008 and January 2009. The last flood event of this magnitude prior to this time period was in 1996. These three recent events were used in this project to calibrate and validate the hydraulic model and are described below.

November 6, 2006

The November 2006 flood event was the flood of record at USGS Gage 12144000 (at North Bend) and USGS Gage 12143600 (at Edgewick). This event had the characteristics of an atmospheric river (See Section 1.3.6) with rainfall occurring over several days and warm air that raised freezing levels to over 10,000 feet (Mass, 2008). Peak flow at the Edgewick gage was about 13,500 cfs. Based on the flood frequency estimates developed for this study, this was about a 2-percent-annual-chance event. Levee overtopping occurred on the left bank from RM 3.35 to RM 3.39 and from RM 2.97 to RM 3.02, and on the right bank near the Bendigo Boulevard South bridge (RM 2.85). The river nearly overtopped the left bank at RM 4.17 (King County, 2011). Oblique aerials photographs from November 9, 2006 were obtained the day after the peak event, after floodwaters had receded, missing the full extent of flooding in the study area (King County 2011). Photos can be viewed on the County historical flood photograph web site http://www.kingcounty.gov/environment/waterandland/flooding/historical-flood-photos.aspx.

November 12, 2008

The November 2008 flood event generated a peak flow of 10,500 cfs at USGS Gage 12143600 (at Edgewick), which is equivalent to about a 10-percent-annual-chance peak flood event. Weather observations reported at the time indicate that this event was driven by heavy rainfall from warm, moist air flowing out of the south Pacific Ocean (Mass, 2008). Levee overtopping was not reported during this event (King County, 2011), but flooding was observed by King County staff in the Shamrock Park subdivision (SE 125th Street and SE 415th Avenue). Figure 1-2 shows flooding during this event.

Source: King County

Figure 1-2. Flooding in Shamrock Park, November 12, 2008

January 7, 2009

The January 2009 event had a recorded peak flow rate of 12,900 cfs at USGS 121436000 (at Edgewick), estimated to be a 4- to 5-percent-annual-chance event. This event was caused by an atmospheric river (see Section 1.3.6), with rainfall over a three-day period, accompanied by significant snowmelt (Mastin et al., 2010). King County staff observed flooding due to levee overtopping about the time of the peak of the event along the South Fork Snoqualmie River from RM 2.8 to RM 4.2 and along Ribary Creek (Bean, 2011). Flooding was also observed between South Fork Avenue SW and the river south of Bendigo Boulevard South, on Bendigo Boulevard South at South Fork Avenue, and on Bendigo Boulevard North at 415th Way NE. Minor flooding occurred at 412th Avenue SE. Other flooding observed at Bendigo Boulevard North (RM 2.23) and on the landward side of the levee at SE 130th near RM 4.2 is assumed to be the result of seepage through the levee (Bean, 2011). Figures 1-3 through 1-5 show flooding during this event. The estimated flood inundation extents for this event are shown in Appendix A.

1.3.6 Climate

The climate in the South Fork Snoqualmie River basin varies from moist alpine conditions in the headwaters to moist temperate conditions in the valley near North Bend. The North Bend area receives an average annual rainfall of 90 to 100 inches (Western Regional Climate Center, 2012). Most precipitation in the headwaters of the South Fork Snoqualmie River east of North Bend falls as snow from October through March and as rain at other times. Snoqualmie Pass, located approximately 16 miles east of the study area in the headwaters of the South Fork Snoqualmie River watershed, receives an average annual rainfall of 100 inches in addition to an average annual snowfall of 420 inches (Western Regional Climate Center, 2012). Rainfall dominates the lower elevations of the river basin between October and June. The spring snow pack commonly experiences rain with melting snow after March, but it stores water and melts in steps.

Source: King County

Figure 1-3. South Fork Snoqualmie River Overtopping Left Bank at RM 3.35, January 7, 2009

Source: King County

Figure 1-4. Flooding on Bendigo Blvd. South/SR 202 at South Fork Avenue SW, January 7, 2009

Source: King County

Figure 1-5. Flooding in Shamrock Park, January 10, 2009

The Cascade Mountains influence rainfall patterns in the South Fork Snoqualmie River basin by blocking the flow of moist air, causing weather fronts to stall over the basin and increasing the duration of rainfall (Mass, 2008). The Cascade Mountains also increase rainfall on the windward (west) side as moist air flowing over the mountains experiences cooling and lower air pressure. As the air cools, it loses its ability to hold water vapor and the excess falls as precipitation.

Extreme floods in the Pacific Northwest are caused by the flow of warm moist air originating in the tropics and subtropics, which brings an extended period of heavy rainfall commonly called “the Pineapple Express” (Mass, 2008) or atmospheric rivers. All major floods in the Pacific Northwest are caused by atmospheric river events (Schick, 2009). Extended rainfall saturates the ground and increases runoff as rain continues to fall. Warm air associated with an atmospheric river can also raise the freezing level so that melting snow further increases the severity of flooding. The strongest events usually occur in fall and early winter (Mass, 2008).

1.3.7 Geology and Geomorphology

Sediment is delivered to the South Fork Snoqualmie River through landslides, road failures, streambank erosion, land management activities and natural geologic processes in the upper river valley above Twin Falls (RM 10.0). These sediments are transported downstream through relativity steep upper valley reaches. Below Twin Falls, the channel gradient flattens considerable and the natural valley confinement decreases dramatically resulting in a commensurate reduction in the river’s ability to transport sediment (Bethel, 2004). The location of the study reach at the downstream end of a drainage basin with ample sediment supply, a steadily decreasing channel gradient, and the widening of the valley bottom relative to the upstream areas all favor sediment deposition (King County 2011). The South Fork Snoqualmie River has a steep gradient of 1 to 3 percent in the mountainous headwaters above Twin Falls, and an average

channel gradient of 0.3 to 0.4 percent within the study area. As a result, a coarse alluvium depositional fan underlies the North Bend area. Current geologic mapping (see Figure 1-6) indicates recent alluvium (Qa) throughout the study area. The alluvium typically consists of gravel and sand with variable silt content. This is consistent with explorations completed at the site, in which alluvium encountered below the levee fill mostly consisted of gravel with sand and silt and occasional cobbles. The study reach upstream of RM 4.2 is relatively steeper and sediment is transported through this reach. Between RM 4.2 and 3.3, the gradient flattens and the channel widens promoting sediment deposition with large and active gravel bar formation. Downstream of RM 3.3, the channel narrows which increases sediment transport although backwater from bridges in this reach may locally increase deposition (King County, 2011).

Source: Geologic Map of the North Bend 7.5-Minute Quadrangle, King County, Washington (from Dragovich 2009)

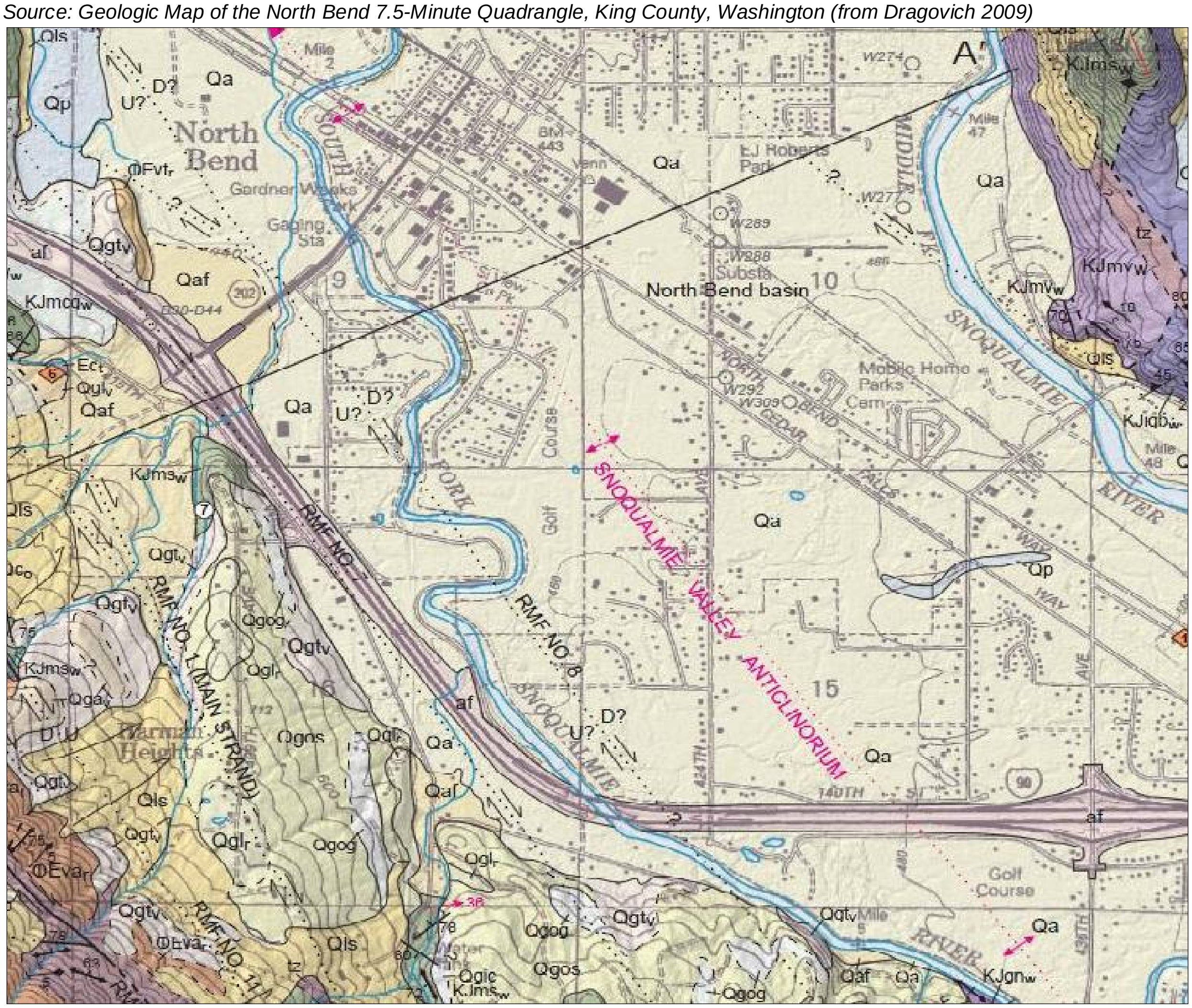


Figure 1-6. Geologic Mapping of the North Bend Quadrangle

The South Fork Snoqualmie River floodplain shows evidence of numerous former channel locations indicating a highly mobile channel in the past. Channel mobility is now constrained by the levee system constructed in the 1960s (Bethel, 2004). The levees have effectively prevented channel migration upstream of Snoqualmie Valley Trail. Furthermore, the bridge at Snoqualmie Valley Trail and five other road crossings located in the study reach have also impeded channel migration (Perkins, 1996). The levee system has also disconnected the floodplain from the channel during more frequent flood events so that fine sediments are flushed downstream and no longer deposited on the floodplain.

The nearest downstream geologic control is Snoqualmie Falls, a natural waterfall located approximately 5 miles downstream of Snoqualmie Valley Trail. Twin Falls, a natural waterfall located about 4 miles upstream of 436th Avenue SE is the nearest upstream geologic control. There are no geologic controls within the study reach between Snoqualmie Valley Trail and 436th Avenue SE.

The North Bend aquifer is a substantial body of groundwater contained within the relatively permeable sand and gravel alluvium that fills the valley. Under normal river flow conditions (neither flood nor drought, with no significant inflow from surface runoff), the river level typically drops gradually over time. Groundwater from the aquifer usually drains into the river at a slightly higher level than the river, sustaining long-term base flow to the river and the entire system draining the valley.

Under flood conditions, the trend of gradually declining river level is reversed by a flood wave in the South Fork Snoqualmie River. Groundwater in the North Bend aquifer responds rapidly to increases in river water level, directly reflecting the flood event as it propagates along the South Fork Snoqualmie River. Groundwater levels rise in a flood wave response, with wells installed in the levee crest showing almost the same rise in water level as measured in the adjacent river. Monitoring wells set back from the levee typically show a smaller and delayed response, reflecting the added distance the flood wave has to travel through the aquifer. The dynamic of transmission time through the aquifer attenuates the magnitude of response in wells further away.

Even though the North Bend aquifer is relatively permeable, the volume of stream flow loss to infiltration and bank storage during flood events appears to be limited by hydraulic conductivity and hydraulic gradient in the subsurface. These constraints control the flow of surface water into the streambed and stream banks during flooding events. However, where low-lying land is present behind the levees, rising groundwater levels can contribute to flooding directly, or indirectly by reducing or eliminating the infiltration of stormwater runoff.

Generally, seepage below and through the permeable levee soils appears to be widespread. In some locations, rapid seepage may occur via discrete channels caused by the presence of highly permeable open-work gravel zones that lack a matrix of less-permeable sand or silt. In places, these may appear as seeps or springs during a flood event. They pose the risk of seepage forces promoting or exacerbating piping or internal erosion, which could compromise the stability of the levees.

1.3.8 Land Use

About half of the South Fork Snoqualmie River basin area is managed by the U.S. Forest Service or Washington state agencies. The remainder is privately owned. Timber harvesting is the predominant land use in the upper basin Cascade Mountains and foothills east of North Bend. Residential, commercial and agricultural land uses are found in the lower basin near the City of North Bend.

The City of North Bend lies on both sides of the South Fork Snoqualmie River from the downstream project limit up to RM 3.1 on the left bank and RM 4.1 on the right bank. No other incorporated areas are found in the project area.

Land use from RM 2.0 to RM 4.0 includes undeveloped parkland, pasture agricultural land, low-density residential, the Nintendo industrial property and two larger commercial developments on the left bank, and medium-density residential and commercial land use on the right bank. Land use on both sides of the river from RM 4.0 to RM 5.9 is low-density residential. The North Bend Wastewater Treatment Plan, Bendigo Boulevard South, and Interstate 90 are considered to be critical facilities.

1.3.9 Fish and Wildlife Habitat

Fish and wildlife habitat in the riparian corridor, which includes the channel and the riparian buffer area, is fragmented and ecologically impaired. Land use activities associated with agricultural, residential, commercial, and transportation uses, have fragmented the riparian areas along the river in many places. Residential and commercial development and levee construction have reduced the scale and overall quality of the riparian habitats along the river, with less accumulated downed wood and snags, resulting in fewer places for mammals, birds, and amphibians to find cover or suitable nesting and rearing sites. Portions of the riparian corridor that are vegetated predominantly include cottonwood, Douglas fir, western red cedar, big leaf maple, and alder trees. Understory plants include sword fern, salmonberry, red-twig dogwood, and snowberry. Although impaired, the riparian South Fork Snoqualmie River riparian corridor still provides habitat for a variety of native wildlife species typical of the area. In some areas, riparian habitats are degraded by invasive species, such as Himalayan blackberry and English ivy.

Channelization of the South Fork Snoqualmie River by levees has affected habitats by increasing flow velocities and disconnecting floodplains, wetland and side channels. Levees along the South Fork Snoqualmie River prevent normal flooding in riparian areas during high flows. Levee construction has also blocked access to important refuge areas used by fish during high flows, such as side channels, sloughs and ponds. Rock armoring on the levee face has eliminated a key high-flow refuge area along the streambanks of the river. However, sediment deposition over the riprap has allowed the establishment of small trees and shrubs which may provide some degree of refuge from high water velocity during high flow events. Levees also altered the dynamics of downed wood entering the river from riparian areas, thereby reducing large woody debris and log jams that influence the quality of instream habitats.

Many species and habitats that are uniquely important in the State of Washington are documented to be present in the South Fork Snoqualmie River corridor. Resident populations of cutthroat and rainbow trout, both state priority species, mountain whitefish, sculpin, and other species are present. Tributaries support cutthroat trout and rainbow trout (City of North Bend, 2001; WDFW, 2008). Snoqualmie Falls, located 5 miles downstream of the study reach, blocks upstream migration of anadromous salmonids that use the Snoqualmie River below the falls. Elk is another State priority species that uses habitats in the study area.

Federally listed threatened or endangered species have not been documented in the South Fork Snoqualmie River Corridor. However, marbled murrelets, currently listed as threatened under the federal Endangered Species Act are likely to use the river corridor to fly to old-growth nesting areas in the upper parts of the watershed (King County 2011).

The WDFW Priority Habitats and Species program identified the western toad as having been mapped within a riparian area associated with the South Fork Snoqualmie River. This species is a Washington State Candidate species and a federal species of concern.

These and other instream habitat conditions are presented in more detail in Chapter 4 and Appendix B.

1.4 PREVIOUS WORK

Several previous hydraulic, flood control, geotechnical and hydrogeologic investigations have been conducted in the vicinity of the project study area. Each provided useful data and findings for a part of the study area, but none provided a comprehensive overview of problems or developed integrated solutions.

1.4.1 South Fork Snoqualmie River/SR 202/Ribary Creek Flood Study

The draft *South Fork Snoqualmie River/SR 202/Ribary Creek Flood Study* (Kato and Warren 2000) sponsored by WSDOT investigated flooding near the Bendigo Boulevard South (SR 202) bridge. This

report was issued as a draft but never finalized. The study focused on the South Fork Snoqualmie River between RM 2.6 and RM 3.7 and used HEC-RAS hydraulic models previously developed by the U.S. Army Corps of Engineers. The South Fork Snoqualmie River peak flow values used in the study were from a 1998 Corps of Engineers hydrology study, which reported peak flow values of 9,600 cfs, 13,500 cfs, 15,100 cfs and 18,900 cfs for the 10-, 2-, 1- and 0.2-percent-annual-chance flood events. The Kato and Warren study found these peak flow rates to be reasonably consistent with those from previous studies (Shannon & Wilson 1993; King County 1995; FEMA 1989; FEMA 1999), although they are noticeably higher than those shown on WSDOT bridge plans and scour summary sheets for the Bendigo Boulevard South bridge. The Kato and Warren study states that this discrepancy may imply that the bridge opening is under-designed for current and historic peak flow rate estimates and that the bridge plans suggest that the design flood for the bridge is the 50-year event (Kato and Warren 2000). Sources of flooding were documented from local drainage from the commercial area, overbank flooding from Ribary Creek, and also overbank flooding from the South Fork Snoqualmie River.

The hydraulic analysis concluded that the Bendigo Boulevard South bridge and the bridge approaches create a local constriction in the river and result in increased water surface elevations upstream of the bridge. Furthermore, the study concluded that the existing bridge opening would not provide any freeboard for flood events with a 2-percent-annual-chance magnitude or greater. The resulting backwater effect of the bridge constriction for these flood events was predicted to extend upriver to RM 3.23.

The report indicates a limitation in the hydraulic analysis. The analysis showed that for the 2-percent-annual-chance and greater flood events, the left bank levee upstream of the bridge overtops between RM 3.02 and RM 3.39, and the right bank levee upstream of the bridge overtops between RM 3.15 and RM 3.02. However, a basic assumption in the hydraulic analysis was that for each flood event, the entire peak flow would be conveyed through the bridge opening. This is physically not possible since water that overtops the levees upstream of the bridge would bypass the bridge opening. Furthermore, this loss of flow to the overbanks would reduce the backwater effect caused by the bridge (Kato and Warren 2000).

The Kato and Warren study concluded that no single feature can be modified to resolve both the internal and overbank flooding problems in the study area. For instance, raising levees upstream of the bridge to contain flood flows would require larger riprap through the bridge section to stabilize the channel banks. Recommended options in the study include the following:

- Buy out residences or properties on the left bank between Bendigo Boulevard South upstream to about RM 3.4. Buyouts would reduce the greatest flood hazard in the area.
- Bridge Option 1: Replace the Bendigo Boulevard South bridge with a new 400-foot span, set back the left bank Reif Road Levee 600 feet upstream and 600 feet downstream of Bendigo Boulevard South, and raise the 2,200 feet of left bank Reif and right bank Si View levees to the 1-percent-annual-chance flood level plus 3-feet for freeboard upstream of Bendigo Boulevard South. It was estimated that his option would lower the flood elevation by 4.0 feet at RM 3.1 and 1.8 feet at RM 3.3.
- Bridge Option 2: Replace the Bendigo Boulevard South bridge with a new 200-foot span, install a 4- to 6-foot-diameter culvert to convey Ribary Creek under Bendigo Boulevard South, buy out 13 properties, and set back the left bank Reif Road Levee 600 feet downstream and 1,900 feet upstream. It was estimated that this would reduce the flood elevation by 3.0 feet at RM 3.1 by 1.3 feet at RM 3.3.

1.4.2 South Fork Snoqualmie Gravel Removal Study

The *South Fork Snoqualmie Gravel Removal Study* (King County 2011) characterized sediment accumulation, documented flood history, and evaluated gravel bar scalping as a technique to reduce flood

levels in the South Fork Snoqualmie River. The study area is the South Fork Snoqualmie River from the Bendigo Boulevard South bridge upstream 1.6 miles to near the Interstate 90 bridges. The study determined that levee capacity for 2009 channel conditions in the reach between RM 2.85 and RM 3.54 ranged from 11,300 to 14,500 cfs. The levee segment with lowest capacity was on the left bank between RM 3.23 and RM 3.39. Levee capacity between RM 3.65 and RM 4.46 was greater than 15,700 cfs except at one location near RM 3.99 where capacity was 14,200 cfs. Levee capacity for the gravel removal study was defined as the "water surface elevation as just contained by the top of the riverbank or levee." The study evaluated three gravel bar scalping scenarios using a HEC-RAS model:

- **Scalp Scenario 1** was based on potential conditions for gravel removal outlined by Washington State Department of Fish and Wildlife (WDFW) staff and existing regulatory provisions in WAC 220-110-140. These conditions assume gravel bar scalping to 2 vertical feet above the low flow water surface. The bottom slope of the scalped area would be at 2 percent from the river toward the bank or levee. No excavation would occur where live, woody vegetation is present, or in the area within the steeper embankment slope of the riverward side of the levee top and at the upstream point of the bar. The analysis showed that this scenario would decrease the water surface elevation in the river for the 2-percent-annual-chance event (estimated to be 13,000 cfs for this study) between 0.2 and 0.5 feet adjacent to Berry Estates and would have no effect on the water surface elevation in the river near Shamrock Park. Levee overtopping would still occur near Berry Estates and Shamrock Park. The analysis also showed that water surface elevation at the bend in the river near SE 131st Street (RM 3.95 to 4.04) would be reduced between 0.6 to 1.6 feet for the 2-percent-annual-chance-event. The scalping was estimated to be effective for five and eight years. Scenario 1 was reported to have the least impact and the least flood hazard benefit of all the scenarios.
- **Scalp Scenario 2** is similar to Scenario 1 but includes more extensive gravel removal: the lowest point of gravel extraction would be to 1 foot above the low flow. The scalping surface would also be sloped at 2 percent away from the river toward the levee. Extraction would occur regardless of presence of live, woody vegetation; however, no extraction was assumed in the area within the steeper embankment slope of the riverward top of levee. This scenario was analyzed to represent the maximum practical gravel extraction regardless of regulatory constraints. The analysis showed that this scenario would decrease the water surface elevation in the river for the 13,000-cfs flood between 0.4 and 0.7 feet adjacent to Berry Estates. The water surface elevation reduction in the river near Shamrock Park would be very small at 0.1 feet. Levee overtopping would still occur near Berry Estates and Shamrock Park. The analysis also showed that water surface elevation at the bend in the river near SE 131st Street (RM 3.95 to 4.04) would be reduced between 0.6 to 2.1 feet for the 2-percent-annual-chance-event. The scalping was estimated to be effective for 12 and 19 years. This scenario would have greater impact due to the larger excavation area. The sediment excavation proposed for this scenario would be far in excess of the average annual influx and would induce scour at the levee toe and possibly threaten the Bendigo Boulevard South bridge. These constraints were recognized as having limited practicality of implementation.
- **Scalp Scenario 3** simulated gravel removal only in areas where hydraulic modeling and historical flooding indicated that levee overtopping would be most likely to occur. This scenario evaluated the effectiveness of limited gravel removal at critical sites in lowering water surface elevations and reducing flood hazards. The study concluded that this scenario would decrease the water elevation for the 13,000-cfs flood between 0.4 and 0.7 feet adjacent to Berry Estates. The water surface elevation reduction in the river near Shamrock Park would be very small at 0.1 feet. Levee overtopping would still occur near Berry Estates and Shamrock Park. The analysis also showed that water surface elevation at the bend in the river near SE 131st Street (RM 3.95 to 4.04) would be not change for the 2-percent-annual-chance-

event. The scalping was estimated to be effective for six and nine years. Scenario 3 was reported to best meet all evaluation criteria for flood hazard reduction and avoiding adverse impacts. However, as in Scalp Scenario 2, this scenario has the potential to induce local scour and threaten levee or bridge stability.

The HEC-RAS model used in the gravel removal study was developed using the model created for FEMA's 2005 *South Fork Snoqualmie River Flood Insurance Study* updated with surveyed cross-section information obtained in 1992/1995, 1999, 2006, 2007 and 2009. The evaluation found that gravel bar scalping near the Bendigo Boulevard bridge would not affect water surface elevations because of backwater from the bridge for about a mile upstream. The HEC-RAS model developed for the gravel-removal study was updated and used in the development of the two-dimensional model for this study, as described in Appendix A.

1.4.3 South Fork Tributaries Action Plan Phase II Report

The *South Fork Tributaries Action Plan Phase II Report* (SOFTAP) (Northwest Hydraulic Consultants 2001b) assessed flooding problems and proposed solutions for Clough, Ribary and Gardiner Creeks. Two steady-state HEC-RAS models were developed for the SOFTAP study: one for Clough Creek and one combining Gardiner and Ribary Creeks and the South Fork Snoqualmie River. The SOFTAP report documented several recommendations for projects and additional studies for Clough, Ribary and Gardiner Creeks. Results of the study were used to assess existing conditions, particularly in the Ribary Creek basin. The HEC-RAS models developed for the SOFTAP study were used as the basis for the hydraulic modeling of Ribary Creek in this levee repair plan (see Appendix A).

Clough Creek

Problems

Clough Creek has experienced increased sediment loading and deposition, which has reduced the channel and conveyance capacity. Backwater from the South Fork Snoqualmie River also restricts conveyance through the Interstate 90 culverts.

Recommendations

SOFTAP recommendations for Clough Creek include the following:

- Implement a regular cross-section or profile survey along 415th Way and downstream. A regular survey would identify when remedial sediment removal action is needed and provide a more accurate estimate of sediment loading.
- Install a sediment trap along 415th Way and remove sediment from Interstate 90 culverts. A sediment trap would create sufficient storage so that removal would only need to occur on a 10-year interval.

Ribary Creek

Problems

Ribary Creek overtops Bendigo Boulevard South, South Fork Avenue and NW 8th Street during the 1-percent-annual-chance peak flood event (estimated to be 306 cfs for the SOFTAP study). Increased sediment loading from upstream sources has reduced conveyance capacity in the channel and culverts. The SOFTAP hydraulic analysis showed 3,000 cfs overflowing the South Fork Snoqualmie River levee near Berry Estates during the 1-percent-annual-chance peak flood event (given as 15,000 cfs in the HEC-RAS model). However, the SOFTAP analysis did not consider levee overtopping at other locations in the

river and therefore assumed that all flow is contained within the upstream leveed river corridor. The SOFTAP report indicated that overflow from the South Fork Snoqualmie River increases peak flows in Ribary Creek from 1,000 cfs at Mt. Si Boulevard to 3,400 cfs at South Fork Avenue SW. The report also indicated overflow occurs from Ribary Creek to Gardiner Creek.

Recommendations

SOFTAP recommendations for Ribary Creek include the following:

- Investigate raising the height of the Reif Road Levee (RM 2.85 to RM 3.65). Levee improvements would benefit residences in Shamrock Park and Berry Estates, and prevent or reduce overflow to Ribary and Gardiner Creeks. A major conclusion documented in the report was that flooding from levee overtopping at Berry Estates and Shamrock Park could not be solved by downstream conveyance improvements to existing road crossing structures. Therefore, levees need to be raised to prevent overtopping.
- Remove sediment from the Ribary Creek channel between Mt. Si Boulevard and South Fork Avenue and from the Ribary Creek channel between Bendigo Boulevard South (SR 202) and South Fork Avenue SW. Sediment removal would more than double the conveyance capacity of the Bendigo Boulevard South culverts, but they still would not be able to pass the 1-percent-annual-chance Ribary Creek flood event.
- Replace the culverts at Bendigo Boulevard South (SR 202) with a 20-foot-wide by 6-foot-high box culvert and the culvert at South Fork Avenue with a 16-foot-wide by 6-foot-high box culvert. Culvert replacement combined with sediment removal would increase capacity to convey the 1-percent-annual-chance Ribary Creek flood event without overtopping.

Gardiner Creek

Problems

Gardiner Creek overtops NW 8th Street, Alm Way, Snoqualmie Valley Historical Railroad, North Bend Way, and Bendigo Boulevard North during the 1-percent-annual-chance flood event. This event was estimated to be 218 cfs above North Bend Way but increases significantly to 1,460 cfs due to overflows from the South Fork Snoqualmie River through the Ribary Creek drainage. Gardiner Creek has also experienced high sediment loading, which results in overflows downstream of Interstate 90.

Recommendations

SOFTAP recommendations for Gardiner Creek include the following:

- Install and maintain a sediment trap downstream of Interstate 90. Elimination of sediment would lower flood levels during the 1-percent-annual-chance Gardiner Creek flood event in this area by 3 feet.
- Construct a berm to contain Ribary Creek overflows near Nintendo property. This berm would eliminate overtopping at Alm Way, Snoqualmie Valley Historical Railroad and North Bend Way. Flooding would still occur at NW 8th Street and Bendigo Boulevard North but would be reduced to about 0.7 feet.
- Replace the culvert at Bendigo Boulevard North (SR 202) with a 20-foot-wide by 4-foot-high box culvert and the culvert at NW 8th Street with a 16-foot-wide by 4-foot-high box culvert. Culvert replacement combined with berm installation would increase capacity to convey the 1-percent-annual-chance event without overtopping.

1.4.4 County Engineer's Letter

A 1969 letter from the King County Engineer to the president of the Shamrock Park Company (Gillespie 1969) states that the plat of Shamrock Park on the left bank of the South Fork Snoqualmie River "is protected from the greatest flood of record plus 1 foot of freeboard. This gives the plat protection from a flood greater than the 100-year flood." The letter does not indicate the magnitude of the 1-percent-annual-chance flood the protection assumption is based on, but the USGS estimated the peak flow to be 13,000 cfs during a November 1959 event (USGS, 2010) which is the peak flow of record prior to 2006. The estimated peak flow is lower than current estimates of the 1-percent-annual-chance flood, considering the larger peak flows that have occurred in the intervening years. This letter forms the basis for the assumed levee design condition.

1.4.5 Flood Control Project Feasibility Report

The *Feasibility Report, South Fork Snoqualmie River Flood Control Project, SR-202 to Downstream of I-90, King County, Washington* (Shannon & Wilson, Inc. 1993) provided a preliminary evaluation of the hydrologic, hydraulic and geotechnical conditions of the study area, including preliminary alternatives to reduce the flood hazard. Five preliminary alternatives were developed for the feasibility report:

- **Alternative 1, Repair and upgrade existing levees and bank protection between Bendigo Boulevard South and Interstate 90**—Shannon & Wilson documented a number of deficiencies in the existing levees, including failure of toe protection, piping, unstable slopes, inadequate slope protection and problems with culverts and flap valves. Shannon & Wilson recommended reconstructing the toe on the riverward side to protect from scour, installing a toe drain and drainage blanket on the landward side, overlaying riprap to reestablish the levee face where needed, regrading existing steep slopes, and installing a culvert at Shamrock Park. Levee repairs would not prevent overtopping but would reduce the risk of catastrophic failure. Culvert and flap valve replacement would eliminate or reduce any interior flooding in the Shamrock Park neighborhood during peak flood events. Shannon & Wilson recommended that Alternative 1 be included as part of all the following alternatives.
- **Alternative 2, Setback levees**—Setback levees were proposed at Station 15+00 (RM 4.2) and Station 40+00 (RM 3.65). The hydraulic analysis performed for the feasibility report showed that the reduction in channel velocity would be 4 and 5 percent and flood stage reduction would be less than 0.2 feet for the 1-percent-annual-chance flood event (assumed to be 14,800 cfs by Shannon & Wilson). Shannon & Wilson concluded that the cost of the project was greater than its benefit.
- **Alternative 3, Levee raising with bar-scalping**—This alternative evaluated maximum gravel removal from bars (scalping) to provide 3 feet of freeboard for the 1-percent-annual-chance flood event (assumed to be 14,800 cfs by Shannon & Wilson). Bar scalping was proposed to be within 1 foot of the typical summer low-flow depth, maintaining a 5-foot buffer from the levee toe. Scalping would occur between Interstate 90 and Bendigo Boulevard South. Scalping alone was found to not provide sufficient freeboard, so raising the right and left bank levees was also proposed. The hydraulic analysis performed for the Feasibility Study showed that the top of the right bank levee would need to be raised 2 feet between Stations 79+00 (RM 3.33) and 62+00 (RM 3.10) and the top of the left bank levee raised 3 feet between Stations 79+00 (RM 3.33) and 45+00 (RM 3.5), 1 feet between Stations 45+00 (RM 3.5) and 36+00 (RM 3.6), and 0.5 feet at Station 14+00 (RM 2.0). Shannon & Wilson determined that bar scalping in combination with raising levees provided adequate freeboard for the 1-percent-annual-chance flood event and protected adjacent properties from overbank flooding.

- **Alternative 4, Levee raising without bar scalping**—This alternative evaluated raising levee heights with minimal gravel bar scalping to provide 3 feet of freeboard for the 1-percent-annual-chance flood event (assumed to be 14,800 cfs by Shannon & Wilson). Bar scalping was proposed to maintain pre-1991 sediment depths established by dredging the river bed. The hydraulic analysis performed for the Feasibility Study showed that the top of the right bank levee would need to be raised 2 feet between Stations 79+00 (RM 3.33) and 36+00 (RM 3.6) and the top of the left bank levee raised 3 feet between Stations 79+00 (RM 3.33) and 34+00 (RM 3.65), and less than 0.5 feet between Stations 34+00 (RM 3.65) and 12+00 (RM 2.2). The proposed length of levee modification in Alternative 4 was greater than the length proposed for Alternative 3. Shannon & Wilson determined that raising levees provided adequate freeboard for the 1-percent-annual-chance flood event and protected adjacent properties from overbank flooding.
- **Alternative 5, Reif Road overbank drainage improvements—**Drainage improvements evaluated for the Feasibility Study included flood-proofing homes and creating a controlled overflow channel formed with collection dikes and culverts to safely funnel overflow from the South Fork Snoqualmie River through Shamrock Park, into Ribary Creek, and back into the South Fork Snoqualmie River. The Feasibility Study did not quantify the direct benefits of this alternative.

1.4.6 South Fork Snoqualmie Levee Study Phase I Geotechnical Report

The *Phase I Geotechnical Report, South Fork Snoqualmie Levee Study Project, King County, Washington*, (Shannon & Wilson, Inc., 2009) included a collection of existing geotechnical, geological and construction data for the levee system; a reconnaissance of existing levee conditions; observations of test pits excavated at depressions in the levees; and analyses to evaluate the stability of the existing levees. Detailed reconnaissance, photographic documentation, and ratings of the levees were completed. This report presented the results of the Phase I study and recommended additional services, including preparation of a Phase II data report (below), and a final recommendations report.

1.4.7 South Fork Snoqualmie Levee Study Phase II Geotechnical Report

The *South Fork Snoqualmie Levee Study—Phase II, Geotechnical and Hydrogeologic Data Report, King County, Washington* (Shannon & Wilson, Inc., 2009) included 20 borings, of which 17 were completed as monitoring wells. Data loggers were installed in the monitoring wells for long-term groundwater monitoring. Hydraulic conductivity testing was also completed (slug tests and falling head percolation tests). No analysis or findings were documented in this report. However, data provided in these reports was used in the geotechnical analysis for this study.

1.4.8 Recent Levee Repairs

King County has repaired nearly 1,600 of feet of levee in the study area, including an emergency repair in 2011. Much of the repair effort is associated with river bends and constrictions where flow energy is the greatest. Multiple repairs were performed at the Reif Road levee on the left bank of the river at RM 3.7 near the downstream end of the large bend between RM 3.6 and RM 4.2. The largest repair occurred on the Si View Levee on the right bank of the river downstream of the Interstate 90 bridge. Table 1-4 shows the repair history for levees under the County's jurisdiction. Figure 1-7 shows a recent repair at the Reif Road levee at RM 3.05.

TABLE 1-4.
REPAIR HISTORY KING COUNTY LEVEES, 1991 TO PRESENT

River Mile	Year Repair Completed	Repair Length (feet)	Repair Cost	Description
Reif Road (Left Bank)				
3.10	1991	—	—	Material added to re-establish as-built conditions
3.70	1996	250	$128,000	Rock and log repair
3.70	1998	400	$125,000	Rock Repair and planting
4.10	2009	85	$24,400	
3.65	2011	55	$23,900	Emergency repair
3.05	2013	50	$85,800	
Si View Park (Right Bank)				
3.16	2009	100	$112,500	
Si View Levee (Right Bank)				
3.30	1998	190	$76,000	Rock and wood repair
4.00	1998	11	$31,200	Rock and wood repair
4.80	1998	345	—	Rock and wood repair
4.40	2012	40	$73,500	
4.00	2012	80	$70,400	

Figure 1-7. Repair to Reif Road Levee at RM 3.05

1.4.9 Previous Work for This Project

Development of Hydraulic Modeling Approach and supplemental memorandums (Tetra Tech, 2011a, 2011b) were prepared during the preliminary phases of this project. These memorandums outline the approach used to model the South Fork Snoqualmie River, tributary streams and floodplain area with the FLO-2D model. They describe the following significant modeling assumptions:

- The model domain extends from RM 1.1 to RM 5.9 with a 75-foot grid spacing.
- Existing HEC-RAS models are used to develop rating curves for hydraulic structures for input to the FLO-2D model.
- The left overbank is modeled with a relatively high level of detail and includes tributary streams, hydraulic structures, floodplain channels and calibrated roughness. The right overbank is modeled with less detail.
- Inflow hydrographs are developed for the upstream boundary conditions and a stage hydrograph is developed for the downstream boundary condition.
- Calibration criteria are established as ±0.5 feet for observed water surface elevations.

The *Phase 1A Hydraulic Report* (Tetra Tech, 2011c) used HEC-RAS modeling, field visits, interviews, recent flood history and previous reports to identify hydraulic problem areas in the study area. The report provides a preliminary prioritization of problems and a list of potential solutions. This report identified 18 potential hydraulic problem areas associated with levee overtopping and elevated backwater inundating residential and commercial areas during flood events.

The *Preliminary Geotechnical Summary* (GeoEngineers, 2011) identified 46 potential geotechnical problem locations in the study area through a review of previous reports and additional field reconnaissance. This report documents bank erosion, seepage and piping, subsidence, over-steepened slopes, absence of slope protection, trees on the levee, and numerous culvert penetrations.

A preliminary assessment of the hydraulic and geotechnical problems was presented in the *Integrated Matrix of Geotechnical and Hydraulic Problem Areas*.

CHAPTER 2.
LEVEE HYDRAULIC CONDITION ASSESSMENT

The levee hydraulic condition assessment comprehensively considers hydraulic characteristics and deficiencies of the levee system to characterize the current level of function and protection that the system provides.

2.1 HYDRAULIC MODEL SELECTION AND DEVELOPMENT

The hydraulic performance of the South Fork Snoqualmie River levee system was evaluated using a hydraulic simulation model. The findings of the analysis were used—together with a review of photographs of flood events, anecdotal observations and previous analysis—to identify hydraulic problems in the study area.

South Fork Snoqualmie River flood conditions are complex. Levee overtopping allows flood flows to spread along uncertain flow paths across the floodplain that may be dispersed or concentrated. In the floodplain, river flow overtops low watershed divides and significantly increases flow in tributary streams flowing across the floodplain. Flows from tributary streams may in turn contribute to the flooding. Man-made structures, such as road crossings, restrict flow, causing upstream diversions and exacerbating backwater flooding. For this study, the two-dimensional modeling software FLO-2D was selected to assess existing conditions in the study area and to represent the effects of future potential gravel accumulation. This two-dimensional hydraulic model is well-suited for analyzing the conditions described above because it uses a floodplain grid that allows flow in eight compass directions (north, south, east, west, northeast, southeast, southwest, and northwest).

The model domain extends from RM 1.1 to RM 5.9 and includes the river channel and associated floodplain areas (see Figure 2-1). The primary focus of the study was to evaluate the capacity of the left and right bank South Fork Snoqualmie River levees and resulting inundation extents in the left bank floodplain area between RM 2.0 and RM 5.9. The left bank floodplain area had considerable calibration data available, which was not the case for the right bank floodplain, so model development and calibration focused on the channel and the left overbank area. Appendix A contains a detailed description of the model input data, development and calibration, and results of the analysis.

Left and right overbank floodplain topography was defined using a 75-foot grid spacing. The elevation of the grid was generally based on average elevations, obtained from a high-resolution digital terrain model. Levee and roadway embankments were included in the model. The model area also contains 29 bridges or culverts. Eighteen bridges were determined to be sufficiently restrictive to be included in the model.

As with any hydraulic model, there are limitations in the ability of the model to precisely predict design flood conditions due to uncertainty in hydrology, data inputs, model resolution, and the quality of the calibration. The findings from this analysis are based on the use of the best available data; calibration of model and field observations may differ slightly.

2.1.1 Model Calibration and Verification

The hydraulic model was calibrated and verified using gage data, anecdotal observations, and post-event surveyed water surface elevations from the November 2006, November 2008 and January 2009 flood events. A calibration criterion of ±0.75 feet was used. The November 2008 and January 2009 events were used for the calibration. The November 2006 event was used to verify the calibration.

The calibrated model replicated not only the post-event surveyed water surface elevations within the main channel of the river, but also the post-event surveyed water surface elevations in the left overbank floodplain, anecdotal observations of levee overtopping at various locations, and the digitized areal extent of overbank flooding for the January 2009 event. Across all three flood events, the calibrated model successfully replicated 65 percent of the post-event surveyed water surface elevation calibration points within the pre-defined calibration criterion, and successfully replicated more than 75 percent of the anecdotal observations of flood conditions. Generally, locations where the model was not able to replicate flood conditions were due to uncertainty in the post-event survey of the water surface elevation and/or were associated with areas where overbank flooding was assumed to be the result of sources other than the South Fork Snoqualmie River, such as tributary creek inflow or the local storm drainage system.

2.1.2 Design Flood Events

Design flood events for this study were the 5-, 2-, 1-, and 0.2-percent-annual-chance flood events (20-, 50-, 100-, and 500-year return period). Design flood event frequencies referred to in this report are flood frequencies for the South Fork Snoqualmie River. Design flood events consist of the inflow hydrographs for the South Fork Snoqualmie River and tributary streams, using the probability of occurrence relationship described in Table 2-1. The relation of the timing and magnitude of peak flows in the tributary streams and the South Fork Snoqualmie River are based on observed conditions. The methodology for developing the inflow hydrographs is summarized in detail in Appendix A.

TABLE 2-1.
RELATIONSHIP BETWEEN SOUTH FORK SNOQUALMIE RIVER AND TRIBUTARY STREAMS RECURRENCE INTERVALS AND DESIGN INFLOW HYDROGRAPHS

South Fork Snoqualmie River Peak Flows		Tributary Stream Peak Flows			
Design Flood Annual Probability of Occurrence (Return Period)	Peak Flow at Upstream Boundary of FLO-2D Model (RM 5.9)	Design Flood Annual Probability of Occurrence (Return Period)	Peak Flow Clough Creek	Peak Flow Ribary Creek	Peak Flow Gardiner Creek
5 (20-year)	12,190 cfs	40 (2.5-year)	180 cfs	130 cfs	110 cfs
2 (50-year)	14,160 cfs	25 (4-year)	220 cfs	160 cfs	140 cfs
1 (100-year)	15,650 cfs	16.7 (6-year)	250 cfs	180 cfs	160 cfs
0.2 (500-year)	19,120 cfs	7.1 (14-year)	330 cfs	240 cfs	210 cfs

2.2 HYDRAULIC PERFORMANCE AND FLOODING INVESTIGATION OF EXISTING LEVEES

The calibrated hydraulic model was used to analyze the performance of the existing levees for design flood events. Hydraulic performance was evaluated in terms of channel hydraulics (depth, velocity and bed shear), levee overtopping, freeboard, and floodplain inundation. The results of the FLO-2D modeling were used to develop the findings presented in this section. Figures 2-2 through 2-5 show the modeled levee overtopping and floodplain inundation and Figures 2-6 through 2-9 show modeled peak floodplain velocity for the design flood events. The FLO-2D analysis of existing conditions is fully documented in Appendix A.

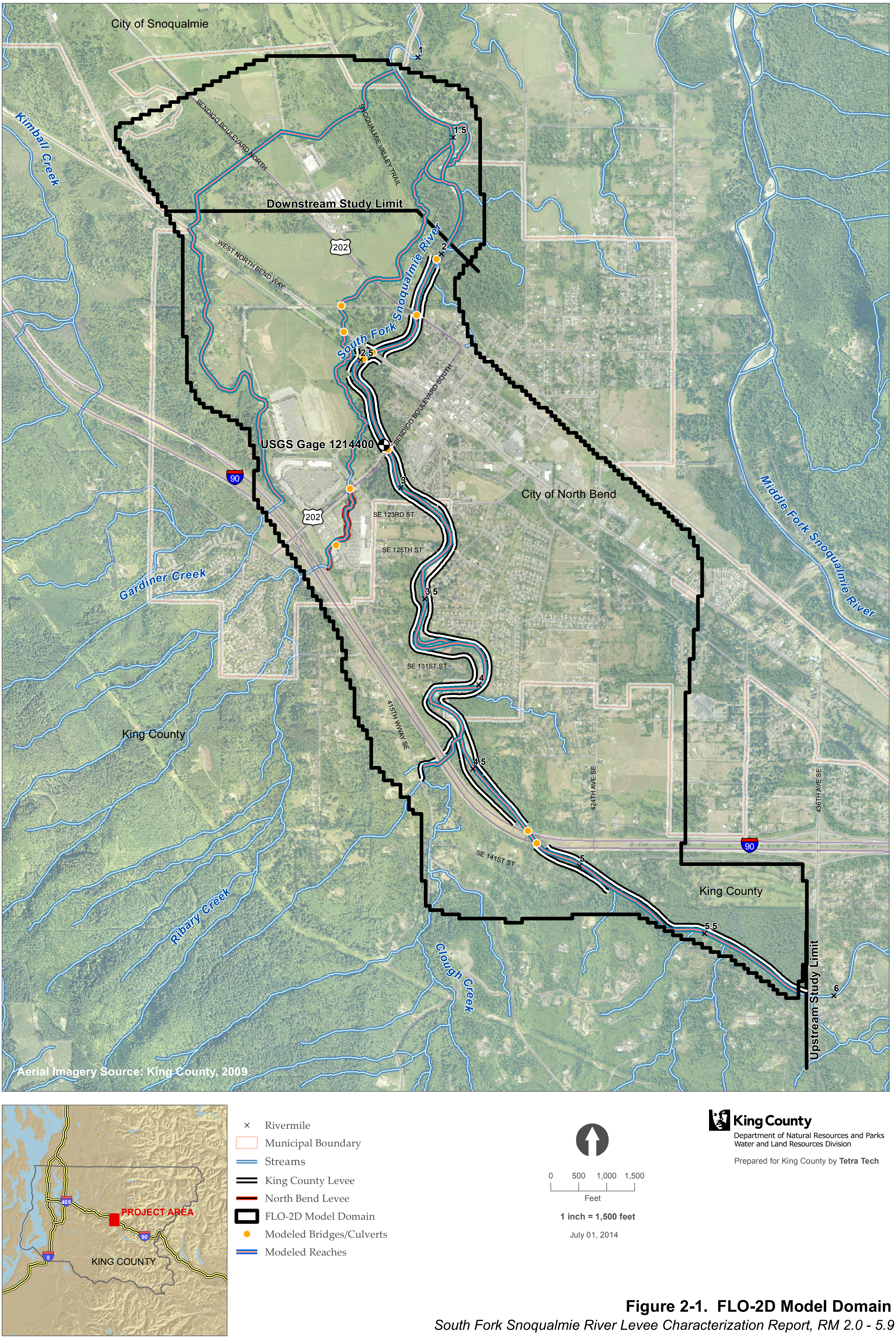
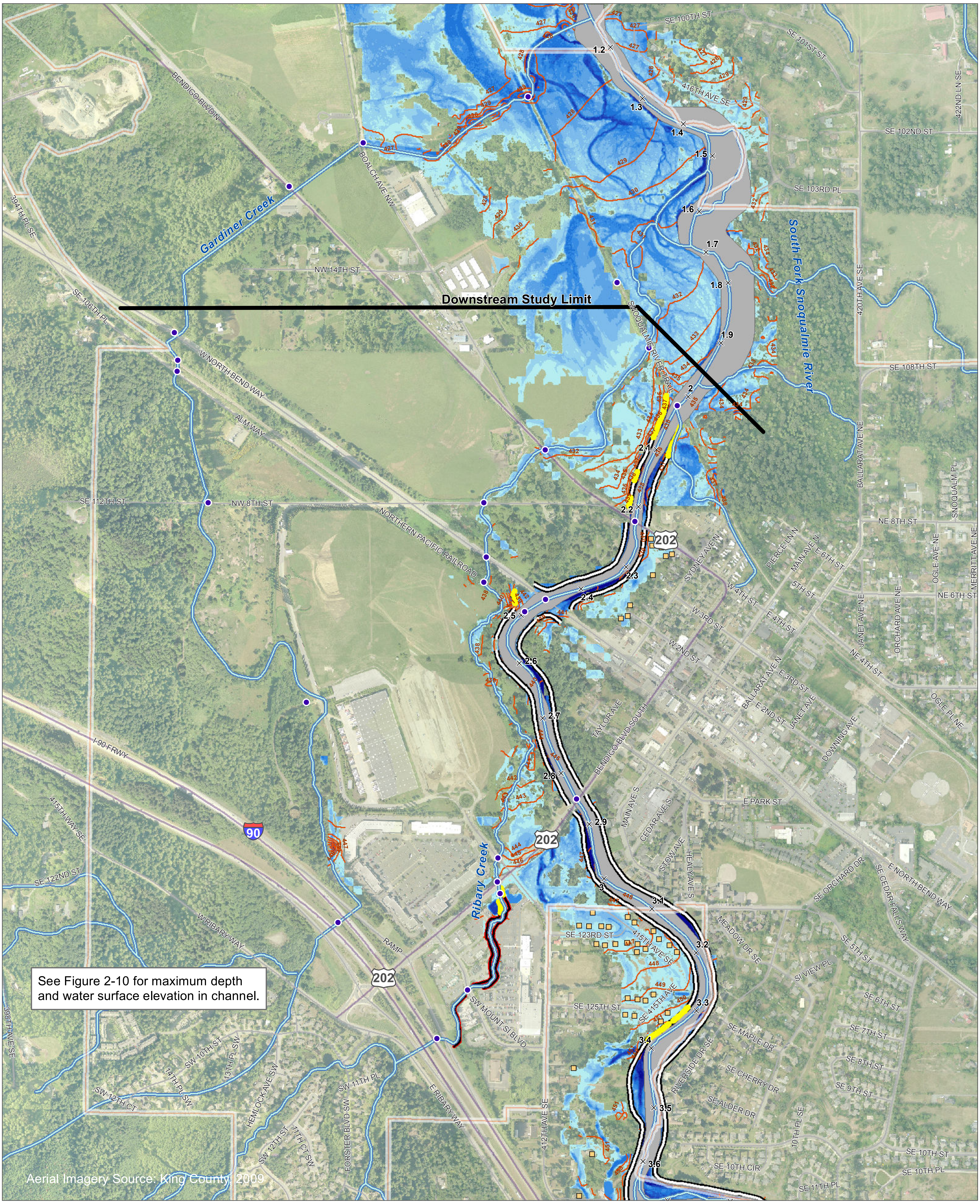
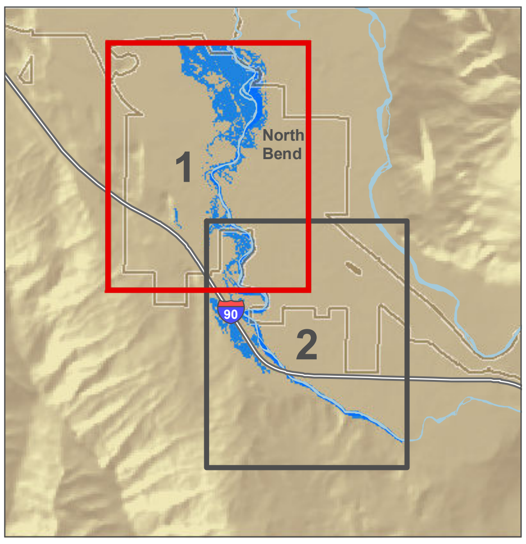


Figure 2-1. FLO-2D Model Domain

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Flow Depth (feet)

- 0 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 9
- 9 +
- 455 Maximum Water Surface Elevation (feet NAVD88)
- Levee Overtopping Locations
- Landward Levee Overtopping
- Inundated Structure
- Rivermile
- Municipal Boundary
- Streams
- Road Crossings
- King County Levee
- North Bend Levee

0 400 800

Feet

1 inch = 800 feet

July 01, 2014

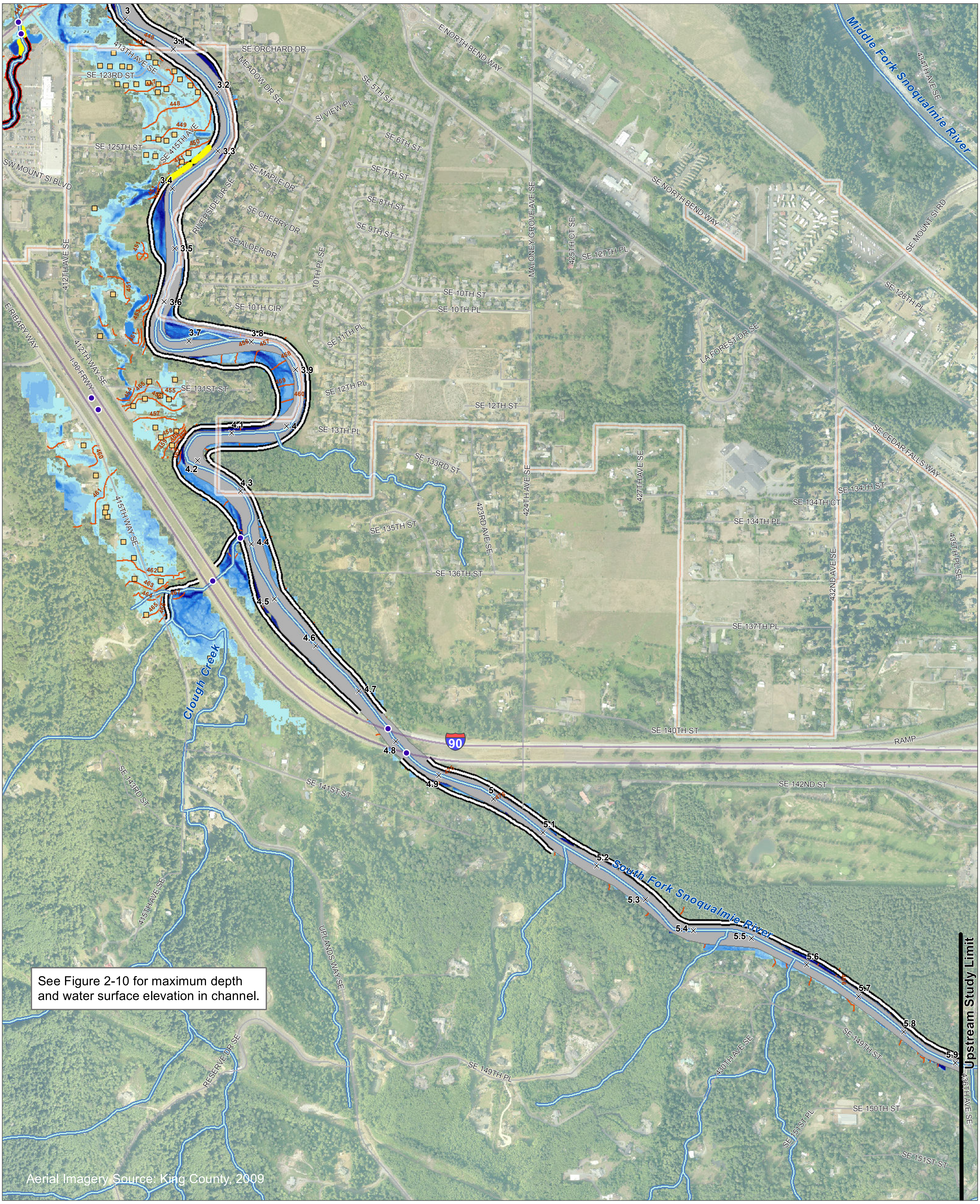
King County

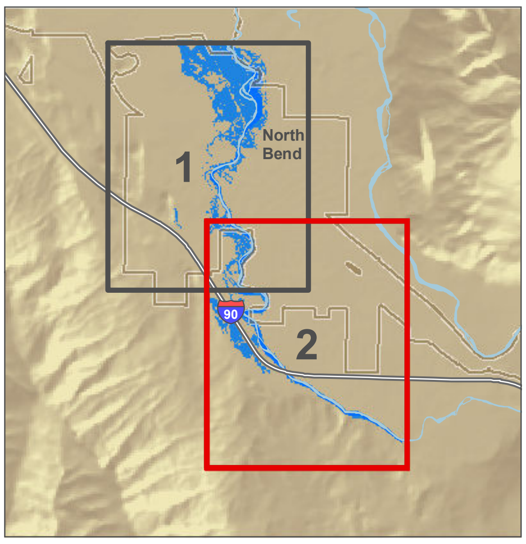
Department of Natural Resources and Parks
Water and Land Resources Division

Prepared for King County by **Tetra Tech**

Figure 2-2. Maximum Floodplain Depth and Water Surface Elevation Existing Conditions, 5 Percent Annual Chance Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Flow Depth (feet)

- 0 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 9
- 9 +

455 Maximum Water Surface Elevation (feet NAVD88)

Levee Overtopping Locations

Landward Levee Overtopping

- Inundated Structure
- Rivermile
- Municipal Boundary
- Streams
- Road Crossings
- King County Levee
- North Bend Levee

0 400 800

Feet

1 inch = 800 feet

July 01, 2014

King County
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Water and Land Resources Division

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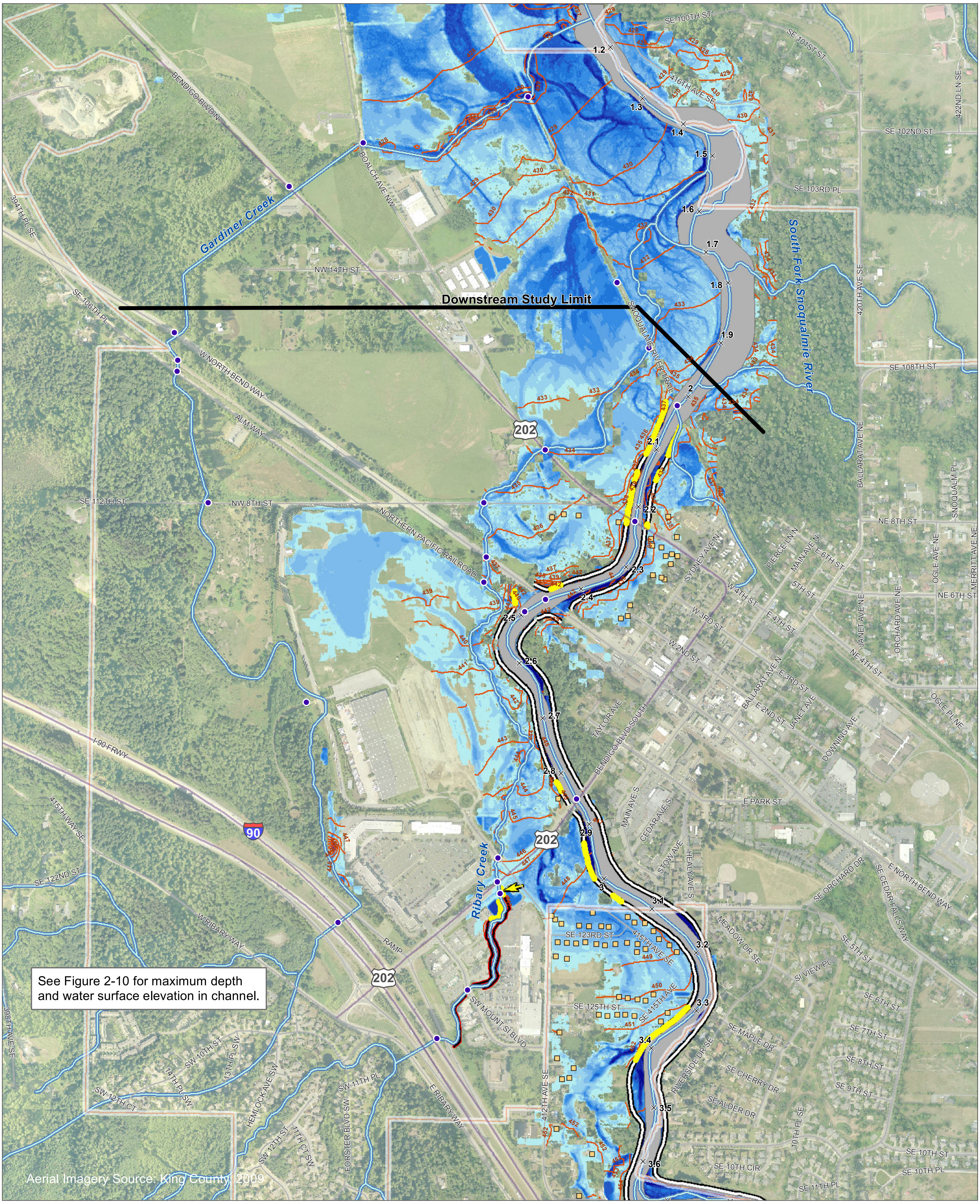
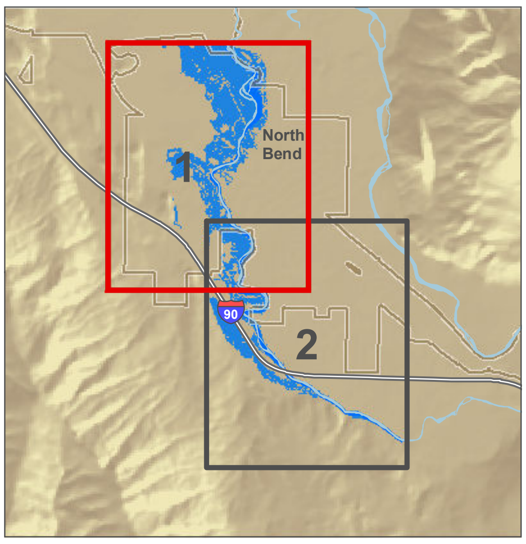
Figure 2-2. Maximum Floodplain Depth and Water Surface Elevation Existing Conditions, 5 Percent Annual Chance Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Flow Depth (feet)

0 - 1	5 - 6
1 - 2	6 - 7
2 - 3	7 - 8
3 - 4	8 - 9
4 - 5	9 +

455 Maximum Water Surface Elevation (feet NAVD88)

Levee Overtopping Locations

Landward Levee Overtopping

Inundated Structure

× Rivermile

Municipal Boundary

Streams

• Road Crossings

King County Levee

North Bend Levee

0 400 800

Feet

1 inch = 800 feet

July 01, 2014

King County

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Water and Land Resources Division

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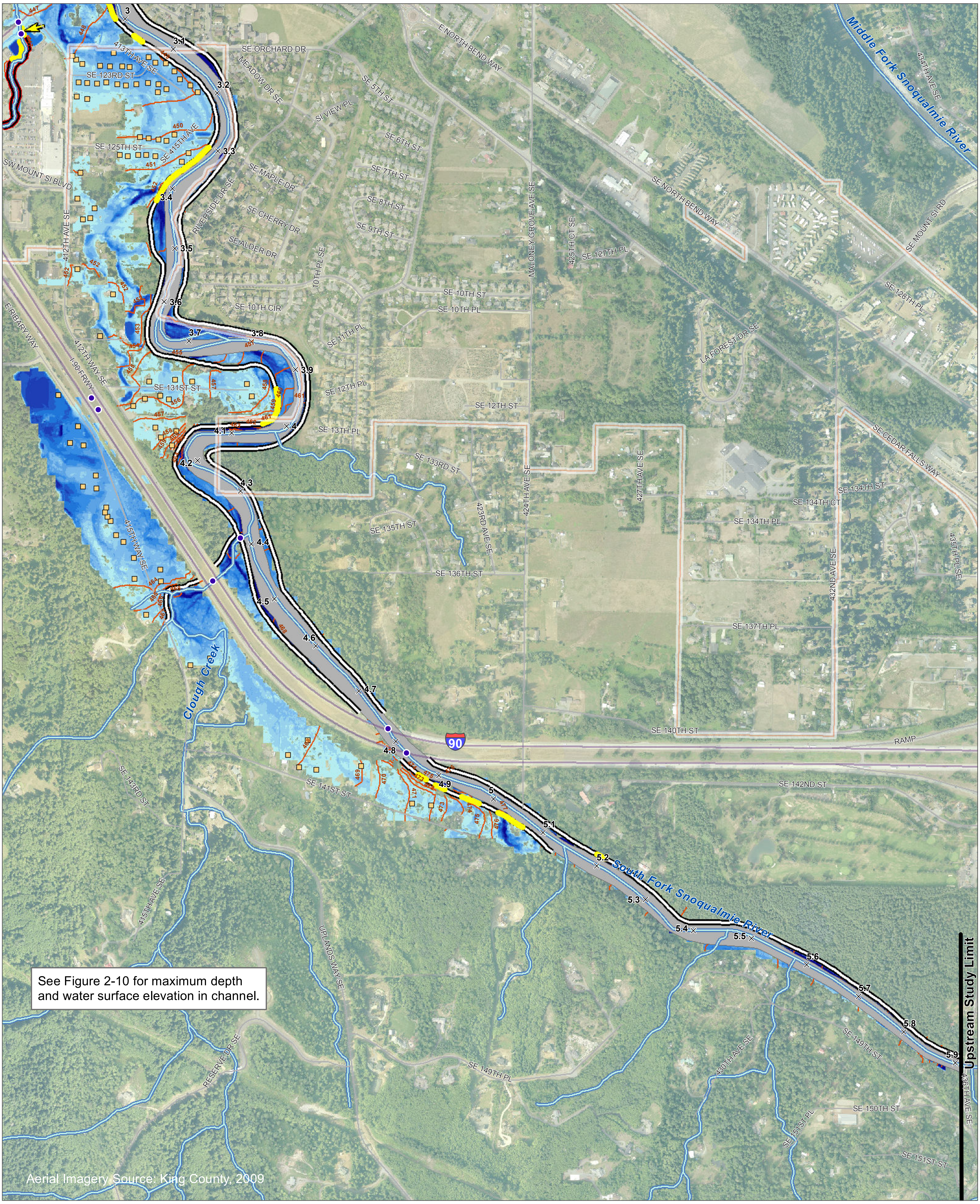
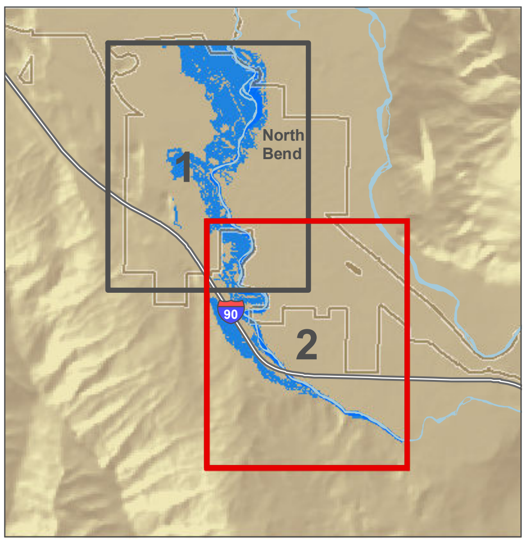
Figure 2-3. Maximum Floodplain Depth and Water Surface Elevation Existing Conditions, 2 Percent Annual Chance Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Flow Depth (feet)

- 0 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 9
- 9 +
- 455 Maximum Water Surface Elevation (feet NAVD88)
- Levee Overtopping Locations
- Landward Levee Overtopping
- Inundated Structure
- × Rivermile
- Municipal Boundary
- Streams
- Road Crossings
- King County Levee
- North Bend Levee

0 400 800
Feet

1 inch = 800 feet

July 01, 2014

King County
Department of Natural Resources and Parks
Water and Land Resources Division

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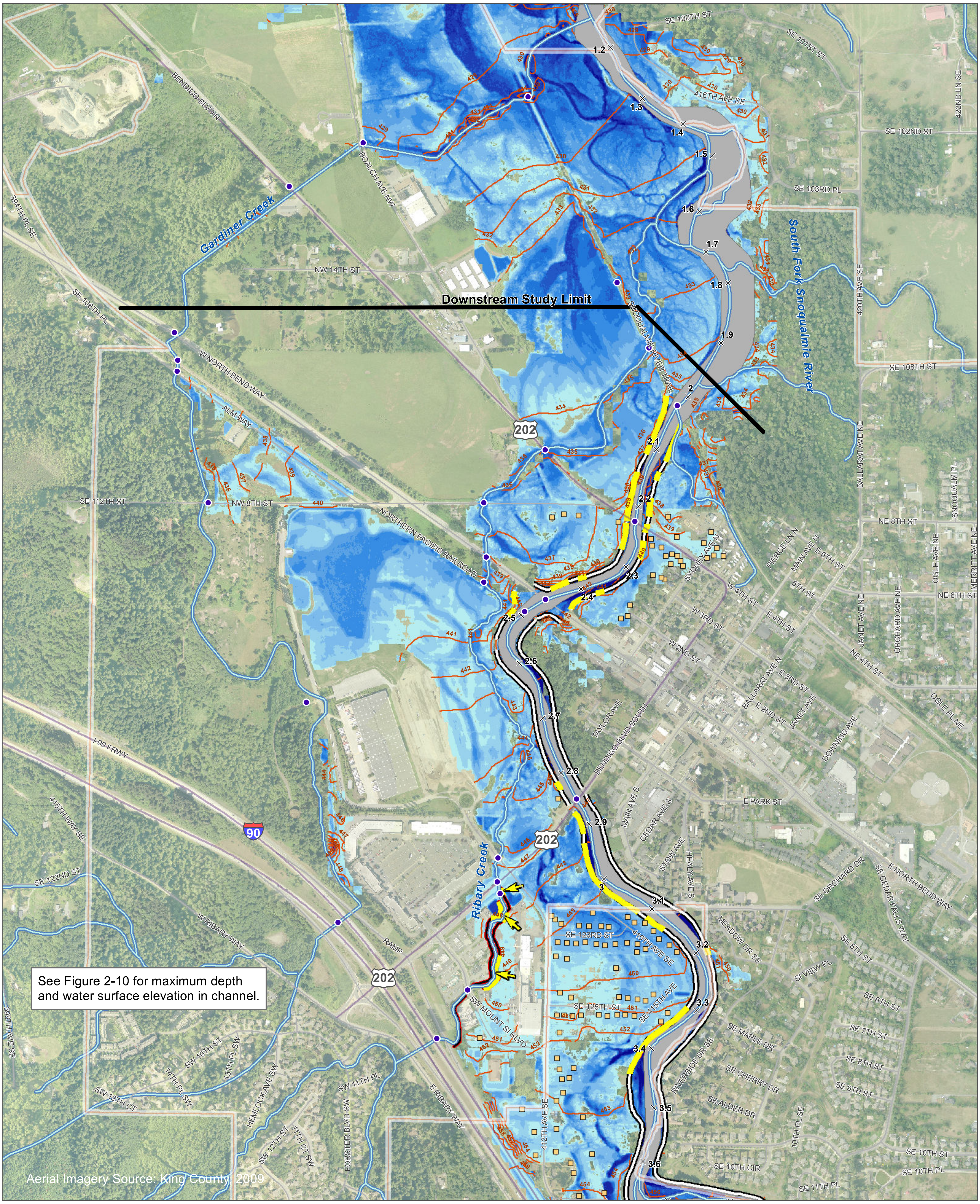
Figure 2-3. Maximum Floodplain Depth and Water Surface Elevation Existing Conditions, 2 Percent Annual Chance Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9



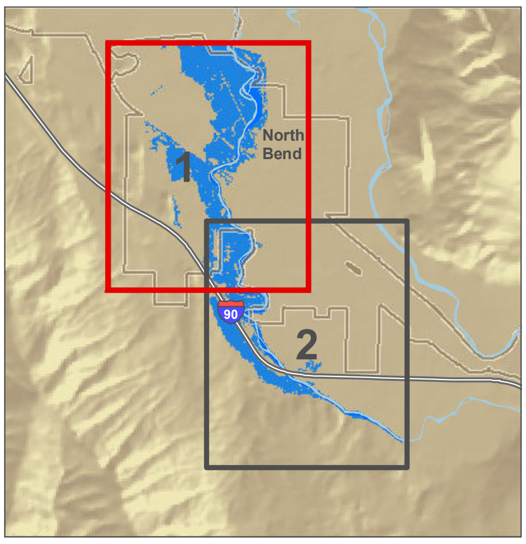
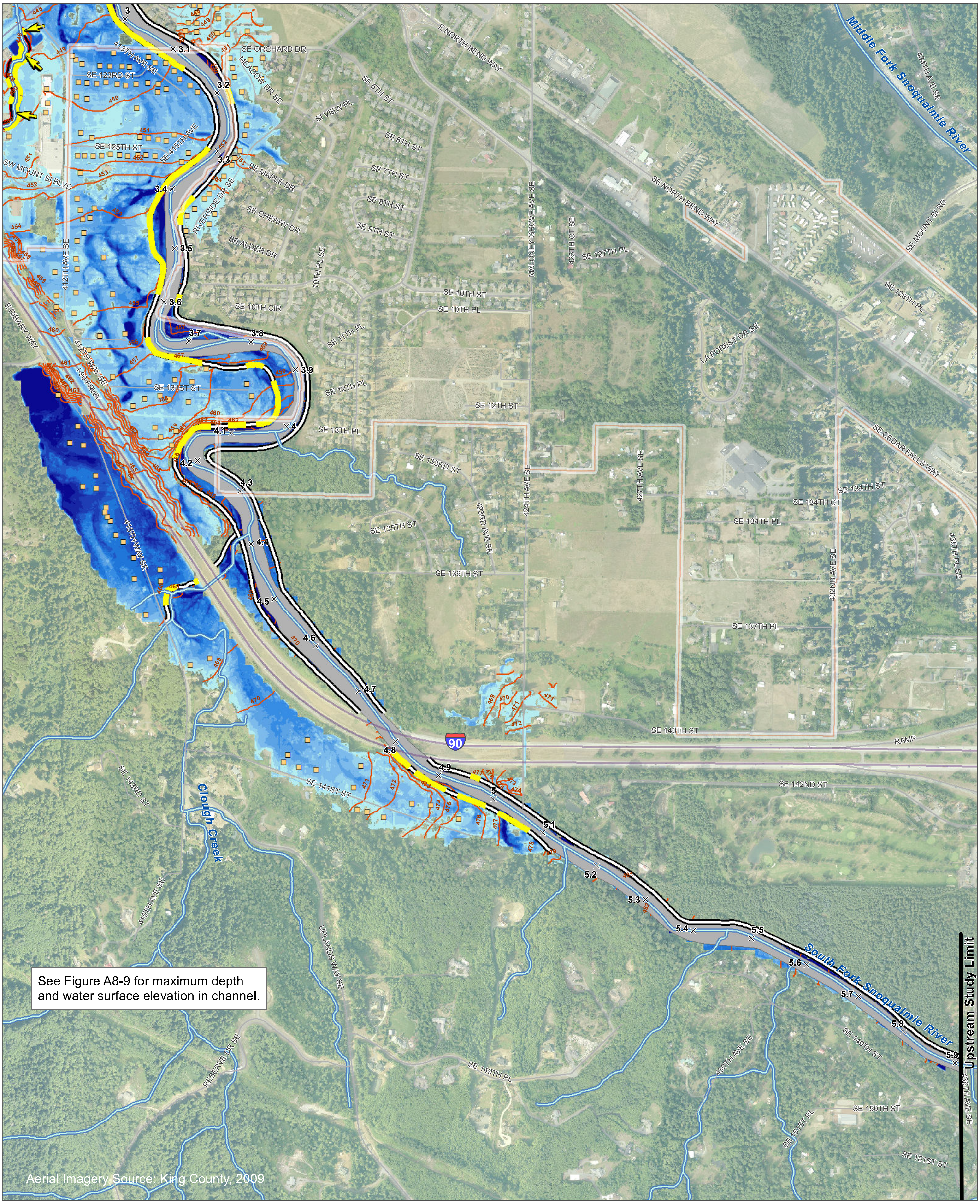


Figure 2-4. Maximum Floodplain Depth and Water Surface Elevation Existing Conditions, 1 Percent Annual Chance Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9



Maximum Floodplain Flow Depth (feet)

0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
9 +

455 Maximum Water Surface Elevation (feet NAVD88)

Levee Overtopping Locations

Landward Levee Overtopping

Inundated Structure

Rivermile

Municipal Boundary

Streams

Road Crossings

King County Levee

North Bend Levee

0 400 800

Feet

1 inch = 800 feet

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Figure A8-3. Maximum Floodplain Depth and Water Surface Elevation Future Aggradation Scenario, 1 Percent Annual Chance Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9

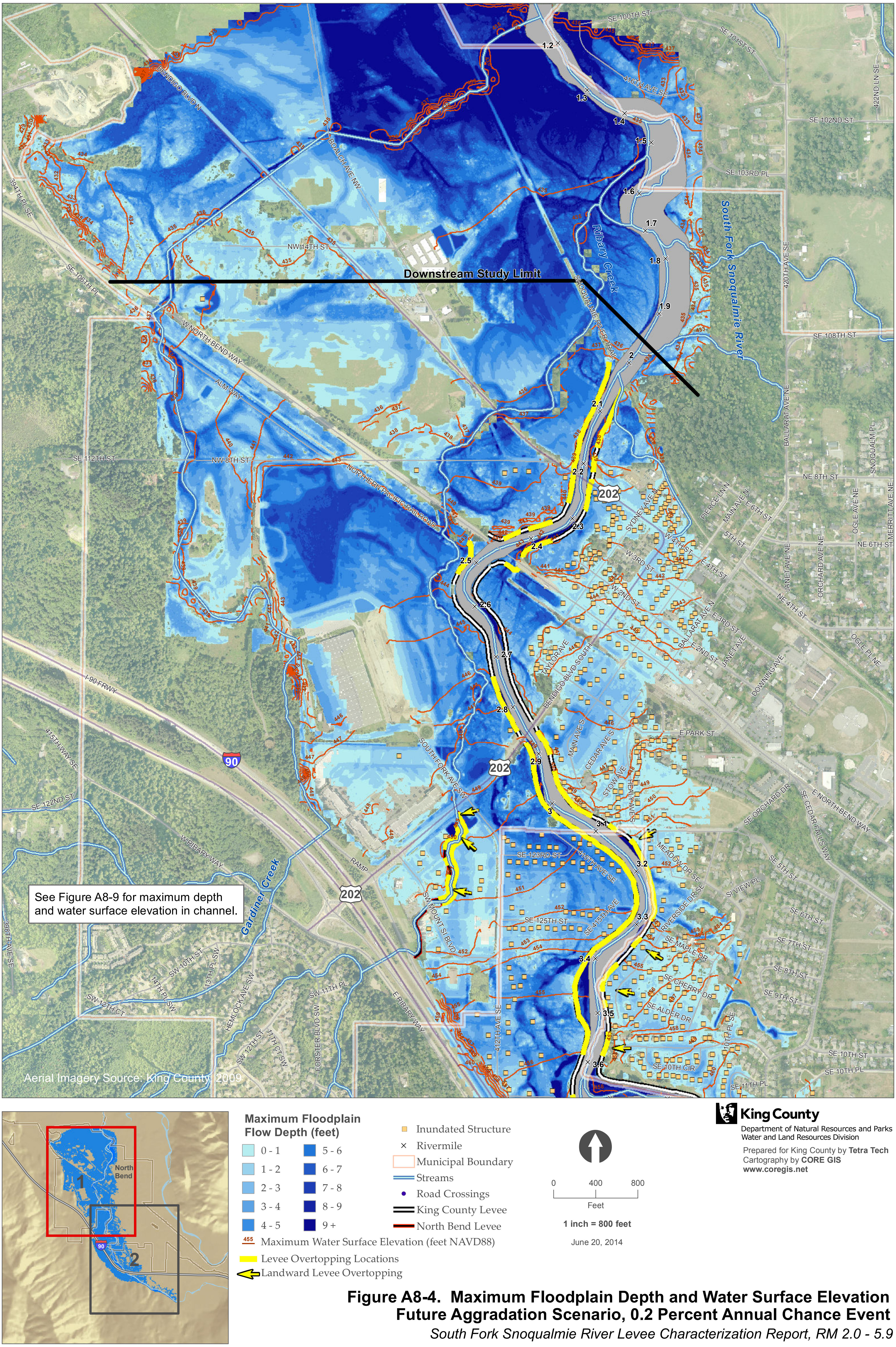
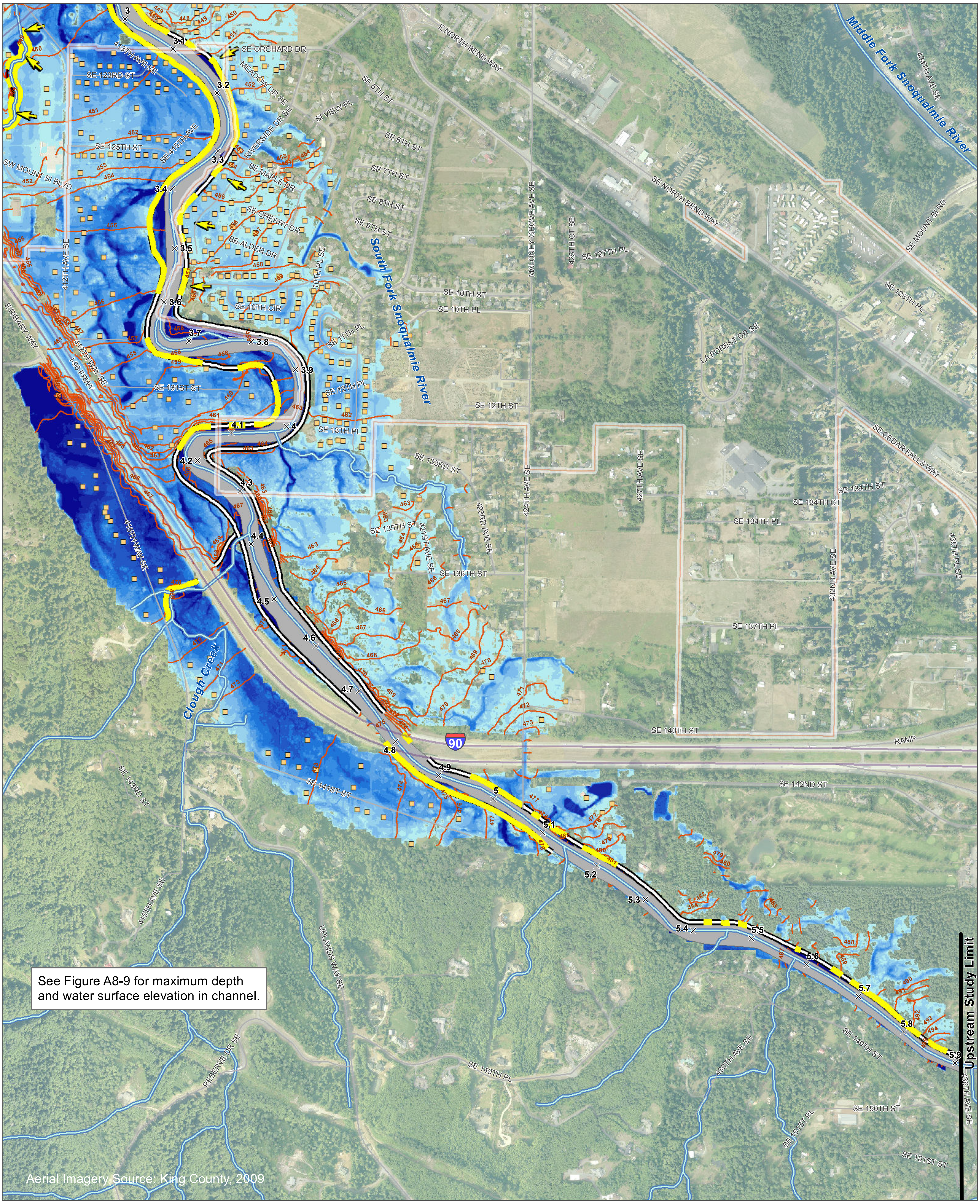
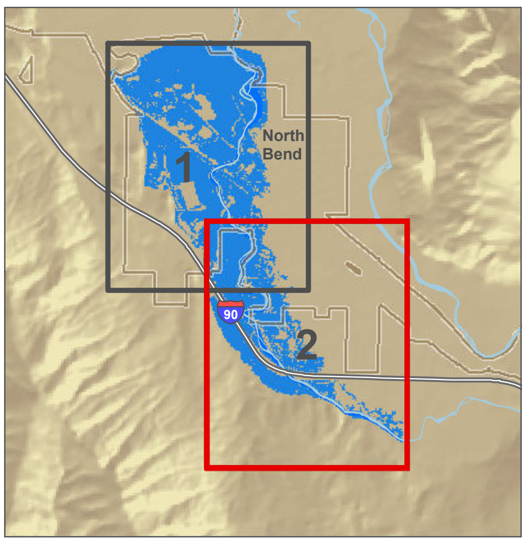


Figure A8-4. Maximum Floodplain Depth and Water Surface Elevation Future Aggradation Scenario, 0.2 Percent Annual Chance Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Flow Depth (feet)

0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
9 +

455 Maximum Water Surface Elevation (feet NAVD88)

Levee Overtopping Locations

Landward Levee Overtopping

Inundated Structure

Rivermile

Municipal Boundary

Streams

Road Crossings

King County Levee

North Bend Levee

0 400 800

Feet

1 inch = 800 feet

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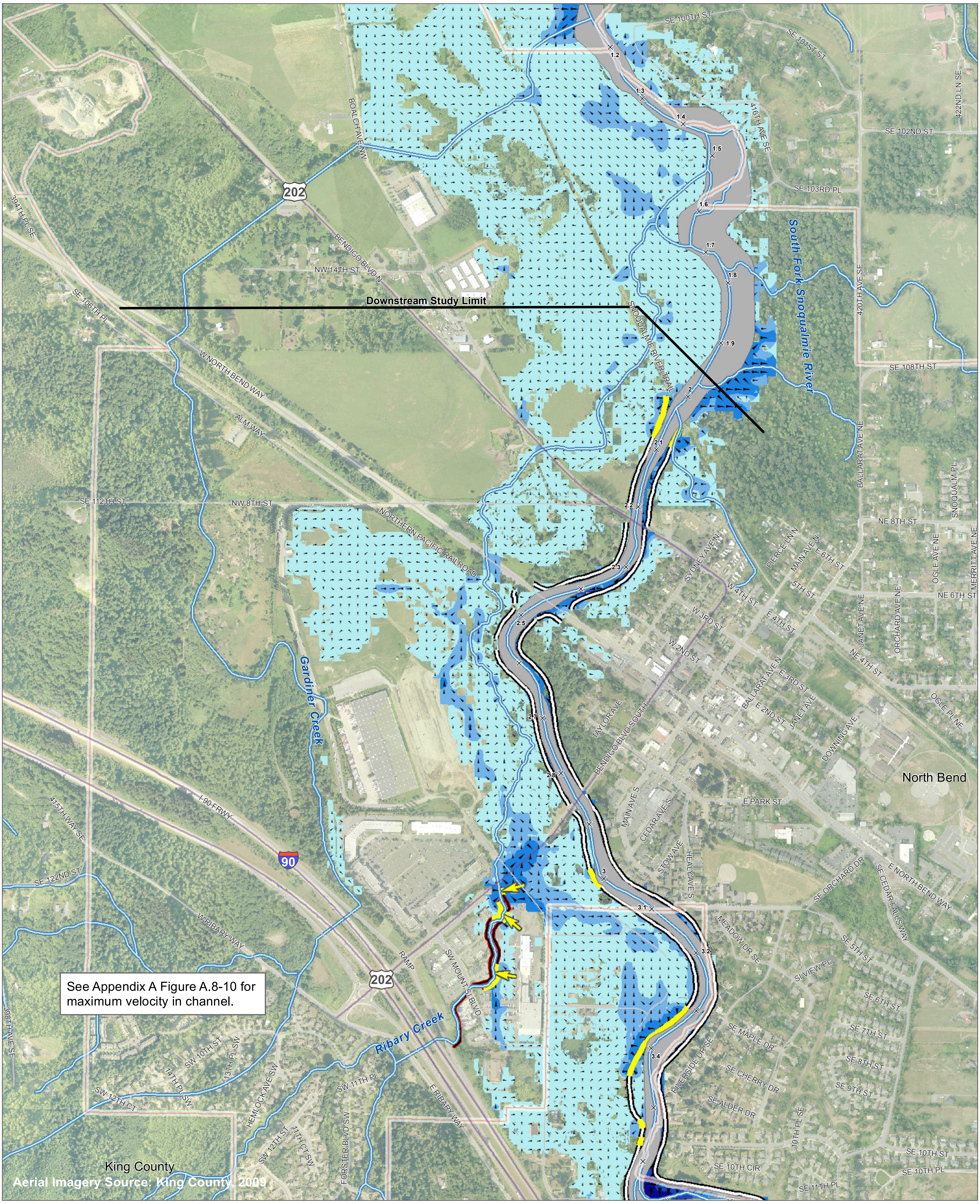
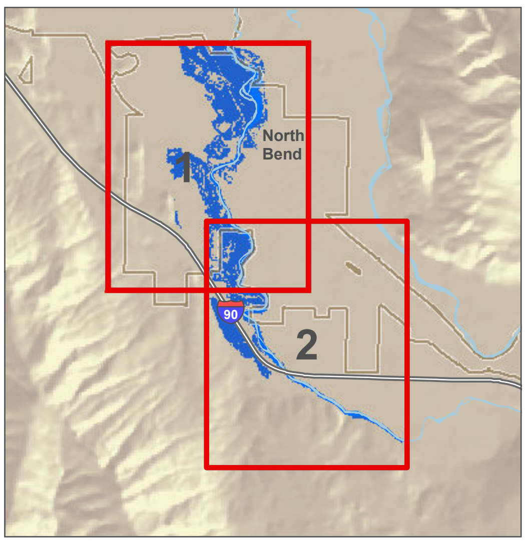
Figure A8-4. Maximum Floodplain Depth and Water Surface Elevation Future Aggradation Scenario, 0.2 Percent Annual Chance Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Velocity

Feet per Second

- 0.0 - 0.5
- 0.5 - 1
- 1 - 3
- 3 - 6
- 6 - 9
- Levee Overtopping Locations
- Landward Levee Overtopping

- × Rivermile
- Municipal Boundary
- Streams
- Road Crossings
- King County Levee
- North Bend Levee

0 400 800
Feet
1 inch = 800 feet

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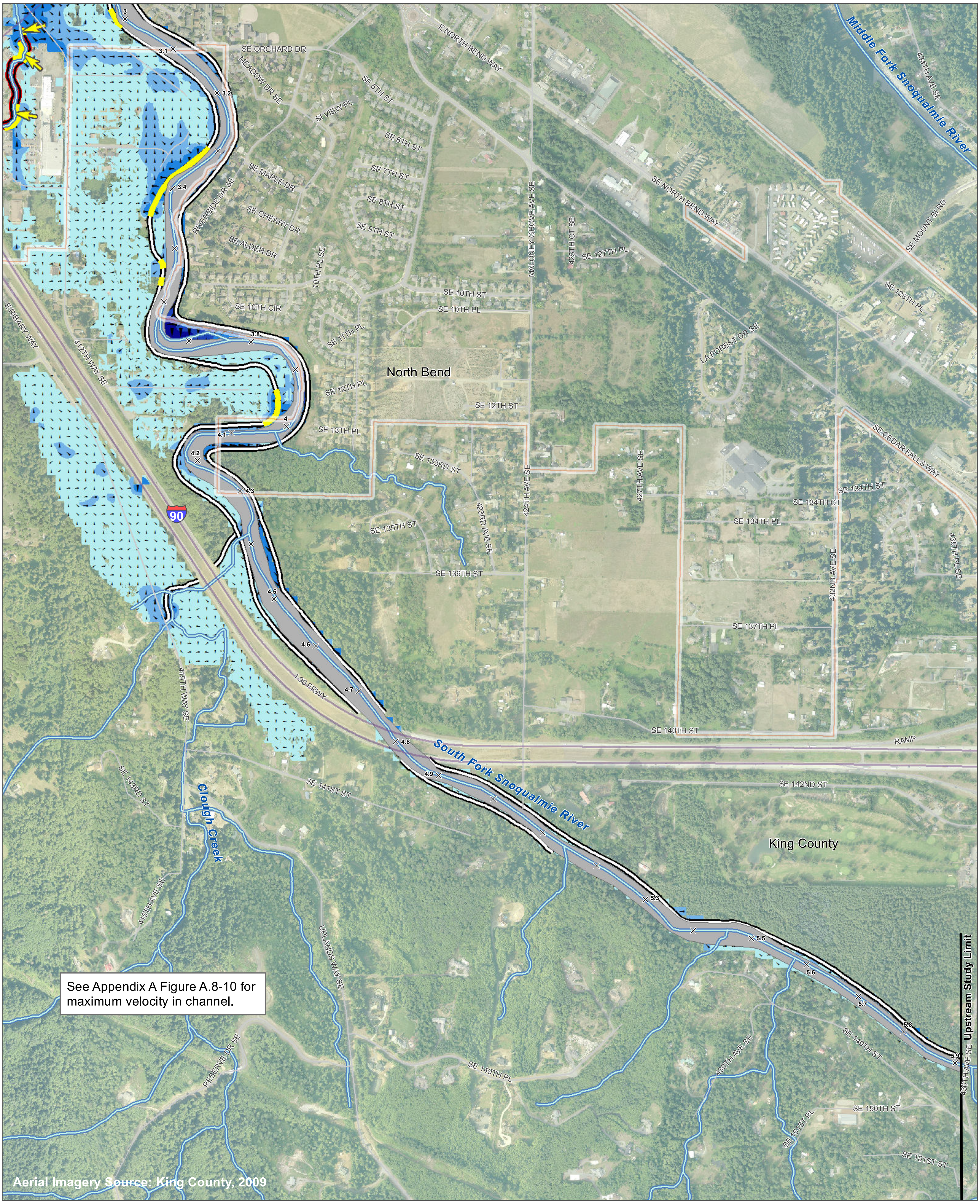
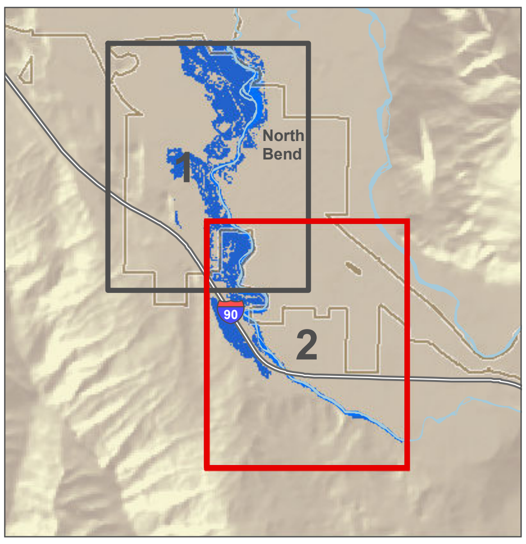
Figure A8-5. Maximum Floodplain Velocity
Future Aggradation Scenario, 5 Percent Annual Chance Design Flood Event
South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Velocity

Feet per Second

- 0.0 - 0.5
- 0.5 - 1
- 1 - 3
- 3 - 6
- 6 - 9
- Levee Overtopping Locations
- Landward Levee Overtopping

- Rivermile
- Municipal Boundary
- Streams
- Road Crossings
- King County Levee
- North Bend Levee

0 400 800

Feet

1 inch = 800 feet

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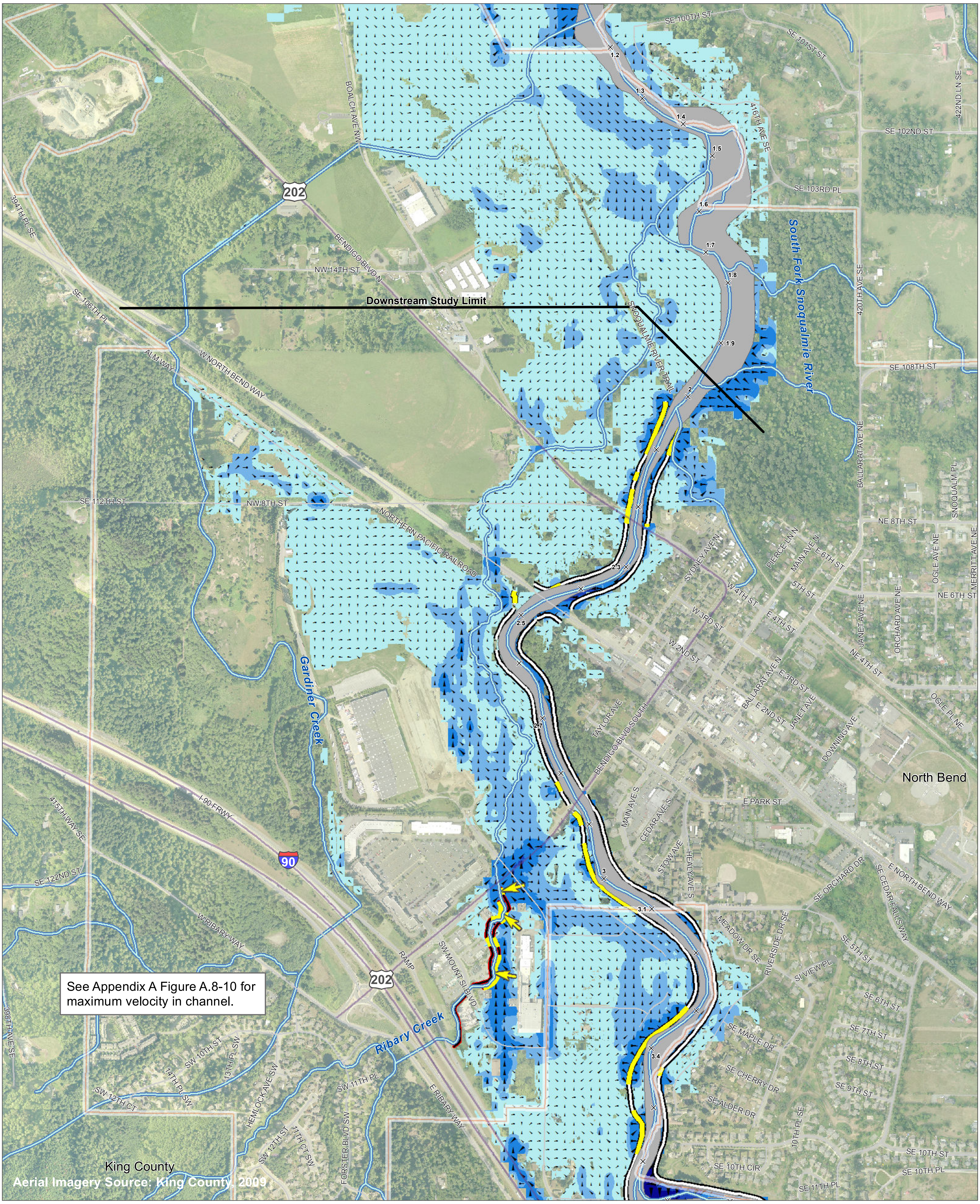
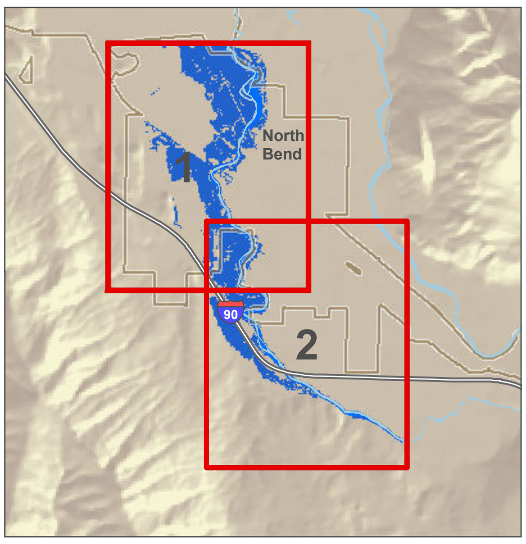
Figure A8-5. Maximum Floodplain Velocity
Future Aggradation Scenario, 5 Percent Annual Chance Design Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Velocity

Feet per Second

- 0.0 - 0.5
- 0.5 - 1
- 1 - 3
- 3 - 6
- 6 - 9
- Levee Overtopping Locations
- Landward Levee Overtopping
- Rivermile
- Municipal Boundary
- Streams
- Road Crossings
- King County Levee
- North Bend Levee

0 400 800
Feet

1 inch = 800 feet

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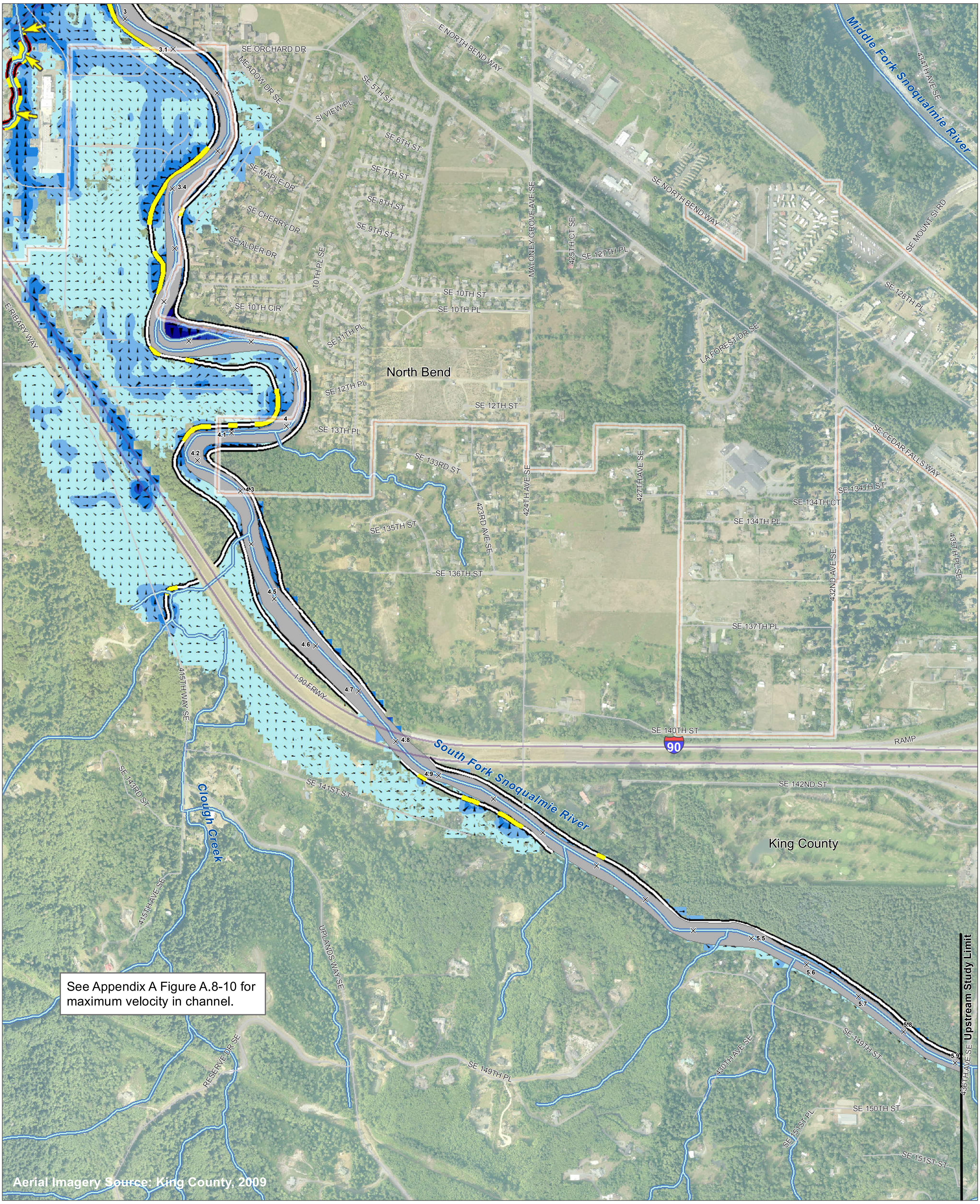
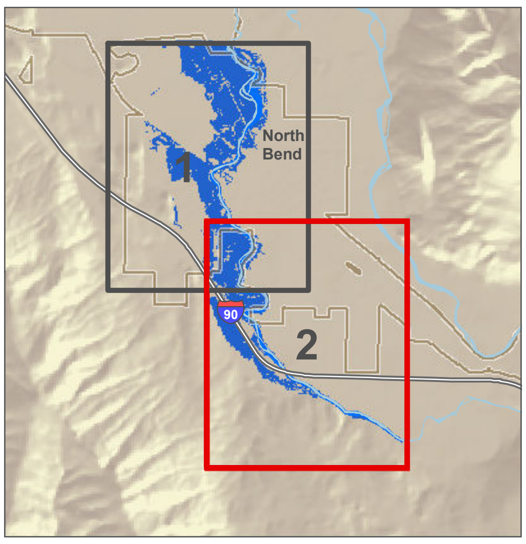
Figure A8-6. Maximum Floodplain Velocity

Future Aggradation Scenario, 2 Percent Annual Chance Design Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Velocity

Feet per Second

- 0.0 - 0.5
- 0.5 - 1
- 1 - 3
- 3 - 6
- 6 - 9
- Levee Overtopping Locations
- Landward Levee Overtopping
- Rivermile
- Municipal Boundary
- Streams
- Road Crossings
- King County Levee
- North Bend Levee

0 400 800
Feet

1 inch = 800 feet

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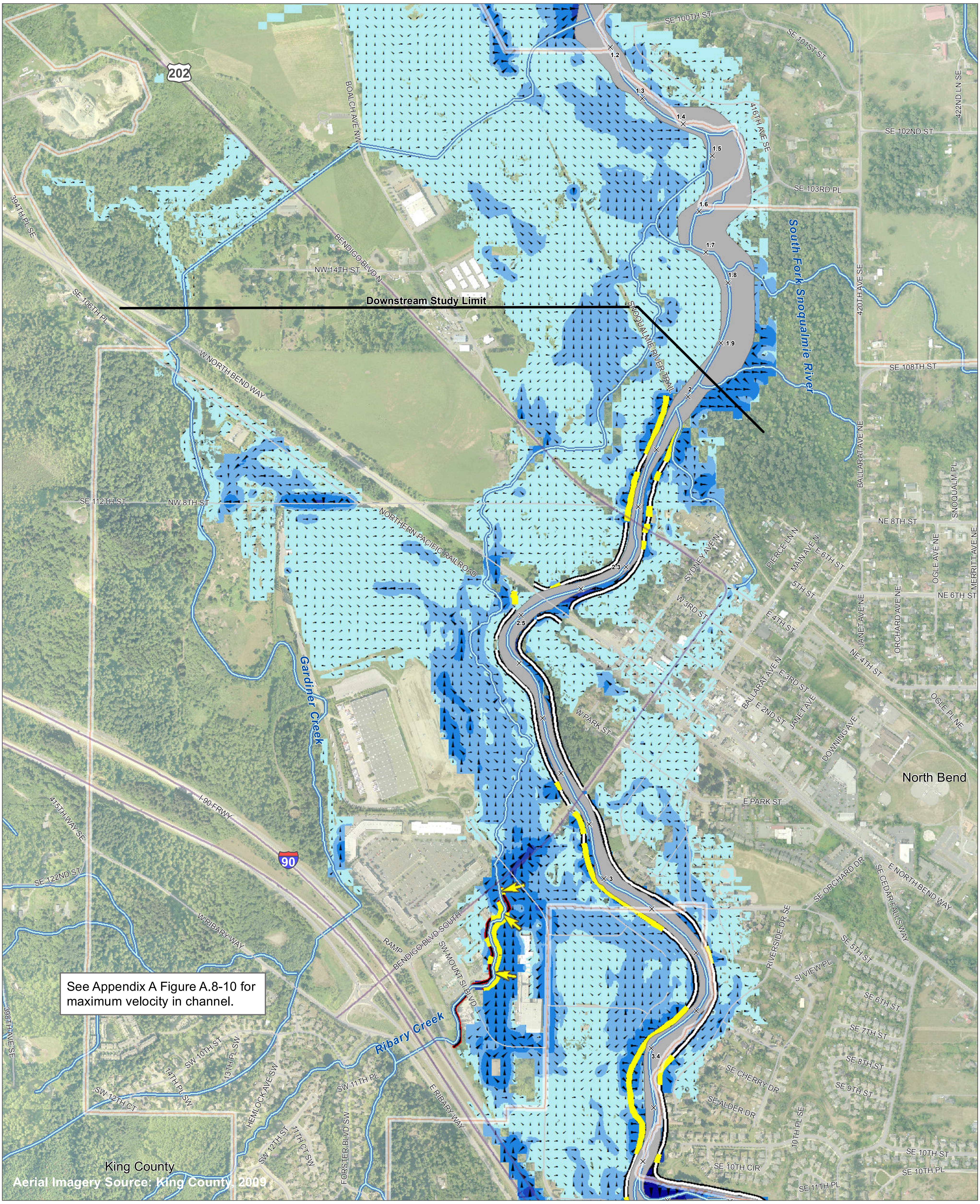
Figure A8-6. Maximum Floodplain Velocity
Future Aggradation Scenario, 2 Percent Annual Chance Design Flood Event
South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9



Maximum Floodplain Velocity

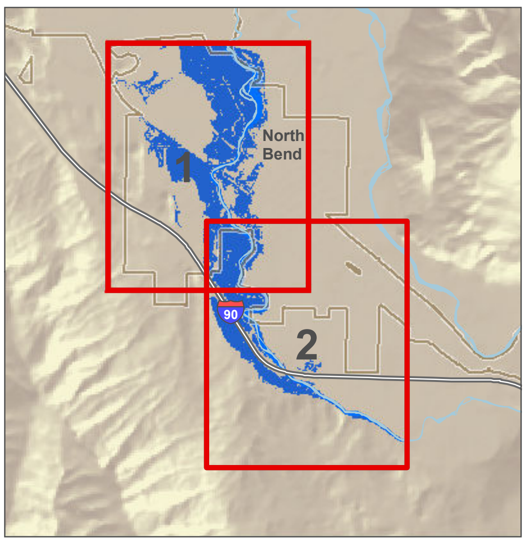
Feet per Second

- 0.0 - 0.5
- 0.5 - 1
- 1 - 3
- 3 - 6
- 6 - 9
- Levee Overtopping Locations
- Landward Levee Overtopping
- Rivermile
- Municipal Boundary
- Streams
- Road Crossings
- King County Levee
- North Bend Levee

0 400 800
Feet

1 inch = 800 feet

June 20, 2014



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Cartography by **CORE GIS**
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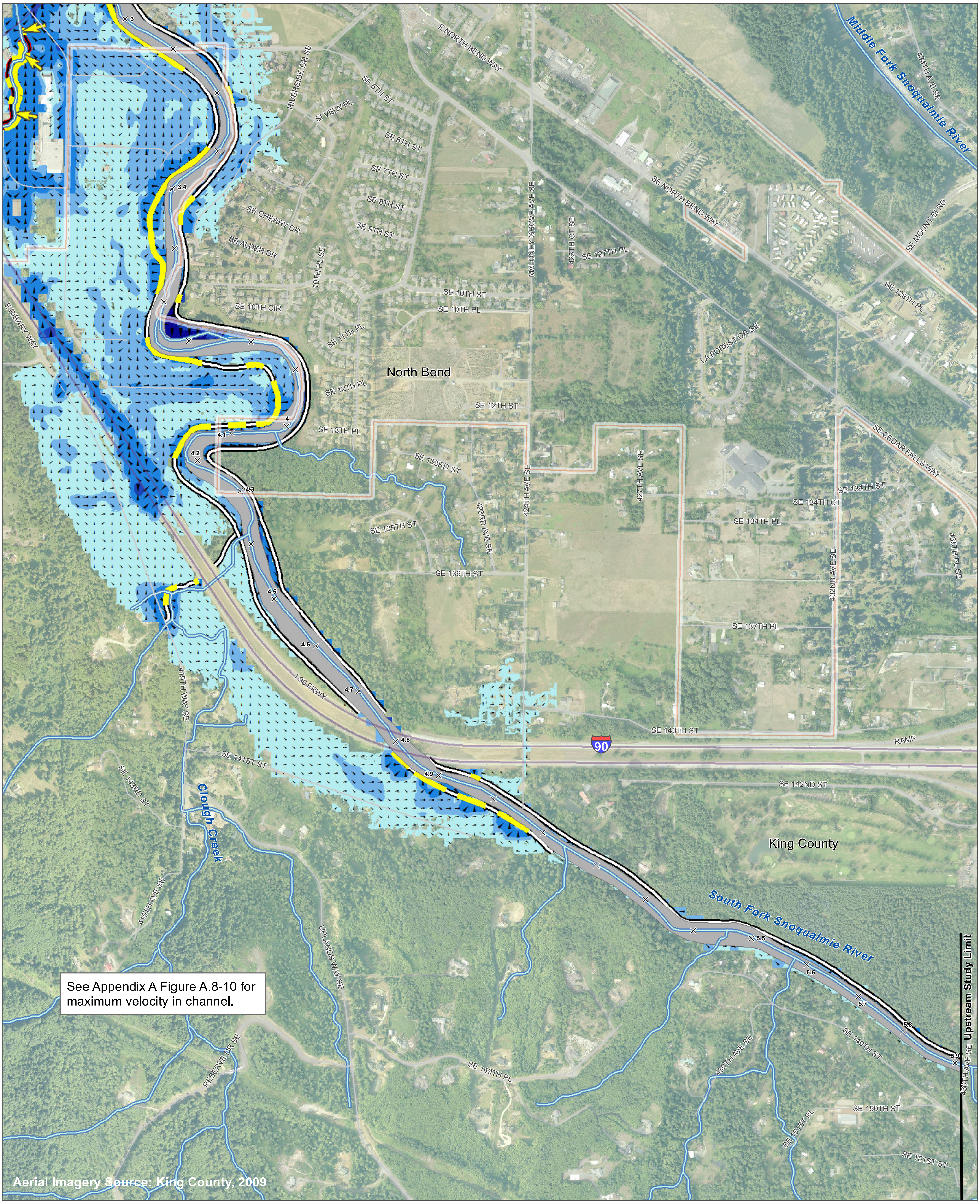
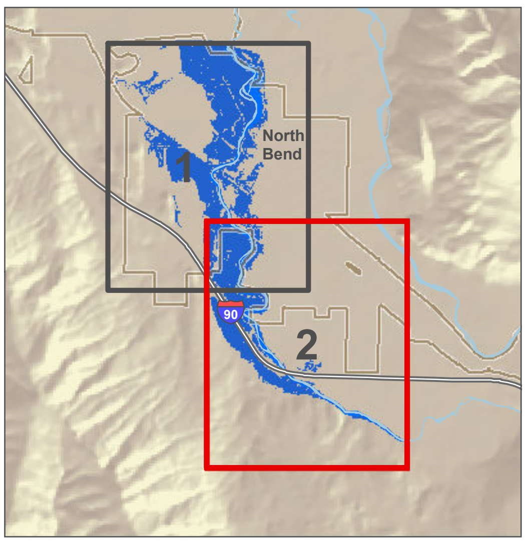
Figure A8-7. Maximum Floodplain Velocity
Future Aggradation Scenario, 1 Percent Annual Chance Design Flood Event
South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Velocity

Feet per Second

- 0.0 - 0.5
- 0.5 - 1
- 1 - 3
- 3 - 6
- 6 - 9

Levee Overtopping Locations

Landward Levee Overtopping

× Rivermile

Municipal Boundary

Streams

Road Crossings

King County Levee

North Bend Levee

0 400 800

Feet

1 inch = 800 feet

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Cartography by **CORE GIS**
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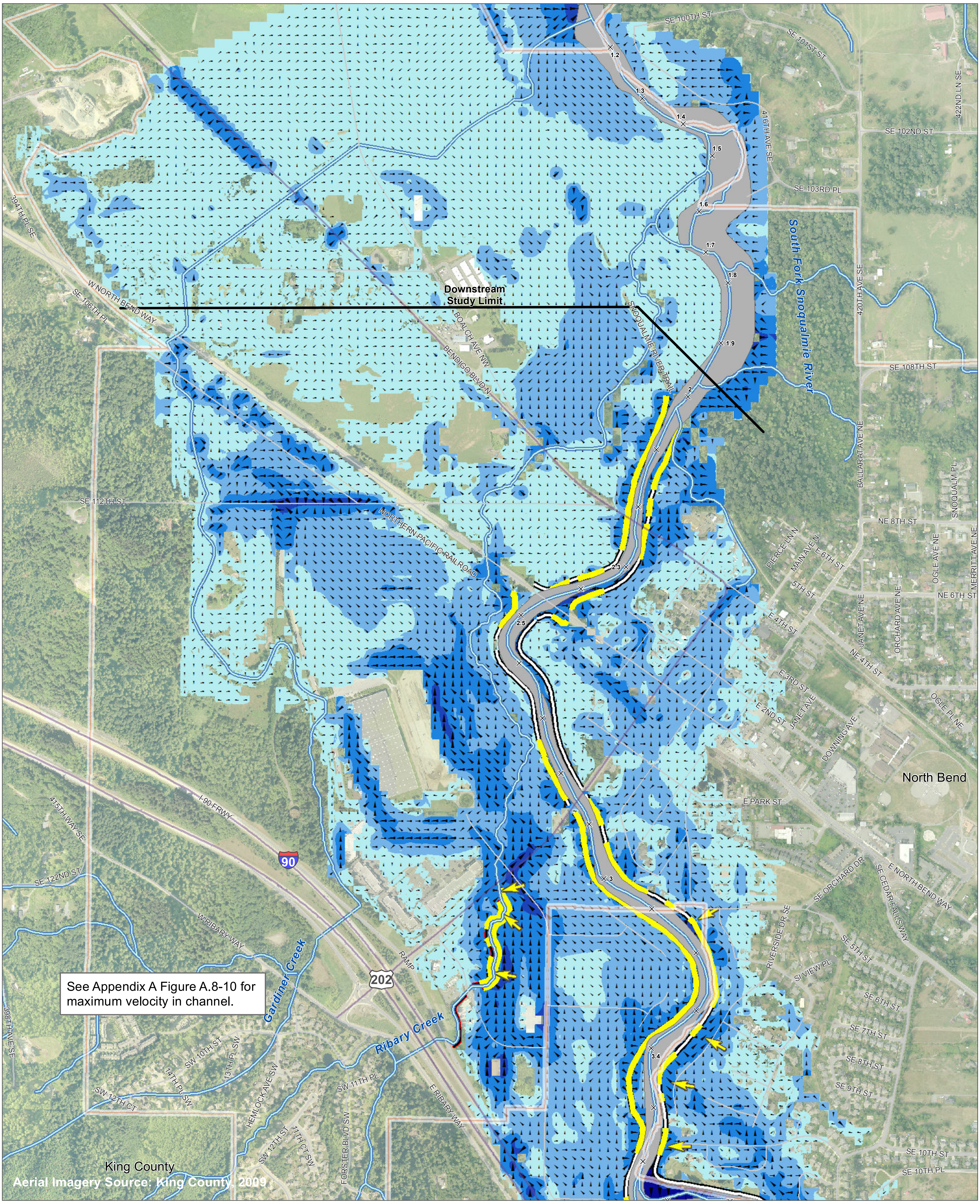
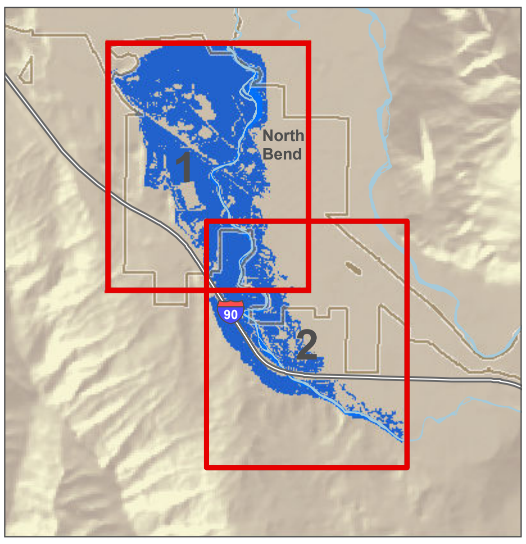
Figure A8-7. Maximum Floodplain Velocity

Future Aggradation Scenario, 1 Percent Annual Chance Design Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Velocity

Feet per Second

- 0.0 - 0.5
- 0.5 - 1
- 1 - 3
- 3 - 6
- 6 - 9
- Levee Overtopping Locations
- Landward Levee Overtopping

- Rivermile
- Municipal Boundary
- Streams
- Road Crossings
- King County Levee
- North Bend Levee

0 400 800

Feet

1 inch = 800 feet

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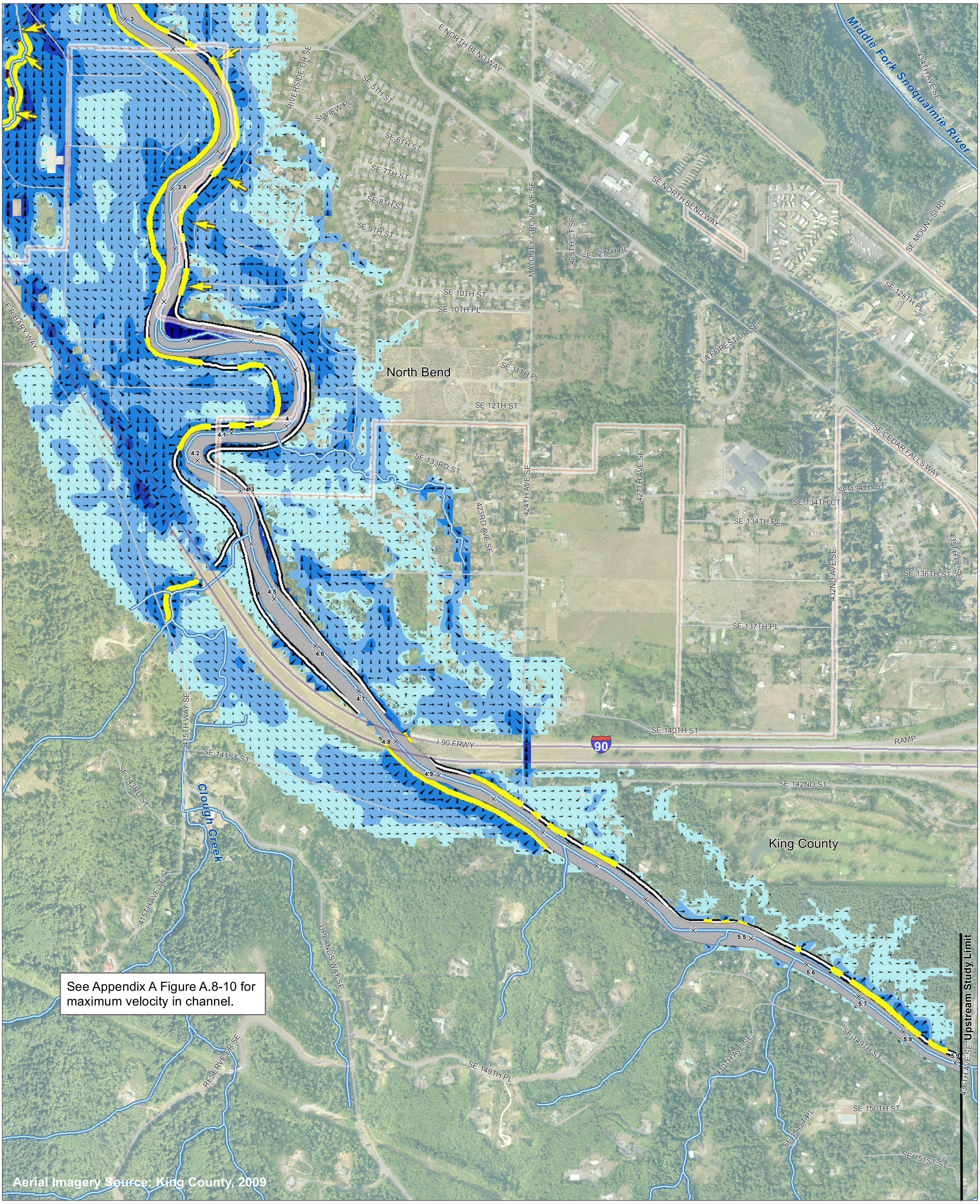
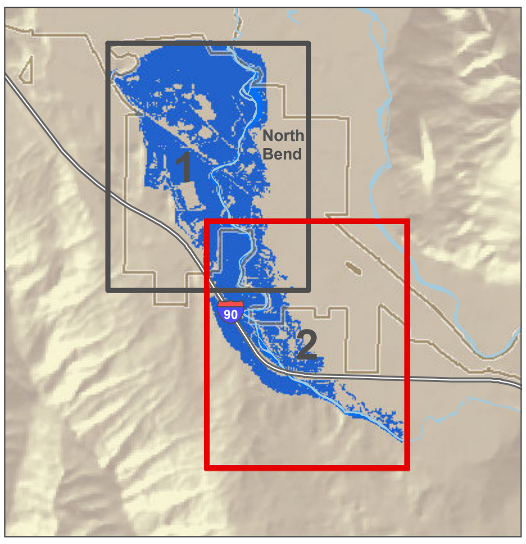
Figure A8-8. Maximum Floodplain Velocity
Future Aggradation Scenario, 0.2 Percent Annual Chance Design Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





Maximum Floodplain Velocity

Feet per Second

- 0.0 - 0.5
- 0.5 - 1
- 1 - 3
- 3 - 6
- 6 - 9
- Levee Overtopping Locations
- Landward Levee Overtopping

- Rivermile
- Municipal Boundary
- Streams
- Road Crossings
- King County Levee
- North Bend Levee

0 400 800

Feet

1 inch = 800 feet

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Figure A8-8. Maximum Floodplain Velocity
Future Aggradation Scenario, 0.2 Percent Annual Chance Design Flood Event

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9

2.2.1 South Fork Snoqualmie River Channel Hydraulics—Existing Conditions

The magnitude of flooding in the left and right bank floodplains is largely determined by the capacity of the South Fork Snoqualmie River levee system and the hydraulic restrictions caused by the bridges along the South Fork Snoqualmie River.

Channel Water Surface Profile

Figure 2-10 shows the longitudinal water surface, thalweg and right and left bank levee height profiles of the South Fork Snoqualmie River for the four flood events. The most significant head loss (drop in water surface elevation) due to instream structures occurs at the Snoqualmie Valley Trail Bridge and at the Interstate 90 Bridges for all simulated events. Significant head loss also occurs at the Bendigo Boulevard South Bridge for the 0.2-percent-annual-chance flood conditions only. Figure 2-10 also shows significant head loss between RM 3.75 and RM 4.00 that is due to the sinuosity of the channel alignment and the high main channel velocities in this vicinity.

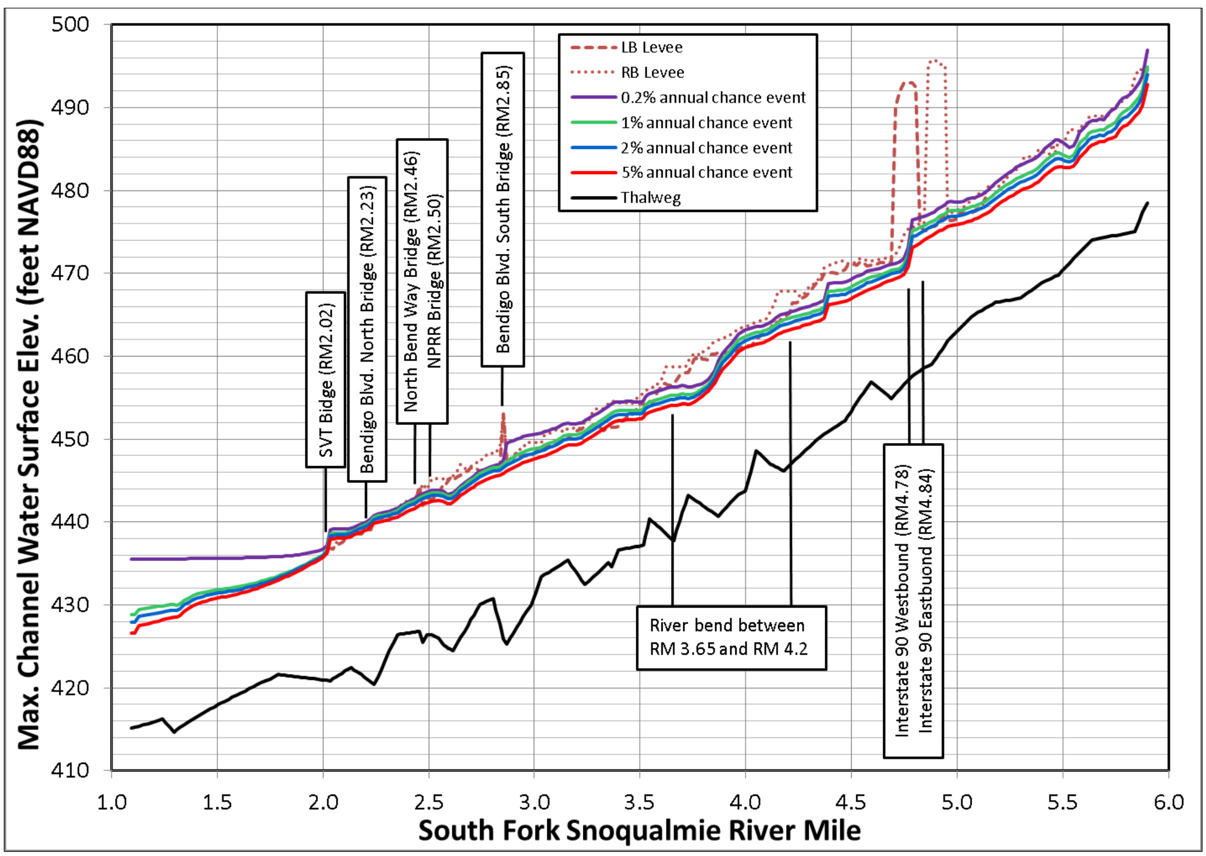


Figure 2-10. Maximum Channel Water Surface Profiles from FLO-2D Model for South Fork Snoqualmie River—Existing Conditions

As seen in Figure 2-10, the existing Bendigo Boulevard South bridge and the adjacent abutments result in a significant increase in upstream water surface elevation for the 0.2-percent-annual-chance flood event. For flood events of lesser magnitude, the increase is less significant. This is due to the fact that the bridge opening is predicted to be surcharged (i.e. the upstream water surface elevation is greater than the low chord of the bridge opening) for the 0.2-percent-annual-chance flood event. Further discussion of the Bendigo Boulevard Bridge is provided in a section below discussing bridge hydraulics.

Channel Flow

High head loss at road crossing structures, coupled with relatively low levee heights, causes flood flows to overtop the levee and inundate the floodplain during high flow conditions. As a result, flow in the South Fork Snoqualmie River channel generally decreases in the downstream direction as flow is diverted to the floodplain. Table 2-2 summarizes the peak channel flow rate predicted by the model at selected locations along the South Fork Snoqualmie River. The values in this table represent the peak flow rate conveyed between the left and right bank cross-section end points of the main channel at four locations, as defined in the FLO-2D model. The downstream flow reduction between RM 5.9 and RM 1.5 due to levee overtopping is about 17 percent for the 5-percent-annual-chance flood event, increasing to about 50 percent for the 0.2-percent-annual-chance flood event.

TABLE 2-2.
PEAK FLOOD CHANNEL DISCHARGE SIMULATED BY THE FLO-2D MODEL FOR EXISTING CONDITIONS

Location on the South Fork Snoqualmie River[a]	Peak Flow[b]			
	5 percent (20-year)	2 percent (50-year)	1 percent (100-year)	0.2 percent (500-year)
RM 1.50	10,080 cfs	10,600 cfs	10,790 cfs	9,450 cfs
RM 2.09	12,060 cfs	13,050 cfs	13,540 cfs	13,870 cfs
RM 2.76	12,170 cfs	13,500 cfs	14,330 cfs	14,760 cfs
RM 3.55	12,190 cfs	14,030 cfs	15,120 cfs	17,370 cfs
RM 5.90[c]	12,190 cfs	14,160 cfs	15,650 cfs	19,120 cfs

a. Channel flow decreases in the downstream direction (RM 5.9 to RM 1.5) are due to levee and bank overtopping.
b. Peak flow computed for channel cross section between top of left bank levee and top of right bank levee.
c. Total flow at upstream study limits.

Channel Velocity and Shear Stress

Peak average channel velocity in the South Fork Snoqualmie River is relatively high in the upstream reaches, generally decreasing in the downstream direction. This decrease is due to the generally decreasing channel gradient as the river flows from the foothills onto the alluvial fan. The highest peak average channel velocity occurs at RM 3.85, near the apex of the large sweeping bend in the river between RM 3.7 and RM 4.2. The highest bed shear stresses occur immediately upstream of the Snoqualmie Valley Trail Bridge (RM 2.0) and in the vicinity of the Interstate 90 bridges for all events and immediately upstream of the Bendigo Boulevard South Bridge for the 0.2-percent-annual-chance event. Relatively high shear stresses also occur at RM 3.8, upstream of the Clough Creek confluence (RM 4.4) and two locations upstream of Interstate 90 (RM 5.6 and RM 5.7).

Generally, high shear stresses are associated with reaches of the river where the energy grade line is steepest and where there are hydraulic restrictions or controls in the channel. High shear stresses can result in undermining of levees and bridge abutments by removing foundation material through channel scour or bank erosion. However, high channel shear stress does not imply channel bed degradation and variability in scour exists along a channel. For instance, the high shear stress at RM 5.6 and RM 5.7 is due to the varying bed form and cross section as a result of the riffle-pool morphology in the channel. Full documentation of the existing-conditions channel velocity and shear stress is provided in Appendix A.

Bridge Hydraulics

Current WSDOT bridge design standards generally require the structure to be able to pass the 1-percent-annual-chance event without surcharging (WSDOT, 2010). Surcharging increases pressure on the bridge structure and could result in excessive scouring of the streambed under the structure. WSDOT recommends and King County requires (King County, 2007) an additional 3 feet of freeboard to safely pass debris and prevent obstruction of the bridge opening. A summary of the hydraulic performance of the bridge structures for existing conditions in the South Fork Snoqualmie River follows; additional documentation is provided in Appendix A. The vertical clearance values reported here are for existing conditions, which accounts for the loss of flows upstream of the bridge due to levee overtopping. The reported clearance would change, maybe significantly, if all flood flows where contained within the levee system.

Interstate 90

The vertical clearance between the maximum water surface elevation and the low chord elevation at the two Interstate 90 Bridges is more than 8 feet for all flood events analyzed for the existing conditions. No surcharging (water surface higher than low chord) is predicted at this location for any of the design flood events. Figure 2-10 shows a significant drop in water surface elevation (between 6 and 8 feet) through this structure. This drop is likely due to the added flow resistance introduced by the bridge piers and the configuration of the roadway in relation to the channel alignment.

Bendigo Boulevard South

At the Bendigo Boulevard South Bridge, the vertical clearance is estimated to be less than 2 feet for the 5- through 1-percent-annual-chance flood events. For the 0.2-percent-annual-chance flood, the water surface elevation exceeds the low chord elevation, creating a surcharged flow regime that results in backwater extending upstream to about RM 3.8. Backwater does not occur for the 5-percent-annual-chance through 1-percent-annual-chance flood events. The backwater condition for the 0.2-percent-annual-chance flood event is almost entirely due to surcharging at the bridge structure. The cross-sectional area of the bridge opening is slightly reduced compared to the upstream channel section, but the reduction is not large enough to create a backwater when the bridge is not surcharged.

These findings should not be interpreted to mean that the existing Bendigo Boulevard South bridge opening can pass the entire peak flow for a given flood event (see Table 2-2) as described, because the existing-conditions analysis accounts for loss of flow upstream due to levee overtopping. In a hypothetical situation with no upstream levee overtopping and all flow contained within the upstream levees, surcharging of the Bendigo Boulevard South Bridge would likely occur for flood events much more frequent than the 0.2-percent-annual-chance flood event.

The finding that the bridge opening is not surcharged for the 5- through 1-percent-annual-chance peak flood events differs from the conclusion of a previous study prepared for WSDOT (Kato and Warren 2000; see Section 1.4.1), which predicted that the Bendigo Boulevard South Bridge opening would be surcharged for the 2-percent-annual-chance flood event (estimated by Kato and Warren to be 13,500 cfs), resulting in upstream backwater conditions.

The discrepancy between the conclusions of this current study and those of the Kato and Warren (2002) study is due primarily to the differing hydraulic modeling methods employed by the two studies. The Kato and Warren study used the HEC-RAS model to conduct the hydraulic analysis of the South Fork Snoqualmie River in the vicinity of the bridge opening and did not account for upstream flows lost from the channel due to levee overtopping. As a result, the peak flow rate for all modeled flood events was assumed to pass through the bridge opening. With the existing levee system, this is not physically

possible, as acknowledged in the Kato and Warren (2000) report, since the left and right bank levee systems upstream of Bendigo Boulevard South would overtop during floods equal to or greater than the 2-percent-annual-chance flood event, thus limiting the magnitude of peak flow conveyed to the bridge opening (Kato and Warren 2000).

The FLO-2D hydraulic model employed for this study accounts for this upstream levee overtopping and more accurately simulates the existing-conditions peak flow rate at the bridge opening for the range of modeled flood events. For example, during the 2-percent-annual-chance flood event, while the peak flow in the South Fork Snoqualmie River at RM 5.9 is 14,160 cfs, the peak flow conveyed through the Bendigo Boulevard South bridge opening is 13,100 cfs (see Table 2-2). It is not until the 0.2-percent-annual-chance flood event, when the peak flow predicted through the bridge opening is 14,200 cfs, that the water surface elevation is high enough to reach the low chord of the bridge opening and result in noticeable upstream backwater conditions.

Snoqualmie Valley Historical Railroad

Vertical clearance at the Snoqualmie Valley Historic Railroad is estimated to be less than 2 feet for the 2-, 1-, and 0.2-percent-annual-chance flood event and 2.6 feet for the 5-percent-annual-chance flood event. Vertical clearance for this bridge was determined from the midpoint of the span over the main channel rather than along the trestle section of the bridge in the floodplain, where the low chord is approximately 1 foot lower. No surcharging is predicted at this location for any of the design flood events.

West North Bend Way

At the West North Bend Way bridge, the vertical clearance is estimated to be less than 2 feet for floods equal to or greater than the 2-percent-annual-chance flood event. No surcharging is predicted at this location for any of the design flood events.

Bendigo Boulevard North

At the Bendigo Boulevard North bridge, vertical clearance is greater than 4 feet for all events analyzed. Vertical clearance for this bridge was determined from the midpoint of the span over the main channel rather than along the trestle section of the bridge in the floodplain where the low chord is lower. No surcharging is predicted at this location for any of the design flood events.

Snoqualmie Valley Trail Bridge

The vertical clearance at the Snoqualmie Valley Trail Bridge is less than 2 feet for floods equal to or greater than the 2-percent-annual-chance flood event. No surcharging is predicted at this location for any of the design flood events.

2.2.2 South Fork Snoqualmie River Levee Freeboard – Existing Conditions

Levee freeboard for the South Fork Snoqualmie River was evaluated to identify locations where freeboard is less than the original design criteria of 1 foot for the 13,000 cfs design flow rate assuming overtopping did not occur in the levee system. The levee freeboard analysis used the calibrated HEC-RAS model developed to support the FLO-2D model (see Appendix A). Figure 2-11 shows that most of the right bank levee system has 1 foot or more of freeboard for a significant portion of the right bank with insufficient freeboard at only 4.6 percent of the length (850 feet). The length of levee with insufficient freeboard was greater on the left bank at 22 percent (3,330 feet) not meeting the 1 foot freeboard criteria. Additional documentation of freeboard for the levee is found in Appendix A.

2.2.3 South Fork Snoqualmie River Levee Capacity – Existing Conditions

Levee capacity for the South Fork Snoqualmie River was estimated to determine where capacity restrictions occur in the levee system. Levee capacity was assumed to correspond to the flow rate at the levee crest with no freeboard. Similar to the freeboard analysis, flow was confined to the channel without overtopping. The calibrated HEC-RAS was used to evaluate capacity (see Appendix A).

The right bank levee system is able to convey higher flow rates before overtopping compared to the left bank levee. The left bank levee has insufficient capacity to convey the 5-percent-annual-chance-event for 13% (2,020 feet) of the length of the levee whereas the right bank has adequate capacity to convey the same event for the entire length of levee. For the 1-percent-annual-chance event, the left bank has adequate capacity over 47 percent (7,310 feet) of the length compared to the right bank which has capacity to convey the same event for nearly 83 percent (14,700 feet) of the length.

Figure 2-12 shows the estimated capacity of the left and right bank levees for the South Fork Snoqualmie River within the study limits. This figure shows that backwater from the bridge structures reduce the capacity of the levee system upstream of all road crossings. The backwater effect at Snoqualmie Valley Trail, North Bend Way, and Bendigo Boulevard South reduce the levee capacity to less than the 5-percent-annual-chance-event flow of 12,190 cfs. Additional documentation of the capacity of the levee is found in Appendix A.

2.2.4 South Fork Snoqualmie River Levee Overtopping—Existing Conditions

The hydraulic analysis predicted that the South Fork Snoqualmie River levee systems would be overtopped for all flood events. Levee overtopping is shown on Figure 2-2 through Figure 2-5. Overtopping is predicted over 1,300 feet of the South Fork Snoqualmie River levee for the 5-percent-annual-chance flood event, increasing to 17,000 feet (3.2 miles) for the 0.2-percent-annual-chance flood event. For the 5-percent-annual-chance through 1-percent-annual-chance events, the overtopping length is significantly greater for the left bank South Fork Snoqualmie River than for the right bank, because the left bank levees are lower in elevation than the right bank levees. Levee overtopping is tabulated in Appendix A.

The locations in the South Fork Snoqualmie River levee system at greatest risk of overtopping are those that experience overtopping during the 5-percent-annual-chance peak flood event (12,190 cfs):

- On the South Fork Snoqualmie River left bank:
  - Between RM 2.05 and RM 2.21. Overflow at this location occurs into a forested and agricultural area between the South Fork Snoqualmie River and Ribary Creek.
  - At RM 2.47 between the West North Bend Way bridge and the Snoqualmie Valley Historic Railroad bridge. Floodwaters are contained between the two bridges, limiting the extent of inundation.
  - Between RM 3.33 and RM 3.40. Overflow from the South Fork Snoqualmie River at this location floods eight homes in Berry Estates (SE 415th Avenue) and then continues north and floods 18 homes in Shamrock Park (SE 123rd Street). Overflow also results in flooding on Bendigo Boulevard South and South Fork Avenue SW.

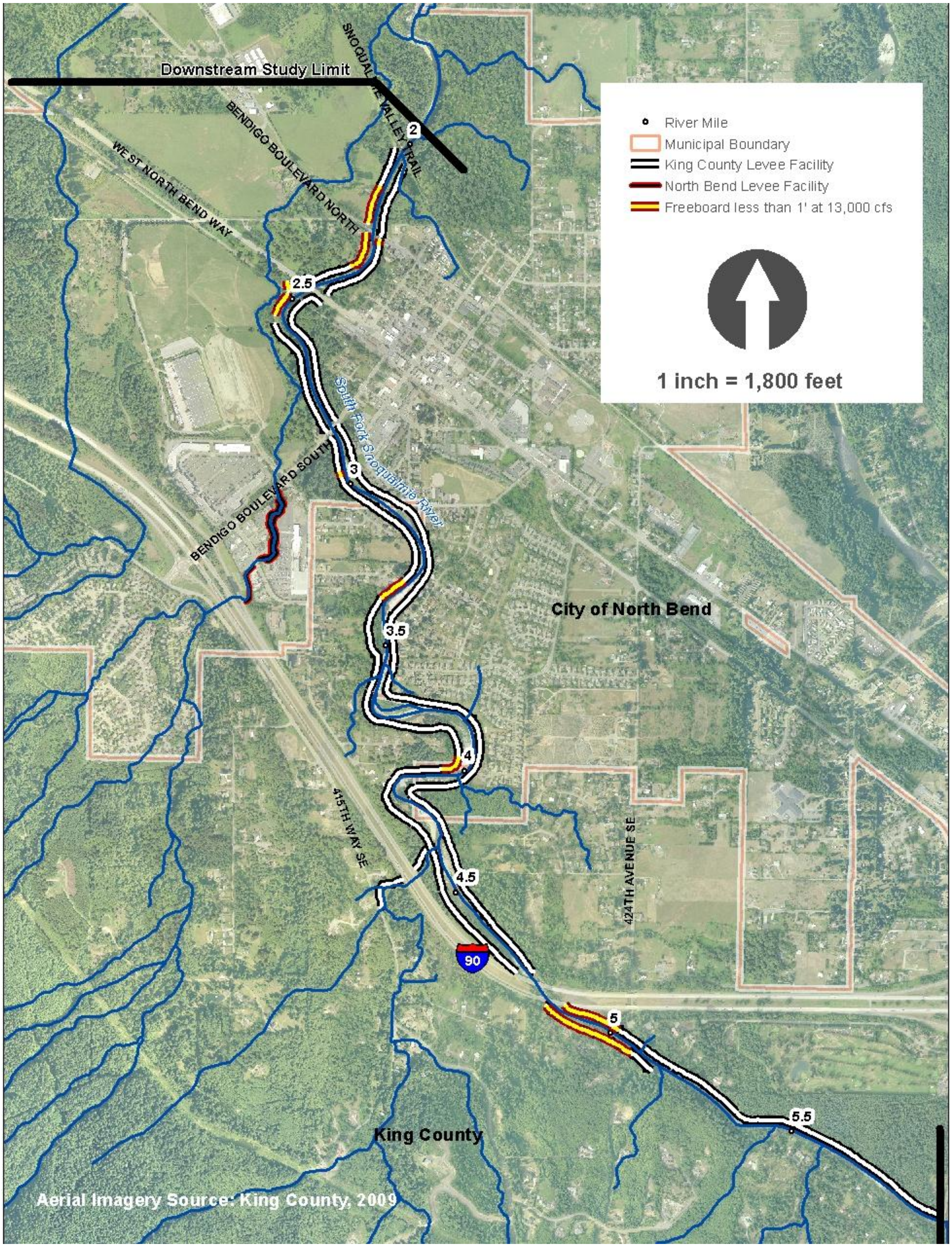


Figure 2-11. Freeboard Less than 1' for 13,000 cfs—Existing Conditions

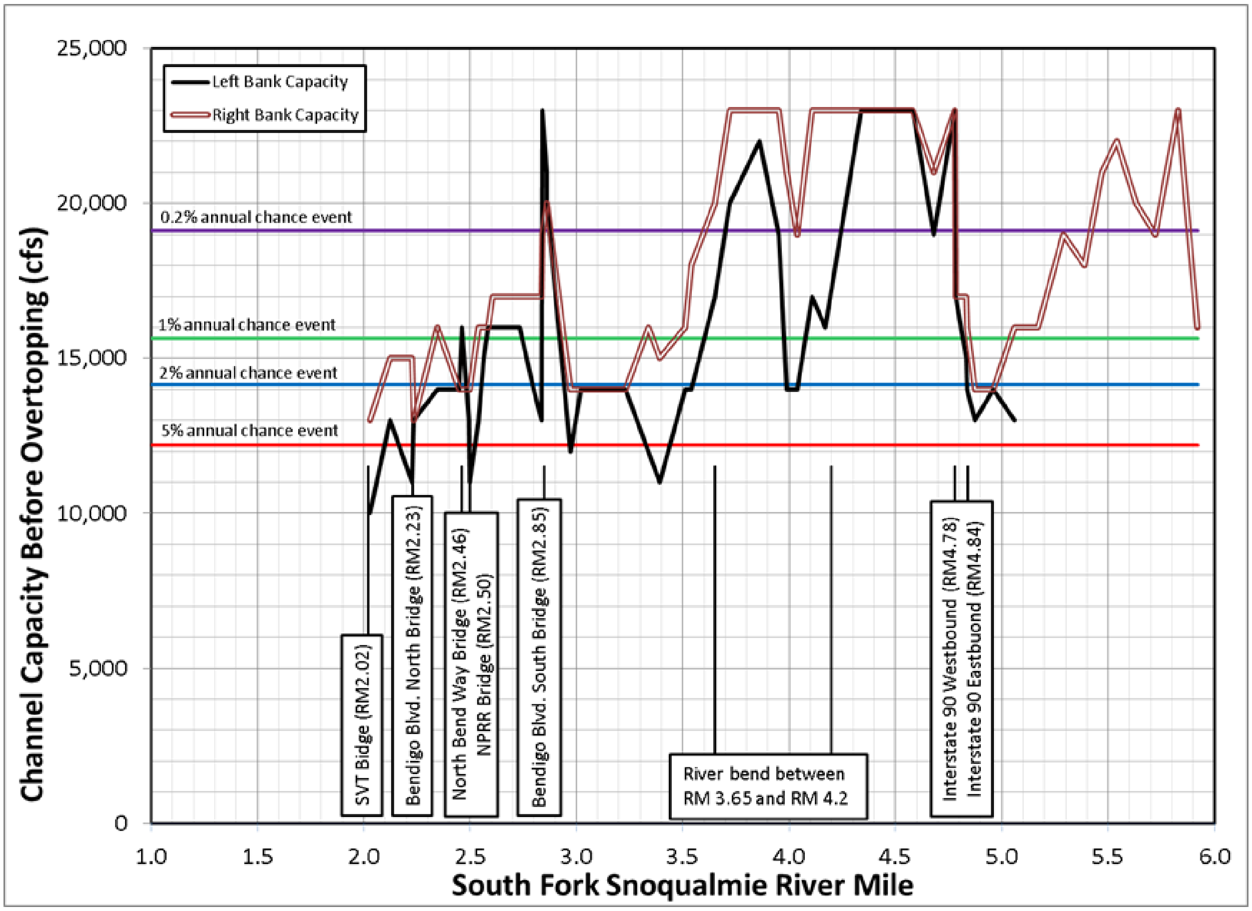


Figure 2-12. Levee Capacity without Overtopping—Existing Conditions

- On the South Fork Snoqualmie River right bank:
  - At the downstream end of the levee system between RM 2.05 and RM 2.12. This location is just upstream of the tie-in to the Snoqualmie Valley Trail embankment and just downstream of the North Bend wastewater treatment plant. Floodwaters overflow into the wooded area north of the wastewater treatment plant, located on Bendigo Boulevard North and Sydney Avenue N.

The next most vulnerable locations for levee overtopping on the South Fork Snoqualmie River levee system are the additional locations where levees are overtopped during the 2-percent-annual-chance flood event (14,160 cfs):

- On the South Fork Snoqualmie River left bank:
  - At RM 2.43. Overtopping river flows at this location contribute to flooding in the wooded area between the left bank levee and Ribary Creek as well as to flooding at four homes and NW 8th Street.
  - At RM 2.81 immediately downstream of Bendigo Boulevard South. South Fork Snoqualmie River flow combines with upstream river overflow and Ribary Creek flows inundating the east portion of the Nintendo property. One home is flooded in this area.

  - Between RM 2.93 and RM 3.02, immediately upstream of Bendigo Boulevard South. Overflow at this location combined with higher overflow volume from RM 3.33 to RM 4.0 (see 5-percent-annual-chance discussion above) increases the inundation extent in Shamrock Park, resulting in flooding at 28 homes along SE 123rd Street and 415th Avenue SE. Additional flooding occurs in Berry Estates, affecting 12 homes along SE 125th Street and SE 415th Avenue.
  - At RM 4.0. Overflow at this location inundates wooded and residential areas along SE 131st Street and causes flooding at 19 locations. SE 131st Street, SE 130th Street and several private drives are also flooded.
  - At discrete locations between RM 4.85 and RM 5.08 upstream of Interstate 90. Flows overtopping the South Fork Snoqualmie River upstream of Interstate 90 travel through the wooded and residential area south and west of Interstate 90 and into Clough Creek. Twenty-seven residential structures are flooded in this area, along with 415th Way SE and SE 141st Street.
- On the South Fork Snoqualmie River right bank:
  - At RM 2.16 and at RM 2.24. Inundation is greater than for the 5-percent-annual-chance event, but no structures are flooded. However, the approach to the Bendigo Boulevard North bridge and the wastewater treatment plant parking area and maintenance yard are flooded for this event.

For the left bank, additional overtopping locations is not predicted for the 1- and 0.2-percent-annual-chance event; however, the overtopping length increased at each of the locations described above. On the right bank, overtopping of the South Fork Snoqualmie River levees upstream of Bendigo Boulevard South is not predicted until the 1-percent-annual-chance event. During this event, overtopping of the right bank levees upstream of Bendigo Boulevard South is predicted at two locations:

- At RM 3.2. Floodwaters are generally contained within a local topographic depression adjacent to the right bank levee.
- At RM 4.96. Overflow from the river is conveyed under Interstate 90 through the 424th Avenue SE underpass, flooding the road on the north side of Interstate 90.

During the 0.2-percent-annual-chance event, overtopping of the right bank South Fork Snoqualmie River levees upstream of Bendigo Boulevard South is significantly more extensive, as seen in Figure 2-5. Between RM 3.57 and RM 3.31, overtopping occurs from the landward side of the levee to the riverward side, conveying right bank floodplain flows back to the river. In this reach, the 0.2-percent-annual-chance water surface elevation in the river is just below the levee crest, the landward height of the levee is fairly low, and the right bank floodplain slopes toward the right bank levee.

Based on the original levee construction plans, it appears that no special provisions were incorporated to protect the backside of the levee from erosion during an overtopping event. Flood flows overtopping the levee could generate high flow velocity on the landward side of the levee potentially causing erosion and headcut through the levee with the potential for causing levee breach and failure.

The vulnerability to backside levee erosion and breaching is tied to the change in waters surface elevation across the levee, levee height, crest width, and landside slopes. Generally, levee height on the landward side is greater than four feet and crest width ranges from 15 to 30 feet at all the locations where levee overtopping is predicted to occur. The exceptions are on the left bank between RM 2.85 and 3.3 where the height ranges from 2 to 4 feet, and the right bank at RM 4.96 where the levee height is between 0 and 2 feet.

2.2.5 Floodplain Inundation and Overland Flow Paths—Existing Conditions

Levee overtopping inundates both left and right floodplains, with more extensive flooding on the left. The right bank floodplain of the FLO-2D model was not calibrated, due to the absence of observed flood data. For this reason, and due to the study focus on the left floodplain area, a limited amount of right bank floodplain detail was included in the model. Table 2-3 shows the area of relative floodplain inundation for each design event. Note that the floodplain inundation shown in this table is based on the 75-foot model grid cell size and does not fully account for variation in topography within the grid. However, the results in this table are useful for a relative comparison between flood events. Figures 2-2 through 2-5 show floodplain inundation, maximum depth and water surface elevation for the 5- through 0.2-percent-annual-chance flood events. Peak velocity is shown in Figures 2-6 through 2-9. Results do not include potential inter-basin flow from the Middle Fork Snoqualmie River. Additional documentation of floodplain inundation and overland flow paths is provided in Appendix A.

TABLE 2-3.
APPROXIMATE FLOODPLAIN INUNDATION IN STUDY AREA FOR EXISTING CONDITIONS

	Inundated Area (acres)[a]			
	5% Annual Chance (20-year)	2% Annual Chance (50-year)	1% Annual Chance (100-year)	0.2% Annual Chance (500-year)
Left Bank[b]	98	221	314	475
Right Bank[c]	14	17	25	241
Total	**112**	**238**	**339**	**716**

a. See Table 2-2 for peak flow rate at the upstream inflow hydrograph at RM 5.9.
b. Left bank inundation includes tributary streams in study area only (RM 2.0 to RM 5.9).
c. Right bank inundation due to South Fork Snoqualmie River flooding only. Potential inter-basin flow from the Middle Fork Snoqualmie River was not simulated in the FLO-2D model.

Structure Flooding

The impacts of overtopping on private property and public facilities are presented in Table 2-4. Structures were identified using building outline coverage prepared for the FEMA flood study (FEMA, 2005) supplemented with aerial photography interpretation. The structure inventory is intended to include residential and commercial buildings only, but some outbuildings may have been included due to the uncertainty in aerial photography interpretation. The structure inundation shown in this table is based on the 75-foot model grid cell size and does not account for variation in topography within the grid.

The results in Table 2-4 show that the potential for structure flooding is greater on the left overbank than on the right overbank for all design flood events except the 0.2-percent-annual-chance flood event. The right-bank area affected by the 0.2-percent-annual-chance event is generally within the City of North Bend and includes the residential area adjacent to the South Fork Snoqualmie River and the downtown commercial area.

On the left overbank, most properties flooded are between RM 2.85 and RM 4.85. The entire Shamrock Park area is predicted to be inundated for the 2-percent-annual-chance flood event and Berry Estates area is inundated during the 1-percent-annual-chance flood event. Additional discussion on structure flooding is provided in the following sections and in Appendix A.

TABLE 2-4.
INUNDATED PROPERTIES WITH POTENTIAL FOR STRUCTURE FLOODING IN STUDY AREA FOR EXISTING CONDITIONS

		Number of Affected Properties			
Location in Study Area	River Mile	5% Annual Chance (20-year)	2% Annual Chance (50-year)	1% Annual Chance (100-year)	0.2% Annual Chance (500-year)
Left Overbank					
Snoqualmie Valley Trail to Bendigo Boulevard South	2.0 - 2.85	0	5	5	8[a]
Shamrock Park, Bendigo Boulevard S. to Private Road	2.85 – 3.25	18	28	29	37[b]
Berry Estates, Private Road to Mt. Si Boulevard	3.25 – 3.40	8	12	20[c]	23[b]
Mt. Si Boulevard to Interstate 90	3.40 – 4.85	12[d]	19	33[e]	39[e]
Interstate 90 to 436th Avenue SE (including Clough Creek area west of interstate)	4.85 – 5.9	12	27	33	39
Total Left Bank Properties with Structure Flooding		**50**	**91**	**120**	**146**
Right Overbank[f]					
Snoqualmie Valley Trail to Bendigo Boulevard South	2.0 – 2.85	7[d]	10	15	89
Bendigo Boulevard South to Stowe Avenue S	2.85 – 3.1	--	--	--	131
Stow Avenue S to Interstate 90	3.1 – 4.85	--	--	--	143
Interstate 90 to 436th Avenue SE	4.85 – 5.9	--	--	--	5
Total Right Bank Properties with Structure Flooding		**7**	**10**	**15**	**368**
Total Properties with Structure Flooding		**57**	**101**	**135**	**514**

a. Includes two buildings in the commercial area north of Bendigo Boulevard South.
b. Includes three buildings in the commercial area south of Bendigo Boulevard South.
c. Includes one building in the commercial area south of Bendigo Boulevard South.
d. Structure flooding in this area due to levee seepage.
e. Includes four buildings in the commercial area west of 412th Avenue SE.
f. The right overbank area includes downtown North Bend and residential neighborhoods. Commercial property is not distinguished from residential in the count of affected properties..

Road Flooding

Table 2-5 summarizes roadway inundation due to levee overtopping under existing conditions. Road flooding during the 5-percent-annual-chance flood event is predicted to affect 1.4 miles of local street and roads. For the 1-percent-annual-chance event, road flooding is predicted to affect almost a mile of Interstate 90. The predicted inundated road length more than doubles between the 2- and 1-percent-annual-chance flood events and nearly triples between the 1- and 0.2-percent-annual-chance flood events. The increase for the 0.2-percent-annual-chance event is attributed to a large area of inundation in the City of North Bend due overtopping of the right bank South Fork Snoqualmie River levee upstream of Interstate 90 combined with right bank overtopping downstream of RM 3.0.

South Fork Avenue SW, Bendigo Boulevard South, 412th Avenue SE, SE 123rd Street, SE 125th Street, SE 131st Street, and SE 415th Street are all at risk of flooding during the 5-percent-annual-chance flood event. Of these, Bendigo Boulevard South is the only arterial roadway. Roadway inundation at SE 131st Street is due to seepage rather than levee overtopping. Roadway flooding is not predicted in the right overbank until the occurrence of the 1-percent-annual-chance flood event. Additional discussion on road flooding is provided in the following sections and in Appendix A.

TABLE 2-5.
INUNDATED ROADWAYS IN STUDY AREA FOR EXISTING CONDITIONS

	Length of Roadway Inundated (miles)			
Road Type	5% Annual Chance (20-year)	2% Annual Chance (50-year)	1% Annual Chance (100-year)	0.2% Annual Chance (500-year)
Local Street	1.2	2.2	4.1	12.0
Arterial Road	0.2	0.3	0.5	1.8
Freeway	0.0	0.0	0.9	1.2
Total	**1.4**	**2.5**	**5.5**	**14.5**

Left Overbank Floodplain Inundation

RM 5.9 to RM 4.85, 436th Avenue SE (Upstream Study Limit) to Interstate 90, Including the Clough Creek Floodplain Area

The most upstream location on the left bank levee system that overtops and contributes to flooding in the left overbank is immediately upstream of the Interstate 90 bridges, between RM 4.9 and RM 5.1. Figure 2-13 shows a detail of the floodplain inundation in this area for the 1-percent-annual-chance flood event.

Flood flows that overtop the left bank levee at this location flow northwest toward Clough Creek and into the low-lying depression bounded by the Interstate 90 embankment to the east, SE 131st Street to the north and natural high ground to the west. Until overtopping of the adjacent embankments occurs, the only surface outlets from this low-lying depression are two small-diameter culverts through the Interstate 90 embankment that discharge to the left bank floodplain east of the Interstate 90 embankment.

The peak floodplain flow rate associated with left bank levee overtopping upstream of Interstate 90 (between SE 141st Street and Interstate 90) ranges from 30 cfs for the 2-percent-annual-chance flood event to 1,320 cfs for the 0.2-percent-annual-chance flood event. The left bank levee upstream of Interstate 90 is not predicted to overtop during the 5-percent-annual-chance flood event. Maximum depth in this area ranges from 0 to 2 feet for the 5-percent-annual-chance event and from 3 to 7 feet for the 0.2-percent-annual-chance event.

Deeper flooding occurs in the depression near SE 131st Street, where flood depths range from 5 feet for the 5-percent-annual-chance event to more than 11 feet for the 0.2-percent-annual-chance event. Property and road flooding occurs for all design events. The predicted number of flooded properties increased from 12 for the 5-percent-annual-chance event to nearly 40 for the 0.2-percent-annual-chance event. More frequent flooding is predicted at 415th Way SE, where roadway overtopping occurs during the 5-percent-annual-chance event. SE 141st Street is inundated during the 2-percent-annual-chance event.

The Interstate 90 roadway embankment is predicted to overtop for the 1- and 0.2-percent-annual-chance flood event when the accumulated floodwater volume fills the low-lying depression adjacent to the embankment. Overtopping of the Interstate 90 roadway embankment is a function of the volume of accumulated floodwater, and not just the magnitude of the peak flow rate in the South Fork Snoqualmie River.

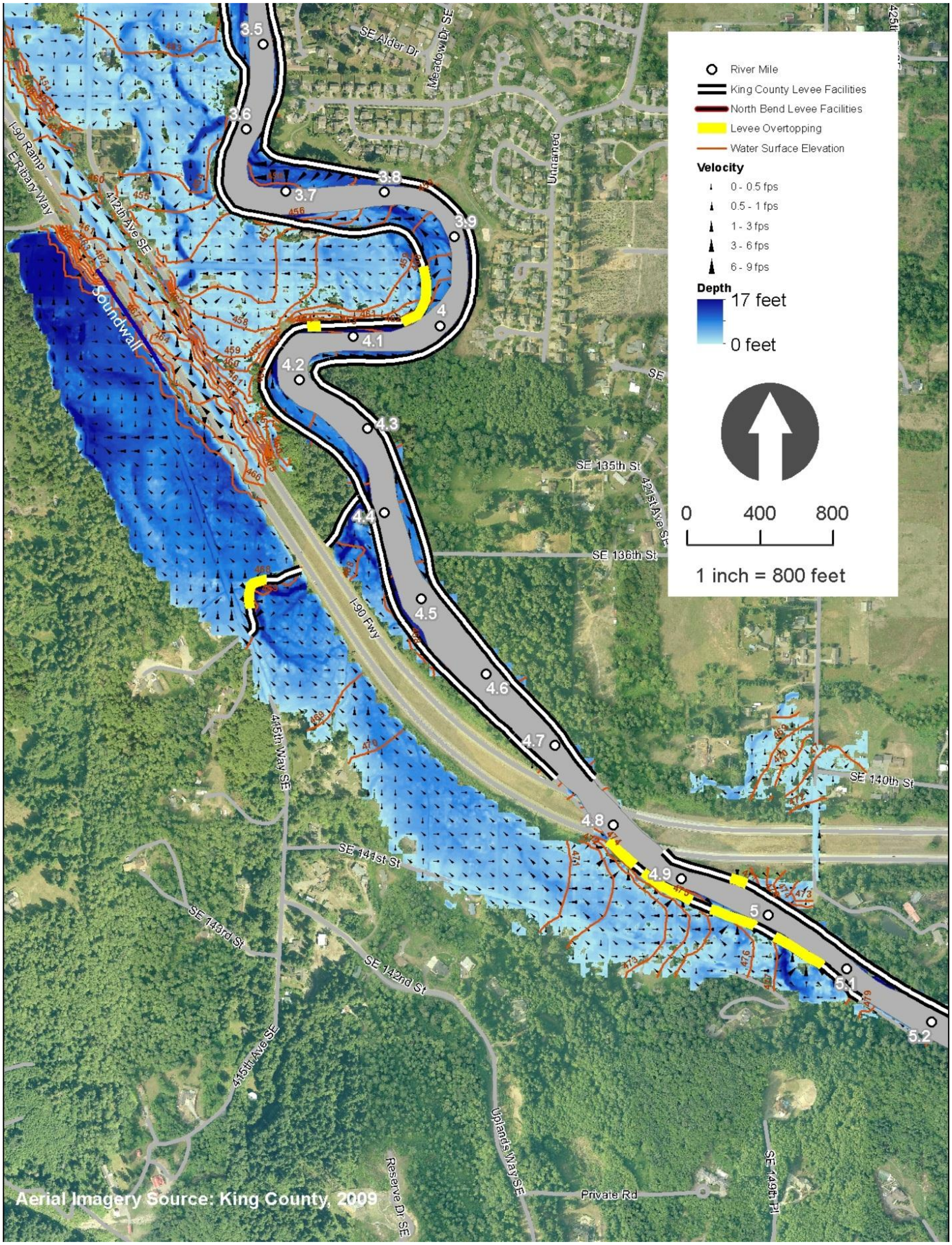


Figure 2-13. Floodplain Inundation RM 4.85 to RM 5.9, Including Clough Creek Floodplain; 1-Percent-Annual-Chance Flood Event

There are four potential sources for the floodwater that accumulates in this low-lying depression:

- Floodwater that overtops the left bank South Fork Snoqualmie River upstream of Interstate 90 between approximately RM 4.9 and RM 5.1
- Backwater from the South Fork Snoqualmie River that is conveyed upstream into Clough Creek
- Local Clough Creek flows that overtop the Clough Creek levees upstream of Interstate 90
- Local drainage from the hillside southwest of the low-lying depression area.

Flood flows overtopping the Interstate 90 embankment are partially obstructed by a 4- to 6-foot high stone sound wall that is located immediately southwest of Interstate 90. The 650-foot-long wall extends from the northwest to the southeast and is located in between the eastbound lane of Interstate 90 and 415th Way SE. The northwest end of the wall starts about 400 feet southeast of SE 131st Street, with no tie in to high ground. The southeast end of the stone wall ties into an earthen embankment, also located in between the eastbound lane of Interstate 90 and 415th Way SE. The earthen embankment extends for another 375 feet to the southeast and ends abruptly with no tie-in to natural high ground. Floodwaters that fill the low-lying depression adjacent to Interstate 90 are capable of flowing around both the northwest end of the sound wall and the southeast end of the earthen embankment and ultimately over the Interstate 90 roadway. It is unlikely that the sound wall and earthen embankment were constructed for purposes of flood protection, however, they do provide some function in this capacity.

The accumulated floodwater is predicted to be of sufficient volume to result in overtopping of the Interstate 90 roadway for both the 1- and 0.2-percent-annual-chance flood events. Flood depths for the 1-percent-annual-chance flood event are predicted to be relatively shallow at less than 0.5 feet. Floodwaters for the 0.2-percent-annual-chance flood event are predicted to be significantly deeper, at 1.5 feet. Flow velocity for both events is predicted to range between 1 to 3 feet per second. Reported velocities are average values for the model grid so locally higher velocity may occur undermining the roadway embankment and erode the pavement.

The predicted peak flow rate of overtopping at the Interstate 90 embankment ranges from nearly 290 cfs for the 1-percent-annual-chance flood to 1,330 cfs for the 0.2-percent-annual-chance flood. For the 2-percent-annual-chance flood event, the predicted volume of floodwater accumulated in the low-lying depression is sufficient to initiate a small volume of water flowing around the southeast end of the earthen embankment, but flow is not predicted over the Interstate 90 roadway but may inundate the right-of-way. Ponding depths are predicted to be about 3 feet below the Interstate 90 roadway. For the 5-percent-annual-chance flood event, the predicted volume of accumulated floodwater is small enough that flow is not predicted to flow around the sound wall or the earthen embankment.

RM 4.85 to RM 2.85, Interstate 90 to Bendigo Boulevard South

Flood flows that overtop the South Fork Snoqualmie River left bank levee downstream of Interstate 90 (i.e. downstream of RM 4.7) travel north-northwest across the left overbank floodplain through Shamrock Park (SE 123rd Street), Berry Estates (SE 125th Street) and the North Bend commercial and retail district near Bendigo Boulevard South. Figure 2-14 shows a detail of the floodplain inundation in this area for the 1-percent-annual-chance flood event.

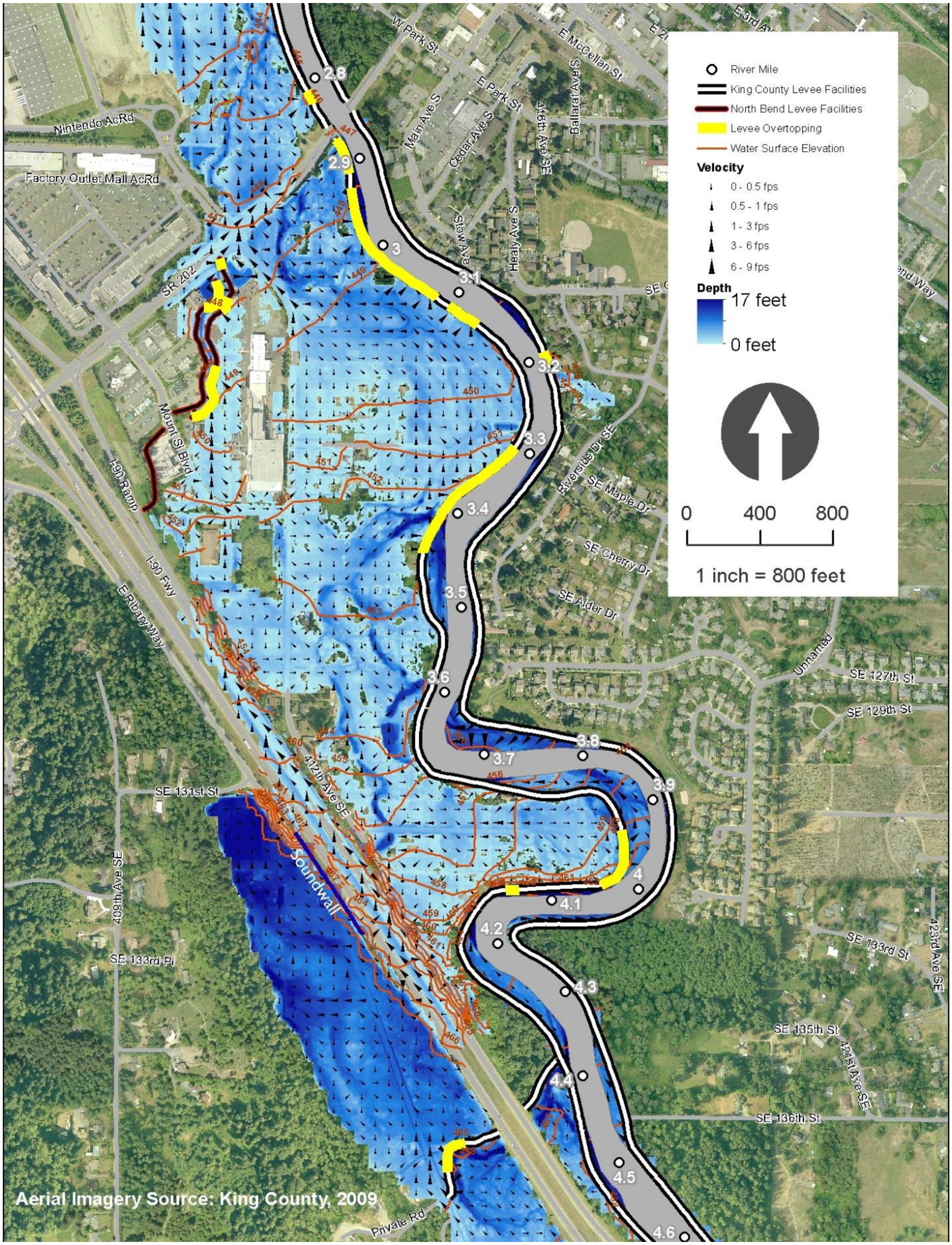


Figure 2-14. Floodplain Inundation RM 2.85 to RM 4.85; 1-Percent-Annual-Chance Flood Event

The most upstream overtopping in this section is predicted during the 2-percent-annual-chance flood event at the inside of the sharp river bend at about RM 4.0. However, seepage through the levee during flood events potentially inundates the area during the 5-percent-annual-chance event. Floodplain inundation due to seepage at this location is shown on Figure 2-15. Maximum depth in the area between Mt. Si Boulevard and Interstate 90 (RM 3.4 to RM 4.85) ranges from 0 to 2 feet for the 5-percent-annual-chance event and from 2 to 5 feet for the 0.2-percent-annual-chance event. Because of seepage through the levee, property and road flooding occurs for all events. The predicted number of flooded properties increases from 12 for the 5-percent-annual-chance event to nearly 40 for the 0.2-percent-annual-chance event. More frequent flooding is predicted at SE 131st Street and several private drives during the 5-percent-annual-chance event. Floodplain inundation extends to 412th Avenue SE during the 2-percent-annual-chance event.

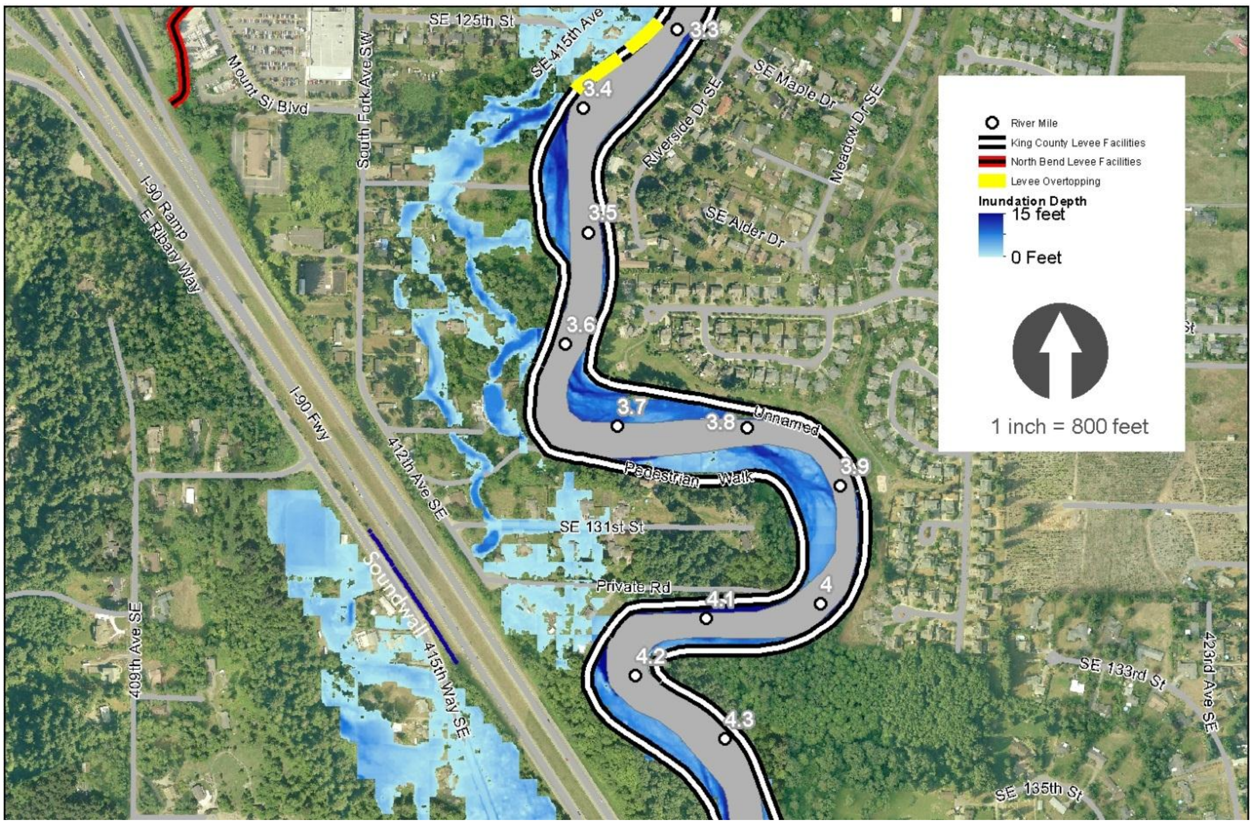


Figure 2-15. Floodplain Inundation Due to Seepage at RM 4.2 for the 5-Percent-Annual-Chance Event

Predicted overtopping of the South Fork Snoqualmie River left bank levee near RM 3.3 during the 5-percent-annual-chance flood event inundates the Berry Estates (SE 123rd Street and 515th Avenue SE) and Shamrock Park areas (SE 125th Street and SE 415th Avenue). Eight properties are flooded in Berry Estates and 18 properties are flooded in Shamrock Park. Property flooding is predicted to increase to 49 locations for the 1-percent-annual-chance event, and flood extents expand to encompass the commercial area south of Bendigo Boulevard South. Twenty-nine additional properties are predicted to be flooded in this area, along with 412th Avenue SE and Mt. Si Boulevard. Twenty properties are also predicted to be flooded in Berry Estates during the 1-percent-annual-chance event.

Maximum flood depth in the Berry Estates and Shamrock Park area (RM 2.85 to RM 3.4) ranges from 0 to 2 feet for the 5-percent-annual-chance event and from 2 to 6 feet for the 0.2-percent-annual-chance event. The deepest flooding is predicted at the north end of Shamrock Park between SE 123rd Street and

Bendigo Boulevard South. Peak velocity is predicted to be relatively low for all design flood events, ranging from 0.2 to 0.5 feet per second. Flood flows range from 330 cfs for the 1-percent-annual-chance flood event to 1,700 cfs for the 0.2-percent-annual-chance flood event.

Overbank flows are conveyed over the Bendigo Boulevard South roadway near a low point in the road northeast of Ribary Creek and through the twin culverts under Bendigo Boulevard South. These culverts normally convey local Ribary Creek flows through the roadway embankment and have a combined capacity of approximately 100 cfs. This capacity is insufficient to convey the combined peak floodplain and creek channel flow rate, which ranges from 130 cfs for the 5-percent-annual-chance flood up to 3,210 cfs for the 0.2-percent-annual-chance flood event.

Predicted flow depths over Bendigo Boulevard South range from less than 0.5 feet for the 5-percent-annual-chance event to 1 foot for the 1-percent-annual-chance event. Velocity is predicted to be less than 0.7 feet per second for the 5-percent-annual-chance event and 2 feet per second for the 1-percent-annual-chance event. Peak depth and velocity are predicted to be 2.5 feet and 3.5 feet per second, respectively, for the 0.2-percent-annual-chance event.

RM 2.85 to RM 2.0, Bendigo Boulevard South to Snoqualmie Valley Trail (Downstream Study Limit)

Flood flows passing over and through the Bendigo Boulevard South roadway embankment are conveyed downstream in Ribary Creek and its adjacent floodplain. During the 0.2-percent-annual-chance flood event, Ribary Creek water surface elevations are high enough to cause creek overflows, which travel west toward Gardiner Creek, between the commercial area north of Bendigo Boulevard South and Nintendo.

Downstream of this overflow location, peak flow in Ribary Creek and its adjacent floodplain ranges from 120 cfs for the 5-percent-annual-chance flood to 3,180 cfs for the 0.2-percent-annual-chance flood. Continuing downstream direction, Ribary Creek flows through a set of bridges beneath the Snoqualmie Valley Historic Railroad and West North Bend Way. Figure 2-16 shows a detail of the floodplain inundation in this area. For the 2-percent-annual-chance and larger design flood events, the Ribary Creek water surface elevation upstream of these two bridges is predicted to be high enough to cause overflows from Ribary Creek, flowing northwest toward the intersection of NW 8th Street and the Nintendo access road. The volume of floodwater associated with this overflow location for the 2-percent-annual-chance flood event is impounded in the undeveloped property just north of Nintendo. For the 1 percent and 0.2-percent-annual-chance flood events, the Ribary Creek overflow results in overtopping of the NW 8th Street roadway, and the flood flows continue northwest toward Gardiner Creek.

Downstream of West North Bend Way, flood flows that overtop the left bank South Fork Snoqualmie River levees and flows that break out of the Ribary Creek channel combine to flow generally north or northwest across the left bank floodplain.

No property flooding is predicted for the 5-percent-annual-chance event, and predicted road flooding is limited to Bendigo Boulevard South (discussed previously), South Fork Avenue SW and the Snoqualmie Valley Trail. Five properties are inundated for the 2- and 1-percent-annual-chance flood events. Extensive flooding is predicted for the 0.2-percent-annual-chance event, including three additional properties in the commercial area north of Bendigo Boulevard South. Bendigo Boulevard North and NW 8th Street are predicted to be flooded during the 2-percent-annual-chance event and Alm Way floods during the 1-percent-annual-chance event.

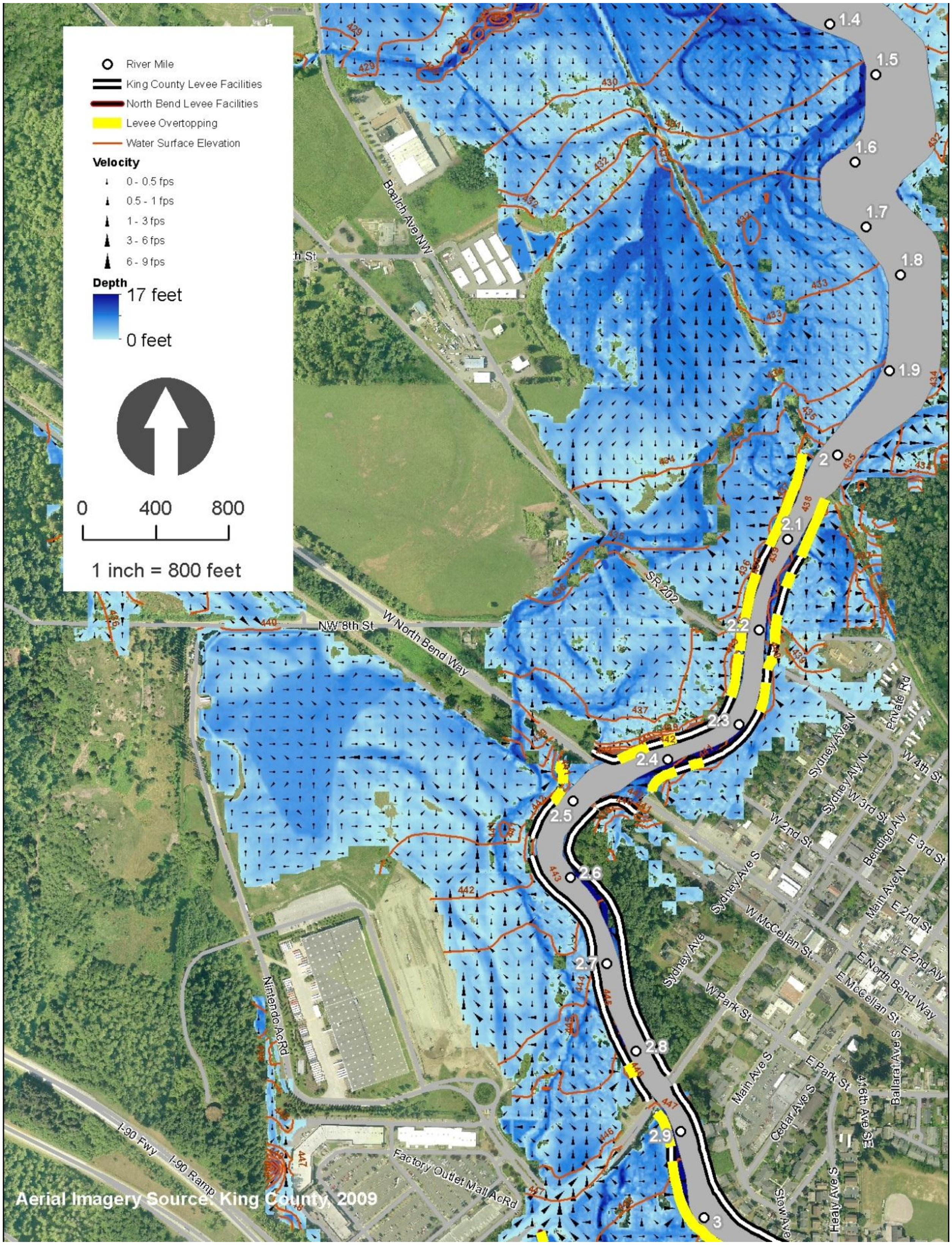


Figure 2-16. Floodplain Inundation RM 2.0 to RM 2.85; 1-Percent-Annual-Chance Flood Event

Maximum flood depth between the Snoqualmie Valley Trail and Bendigo Boulevard South (RM 2.0 to RM 2.85) ranges from 0 to 2 feet for the 5-percent-annual-chance event and from 2 to 6 feet for the 0.2-percent-annual-chance event. The low-lying area near Snoqualmie Valley Trail is predicted to be inundated due to overtopping of the South Fork Snoqualmie River left bank levee near RM 2.1 during the 5-percent-annual-chance flood event. The area north of Bendigo Boulevard South and South Fork Avenue SW also floods during this event due to overtopping of Bendigo Boulevard South.

Peak velocity is predicted to be relatively low for all flood events, ranging between 0.2 to 0.5 feet per second. However, flow velocity greater than 1 foot per second is predicted for isolated locations during the 1- and 0.2-percent-annual-chance events.

Floodplain storage between RM 2.0 and RM 5.9 reduces peak flow in the study area by about 7 percent for the 1-percent-annual-chance flood event. Peak flood flow for this event is predicted to be 15,050 cfs at the downstream study limit, which represents a 1,190-cfs reduction from the peak inflow rate of 16,240 cfs for this event. Table 2-6 summarizes peak flood flows at the downstream study limit.

TABLE 2-6.
PEAK FLOODPLAIN FLOW AT DOWNSTREAM STUDY LIMIT (RM 2.0) FOR EXISTING CONDITIONS

Peak Flow Location	1 % Annual Chance Peak Flow (100-Year Return Period)
Leftmost floodplain extent to Boalch Avenue NW[a, b]	220 cfs
Boalch Avenue NW to Snoqualmie Valley Trail[b]	900 cfs
Snoqualmie Valley Trail[b] to Right Floodplain Extent[c] (acres)	13,930 cfs
Total Peak Flow at RM 2.0	**15,050 cfs**
Peak Inflow at RM 5.9	*16,240 cfs*

a. Includes Gardiner Creek.
b. High point is located at Boalch Avenue NW and Snoqualmie Valley Trail.
c. Includes Ribary Creek and South Fork Snoqualmie River.

Peak flood flow in the left bank floodplain is predicted to be 1,120 cfs. Floodplain flow is distributed between flow paths split at a localized high point where the downstream study limit intersects Boalch Avenue NW. As shown in Table 2-6, Peak flood flow west of this location is predicted to be 220 cfs and includes Gardner Creek flows. Peak flood flow between Boalch Avenue NW and the Snoqualmie Valley Trail is predicted to be 900 cfs and includes floodplain flood flows only. Peak flood flow east of Snoqualmie Valley Trail was estimated to be 13,930 cfs, including Ribary Creek and the South Fork Snoqualmie River; this makes up the largest portion of the 15,050-cfs flow exiting the study area.

Right Overbank Floodplain Inundation

RM 5.9 to RM 4.85, 436th Avenue SE (Upstream Study Limit) to Interstate 90

The most upstream location on the right bank levee system that overtops and contributes to flooding in the right overbank is the reach upstream of the Interstate 90 bridges. For the 1-percent-annual-chance flood event, right bank levee overtopping is limited to the vicinity of RM 4.95. However, for the 0.2-percent-annual-chance flood event, right bank levee overtopping occurs fairly continuously between RM 4.95 and RM 5.22 and between RM 5.43 and RM 5.87. For both of these flood events, all flood flows

that overtop the right bank levee upstream of the Interstate 90 bridges are conveyed under Interstate 90, along 424th Avenue SE and then north toward North Bend. Peak flow conveyed under Interstate 90 ranges from 6 cfs for the 1-percent-annual-chance flood to 250 cfs for the 0.2-percent-annual-chance flood.

For the 1-percent-annual-chance flood event, the predicted volume of overtopping floodwaters is sufficient to inundate only a small part of the right bank floodplain immediately north of Interstate 90 along the 424th Avenue SE corridor. Flood depths on the roadway are predicted to be about 0.5 feet, with peak velocity less than 0.5 feet per second. No structure flooding is predicted for the 1-percent-annual-chance event, but flooding is predicted at five structures for the 0.2-percent-annual-chance event.

RM 4.85 to RM 2.85, Interstate 90 to Bendigo Boulevard South

Extensive flooding is predicted in the right overbank area in the City of North Bend residential and commercial areas only for the 0.2-percent-annual-chance flood event. Floodwater overtopping the right bank levee upstream of Interstate 90 combines with floodwater overtopping the right bank levee upstream of Bendigo Boulevard South. The floodwaters are conveyed north along the landward side of the levee through the main residential and commercial area of the City of North Bend.

For the 0.2-percent-annual-chance flood event, floodwaters in the right bank floodplain overtop the right bank levee from the landward to the riverward side of the levee between RM 3.57 and RM 3.32. The ground surface of the floodplain slopes toward the river at this location, which, combined with the relatively low landward height of the levee, results in flood flows overtopping the right bank levees and flowing back into the South Fork Snoqualmie River. Flows returning to the South Fork Snoqualmie River reduce peak flow in the right bank floodplain downstream of this location.

Right bank levee overtopping downstream of RM 3.32 for the 0.2-percent-annual-chance peak flood event is from the river to the adjacent floodplain. These overtopping flows merge with overtopping flows from further upstream and flow toward the main residential and commercial area of North Bend. Levee overtopping between RM 2.9 and 3.2 results in an increase in peak flows in the right bank floodplain in this area.

Predicted maximum flood depth ranges from 0.5 to 3 feet, with the deepest flooding on residential streets. Flooding is predicted at about 275 properties in this area. Maximum velocity for this event is predicted to be between 0.5 and 1 foot per second.

RM 2.85 to RM 2.0, Bendigo Boulevard South to Snoqualmie Valley Trail (Downstream Study Limits)

For the 5- and 2-percent-annual-chance peak flood events, the only predicted sources of flood flows on the right bank floodplain are levee overtopping at the downstream end of the leveed reach, between West North Bend Way and the Snoqualmie Valley Trail (RM 2.0 to RM 2.1), and levee seepage at RM 2.27 and RM 2.47. River flows for the 5-percent-annual-chance flood event are predicted to be completely contained within the right bank levee system upstream of this location. Inundation due to seepage in this area is shown on Figure 2-17.

Maximum flood depths in the right overbank area are predicted to range from 1 to 4 feet for the 5-percent-annual-chance flood event and 2 to 5 feet for the 1- and 0.2-percent-annual-chance flood event. Peak flood flow velocity is less than 1 foot per second up to the 1-percent-annual-chance flood event but increases to greater than 2 feet per second for the 0.2-percent-annual-chance flood event. Predicted peak flood depth due to levee seepage at RM 2.27 and RM 2.47 is 1 foot for the 5-percent-annual-chance flood event.

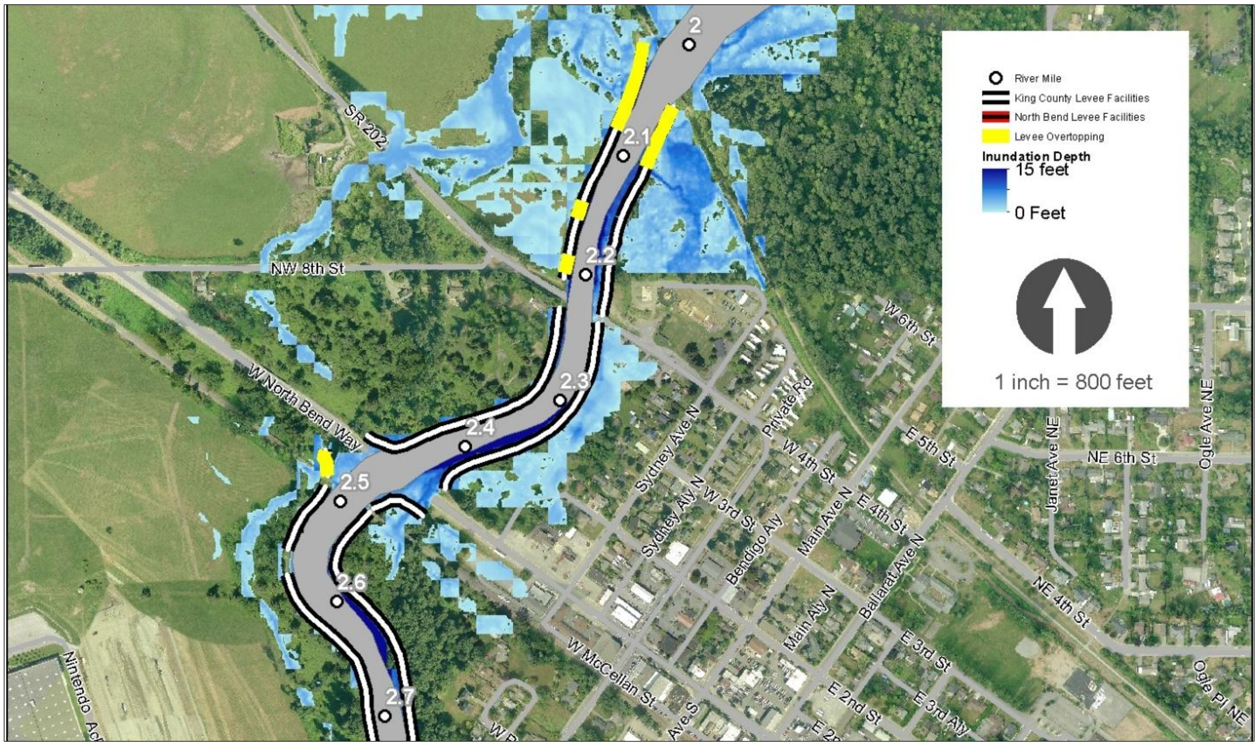


Figure 2-17. Floodplain Inundation Due to Seepage at RM 2.4 for the 5-Percent-Annual-Chance Event

Flood depths are as high as 2 feet for the 1-percent-annual-chance event. Peak flood depths are greater for the 0.2-percent-annual-chance event due to right bank overtopping at RM 3.32. Seven properties are predicted to be flooded during the 5- and 2-percent-annual-chance flood events due to seepage from the right bank levee. The number of inundated properties increases to 15 for the 1-percent-annual-chance flood event and 90 for the 0.2-percent-annual-chance flood event. The wastewater treatment plant is partially flooded during the 5-percent-annual-chance flood event. Ponding depths on the treatment plant site are predicted to range between 0.5 and 1.5 feet for the 1-percent-annual-chance flood event.

2.2.6 Summary of Existing Conditions Hydraulic Analysis

The limited capacity of the South Fork Snoqualmie River levee system combined with the hydraulic losses through the bridge openings determine the magnitude of inundation of the floodplain.

Inundation of the left bank floodplain is predicted for all flood events and is more frequent and extensive than inundation of the right bank floodplain. Left bank flooding for the South Fork Snoqualmie River occurs as follows:

- The left bank levee locations at greatest risk of overtopping are those that experience overtopping during the 5-percent-annual-chance flood event:
  - Between RM 2.03 and RM 2.21 where forested and agricultural land between the South Fork Snoqualmie River and Ribary Creek is inundated
  - At RM 2.47 where overtopping is contained between the West North Bend Way and Snoqualmie Valley Historic Railroad bridges
  - Between RM 3.33 and RM 3.40 where extensive flooding is predicted in the Shamrock Park and Berry Estates neighborhood. Overtopping here also results in flooding on Bendigo Boulevard South.

- Inundation near SE 131st for the 5-percent-annual-chance flood event is due to seepage from the levee near RM 4.2.
- Hydraulic losses through the Interstate 90 bridge, combined with low levee heights upstream of the highway, result in overtopping of the left bank levee for design flood events greater in magnitude than the 1-percent-annual-chance flood event. The overtopping flows are conveyed toward the Clough Creek channel and ultimately to a low-lying depression adjacent to the eastbound lane of Interstate 90. Extensive flooding is predicted in the area along SE 415th Street and 415th Way SE.
- For the 1- and 0.2-percent-annual-chance flood events, the accumulated flood volume in the low-lying depression is enough to cause floodwaters to overtop Interstate 90 and flow across both the eastbound and westbound lanes. Flood depths are predicted to be about 0.5 feet for the 1-percent-annual-chance flood event.
- Flows overtopping the left bank levee downstream of Interstate 90 at RM 4.0 combine with floodwater from over Interstate 90 and increased volume of floodwater overtopping the downstream left bank levee near RM 3.3 and are conveyed north, ultimately over the Bendigo Boulevard South roadway. Floodplain extents expand to inundate the entire SE 131st Street, Berry Estates, and Shamrock Park neighborhoods and the commercial area south of Bendigo Boulevard South.
- Floodwaters that overtop the left bank South Fork Snoqualmie River levees overtop the right bank Ribary Creek system and overwhelm the hydraulic capacity of the creek.
- The limited conveyance capacity of the Ribary Creek culverts at Bendigo Boulevard South and at South Fork Avenue cause backwater flooding in the floodplains adjacent to Ribary Creek, which adds to the flooding in this area caused by the South Fork Snoqualmie River levee overtopping.
- Ribary Creek culverts at Bendigo Boulevard South and South Fork Avenue have insufficient capacity to convey the combined local Ribary Creek flows and South Fork Snoqualmie River overtopping flows. The Ribary Creek bridge at NW 8th Street is surcharged for the 2-percent-annual-chance and higher flood event.

Inundation of the South Fork Snoqualmie River right bank floodplain for the 5- and 2-percent-annual-chance flood events is limited to the area immediately adjacent to the right bank levee between West North Bend Way and the Snoqualmie Valley Trail (between RM 2.05 and RM 2.12). Significant flooding is not predicted in the right bank floodplain until the 0.2-percent-annual-chance flood event. Right bank flooding occurs as follows:

- The right bank levee immediately upstream of the Snoqualmie Valley Trail at RM 2.0 is at highest risk for overtopping during the 5-percent-annual-chance flood event. Flooding occurs in the wooded area north of the wastewater treatment plant. Flooding at the wastewater treatment plant occurs with the 1-percent-annual-chance event.
- Floodplain inundation near RM 2.27 to 2.47 for the 5-percent-annual-chance flood event is due to seepage through the levee.
- Hydraulic losses through the Interstate 90 bridge combined with low right bank levee heights upstream of the highway result in floodwater overtopping the levee and flowing through the underpass at 424th Avenue SE for the 1- and 0.2-percent-annual-chance flood events.
- Right bank floodwaters overtop the right bank levee from the landward side between RM 3.57 and RM 3.32 during the 0.2-percent-annual-chance flood event. Extensive flooding occurs in residential and commercial areas of North Bend for this event.

The potential exists for backside scour to occur on the landward side of the levee during an overtopping event. A scour headcut that erodes through the levee section would result in a breach of the levee.

The South Fork Snoqualmie River bridges that create the most significant head loss are the Snoqualmie Valley Trail Bridge and the Interstate 90 bridges. The Bendigo Boulevard South Bridge also creates significant head loss during the 0.2-percent-annual-chance flood event due to surcharging of the bridge structure. The most significant in-channel head loss occurs between RM 3.8 and RM 4.0. If upstream levee deficiencies were corrected so that flow is contained within the channel and no capacity improvements were made at existing structures, head loss would increase at all structures.

Flooding on the left overbank inundates nearly 40 properties for the 5-percent-annual-chance flood event between Bendigo Boulevard South and Interstate 90 (RM 2.85 and RM 4.85). The entire Shamrock Park area is inundated during the 2-percent-annual-chance flood event and Berry Estates is inundated during the 1-percent-annual-chance flood event. Minimal structure inundation on the right overbank area occurs during the 5-percent-annual-chance flood event and is limited to seven structures in the area near the levee downstream of Bendigo Boulevard South. The number of inundated structures increase to 15 for the 1-percent-annual-chance flood event and nearly 370 for 0.2-percent-annual-chance flood event.

Approximately 1.4 miles of local roads and a short length of Bendigo Boulevard South are inundated during the 5-percent-annual-chance flood event. The length of inundated roadway increases to 5.5 miles for the 1-percent-annual-flood-event with the majority of flooding occurring on local roads but also occurs on 0.5 miles of arterial roadway and almost 1 mile of Interstate 90.

The capacity of the levee system was evaluated to determine the maximum flow rate that could be conveyed within the levees without overtopping. Similar to the FLO-2D analysis, this capacity analysis showed that backwater from the bridges has a significant effect on the capacity of the system. The backwater effect at Snoqualmie Valley Trail, North Bend Way, and Bendigo Boulevard South reduce the levee capacity to less than the 5-percent-annual-chance-event flow of 12,190 cfs.

The levee system was designed to convey a peak flood event of 13,000 cfs with one foot of freeboard. Approximately 80 percent of the left bank levee system and 95 percent of the right bank levee system meet this freeboard criteria. The most notable locations where freeboard is less than include the left bank between Snoqualmie Valley Trail and West North Bend Way, left bank near Berry Estates (SE 415th Avenue) and both left and right bank upstream of Interstate 90.

2.3 FUTURE AGGRADATION SCENARIO HYDRAULIC PERFORMANCE AND FLOODING INVESTIGATION

A modeling scenario was developed to represent future sediment aggradation in the South Fork Snoqualmie River in the study area if no improvements are implemented. This scenario assumes that channel changes and sediment trends observed over the past 14 to 17 years will continue at a similar rate over a future 30-year period. The amount of sediment aggradation is based on information on past channel changes, ongoing channel monitoring performed by King County between RM 2.85 and 4.46, and channel cross-section surveys conducted since 1992 (King County, 2012). The effect of gravel aggradation on the river hydraulics is unknown outside this reach The analysis of the future aggradation scenario considered only local physical adjustments to the South Fork Snoqualmie River channel in the study area; it did not consider changes to the hydrologic flow regime or widespread land use conversion in the watershed. This aggradation scenario assumed gravel deposition up to 3 feet between RM 2.74 and RM 4.58, with a localized scour section near RM 4.0 (see Figure 2-18).

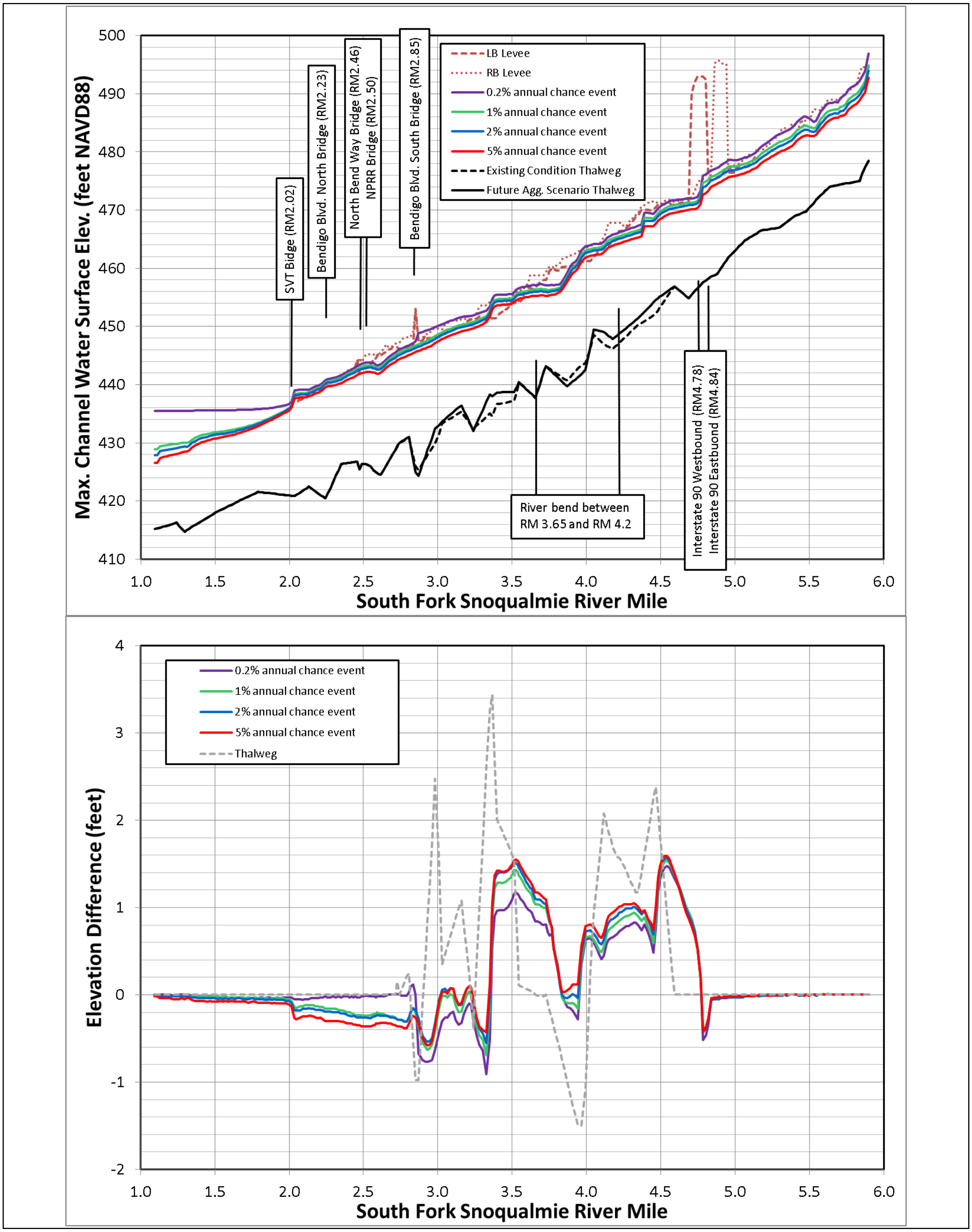


Figure 2-18. South Fork Snoqualmie River Thalweg and Predicted Maximum Water Surface Profiles—Future Aggradation Scenario (top) and Difference Between Future and Existing Scenarios (bottom)

The deposition assumptions were based on a single method estimate of aggradation based on available data and extrapolated into the future. The aggraded estimate varies throughout the reach. Potential future gravel accumulation assumes no other actions are taken, such as gravel removal, levee setback or gravel storage areas. The assumed current rate of accumulation does not factor in hydraulic changes that would occur with changes to the channel geometry due to gravel accumulation, nor does it consider the range of possible hydrologic and sediment production scenarios that would affect accumulation rates (either higher or lower). Actual gravel accumulation rates experienced in the future are uncertain and may be different from the assumptions used in this study. Actual future accumulation rates may result in more or less bed aggradation than predicted.

Ribary Creek has experienced gravel aggradation in recent years and the channel geometry was updated to reflect the condition current in January 2012. However, future gravel aggradation was not simulated in Ribary Creek.

The aggradation assumptions introduce uncertainty in hydraulic characteristics reported in this section (depth, velocity, shear, etc.). The characteristics described for the future aggradation scenario do not consider bed deformation or sediment transport that may occur with higher shear stress and velocity in the South Fork Snoqualmie River channel as a result of the aggradation. Higher shear stress and velocity may actually degrade the channel and reduce the sediment deposition rates.

A series of FLO-2D model runs were conducted to assess the future aggradation scenario with the existing levee alignment and elevations. South Fork Snoqualmie River channel cross-sections from RM 2.74 through RM 4.58 were modified in the FLO-2D hydraulic model to represent reach-wide bed aggradation and localized scour. Cross-section modifications were supplied by King County (King County, 2012) in a HEC-RAS hydraulic model format and were used as the basis for modifying the FLO-2D model South Fork Snoqualmie River channel cross-sections. Otherwise, model inputs were unchanged from the existing-conditions model. The FLO-2D model for the future aggradation scenario was run for the same four design flood events as were used for the existing-conditions analysis: the 5-, 2-, 1-, and 0.2-percent-annual-chance flood events.

Appendix A presents full documentation of the analysis, including maps that show the key hydraulic analysis results: maximum flood depths, levee overtopping locations, maximum floodplain and channel flow velocities, and maximum water surface elevations. The following sections summarize key findings.

2.3.1 South Fork Snoqualmie River Channel Hydraulics—Future Aggradation Scenario

The capacity of the South Fork Snoqualmie River levee system and the hydraulic restrictions caused by the bridges along the South Fork Snoqualmie River determine the magnitude of flooding in the left and right bank floodplains.

Channel Water Surface Profile

Figure 2-18 shows the South Fork Snoqualmie River thalweg, right and left bank levee height profiles, and longitudinal water surface for the four design flood events. This figure shows that, for the future aggradation scenario, water surface elevations increase for all flood events upstream of RM 3.40, as a direct result of the changes in the thalweg profile. The greatest increase is associated with the 5-percent-annual-chance peak flood event, with slightly smaller increases for the 2- and 1-percent-annual-chance peak flood events. The increase in water surface elevations predicted for the 0.2-percent-annual-chance flood event is even smaller because a larger proportion of the floodwaters overtop at upstream locations and much of the flood flow is already being conveyed in the floodplain.

Downstream of RM 3.40, predicted water surface elevations are less for the future aggradation scenario than for existing conditions. The elevated water surface elevations upstream of RM 3.40 cause more flow to overtop the levee, reducing downstream peak flows and water surface elevations in the main channel.

Channel Flow

The magnitude of gravel aggradation between RM 2.74 and RM 4.58 for the future aggradation scenario would be expected to reduce the channel capacity in this reach. The hydraulic analysis results confirmed this assumption and found that the peak flow in the South Fork Snoqualmie River channel is generally less than the existing-conditions peak flow downstream of RM 4.7. Table 2-7 shows the peak channel flow rate predicted for the future aggradation scenario at selected locations along the South Fork Snoqualmie River.

TABLE 2-7.
PEAK CHANNEL FLOW RATE SIMULATED BY THE FLO-2D FUTURE AGGRADATION SCENARIO MODEL

South Fork Snoqualmie River Location	Future Conditions Peak Flow[a] and Difference from Existing Conditions[b] (cfs)							
	5% Annual Chance (20-year)		2% Annual Chance (50-year)		1% Annual Chance (100-year)		0.2% Annual Chance (500-year)	
	Flow	Difference	Flow	Difference	Flow	Difference	Flow	Difference
RM 1.50	9,890	-190	10,470	-130	10,690	-100	9,430	-20
RM 2.09	11,470	-590	12,650	-400	13,200	-340	13,840	-30
RM 2.76	11,510	-660	12,940	-560	13,740	-590	14,810	-50
RM 3.55	12,060	-140	13,560	-470	14,630	-490	16,690	-680
RM 5.9[c]	12,190	0	14,160	0	15,650	0	19,120	0

a. Channel flow decreases in the downstream direction (RM 5.9 to RM 1.5) are due to levee and bank overtopping. Peak flow computed for channel between top of left bank levee to top of right bank levee.
b. Difference from existing conditions. Negative values indicate flow reductions.
c. Total flow at upstream study limits.

As expected, peak flows immediately downstream of the aggraded reach are lower than for existing conditions due to the reduced channel capacity and resulting increased levee overtopping. Further downstream, the peak flows are also lower than for existing conditions, due to the increased levee overtopping upstream. Upstream of RM 4.7, the flow rate in the main channel is approximately equivalent to the peak flow rate for existing conditions.

Channel Velocity and Bed Shear Stress

Peak average channel velocity in the South Fork Snoqualmie River is either unchanged for the future aggradation scenario or increases by 1 or 2 feet per second compared to existing conditions. The exception is at about RM 3.35, where the velocity increases by nearly 4 feet per second. A similar increase in bed shear stress for the future aggradation scenario occurs at roughly the same location. The 2012 gravel aggradation study by King County predicted that more than 3 feet of sediment deposition may occur in the channel upstream of this location to form a locally steepened channel. The ability of this section to be maintained in a static condition under high flows is uncertain, due to high shear stress and velocity. However, sediment transport and changes in river morphology were not investigated as part of

this study. Additional documentation of channel velocity and shear stress for the future aggradation scenario is provided in Appendix A.

Bridge Hydraulics

The vertical clearance for all South Fork Snoqualmie River bridges is slightly greater for the future aggradation scenario than for existing conditions because of the expected peak flow reduction in the reach downstream of the deposition reach. The hydraulic performance of the bridge structures for the future aggradation scenario is provided in Appendix A.

2.3.2 South Fork Snoqualmie River Levee Freeboard – Future Aggradation Scenario

Levee freeboard was also evaluated for the future aggradation scenario to identify locations where freeboard is less than the original design criteria of 1 foot for a 13,000 cfs design flow rate without overtopping. Figure 2-19 shows a similar trend compared to existing conditions with most of the right bank levee system having 1 foot or more of freeboard for a significant portion of the right bank with insufficient freeboard at only 5 percent of the length (920 feet). The length of levee with insufficient freeboard was greater on the left bank with 29 percent (4,325 feet) of levee with freeboard less than 1 foot. Compared to existing conditions, the length of right bank levee with insufficient freeboard was only 70 feet longer for the future aggradation scenario. On the left bank, the length of levee with freeboard less than 1 foot increased by 995 feet. The levee freeboard evaluation is documented in Appendix A.

2.3.3 South Fork Snoqualmie River Levee Capacity – Future Aggradation Scenario

Levee capacity for the South Fork Snoqualmie River was evaluated using the process outlined for existing conditions (See Section 2.2.3) Similar to existing conditions, the right bank levee system is able to convey higher stream flow rates before overtopping compared to the left bank levee. The left bank levee has insufficient capacity to convey the 5-percent-annual-chance-event for 15% (2,360 feet) of the length of the levee whereas the right bank has adequate capacity to convey the same event for the entire length of levee. Compared to existing conditions, the length of the left bank levee system with sufficient capacity to convey the 5% annual-chance-event is reduced by 340 feet. For the 1-percent-annual-chance event, the left bank has adequate capacity over 35 percent (5,500 feet) of the length compared to the right bank which has the capacity to convey the same event for over 70 percent (14,210 feet) of the length. For the left bank, the length of levee capable of conveying the 1-percent-annual-chance event is reduced by almost 1,800 feet compared to existing conditions.

Figure 2-20 shows the flow capacity for left and right bank levee system for the South Fork Snoqualmie River. Similar to existing conditions, this figure shows that backwater from the bridge structures reduces the capacity of the levee system upstream of all road crossings. However, gravel deposition in the aggradation reach (RM 2.7 to 4.6) significantly reduces the capacity near RM 4.0 to less than the peak flow for the 5-percent-annual chance event (12,190 cfs). For existing conditions, the capacity is about equal to the 2-percent-annual chance peak flood event of 14,160 cfs.

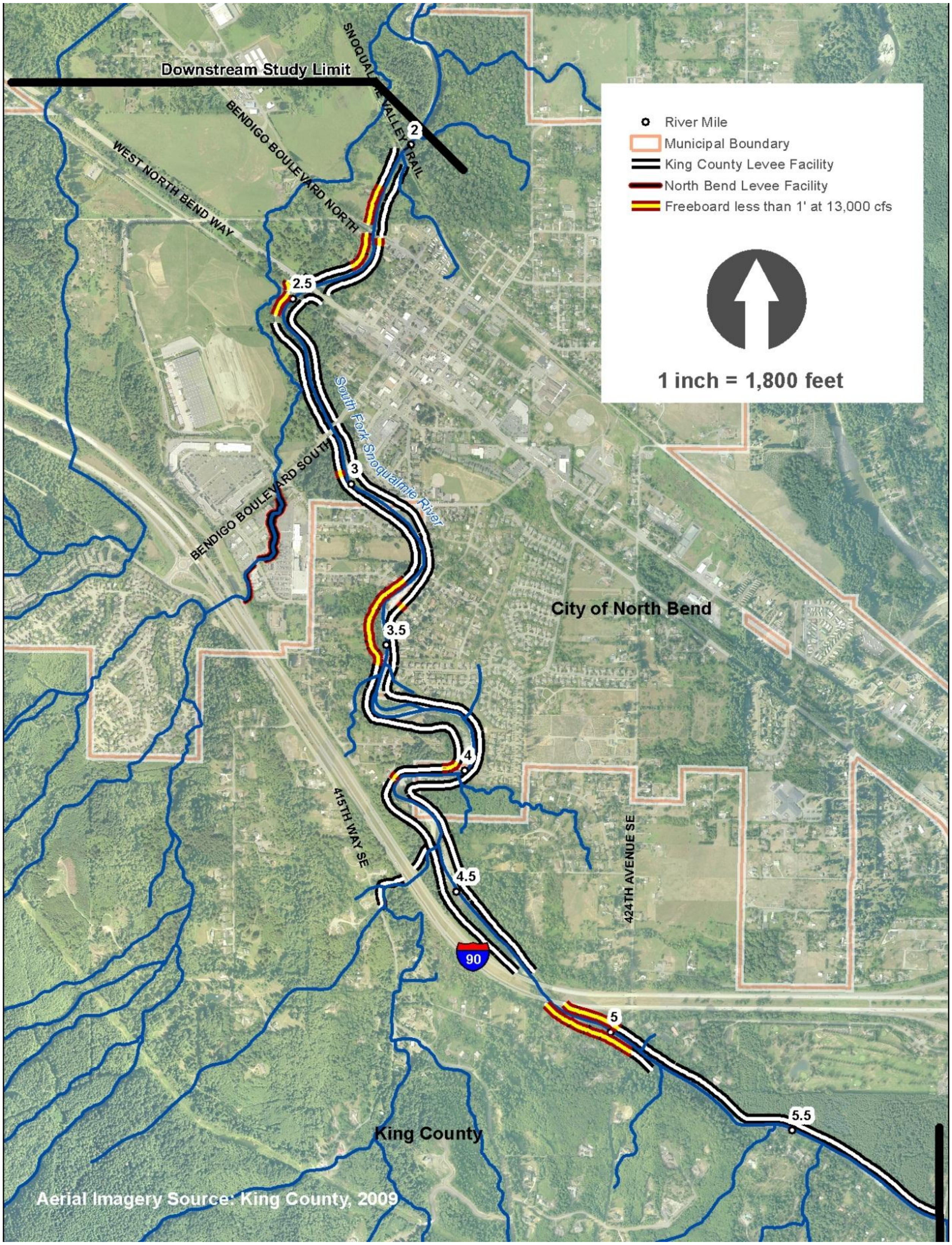


Figure 2-19. Freeboard Less than 1' for 13,000 cfs—Future Aggradation Scenario

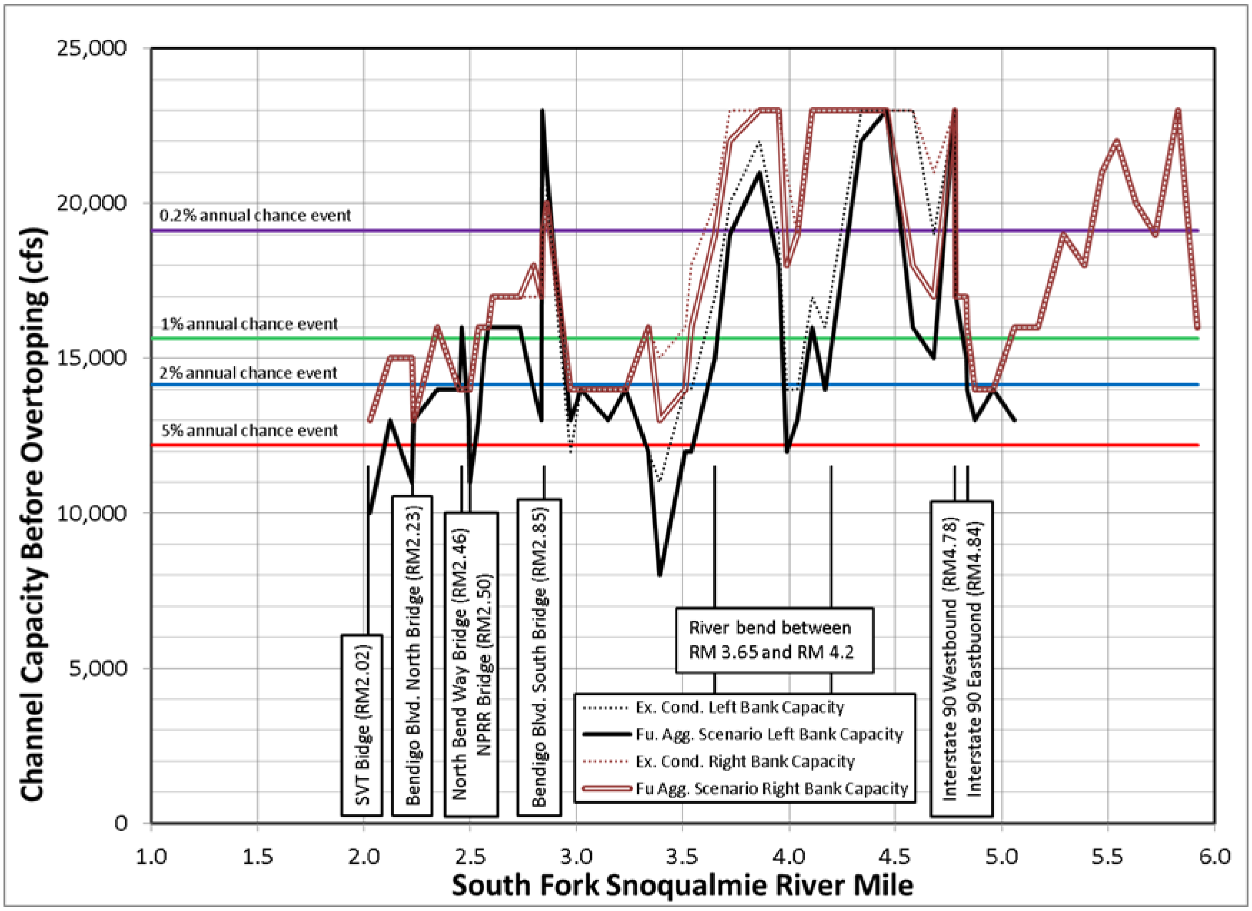


Figure 2-20. Levee Capacity without Overtopping—Future Aggradation Scenario

2.3.4 South Fork Snoqualmie River Levee Overtopping—Future Aggradation Scenario

The hydraulic analysis predicts an increased total length of overtopping of the South Fork Snoqualmie River levee system for the future gravel aggradation scenario compared to existing conditions. Also, the future aggradation scenario analysis indicates overtopping at additional locations where no levee overtopping is predicted under existing conditions. Levee overtopping locations for the future aggradation scenario for each of the design flood events are shown on the model result figures found in Appendix A.

Levee overtopping length by flood event is tabulated in Appendix A. In general, the additional locations where levee overtopping occur for the future aggradation scenario are in the aggradation reach between RM 2.8 and RM 4.2. The length of levee overtopping increases by 770 feet for the 5-percent-annual-chance flood event and 1,630 feet for the 1-percent-annual-chance flood event.

Levee overtopping during the 5-percent-annual-chance flood event (12,190 cfs) defines the most vulnerable points in the levee system. Like the existing-conditions results, the left bank is predicted to have the most levee overtopping during this flood event. The following locations are where the levee system is predicted to overtop during the 5-percent-annual-chance flood event for the future aggradation scenario:

- On the South Fork Snoqualmie River left bank:
  - Between RM 2.03 and RM 2.09. Overflow at this location occurs into a forested and agricultural area between the South Fork Snoqualmie River and Ribary Creek. The inundated area is larger than predicted under existing conditions due to a larger volume of overflow at RM 3.4.
  - At RM 2.98 upstream of Bendigo Blvd South. Overflow from the South Fork Snoqualmie River at this location inundates forested and agricultural area between the South Fork Snoqualmie River and 412th Avenue SE. Under existing conditions, overtopping at this location is not predicted for the 5-percent-annual-chance event but is predicted for the 2-percent-annual-chance event.
  - Between RM 3.33 and RM 3.46. Predicted overflow from the South Fork Snoqualmie River at this location inundates Berry Estates (SE 415th Avenue) and floods 19 homes (eight for existing conditions) and then continues north to Shamrock Park (SE 123rd Street) and floods 24 homes (15 for existing conditions). Overflow also results in flooding on Bendigo Boulevard South and South Fork Avenue SW. The area of inundation at this location is larger than for existing conditions. Inundation is predicted to extend into the commercial area north of 412th Avenue SE; however, no structure flooding is predicted for the 5-percent-annual-chance event. The overflow volume for the future aggradation scenario is predicted to increase compared to existing conditions, which results in higher volume and peak flow conveyed across Bendigo Boulevard South and downstream into Ribary Creek and surrounding floodplain. This larger volume and peak increase the inundation extents downstream on Nintendo property.
  - At RM 3.54. Overflow from the South Fork Snoqualmie River at this location inundates the residential area and commercial between Mt. Si Boulevard and SE 131st Street, flooding 10 properties, including three commercial properties west of 412th Avenue SE. Floodwaters contribute to flooding in Berry Estates (SE 415th Avenue) and combine with overtopping between RM 3.33 and RM 3.46. Under existing conditions, overtopping at this location is not predicted for the 5-percent-annual-chance event but is predicted for the 2-percent-annual-chance event.
  - Between RM 3.94 and RM 4.04. Overflow from the South Fork Snoqualmie River at this location inundates the residential area in the vicinity of SE 131st Street. Floodwaters contribute to flooding in the residential area north of SE 130th Street and combine with overtopping at RM 3.54. Under existing conditions, overtopping at this location is not predicted for the 5-percent-annual-chance event but is predicted for the 2-percent-annual-chance event.
- On the South Fork Snoqualmie River right bank:
  - Between RM 2.03 and RM 2.09 just upstream of the tie-in to the Snoqualmie Valley Trail embankment and just downstream of the North Bend wastewater treatment plant. Floodwaters overflow into the wooded area north of the wastewater treatment plant on Bendigo Boulevard North and Sydney Avenue N. The predicted overtopping length at this location is slightly shorter than the overtopping length predicted for existing conditions.

For the 5-percent-annual-chance flood event, the total length of South Fork Snoqualmie River levee predicted to overtop increases by 800 feet compared to existing conditions. High flows from the additional South Fork Snoqualmie River overtopping cause the Ribary Creek levees to overtop from the landward side. The length of levee overtopping increases for all events in Ribary Creek.

2.3.5 Floodplain Inundation and Overland Flow Paths—Future Aggradation Scenario

Levee overtopping inundates both left and right floodplains, with more extensive flooding on the left. For a given flood event, the predicted floodplain inundation throughout the study area is more extensive and deeper for the future aggradation scenario than for existing conditions. The more extensive inundation is caused by the loss of channel capacity due to the assumed bed aggradation, which results in increased peak flows and increased volume of flow from the channel to the floodplain areas. Floodplain depth and velocity, water surface elevation and inundation extents are provided in Appendix A.

Figures 2-21 through 2-24 show the floodplain inundation for each design flood event and the future aggradation scenario; these figures also show where results differ from existing conditions. Table 2-8 quantifies the area of floodplain inundation for each design event as well as the change in extent of floodplain inundation compared to existing conditions. The table shows an increase in the total floodplain inundation and in left bank floodplain inundation for all design flood events. However, this increase is more substantial for the smaller flood events than for the larger flood events. The extent of floodplain inundation is limited by the natural topography of the study area for the magnitude of floods considered for this study. The foothills on the western edge of the study area limit the extent of floodplain inundation on the left bank and the right bank floodplain area has increasingly higher ground elevations to the east that limit the inundation extent in this direction. For larger flood events, floodplain under existing conditions was already approaching the natural limitation, so the floodplain extent for the future aggradation scenario shows a smaller net increase compared to existing conditions. Similar to existing conditions, the relative floodplain inundation shown in Table 2-8 is based on the 75-foot model grid cell size and does not fully account for variation in topography within the grid.

TABLE 2-8.
APPROXIMATE FLOODPLAIN INUNDATION IN STUDY AREA FOR FUTURE AGGRADATION SCENARIO

	Inundated Area and Difference from Existing Conditions[b] (acres)[a]							
	5% Annual Chance (20-year)		2% Annual Chance (50-year)		1% Annual Chance (100-year)		0.2% Annual Chance (500-year)	
	Area	Difference	Area	Difference	Area	Difference	Area	Difference
Left Bank[c]	220	123	303	82	350	36	501	26
Right Bank[d]	13	-1	21	4	71	46	246	4
Total	**233**	**122**	**323**	**86**	**422**	**82**	**747**	**30**

a. See Table 2-2 for peak flow rate at the upstream inflow hydrograph at RM 5.9.
b. Difference in inundated area from existing conditions. Negative values indicates reduction in inundated area.
c. Left bank inundation includes tributary streams in study area only (RM 2.0 to RM 5.9).
d. Right bank inundation due to South Fork Snoqualmie River flooding only. Potential inter-basin flow from the Middle Fork Snoqualmie River was not simulated with the FLO-2D model.

Table 2-8 indicates anomalies in this trend for the right bank floodplain—a small reduction in inundated area for the 2- and 0.2-percent-annual-chance peak flood events. This reduction occurs downstream near Bendigo Boulevard North and is attributed to increased overflow to the Ribary Creek system bypassing the lower South Fork Snoqualmie River study area.

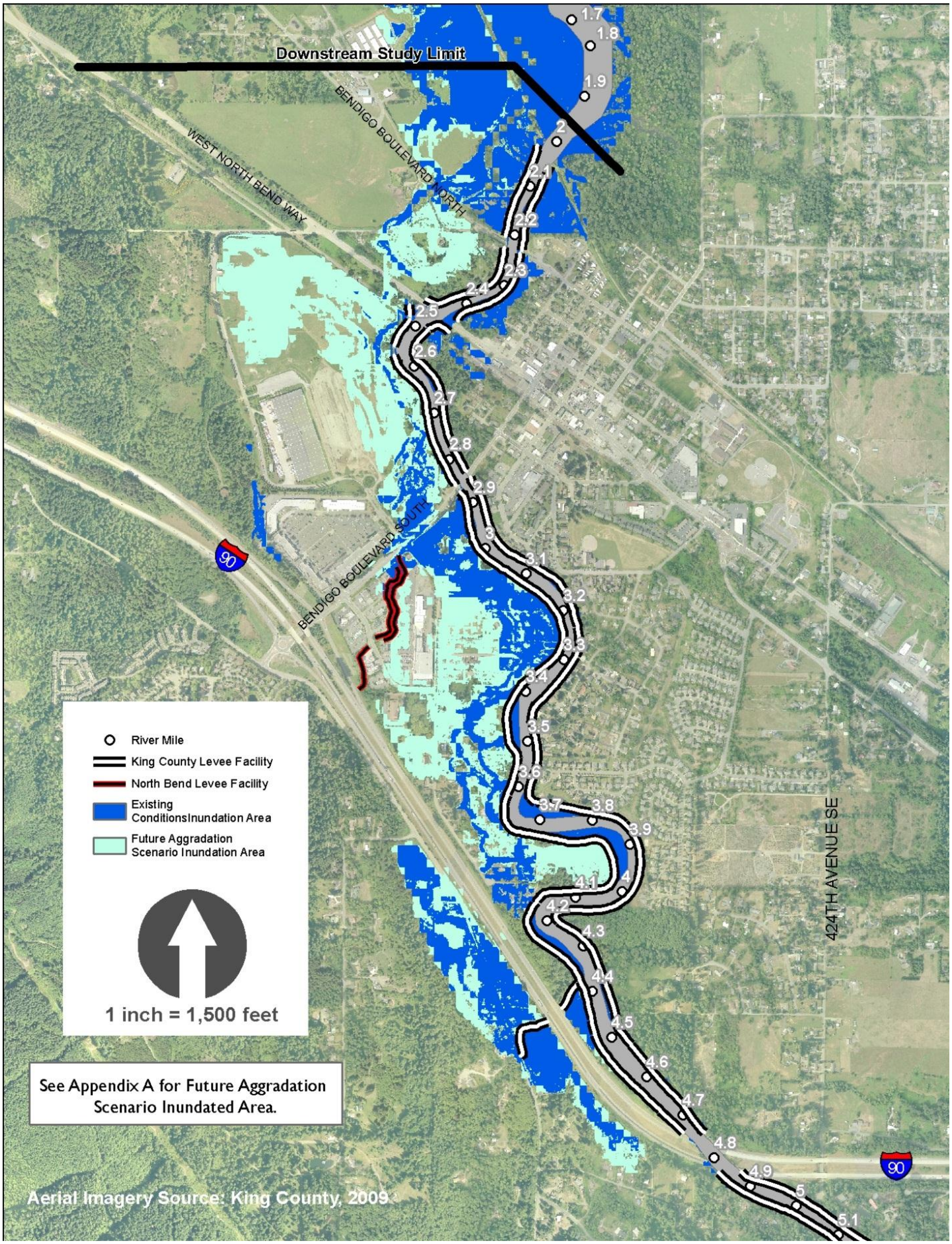


Figure 2-21. Floodplain Inundation for Future Aggradation Scenario—5-Percent-Annual-Chance Flood Event

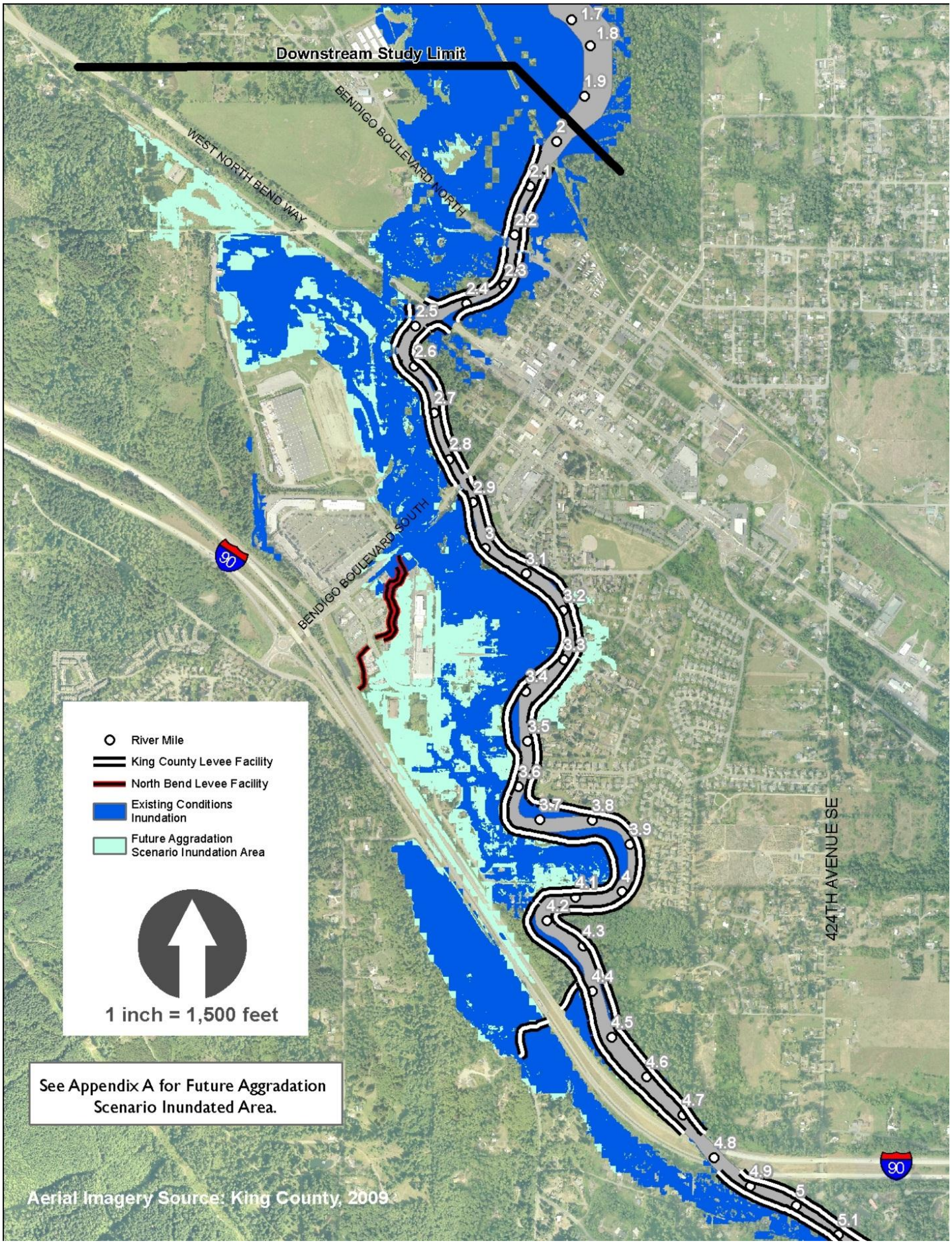


Figure 2-22. Floodplain Inundation for Future Aggradation Scenario—2-Percent-Annual-Chance Flood Event

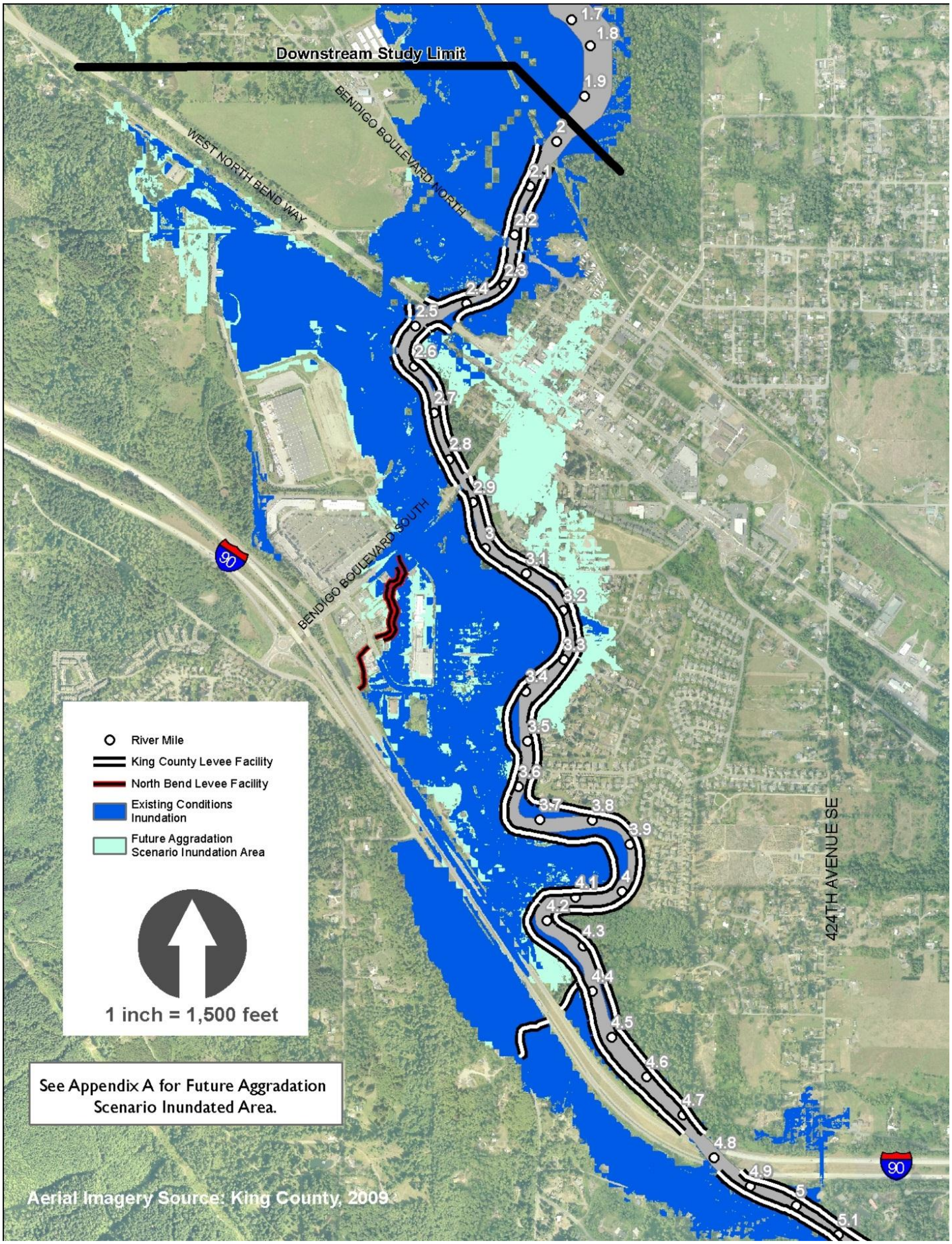


Figure 2-23. Floodplain Inundation for Future Aggradation Scenario—1-Percent-Annual-Chance Flood Event

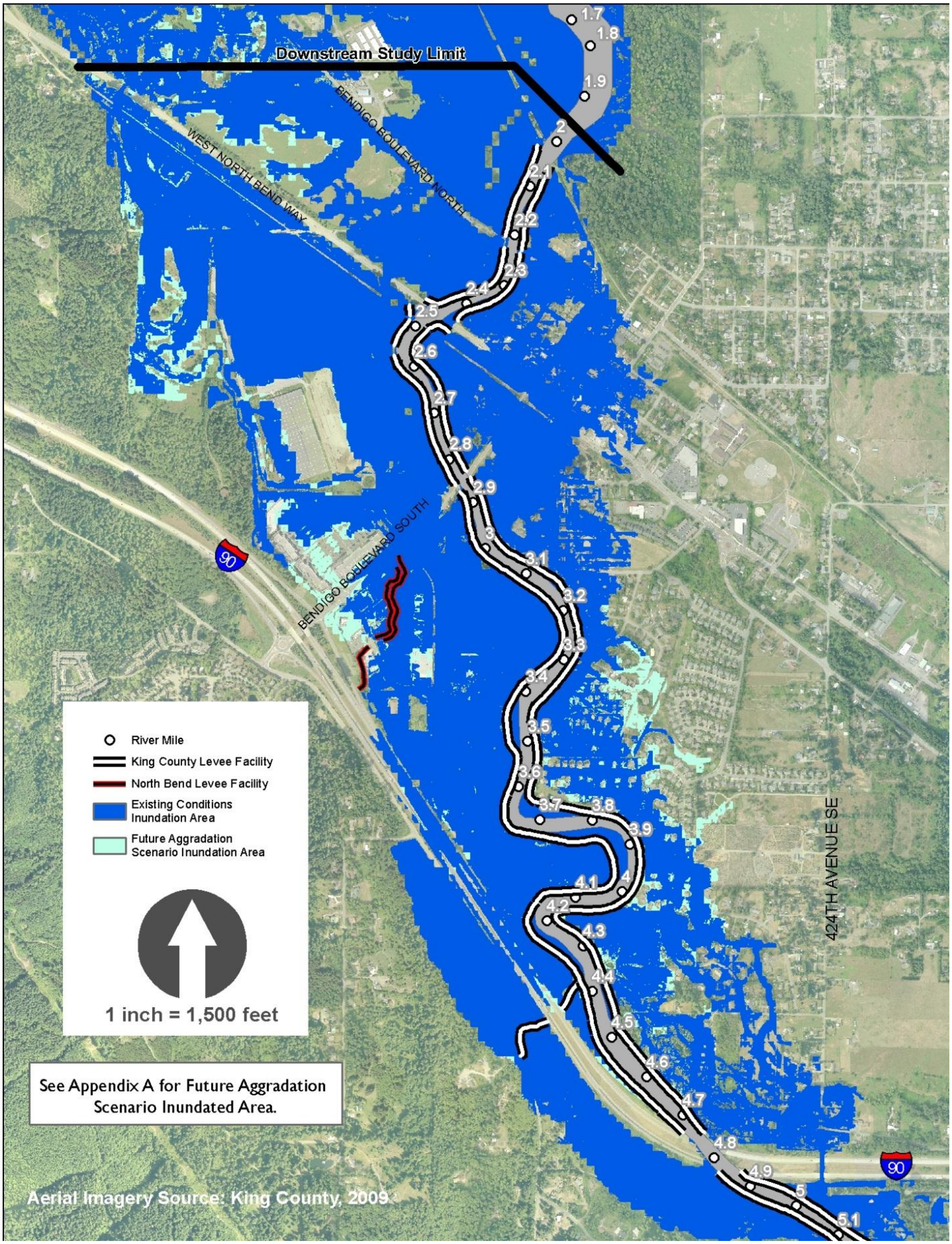


Figure 2-24. Floodplain Inundation for Future Aggradation Scenario—0.2-Percent-Annual-Chance Flood Event

Structure Flooding

The impacts of overtopping on private property and public facilities are presented Table 2-9. Similar to the existing conditions results (Table 2-4), the potential for structure flooding is greater on the left bank than the right bank for the 5- and 2-percent-annual-chance peak flood events. On the left bank, the entire Shamrock Park and Berry Estates area and the commercial district south of Bendigo Boulevard South are completely inundated for the 5-percent-annual-chance flood event. For existing conditions, complete inundation of these areas is not predicted until the 2-percent-annual-chance event for Berry Estates and the 1-percent-annual-chance event for Shamrock Park. On the right bank, many structures are inundated starting with the 1-percent-annual-chance flood event for the future aggradation scenario; for existing conditions, a similar level of inundation is predicted for the 0.2-percent-annual-chance flood event. Additional discussion on structure flooding is provided in the following discussions.

TABLE 2-9.
INUNDATED PROPERTIES WITH POTENTIAL FOR STRUCTURE FLOODING IN STUDY AREA FOR FUTURE AGGRADATION SCENARIO

		Number of Affected Properties and Difference[a] from Existing Conditions			
Location in Study Area	River Mile	5% Annual Chance (20-year)	2% Annual Chance (50-year)	1% Annual Chance (100-year)	0.2% Annual Chance (500-year)
Left Overbank					
Snoqualmie Valley Trail to Bendigo Blvd. South	2.0 – 2.85	4 (4)	5 (0)	5 (0)	8[b] (0)
Shamrock Park, Bendigo Blvd. South to Private Road	2.85 – 3.25	29 (11)	29 (1)	34 (5)	37[c] (0)
Berry Estates, Private Road to Mt. Si Boulevard	3.25 – 3.40	18 (10)	21[d](9)	22[d](2)	23[c] (0)
Mt. Si Boulevard to Interstate 90	3.40 – 4.85	28[e](16)	36[e](17)	37[f](4)	39[f] (0)
Interstate 90 to 436th Avenue SE (including Clough Creek area west of interstate)	4.85 – 5.9	21(9)	27(0)	33(0)	39 (0)
Total Left Bank Properties with Structure Flooding		100 (50)	118 (27)	131 (11)	146 (0)
Right Overbank[g]					
Snoqualmie Valley Trail to Bendigo Blvd. South	2.0 – 2.85	7[h] (0)	7 (-3)	24 (9)	83 (-6)
Bendigo Boulevard South to Stowe Avenue S	2.85 – 3.1	--	--	56 (56)	116 (-15)
Stow Avenue S to Interstate 90	3.1 – 4.85	--	12 (12)	22 (22)	172 (29)
Interstate 90 to 436th Avenue SE	4.85 – 5.9	--	--	--	5 (0)
Total Right Bank Properties with Structure Flooding		7 (0)	19 (9)	102 (87)	376 (8)
Total Properties with Structure Flooding		107 (50)	137 (36)	233 (98)	522 (8)

a. Difference in the number of inundated properties compared to existing conditions shown in parenthesis. Negative value indicates reduction in inundated properties.
b. Includes two buildings in the commercial area north of Bendigo Boulevard South.
c. Includes four buildings in the commercial area south of Bendigo Boulevard South.
d. Includes one building in the commercial area south of Bendigo Boulevard South.
e. Includes three buildings in the commercial area west of 412th Avenue SE.
f. Includes four buildings in the commercial area west of 412th Avenue SE.
g. The right overbank area includes downtown North Bend and residential neighborhoods. Commercial property is not distinguished from residential in the count of affected properties..
h. Structure flooding in this area due to levee seepage.

Roadway Flooding

The predicted length of road flooding for the future aggradation scenario and the 5- and 2-percent-annual-chance event is more than double the predictions for existing conditions (see Table 2-10). Most of the increase in flooding occurs on local roads. More frequent flooding also is predicted for Interstate 90, where 0.8 miles of flooding is predicted for the 2-percent-annual-chance event; under existing conditions, flooding is not predicted until the 1-percent-annual-chance event. An increase of nearly 60 percent in length of inundated roadway is predicted for 1-percent-annual-chance event, distributed between local and arterial roads. Much of the predicted increase in road flooding for the future aggradation scenario is on the right overbank in the densely developed residential and commercial areas of North Bend. Under existing conditions, significant flooding in the right overbank area is not predicted until the 0.2-percent-annual-chance event. Road flooding under the future aggradation scenario for the 0.2-percent-annual-chance event did not change appreciably compared to existing conditions.

TABLE 2-10.
INUNDATED ROADWAYS IN STUDY AREA FOR FUTURE AGGRADATION SCENARIO

	Length of Roadway Inundated and Difference[a] from Existing Conditions (miles)							
	5% Annual Chance (20-year)		2% Annual Chance (50-year)		1% Annual Chance (100-year)		0.2% Annual Chance (500-year)	
Road Type	Length	Difference	Length	Difference	Length	Difference	Length	Difference
Local Street	2.6	1.4	3.9	1.7	6.7	2.6	12.5	0.5
Arterial Road	0.3	0.1	0.4	0.1	1.0	0.5	1.8	0.0
Freeway	0.0	0.0	0.8	0.8	1.0	0.1	1.3	0.1
Total	**2.9**	**1.5**	**5.1**	**2.6**	**8.7**	**3.2**	**15.6**	**0.6**

a. Difference in inundated roadway length from existing conditions. See Table 2-5.

Left bank road flooding during the 5-percent-annual-chance event is predicted for the future aggradation scenario at South Fork Avenue SW, 412th Avenue SE, SE 123rd, SE 125th Street, SE 131st Street, SE 4215th Street, and Bendigo Boulevard South (the only arterial roadway where flooding is predicted for this event). Road flooding for this event is not predicted for Bendigo Boulevard North, Alm Way, Interstate 90, or SE 141st Street. Roadway flooding is not predicted in the right overbank until the occurrence of the 1-percent-annual-chance flood event. Additional discussion on road flooding is provided in the following sections and in Appendix A.

Left Overbank Floodplain Inundation

RM 5.9 to RM 4.85, 436th Avenue SE (Upstream Study Limit) to Interstate 90, Including Clough Creek Floodplain Area

The Interstate 90 bridge functions as a hydraulic control which prevents downstream backwater effects from transmitting upstream through the structure. Also, changes to channel morphology associated the future aggradation scenario were not assumed to occur in the South Fork Snoqualmie River reach upstream of the Interstate 90 bridge. For these reasons, floodplain inundation and overbank flow upstream of Interstate 90 (RM 4.85) are nearly identical for the future aggradation scenario and the existing conditions — overtopping occurs immediately upstream of the Interstate 90 bridges, between approximately RM 4.9 and RM 5.1, and the flow travels northwest toward Clough Creek and into the low-lying depression bounded by the Interstate 90 embankment to the east, SE 131st Street to the north and natural high ground to the west. As with the existing conditions, backwater from the South Fork

Snoqualmie River also causes Clough Creek to overtop its left bank levees upstream of Interstate 90, contributing to the flood volume that is conveyed into this low-lying depression.

For the future aggradation scenario, the water surface elevation in the South Fork Snoqualmie River at the confluence with Clough Creek (near RM 4.40) is higher than for existing conditions for all of the modeled flood events, ranging between 1.6 feet higher for the 5-percent-annual-chance flood event to 0.8 feet higher for the 0.2-percent-annual-chance flood event. This exacerbates the backwater condition and results in increased peak flows and flood volumes conveyed into this low-lying depression, compared to existing conditions. Peak flows conveyed into this low-lying depression increased for the future aggradation scenario for all design flood events. Gravel aggradation in Clough Creek was not simulated with the FLO-2D model, but it is noted that Clough Creek has experienced recent and dramatic gravel aggradation and is the subject of a separate analysis and design effort being led by King County.

The predicted backwater increase in the South Fork Snoqualmie River and Clough Creek for the future aggradation scenario also increases flood depth in the floodplain area west of Interstate 90 for the 5- and 2-percent-annual-chance flood event. Compared to existing conditions, maximum depth in this area is predicted to increase by 1 to 2 feet near Clough Creek. Flooding in the depression near SE 131st Street is predicted to increase 4 to 5 feet for the 5-percent-annual-chance event and about 2 feet for the 2-percent-annual-chance event. The increase in flood depth to the south was limited to the extent of backwater increase for Clough Creek, which corresponds to about SE 141st Street. The depth of flooding for the 1- and 0.2-percent-annual-chance flood events is predicted to be slightly higher (0.2 feet maximum) than existing conditions because overflow from the floodplain area is controlled by the Interstate 90 embankment.

Flooding is predicted at nine additional properties for the 5-percent-annual-chance flood event. No change in property flooding is predicted for the other design flood events. Similarly, the timing of road inundation remains as predicted for existing conditions, with more frequent flooding at 415th Way SE (5-percent-annual-chance flood event) followed by SE 141st Street (2-percent-annual-chance flood event). Peak velocity predicted for the future aggradation scenario is generally less than 0.5 feet per second, similar to velocity predicted for existing conditions.

Overtopping of the Interstate 90 roadway embankment northwest of Clough Creek depends on the volume of floodwater that has accumulated in the low-lying depression, not just on the peak flow in the South Fork Snoqualmie River. For the future aggradation scenario, overtopping is predicted for the 2-percent-annual-chance and greater flood events; for existing conditions, overtopping of the Interstate 90 roadway embankment is predicted for the 1-percent-annual-chance and larger flood events. However, floodwaters may inundate a small area of right-of-way during the 5-percent-annual-chance flood event. Additionally, the magnitude of the peak flow rate overtopping the Interstate 90 roadway embankment increases for the future aggradation scenario, ranging from about 90 cfs for the 2-percent-annual-chance flood to 1,550 cfs for the 0.2-percent-annual-chance flood event.

Flow depth on Interstate 90 during the future aggradation scenario is predicted to range from 0.5 feet or less for the 2- and 1-percent-annual-chance flood event to about 1.5 feet for the 0.2-percent-annual-chance event. Shallower flow depths are predicted on the westbound lane for all events. The flow depth is predicted to be 0.5 feet deeper for the future aggradation scenario than for existing conditions.

Predicted peak flow velocity on Interstate 90 during the future aggradation scenario ranged from 1 to 3 feet per second for the 2-percent-annual-chance flood event. Peak flow velocity for the 1- and 0.2-percent-annual-chance flood event also ranged between 1 and 3 feet per second but exhibited localized areas with velocity between 4 and 5 feet per second. High flow velocity may undermine the roadway embankment and result in erosion of the pavement.

RM 4.85 to RM 2.85, Interstate 90 to Bendigo Boulevard South

Flood flows that overtop the South Fork Snoqualmie River left bank levee downstream of Interstate 90 (i.e. downstream of RM 4.7) are conveyed through Shamrock Park, Berry Estates and the North Bend commercial and retail district near Bendigo Boulevard South, generally following the same flow path as predicted under existing conditions, but the inundated area increases for all design flood events. The most upstream overtopping in this section is predicted during the 5-percent-annual-chance event at the inside of the sharp bend located at about RM 4.0. Under existing conditions, overtopping is not predicted until the 2-percent-annual-chance flood event. Maximum depth in the area between Mt. Si Boulevard and Interstate 90 (RM 3.4 to RM 4.85) ranges from 0 to 3 feet (a 1-foot increase from existing conditions) for the 5-percent-annual-chance event and from 2 to 5 feet (a 0.5-foot increase from existing conditions) for the 0.2-percent-annual-chance event.

Higher flood depth due to overtopping at RM 4.0 increases the area of inundation, covering a significant portion of the area within the river bend (RM 3.65 to 4.2) and extending into the commercial area across 412th Street SE. Inundation extent for the 5-percent-annual-chance event for the future scenario is about equal to the extent experienced for the 2-percent-annual-chance event for existing conditions. The larger inundation area for the 5-percent-annual-chance flood event resulted in an increase of properties with structure flooding, from 38 to 75. For the 2-percent-annual-chance event and greater, the entire area is inundated, with 86 properties flooded. Similarly, road flooding is predicted starting with the 5-percent-annual-chance flood event.

Comparing the future aggradation scenario results to the existing-conditions results generally shows that the magnitude of peak flows in the floodplain is greater for the future aggradation scenario than for existing conditions. Higher floodplain flows are due to the loss of channel capacity caused by bed aggradation, which results in overtopping of the levees earlier on the rising limb of the hydrograph and greater total overtopping flow. There are only a few locations where the peak flow in the floodplain decreases slightly for the future aggradation scenario. The most notable are on the left overbank upstream of Bendigo Boulevard South for the 2- through 0.2-percent-annual-chance flood event, and near 415th Avenue SE. At these locations, the decreased peak flow for the future aggradation scenario is due to the reduction in overtopping volume caused by the localized decrease in water surface elevation in the South Fork Snoqualmie River channel downstream of the gravel aggradation reach (RM 2.74 to RM 4.58). Additional documentation of floodplain flows is provided Appendix A.

Under the future aggradation scenario, the magnitude of the combined peak flow conveyed across the floodplain and within the Ribary Creek channel, upstream of Bendigo Boulevard South, increases by roughly the same amount for all four design flood events. The predicted peak flow rate at Bendigo Boulevard South increases as follows:

- From 130 cfs to 660 cfs for the 5-percent-annual-chance flood event, an increase of 530 cfs
- From 630 cfs to 1,190 cfs for the 2-percent-annual-chance flood event, an increase of 560 cfs
- From 1,040 cfs to 1,690 cfs for the 1-percent-annual-chance flood event, an increase of 650 cfs
- From 3,210 cfs to 3,820 cfs for the 0.2-percent-annual-chance flood event, an increase of 610 cfs.

Overtopping of the South Fork Snoqualmie River left bank levee near RM 3.3 during the 5-percent-annual-chance flood event inundates the Berry Estates (SE 123rd Street and 515th Avenue SE) and Shamrock Park (SE 125th Street and SE 415th Avenue) areas. Berry Estates and Shamrock Park are predicted to be completely inundated for this event. Compared to existing conditions, maximum flood

depth in the Berry Estates and Shamrock Park area (RM 2.85 to RM 3.4) is predicted to be about 1 foot higher (between 0 and 3 feet) for the 5-percent-annual-chance event. However, the maximum increase is predicted to be less than 0.5 feet (flood depth between 2 and 6 feet) for the 0.2-percent-annual-chance event. Peak velocity is predicted to be relatively low for all design flood events, ranging from 0.2 to 0.5 feet per second.

Flow depths over the Bendigo Boulevard South roadway near the low point in the road northeast of Ribary Creek are predicted to increase by 0.5 feet or less for all design flood events analyzed, with peak flow depths ranging from about 0.6 feet for the 5-percent-annual-chance event to almost 1.5 feet for the 1-percent-annual-chance event. Floodplain velocity is predicted to increase to about 2.5 feet per second (0.7 feet per second for existing conditions) for the 5-percent-annual-chance event. For the 1-percent-annual-chance flood event, peak velocity increased to 3 feet per second (2 feet per second under existing conditions). Peak depth and velocity are predicted to be 3 feet and 3.5 feet per second respectively for the 0.2-percent-annual-chance event.

RM 2.85 to RM 2.0, Bendigo Boulevard South to Snoqualmie Valley Trail (Downstream Study Limit)

Peak flows in the Ribary Creek channel and its adjacent floodplain between Bendigo Boulevard South and West North Bend Way increase under the future aggradation scenario. The increases are similar to those upstream at Bendigo Boulevard South for the 5- through 1-percent-annual-chance flood events. For the 0.2-percent-annual-chance flood event, a portion of the flow that overtops Bendigo Boulevard South follows a secondary flow path to the east between the outlet malls and the Nintendo levee, toward Gardiner Creek instead of continuing downstream in Ribary Creek. This secondary flow path absorbs some of the increased peak flow, such that the peak flow in the Ribary Creek floodplain for the 0.2-percent-annual-chance flood event increases by only 480 cfs, from 3,180 cfs to 3,660 cfs.

Property and road flood are predicted at the following locations:

- Four properties for the 5-percent-annual-chance event and road flooding is predicted at Bendigo Boulevard South (discussed previously), South Fork Avenue SW, and NW 8th Street. No properties are predicted to be flooded in this area under existing conditions, and flooding at NW 8th Street is not predicted until the 2-percent-annual-chance flood event.
- Five properties are inundated for the 2- and 1-percent-annual-chance flood events.
- For the 0.2-percent-annual-chance event, inundation extents are predicted to increase significantly to include three additional properties in the commercial area north of Bendigo Boulevard South. However, the extent of property flooding does not change from that predicted under existing conditions.
- Bendigo Boulevard North and Alm Way are predicted to be flooded during the 2-percent-annual-chance event.
- Structure and road flooding are described in Tables A-8.7 and A-8.8 in Appendix A.

Maximum flood depth between the Snoqualmie Valley Trail and Bendigo Boulevard South (RM 2.0 to RM 2.85) ranges from 0 to 3 feet for the 5-percent-annual-chance event to 2 to 6 feet for the 0.2-percent-annual-chance event. Similar to existing conditions, the low-lying area near Snoqualmie Valley Trail is predicted to be inundated due to overtopping of the South Fork Snoqualmie River left bank levee near RM 2.1 during the 5-percent-annual-chance flood event. Flood depths are predicted to be about 1 foot higher than existing conditions for much of the floodplain area between Bendigo Boulevard South and Snoqualmie Valley Trail. For larger events, the predicted maximum depth decreases as the size of the event increases. For the 1-percent-annual-chance event, the predicted maximum depth is 1 foot upstream

of West North Bend Way, 0.5 feet between West North Bend Way and Bendigo Boulevard North, and 0.2 feet between Bendigo Boulevard North and Snoqualmie Valley Trail. For the 0.2-percent-annual-chance flood event, the predicted maximum depth is only slightly higher than existing conditions (0.1 to 0.2 feet) upstream of West North Bend Way and there is no change in flood depth downstream of West North Bend Way.

Peak velocity is predicted to be relatively low for all flood events, ranging from 0.2 to 0.5 feet per second. Flow velocity greater than 1 foot per second is predicted for isolated locations during the 1- and 0.2-percent-annual-chance event.

Floodplain storage in the South Fork Snoqualmie River between RM 2.0 and RM 5.9 reduces peak flow in the study area by about 6 percent for the 1-percent-annual-chance flood event. Peak flood flow for this event is predicted to be 15,250 cfs at the downstream study limit, 990 cfs less than the total peak inflow of 16,240 cfs for this event. Table 2-11 summarizes peak flows at the downstream study limit.

TABLE 2-11.
PEAK FLOODPLAIN FLOW AT DOWNSTREAM STUDY LIMITS (RM 2.0) FOR FUTURE AGGRADATION SCENARIO

Peak Flow Location	1% Annual Chance Peak Flow (cfs) (difference from existing)
Leftmost floodplain extent to Boalch Avenue NW[a, b]	460 (240)
Boalch Avenue NW to Snoqualmie Valley Trail[b]	1,010 (110)
Snoqualmie Valley Trail[b] to Right Floodplain Extent[c] (acres)	13,780 (-150)
Total Peak Flow at RM 2.0	**15,250 (200)**
Peak Inflow at RM 5.9	*16,240*

a. Includes Gardiner Creek.
b. High point is located at Boalch Avenue NW and Snoqualmie Valley Trail.
c. Includes Ribary Creek and South Fork Snoqualmie River.

Peak flood flow in the left bank floodplain is predicted to be 1,470 cfs. Floodplain flow is distributed between flow paths split at a localized high point where the downstream study limit intersects Boalch Avenue NW. As shown in Table 2-11, peak flood flow west of this location is predicted to be 460 cfs and includes Gardner Creek flows. Peak flood flow between Boalch Avenue NW and the Snoqualmie Valley Trail is predicted to be 1,010 cfs and includes floodplain flood flows only. Peak flood flow east of Snoqualmie Valley Trail was estimated to 13,780 cfs includes Ribary Creek and the South Fork Snoqualmie River and makes up the largest portion of the flow exiting the study area at 15,250.

Right Overbank Floodplain Inundation

RM 5.9 to RM 4.85, 436th Avenue SE (Upstream Study Limit) to Interstate 90

Upstream of Interstate 90, flows overtopping the right bank levee system are conveyed through the 424th Avenue SE underpass and then north into North Bend. The peak flow conveyed through the underpass for each of the flood events is roughly the same magnitude as for existing conditions, since the effects of the assumed bed aggradation do not extend upstream of the Interstate 90 bridges. Flood flows conveyed through the underpass are then conveyed generally north through a relatively narrow swath of low-lying land adjacent to the right bank levee and toward Bendigo Boulevard South.

RM 4.85 to RM 2.85, Interstate 90 to Bendigo Boulevard South

Between Interstate 90 and Bendigo Boulevard South, the extent of right bank levee overtopping is increased for the future aggradation scenario, which also increases the right bank inundation extent. For existing conditions, there was no overtopping of the right bank levee between Interstate 90 and Bendigo Boulevard South for the 5- and 2-percent-annual-chance flood events. Right bank levee overtopping under the future aggradation scenario for the 2-percent-annual-chance flood event in the vicinity of RM 3.44 contributes to the right overbank inundation. For the future aggradation scenario, the volume of water that overtops the right bank levees during the 1-percent-annual-chance flood event is sufficient to allow the inundation to extend north to the main retail and commercial area of North Bend. This is not the case for the 1-percent-annual-chance flood event under existing conditions, for which flooding during this flood event is limited to the immediate vicinity of the levee.

Under the future aggradation scenario, a peak flow of nearly 240 cfs is conveyed through the 424th Avenue SE underpass into the right overbank during the 0.2-percent-annual-chance flood. Similar to existing conditions, flows in the right overbank floodplain from this source overtop the right bank levee and flow back into the South Fork Snoqualmie River between RM 3.57 and RM 3.32. See Figure A-4 in Appendix A.

Downstream of RM 3.32, levee overtopping is primarily from the riverward side to the landward side. Under the future aggradation scenario, this same behavior occurs, as evident by the reduction in peak flow in the downstream direction between SE 131st Street and SE Maple Drive for the 0.2-percent-annual-chance flood event. However, riverward-to-landward levee overtopping downstream of RM 3.32 for the 0.2-percent-annual-chance flood event is less significant for the future aggradation scenario than it is for existing conditions, due to the reduction in the 0.2-percent-annual-chance flood event water surface elevation in the main channel.

In general, floodplain inundation in the right overbank of the South Fork Snoqualmie River under the future aggradation scenario is the same as under existing conditions for the 5- and 2-percent-annual-chance flood event. The exception is the area between RM 3.25 and RM 3.45, where 12 properties are flooded along Riverside Drive for the 2-percent-annual-chance event.

RM 2.85 to RM 2.0, Bendigo Boulevard South to Snoqualmie Valley Trail (Downstream Study Limit)

For the 5-percent-annual-chance flood event, levee overtopping at the downstream end of the leveed reach between West North Bend Way and the Snoqualmie Valley Trail (RM 2.0 to RM 2.1) and levee seepage at RM 2.27 and RM 2.47 inundate the right overbank floodplain, similarly to the behavior under existing conditions. However, for the larger design flood event, right bank levee overtopping in the reach between Bendigo Boulevard South and Interstate 90 and in the reach upstream of Interstate 90 results in a significantly larger area of right bank inundation for the future aggradation scenario.

Extensive flooding occurs in the right overbank between RM 2.5 and RM 3.5 under the future aggradation scenario during the 1-percent-annual-chance event. Under existing conditions, no flooding is predicted in this area. Over 100 properties are predicted to be flooded in the area between the South Fork Snoqualmie River and Riverside Drive SE, SE Orchard Drive, Healy Avenue S, Main Avenue S and W 4th Street. Flooding predicted between RM 2.0 and RM 2.45 remains unchanged compared to existing conditions.

For the 0.2-percent-annual-chance flood event, the predicted area of inundation is only slightly greater for the future aggradation scenario than for existing conditions. Floodplain extents increase to include the area near SE Maple Drive and Meadow Drive SE, East 2nd Avenue and the higher ground near Sydney

Avenue North and West 3rd Street. An additional six properties (90 total) are predicted to be inundated in this area for the future aggradation scenario.

2.3.6 Summary of the Future Aggradation Scenario Hydraulic Analysis

The following are the key findings of the future aggradation scenario analysis:

- The future aggradation scenario uses an estimate of aggradation based on measured rates over a period of 14 to 17 years at each cross section, extrapolated 30 years into the future, assuming no other actions are taken (gravel removal, levee setback or gravel storage). The aggraded bed estimate varies throughout the reach. Uncertainty in future accumulation rates may result in more or less bed aggradation than predicted.
- Cross section were monitored from RM 2.85 to 4.46 so the effect of gravel aggradation on the river hydraulics is unknown outside this reach.
- The characteristics of the gravel aggradation scenario do not consider bed deformation and sediment transport that may occur with higher shear stress and velocity in the South Fork Snoqualmie River channel as a result of the aggradation. Higher shear stress and velocity may actually degrade the channel and reduce sediment deposition rates. For this reason, results presented in this section are likely conservative.
- The assumed level of gravel aggradation in the South Fork Snoqualmie River is expected to increase the peak river stage by as much as 1.6 feet between RM 3.3 and Interstate 90 for the range of flood events that were simulated.
- Peak flow rates in the South Fork Snoqualmie River are predicted to decrease slightly within the aggradation reach, as well as downstream of the aggradation reach due to increased levee overtopping resulting from the elevated river stage.
- Left bank levee overtopping is predicted to increase significantly under the future aggradation scenario compared to existing conditions, inundating a larger area of floodplain. The most significant impact is expected for the 5-percent-annual-chance flood event. The difference between existing conditions inundated area and the area inundated predicted for the future aggradation scenario decreases as the flood frequency increases; for the 0.2-percent-annual-chance flood event there is essentially no difference in inundated area because extensive flooding already occurs for existing conditions.
- The right bank levee between Bendigo Boulevard South and Interstate 90 is predicted to be overtopped starting at the 2-percent-annual-chance flood event, compared to overtopping at the 1-percent-annual-chance flood event for existing conditions.
- Future-condition right bank levee overtopping and floodplain inundation are relatively unchanged compared to existing conditions for the 5-percent-annual-chance flood event. Right bank levee overtopping and floodplain inundation increase the most for the 1-percent-annual-chance flood event under the future aggradation scenario.
- A very small reduction in inundated area is predicted in the downstream reach near RM 2.3 due to the lower peak flow rates in this reach.
- The extent of levee overtopping is unchanged upstream of Interstate 90; however, the depth of inundation in the low-lying depression north of Clough Creek is increased for all flood events.
- Accumulated flood volume in the low-lying depression results in overtopping of the Interstate 90 roadway embankment during the 2-percent-annual-chance flood event for the future aggradation scenario, compared to existing conditions, for which overtopping of the Interstate

90 roadway embankment did not occur for the 2-percent-annual-chance flood event but did occur for the 1-percent-annual-chance flood event.

- The available vertical clearance is predicted to decrease at all Ribary Creek bridge structures due to the increase in South Fork Snoqualmie River levee overtopping flows being conveyed into Ribary Creek. Surcharging is predicted at the NW 8th Street bridge during all flood events, compared to existing conditions, for which surcharging at this bridge structure is predicted for the 2-, 1- and 0.2-percent-annual-chance flood events only. If upstream levee deficiencies are corrected, head loss at all structures would increase if flow is contained within the channel and no capacity improvements were made at existing structures.
- The number of inundated structures doubles to 100 on the left overbank for the 5-percent-annual-chance flood event including properties in the commercial area. The increase in structure flooding is smaller for the 1-percent-annual-chance-event with about 130 structures inundated. On the right bank floodplain, structure flooding upstream of Bendigo Boulevard South occurs starting the with 2-percent-annual-chance event. For the 0.2-percent-annual-chance-flood event, there is not a significant change in the number of inundated structures.
- Roadway flooding increases by 1.5 miles for the 5-percent-annual-chance flood event but is still confined to local roads except for Bendigo Boulevard South are inundated during the 5-percent-annual-chance flood event. The length of inundated roadway increases to 8.7 miles for the 1-percent-annual-flood-event with the majority of flooding still occurring on local roads but also on 1 mile of arterial roadway and 1 mile of Interstate 90.
- Approximately 70 percent of the left bank levee system and 95 percent of the right bank levee system meet the design freeboard criteria of one foot for a 13,000 cfs flood event. The locations where freeboard is deficient are generally the same locations identified for the existing condition analysis. Nearly all of the decrease in length meeting the criteria occurred at left bank at RM 3.5 upstream of Berry Estates (SE 415th Avenue).

CHAPTER 3.
GEOTECHNICAL AND HYDROGEOLOGIC INVESTIGATIONS

Geotechnical and hydrogeologic investigations were completed to evaluate the current condition of the levee embankments and assess levee stability and seepage characteristics. Investigations included review of levee characteristics and integrity ratings developed during previous studies, additional reconnaissance and subsurface explorations, review of groundwater monitoring data, stability and seepage analyses, and ground penetrating radar (GPR) testing.

Detailed levee data collected during previous phases of the project by other consultants and county staff was reviewed and incorporated to develop a preliminary assessment of levee stability and to identify potential geotechnical and hydrogeologic problems. Levee data includes detailed information for each subreach of the levee system, including field reconnaissance rating tables, photographs, text summaries, and levee configuration data (Shannon & Wilson 2009, 2010). Subreaches (e.g. AL-A, AL-B) were defined by grouping levee sections with relatively uniform features (e.g., crest widths, side slopes, riprap). The first letter designates the general reach, the second letter designates the bank, and the third letter designates the subreach. Ratings for each subreach of the levee system were divided into levee geometry (crest width, height, and slope inclinations), erosion (protection on riverside slope, landside slope, and toe), observed depressions and sinkholes, observed seepage and piping, and observed settlement. These data were used along with new data collected for this study to map and prioritize potential geotechnical and hydrogeologic problems along the levee system.

Following review of existing data and additional geologic reconnaissance, potential geotechnical and hydrogeologic problems were identified and prioritized. Prioritization was achieved by development of ratings for levee vulnerability or likelihood of failure. Locations and descriptions of higher priority problems are summarized in Section 3.2.1, and a complete listing is provided in Appendix C.

Additional subsurface explorations, including six new borings, were completed to supplement the existing borings, and a GPR survey of 9,000 lineal feet of the left bank was completed. The left bank was selected for GPR survey because the levee heights are greater and therefore contain higher geotechnical and hydrogeologic risk, and because large stumps were previously found within the left bank levee. Following review of all data and identification of the potential problems, seven critical sections were selected for stability and seepage analyses and three sections were analyzed for scour and stability. Detailed descriptions and results of the field exploration, GPR survey, stability and seepage analyses, and groundwater monitoring are provided in Appendix C. A summary of these tasks is also provided below.

3.1 LEVEE DATA REVIEW AND GEOLOGIC RECONNAISSANCE

3.1.1 Levee Configuration and Geometry

Levees evaluated for this study extend from the Snoqualmie Valley Trail (RM 2.0) to just upstream of 436th Avenue SE (RM 5.9). Levee heights are greatest at the downstream and upstream ends of the study. Specifically, the height on both the left and right bank varies from approximately 4 to 10 feet downstream of Bendigo Boulevard South (RM 2.85) to the Snoqualmie Valley Trail (RM 2.0). Within the central area between RM 2.85 and RM 4.0, the levee heights are 4 feet or less on both the left and right banks, and levee heights are between about 5 and 10 feet upstream of RM 4.0.

The steepest riverside levee slopes are concentrated in the downstream portion of the study area, between Bendigo Boulevard South and the Snoqualmie Valley Trail on the right bank. Slope inclinations on the

right bank vary from 1.5H:1V (horizontal to vertical) to 2H:1V to steeper than 1.5H:1V in this area. Right bank slope inclinations in the remaining study area upstream of Bendigo Boulevard are typically 1.5H:1V to flatter than 2H:1V.

Slope inclinations on the left bank are typically between 1.5H:1V and 2H:1V, to flatter than 2H:1V throughout the study area, with the exception of steeper riverside slopes within a half-mile downstream of the Interstate 90 crossing (RM 4.36 to 4.85). Specific levee height, crest width, and typical slope inclination ratings by river mile are shown in Table 3-1.

TABLE 3-1
SOUTH FORK SNOQUALMIE RIVER LEVEE CONFIGURATION

	Left Bank Levee Facility Configuration				Right Bank Levee Facility Configuration			
River Mile	Reach	Height[a] (feet)	Crest Width (feet)	Typical Slope[b] (landside/riverside)	Reach	Height[a] (feet)	Crest Width (feet)	Typical Slope[b] (landside/riverside)
2.0 – 2.23	AL	5	15 – 25	M/M	AR	5 – 10	15 – 17	N to M / M
2.23 – 2.46	BL	4 - 6	15 - 20[c]	M / M to S	BR	4 – 8	15 – 20	M / M to S
2.46 - 2.85	CL	5 - 10	20 – 30	M / M	CR	5 – 10	15 – 20	N / N
2.85 – 2.97	DL				DR	2 to 3	16	N / N
2.97 – 3.14	DL				DR	<2		– / N
3.14 – 3.20	DL			N / M	DR	3	10 – 15	N / M
3.20 – 3.25	DL	2 - 4	15 – 20		DR	<2		– / M
3.25 – 3.29	DL				DR	4 to 6	20	N / S
3.29 – 3.31	DL			N / S	DR	<2		– / M
3.31 – 3.45	DL	<2		– / M	DR			
3.45 – 3.55	DL				DR	<2		– / N
3.55 – 3.73	EL	2 - 7	20 – 50	N / M	ER	<2		– / M
3.73 – 4.02	FL	2 - 8	15 – 20	M / M	FR			
4.02 – 4.16	FL	5 - 8	10 – 15	N / N	FR	5		
4.16 – 4.36	GL	5 - 10		M / M to S	GR		15 – 20	M / M
4.36 – 4.47	GL			S to M / S	GR			
4.47 – 4.49	HL	0 - 5	15 – 20		GR	5 – 10		
4.49 – 4.81	HL			M / M to S	HR			
4.81 – 4.85	IL	3 - 7	15 – 25		HR		15 – 25	N – M / N – S
4.85 – 5.1	IL				IR	0 – 5		
5.1 – 5.18					IR			
5.18- 5.29		Slopes to higher ground			JR	1 – 4	15 – 18	N / M
5.29 – 5.9					JR	<2		– / M

a. Levee height measured on the landward side
b. N = Noncritical slope 2:1 horizontal to vertical (2H:1V) or flatter; M = Moderate slope from 2H:1V to 1.5H:1V; S = Severe slope steeper than 1.5H:1V. From Shannon & Wilson, 2009.
c. Crest narrows to 10 feet near Bendigo Boulevard South.

Geotechnical and hydrogeologic stability of a levee is a function of its physical characteristics. To assess the overall vulnerability of the levees, geometry was evaluated in terms of height, crest width, and riverside slope. Generally, low levees, wide crests and flatter riverside slopes are more stable than high levees, narrower crests and steeper riverside slopes. Table 3-2 presents ratings based on these conditions.

TABLE 3-2
LEVEE VULNERABILITY RATINGS

Rating	1	2	2.5	3
Levee Height (feet)	<5	5 to 10	-	>10
Crest Width (feet)	>20	15 to 20	10 to 15	<10
Riverside Slope (horizontal: vertical)	>2H:1V	1.5 -2H:1V	-	<1.5H:1V

The vulnerability value was obtained by multiplying the ratings for the levee height, crest width and riverside slope. A vulnerability value less than 4 indicates a levee section with low vulnerability. A value between 4 and 8 indicates moderate vulnerability. A value greater than 8 indicates high vulnerability. Levee vulnerability is shown graphically in Figures 3-1 to 3-4.

3.1.2 Geologic Reconnaissance

Previous Investigations

Two previous investigations were completed along the levees:

- The *Phase I Geotechnical Report, South Fork Snoqualmie Levee Study Project, King County, Washington,* (Shannon & Wilson, Inc., 2009) included a collection of existing geotechnical, geological and construction data for the levee system; a reconnaissance of existing levee conditions; observations of test pits excavated at depressions in the levees; and analyses to evaluate the stability of the existing levees. Detailed reconnaissance, photographic documentation, and ratings of the levees were completed. This report presents the results of the Phase I study and recommended additional services, including preparation of a Phase II data report (below), and a final recommendations report.
- The *South Fork Snoqualmie Levee Study—Phase II, Geotechnical and Hydrogeologic Data Report, King County, Washington* (Shannon & Wilson, Inc., 2009) included 20 borings, of which 17 were completed as monitoring wells. Data loggers were installed in the monitoring wells for long-term groundwater monitoring. Hydraulic conductivity testing was also completed (slug tests and falling head percolation tests). No analysis or findings were documented in this report. However, data provided in these reports was used in the geotechnical analysis for this study.

Figure 3-1. Levee Vulnerability Rating, RM 2.0 to RM 2.7

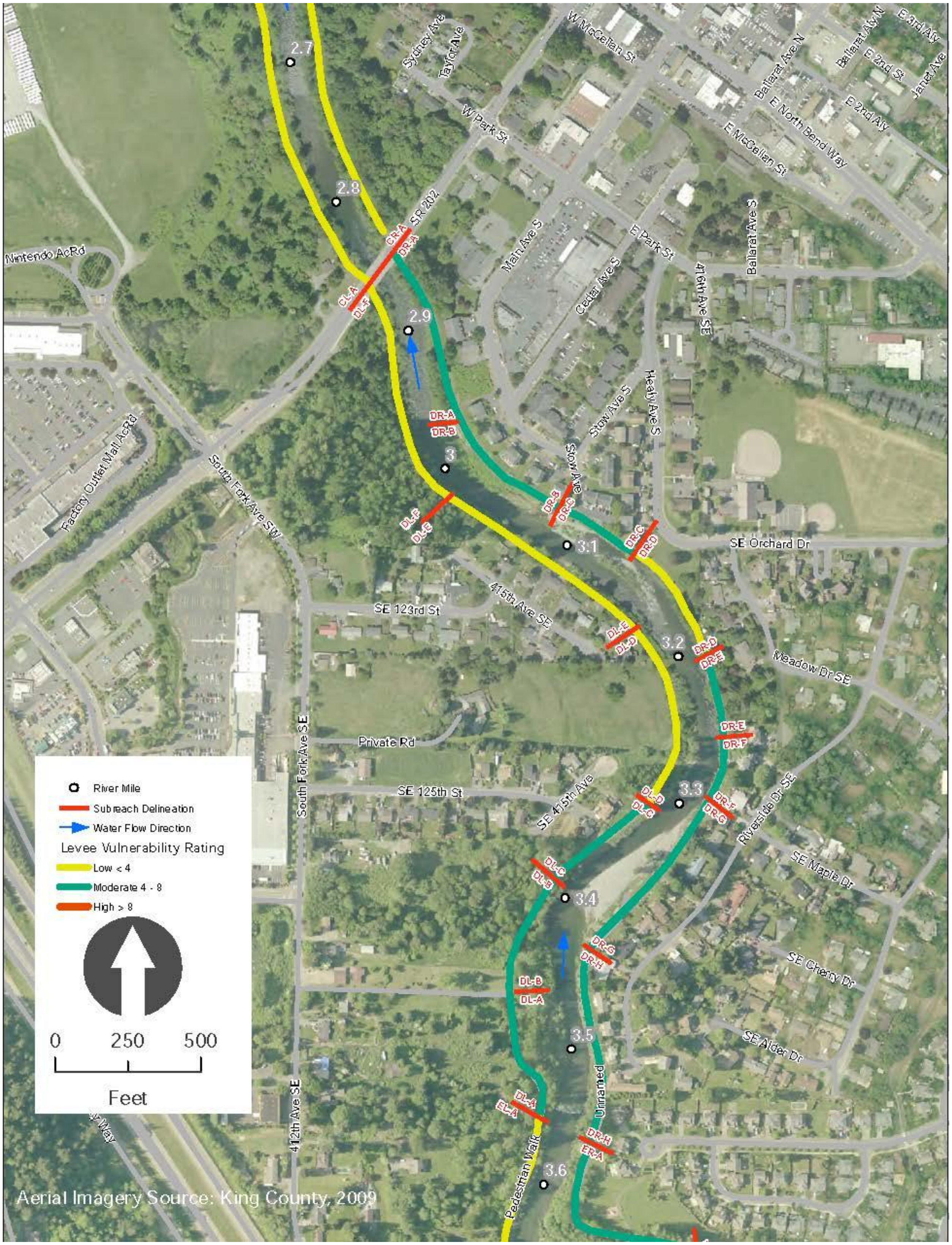


Figure 3-2. Levee Vulnerability Rating, RM 2.7 to RM 3.6

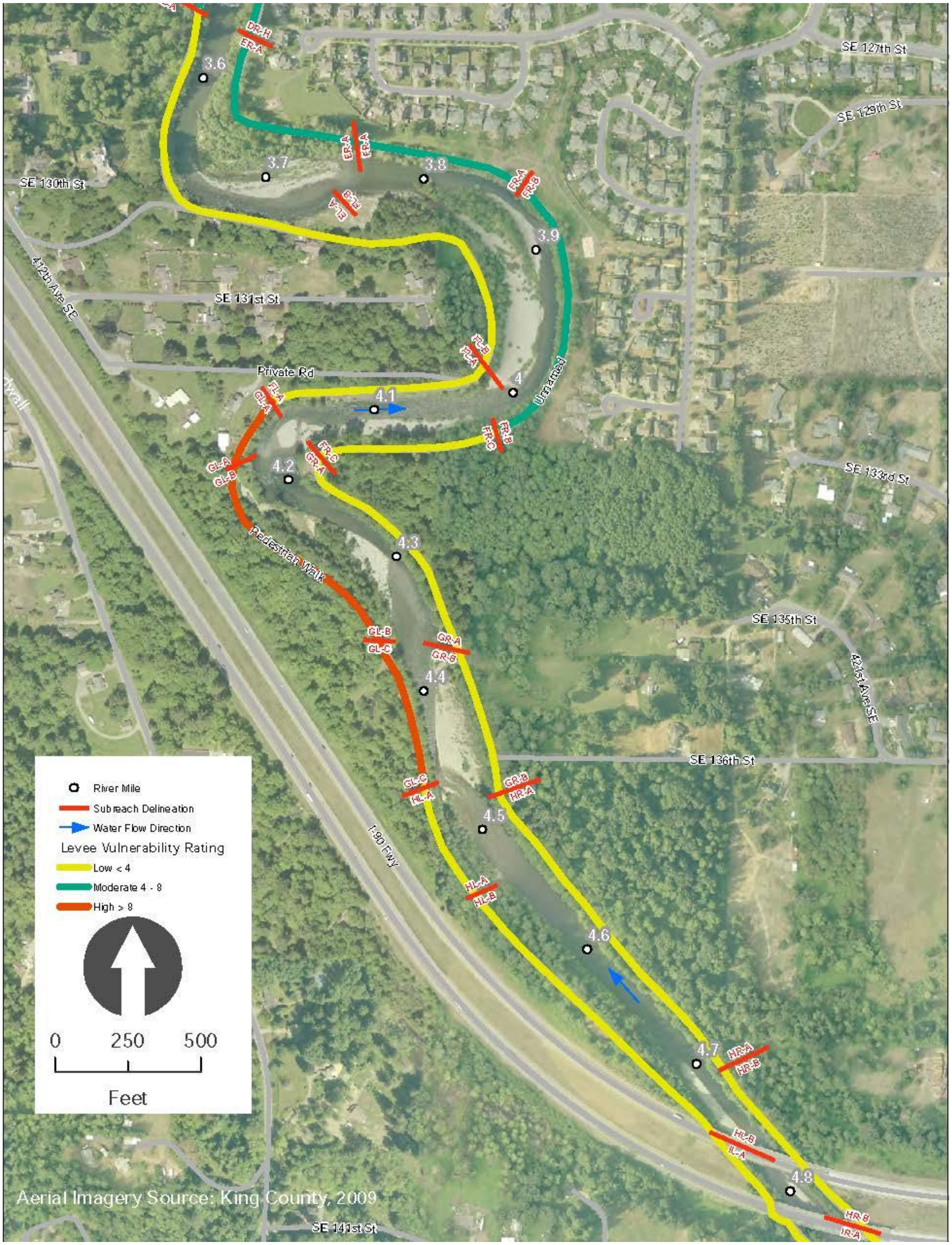


Figure 3-3. Levee Vulnerability Rating, RM 3.6 to RM 4.8

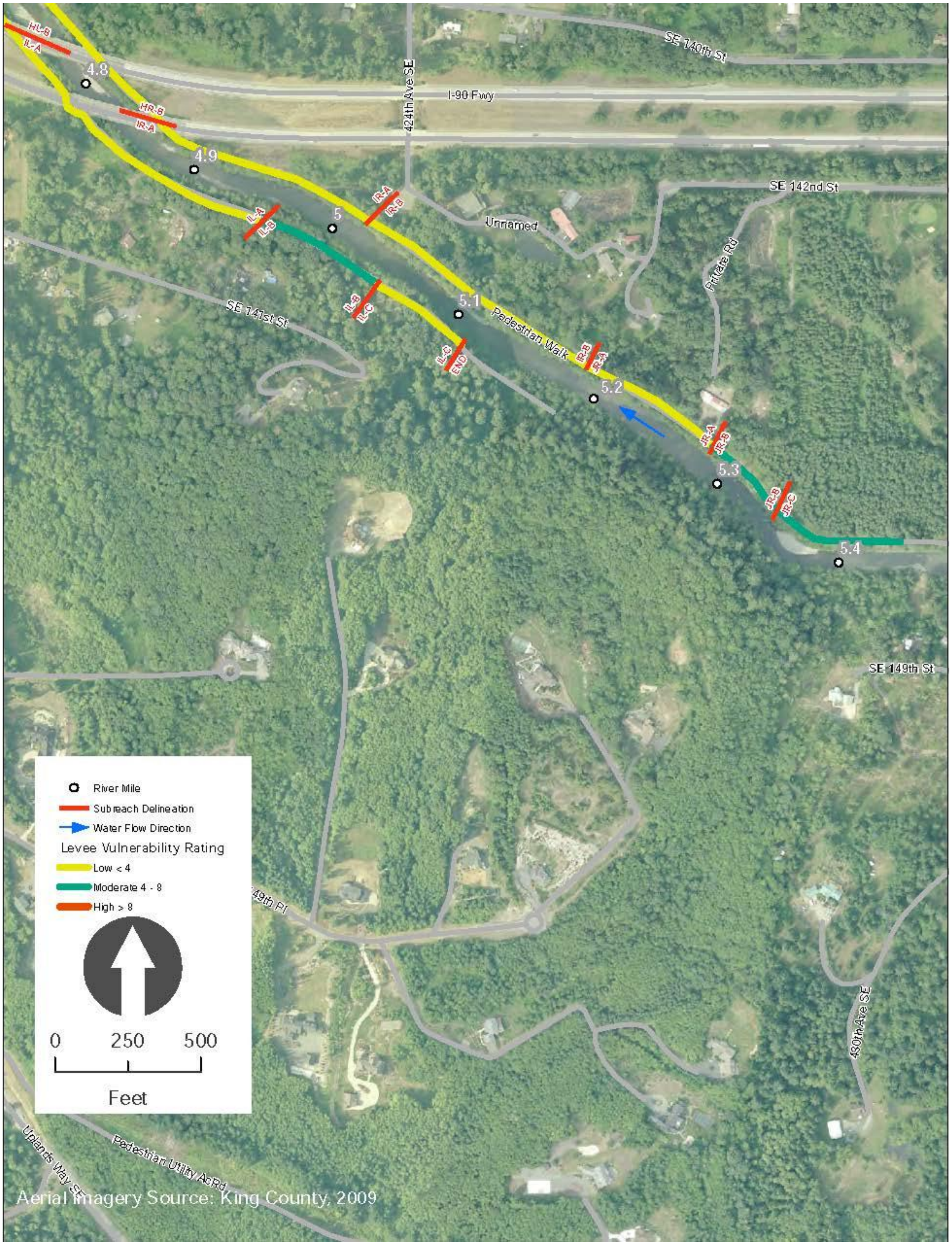


Figure 3-4. Levee Vulnerability Rating, RM 4.8 to RM 5.3

Investigations Performed for this Study

Investigations performed for this study included a detailed review of historical levee plan documents, previous levee repair plans, existing explorations (monitoring wells, borings, and test pits), water level monitoring data, slug tests, laboratory analyses, and the two previous investigations described above. Potential geotechnical problems were identified during the previous investigation and new potential problems were identified based on review of existing data. Key elements for evaluating potential geotechnical and hydrogeologic problems include levee configuration (height, slope and crest width), observations of slope protection and riprap armor, depressions or settlement, seepage and piping, and levee culvert penetrations. The data review also incorporated riverside slope conditions observed during a reconnaissance completed using a raft to observe the levees from the river (Shannon & Wilson, 2009).

Following detailed review of the previous levee characterization, additional geologic reconnaissance was completed between May 25 and June 10, 2011 to evaluate existing surficial conditions. Geologic reconnaissance was also completed to review potential geotechnical problems identified in the previous study characterization, and to identify potential new problems. This included development of the identified potential problems into summary tables as discussed in Section 3.2.

Additional investigations were completed to supplement the existing explorations. This included drilling six supplemental borings, installing monitoring wells in three of the borings, laboratory testing, collecting additional groundwater level data, excavation of test pits to evaluate the presence of riprap, and completing additional GPR study.

3.2 PROBLEM EVALUATION AND CRITICAL SECTIONS

3.2.1 Geotechnical and Hydrogeologic Problem Evaluation

Geotechnical and hydrogeologic conditions of the levee system were evaluated by reviewing geotechnical and hydrogeologic reports and levee rating tables, photographs, text summaries and riverside slope reconnaissance data observed from the river, and by completing additional geologic reconnaissance. The review identified potential geotechnical and hydrogeologic problems in the levee system. A subset of critical problems was selected from the list of identified problems for additional detailed analysis of stability, scour, and seepage.

A preliminary list of 46 potential geotechnical and hydrogeologic levee problem locations was identified based on the findings from previous investigations and the additional geologic reconnaissance performed for this study. The preliminary list was divided into higher and lower priority by the project team and King County, based on a qualitative assessment of the observed presence of potential failure mechanisms (seepage, piping, stability, erosion and subsidence) and considering the adjacent land use.

Problems with higher priority (G-1 through G-24) were retained for additional evaluation and rated in terms of geotechnical likelihood of failure on a scale of 2 to 10, with 10 representing the highest potential for failure. High ratings were assigned to areas of observed piping and seepage, moderate to high ratings were assigned to areas of noted erosion and slope instability, moderate ratings were assigned to areas of depressions and toe erosion, and lower ratings were assigned to areas of levee penetrations (pipes or culverts) and areas of outside bends. The basis of failure ratings is presented in Table 3-3, and the complete list of problems is provided in Table 3-4.

TABLE 3-3
BASIS OF GEOTECHNICAL FAILURE RATINGS

	Failure Rating	
Geotechnical Issues	Levee Height >4’	Levee Height <4’
Observed piping, potential void development and crest settlement	10	10
Observed seepage with surface depression leading to piping, potential void development and crest settlement	9	8
Observed toe erosion with evidence of slope instability leading to slope failure and levee breach	9	8
Observed seepage with less than 12-foot wide crest resulting in short seepage path and, potential piping, void development and crest settlement	8	7
Observed seepage with erosion or penetration leading to piping, potential void development and crest settlement	8	7
Severe toe erosion with less than 12-foot wide crest leading to slope instability and settlement of crest	7	6
Severe toe erosion leading to slope instability and settlement of crest	5	4
Depression/sinkhole as a result of internal erosion and piping, potential void development and crest settlement	5	4
Levee penetration resulting in piping and erosion of particles along pipe, potential void development and crest settlement	4	4
Outside bend with high scour potential leading to levee instability and loss of embankment	3	2

TABLE 3-4
POTENTIAL GEOTECHNICAL AND HYDROGEOLOGIC PROBLEM LOCATIONS

Location ID[a]	RM/ Reach	Potential Problem Description	Outside Bend (Y/N/S) [b]	Riverside Slope[c]	Levee Configuration: Height (feet) [d]	Levee Configuration: Crest Width (feet)	Observed/ Potential Conditions: Seepage	Observed/ Potential Conditions: Piping	Observed/ Potential Conditions: Scour/Erosion	Failure Rating
G-1	2.27 BR-A	Outside bend, moderate slopes, sparse to no riprap observed within upper 5 feet of riverside slope, riprap observed at toe, nearby bridge abutment, erosion at levee crest	Y	M	4	12			x	8
G-2	2.51 CL-B	Outside bend to straight, seepage observed from river to landside Jan 09, moderate slopes, severe depression, sparse riprap, nearby bridge abutment	Y	M	6	25 - 30	x	x	x	9
G-3	2.70 CL-A	Piping and sand boil observed Jan 09, depression, moderate slopes, sparse riprap	N	M/S	5	20 - 25	x	x	x	10
G-4	2.87 DR-A	Toe erosion on riverside slope, outside bend, sparse riprap, nearby bridge abutment	Y	N	3	10 - 15			x	6
G-5	3.10 DL-E	Recent repair completed (issues included seepage from landside to river, scoured rills and soft areas, near vertical face, rubber tires, nearby flap gate	N	S	3	15 - 20	x	x		7
G-6	3.54 DL-A/ EL-A	Outside bend to straight, undulating crest surface, moderate slopes, telephone crossing with boulder protection in river, penetration	N	M	2	20	x		x	4
G-7	3.68 EL-A	Outside bend, toe erosion, undulating crest surface, moderate slopes	Y	M	2	20			x	4
G-8	4.18 GL-A	Outside bend, narrow crest, moderate slopes, reported seepage during Jan 2009 flood	Y	M	5	10-15	x	x		8
G-9	4.47 GR-B	Toe erosion, moderate slopes, narrow crest, sparse riprap observed, bar protects levee toe	N	M	8	12-20	x		x	5
G-10	5.03 IR-B	Moderate slopes, locally 1.4H:1V, sags, depressions in crest 6 to 10 inches deep, I-90 nearby	N	M	6	15			x	5
G-11	2.04 to 2.11 AR-A	Severe toe erosion, 50 to 400 feet upstream of pedestrian bridge, some large trees midslope, levee protection is offset from current toe	N	M/S	6	12-17			x	5
G-12	2.11 AR-A	48-inch Diameter culvert penetration	N	M/S	9	12-17	x	x		4
G-13	2.28 BL-B	Depression, 2 feet by 4 feet with two interior circles, probe depth 18 inches to 3 feet, moderate to severe riverside slope	N	M/S	4	12	x	x		5
G-14	2.39 BR-A	Small 14-inch Dia. sinkhole, probe depth 15 inches to 3 feet	N	M	4	12	x	x		5
G-15	2.47 CR-A	Culvert penetrations at levee bend, severe riverside slopes in subreach, water ponding behind pier, seepage noted during January 2009 flood	N	S	6	10-20	x	x		7

TABLE 3-4
POTENTIAL GEOTECHNICAL AND HYDROGEOLOGIC PROBLEM LOCATIONS

Location ID[a]	RM/ Reach	Potential Problem Description	Outside Bend (Y/N/S)[b]	Riverside Slope[c]	Levee Configuration		Observed/ Potential Conditions			Failure Rating
					Height (feet)[d]	Crest Width (feet)	Seepage	Piping	Scour/Erosion	
G-16	3.04 DL-E	Overtop area at flap gate	N	M	3	15			x	2
G-17	3.19 DL-D	Channel split, gravel bar in center. Left channel lower than right, rapid water on left and potential erosion. Soft crest (12 to 14 inch probe). Riprap slope protection observed in July 2013 excavation.	N	M	4	15-20	x	x		5
G-18	3.26 DR-F	Outside bend with severe riverside slopes	Y	S	4	20			x	3
G-19	3.36 DL-C	Resident reported 1 foot overtop, low area	N	M	<2	0				2
G-20	3.68 EL-A	Oversteepened slope, recent riprap placement on riverside slope	Y	M/S	2	20-50			x	4
G-21	3.73 EL-A	End of large bar, riprap covered by vegetation and recent alluvium	Y	M/S	2	0-50			x	4
G-22	4.00 FR-B	Moderate to severe slopes on outside bend	Y	M/S	<2	0				2
G-23	4.5 to 4.6 HL-A,B	Side channel developing and undercutting riverside toe, severe riverside slope, evidence of slope movement	S	M/S	5	15-20			x	9
G-24	4.83 IL-A	Slight outside bend approaching I-90 abutment	S	M	4	15			x	3
G-25	2.13 to 2.23 AR-A	Toe erosion, no riprap observed, subsurface conditions unknown	N	M	5 to 10	15 to 17			x	*e*
G-26	2.24 AR-A	Outflow through levee, levee penetration	N	M	5 to 10	15 to 17	x	x		*e*
G-27	2.3 to 2.5 BR-A	Toe erosion and oversteepened toe	N	M	4 to 8	15 to 20			x	*e*
G-28	2.45 BR-A	Dense tree growth at levee toe, North Bend Way Bridge abutment	N	M	4 to 8	15 to 20	x			*e*
G-29	~2.7 CR-A	Toe erosion, severe slopes	N	S	5 to 10	15 to 20			x	*e*
G-30	2.5 to 2.9 CR-A	Numerous 1- to 2-foot diameter trees along riverside slope, severe slopes	N	S	5 to 10	15 to 20	x			*e*
G-31	2.87 DL-F	No riprap observed subsurface conditions unknown, potential toe erosion near Bendigo Boulevard bridge abutment	S	M	3	15 to 20			x	*e*
G-32	3.12 to 3.19 DR-D	Moderate to severe slopes, outside bend	Y	M to S	3	10 to 15			x	*e*

TABLE 3-4
POTENTIAL GEOTECHNICAL AND HYDROGEOLOGIC PROBLEM LOCATIONS

Location ID[a]	RM/ Reach	Potential Problem Description	Outside Bend (Y/N/S)[b]	Riverside Slope[c]	Levee Configuration: Height (feet)[d]	Levee Configuration: Crest Width (feet)	Observed/ Potential Conditions: Seepage	Observed/ Potential Conditions: Piping	Observed/ Potential Conditions: Scour/Erosion	Failure Rating
G-33	4.03 FR-C	Two 48-inch diameter culverts with flap gates	Y	M	5	15 to 20	x	x		*e*
G-34	4.2 to 4.4 GR-A	Numerous trees near toe of slope	S	M	5 to 10	15 to 40	x			*e*
G-35	4.4 to 4.5 GL-B/-C	Moderate to severe slopes	N	M to S	5 to 10	15 to 20			x	*e*
G-36	4.48 to 4.72 HR-A	Numerous alder trees on slope, Toe erosion and scattered riprap	N	M	5 to 10	15 to 20	x			*e*
G-37	4.53 HL-A	Culvert with missing flap gate	N	M to S	5	15 to 20	x	x		*e*
G-38	4.72 to 4.84 HR-B	Moderate to severe slopes	N	M to S	7 to 10	20 to 25			x	*e*
G-39	4.72 HR-B	Culvert with flap gate	N	M to S	7 to 10	20 to 25	x	x		*e*
G-40	5.01 to 5.19 IR-B	Moderate to severe slopes	N	M to S	<5 to 12	15 to 25			x	*e*
G-41	5.05 to 5.12 IL-C	Moderate to severe slopes	N	M to S	5 to 7	15 to 20			x	*e*
G-42	~5.08 IL-C	Toe erosion, little to no riprap observed during river reconnaissance, subsurface conditions unknown	N	M to S	5 to 7	15 to 20			x	*e*
G-43	~5.08 IL-C	5-foot diameter maple growing on landside crest	N	M to S	5 to 7	15 to 20	x			*e*
G-44	5.21 JR-A	Drainage collecting on landside / riverside toe erosion, abundant trees midslope	N	M	1 to 4	15 to 18	x			*e*
G-45	5.58 JR-C	Soft ground/depression at crest / 20-inch probe depth	N	M	0	Slopes to high ground	x	x		*e*
G-46	5.6 JR-C	Soft ground/depression at crest / 14-inch probe depth	N	M	0	Slopes to high ground			x	*e*

a. See Figure 3-5 for problem locations.
b. Outside Bend (Y = yes, N = no, S = slight)
c. N = Noncritical slope 2:1 horizontal to vertical (2H:1V) or flatter; M = Moderate slope from 2H:1V to 1.5H:1V; S = Severe slopes steeper than 1.5H:1V. From Shannon & Wilson, 2009.
d. Levee height measured from the landward side
e. Failure rating not computed for Problems G-25 through G-48.

The preliminary evaluation identified representative problem types and locations. Findings from this evaluation were applied to the larger list of potential problems to determine the geotechnical and hydrogeological problems that warrant full consideration of failure potential.

As noted in Table 3-4, sparse riprap was observed at several locations. These observations were made primarily during a river reconnaissance and are not based on subsurface exploration. Alluvial deposits obscure riprap in some locations, so the extent of riprap is unknown. Only observed riprap at the ground surface was used in the initial potential problem area assessment and rating presented in the table. As a result, the table may overstate levee vulnerability to erosion and slope instability. Detailed stability analysis completed for this project as discussed in Section 3.6 incorporated the uncertainty in the distribution and thickness of riprap. Additional discussion of riprap and original design configurations is provided in Section 3.3. Following assignment of failure ratings for problems G-1 through G-24, four of the problems were removed:

- Problem G-7 was removed because King County reported that additional riprap had been placed in this area following the original levee ratings in 2009.
- Problem G-16 and G-19 were removed because these problems are hydraulic issues.
- Problems G-22 was removed because the levee height is less than 2 feet.

The remaining 20 problems selected for a higher level of evaluation include 11 potential seepage or piping problems (combined with erosion, depression, or steep slopes) and nine steep slope or bank erosion problems. The geotechnical and hydrogeological problem locations of the top 20 are shown in Figures 3-5 through 3-8.

3.2.2 Critical Sections

Following the determination of potential geotechnical and hydrogeologic problem ratings, the project team and King County selected seven critical sections for additional stability and seepage analyses. Potential problems with a likelihood of failure rating of 7 or greater were selected as critical sections. Five of the sections are on the left bank and two are on the right bank. Critical section locations are listed in Table 3-5; locations are also shown in Figures 3-5 through Figure 3-8. The levee height of the critical sections as measured from the landside toe is typically 4 to 5 feet, with the exception of locations G-3 and G-23 which are 8 and 10 feet high, respectively. Levee crest widths vary from 15 feet at locations G-1 and G-23 to greater than 20 feet at the other locations. Riverside slope inclinations are severe (steeper than 1.5H:1V) at locations G-3, G-5, G-15, and G-23, and moderate (1.5 -2H:1V) at the remaining locations.

TABLE 3-5
CRITICAL SECTION LOCATIONS

Location ID	River Bank	River Mile
G-1	Right	2.27
G-2	Left	2.51
G-3	Left	2.70
G-5	Left	3.10
G-8	Left	4.18
G-15	Right	2.47
G-23	Left	4.5 to 4.6

Figure 3-5. Potential Geotechnical Problem and Critical Section Locations RM 2.0 to RM 2.7

Figure 3-6. Potential Geotechnical Problem and Critical Section Locations RM 2.7 to RM 3.6

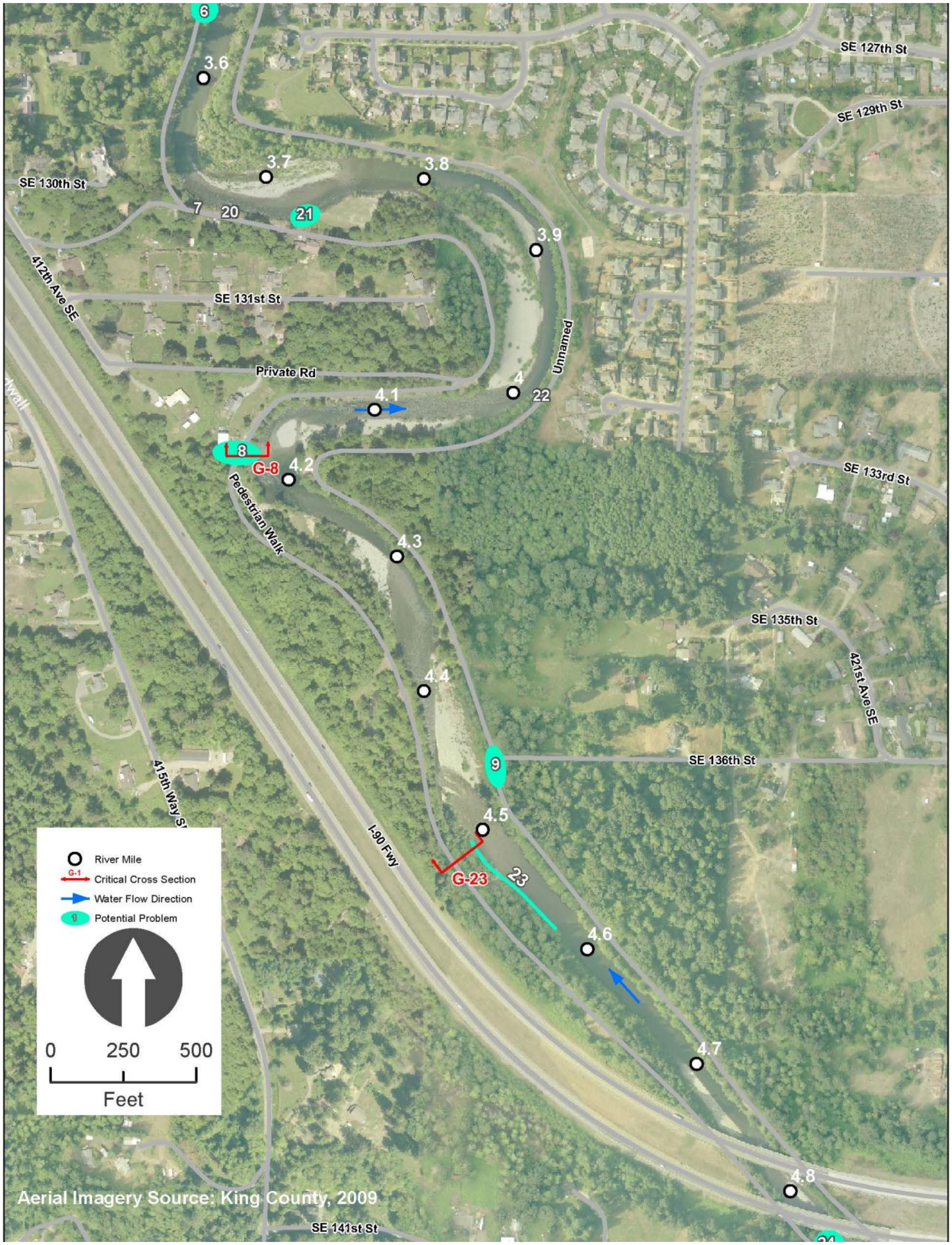


Figure 3-7. Potential Geotechnical Problem and Critical Section Locations RM 3.6 to RM 4.8

Figure 3-8. Potential Geotechnical Problem and Critical Section Locations RM 4.8 to RM 5.4

Ground surface profiles based on elevation (NAVD88) for each of the cross sections were obtained from HEC-RAS modeling used in the hydraulic analysis described in Chapter 2. Figures 3-9 through 3-15 present the levee cross section at each critical location. Generalized subsurface conditions are shown in the figures and discussed in more detail in Section 3.3. Representative photographs of the seven critical sections are presented in Appendix C.

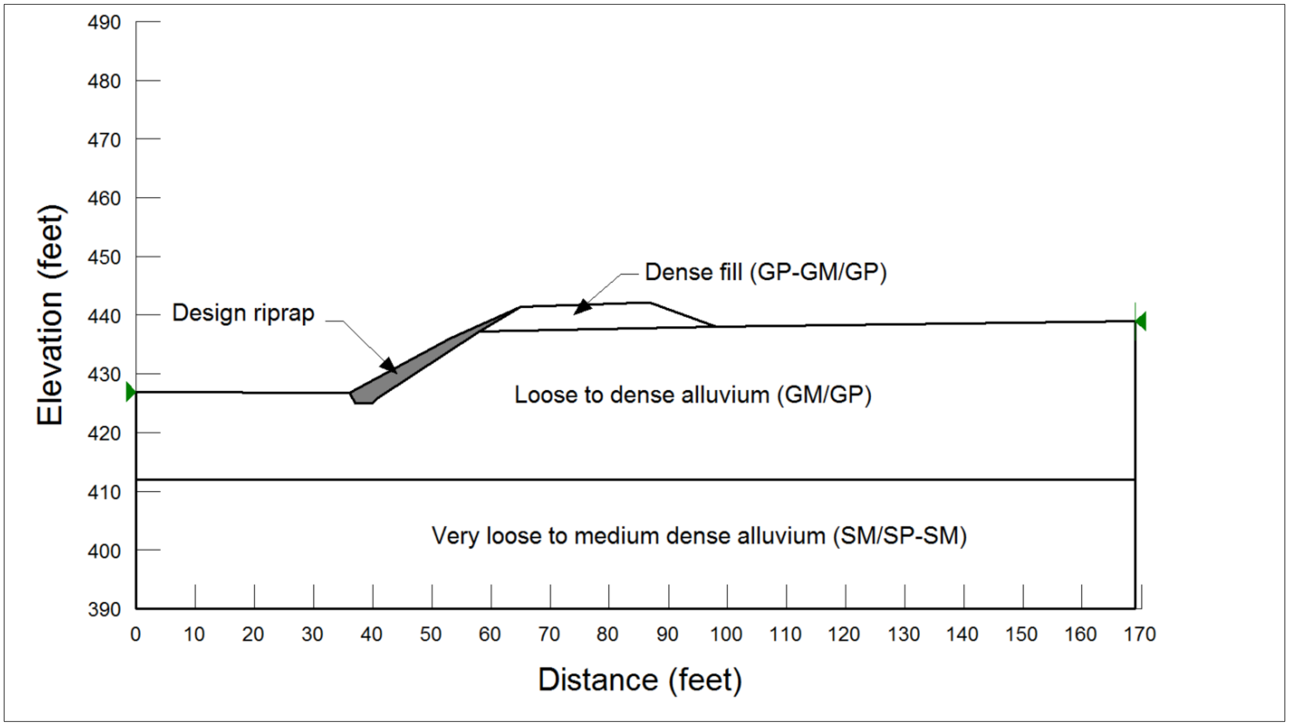


Figure 3-9. Levee Cross Section, Critical Section Location G-1

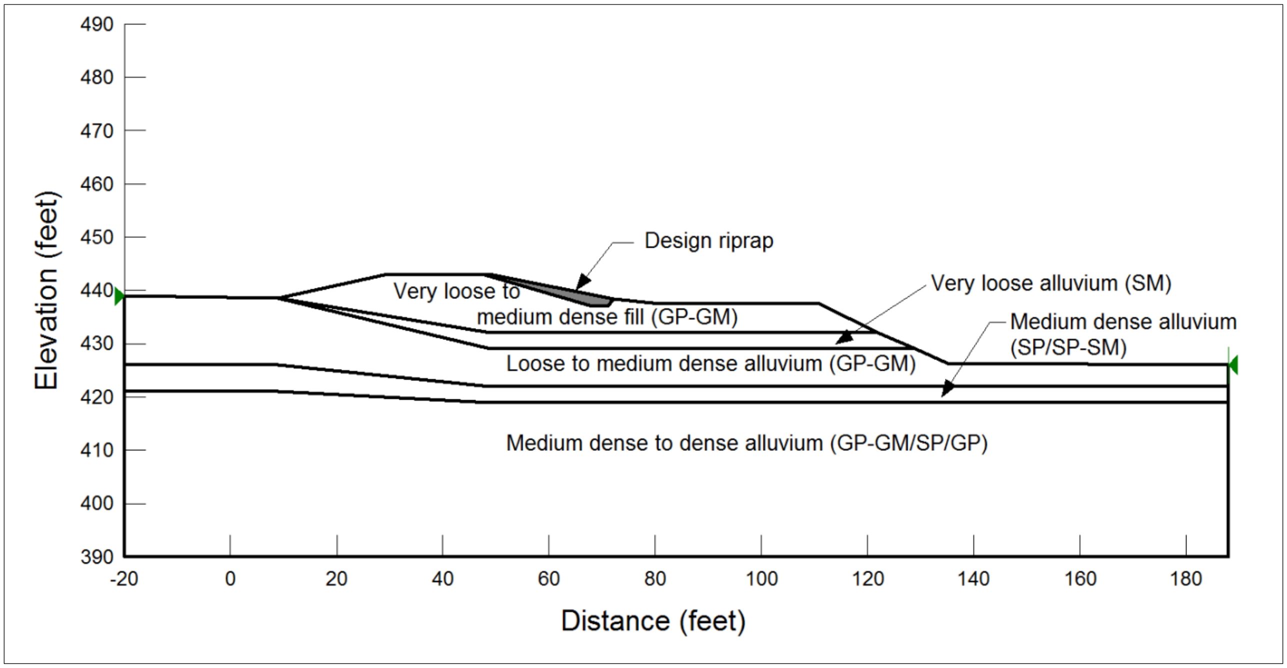


Figure 3-10. Levee Cross Section, Critical Section Location G-2

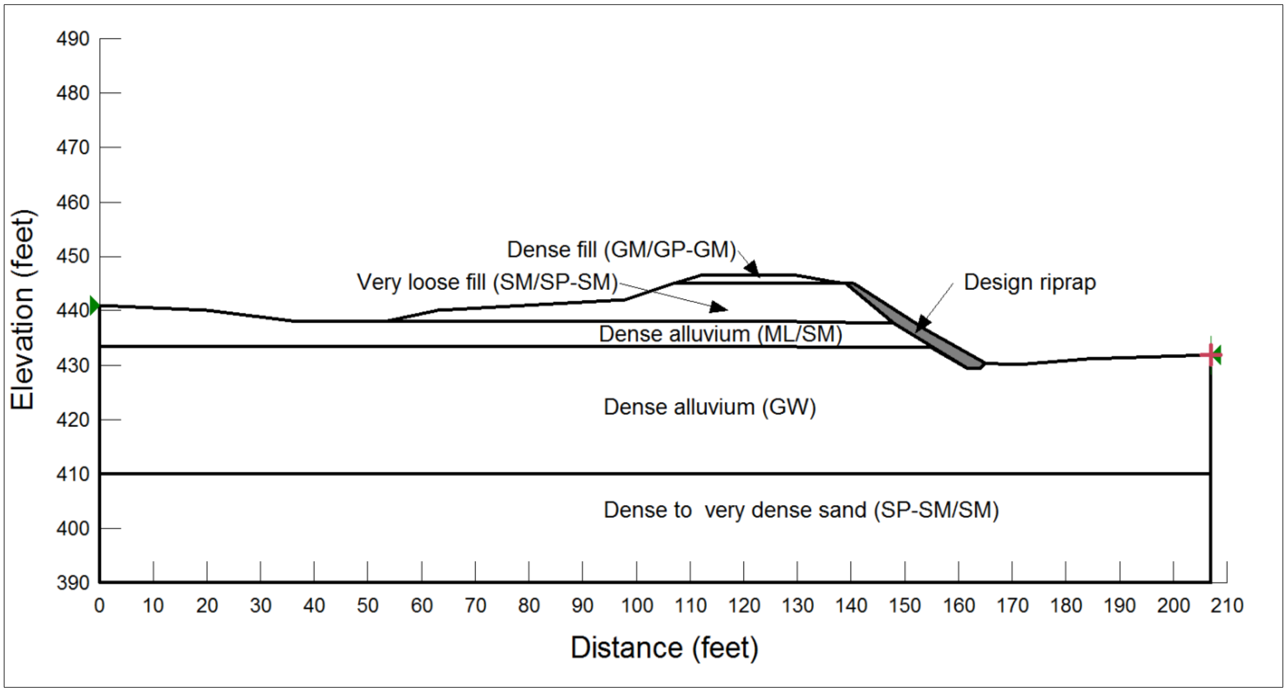


Figure 3-11. Levee Cross Section, Critical Section Location G-3

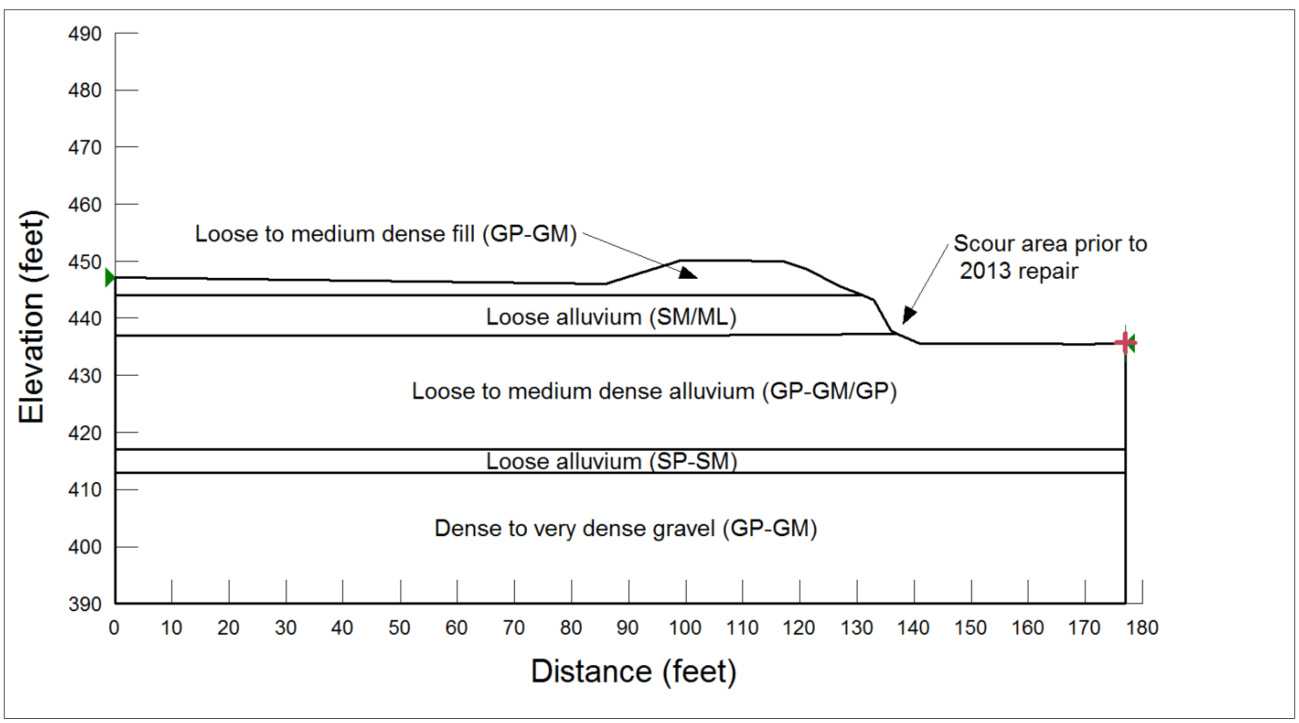


Figure 3-12. Levee Cross Section, Critical Section Location G-5

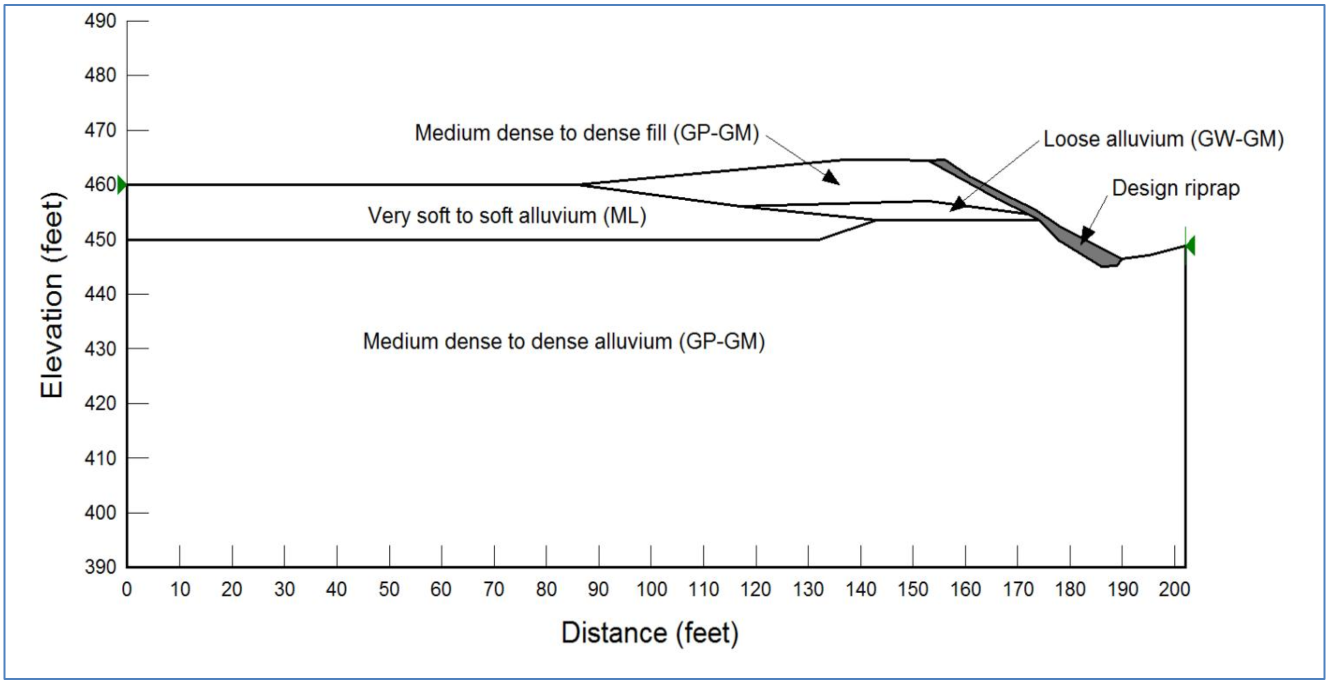


Figure 3-13. Levee Cross Section, Critical Section Location G-8

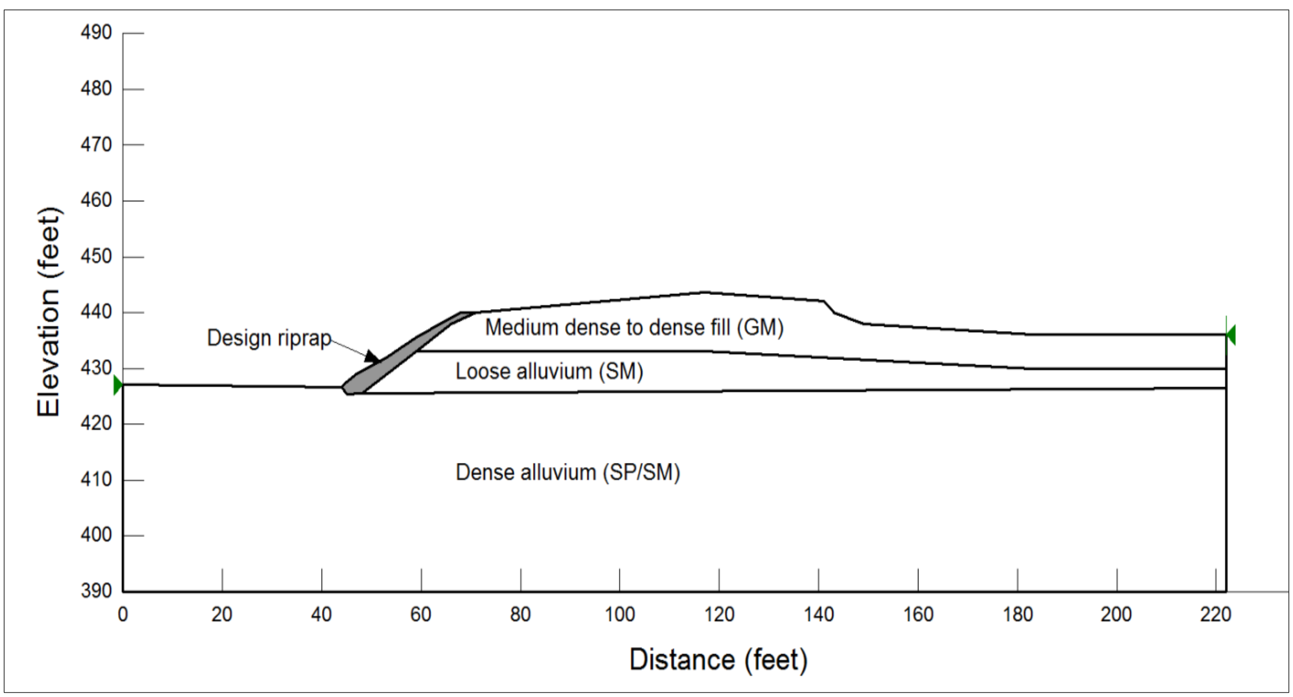


Figure 3-14. Levee Cross Section, Critical Section Location G-15

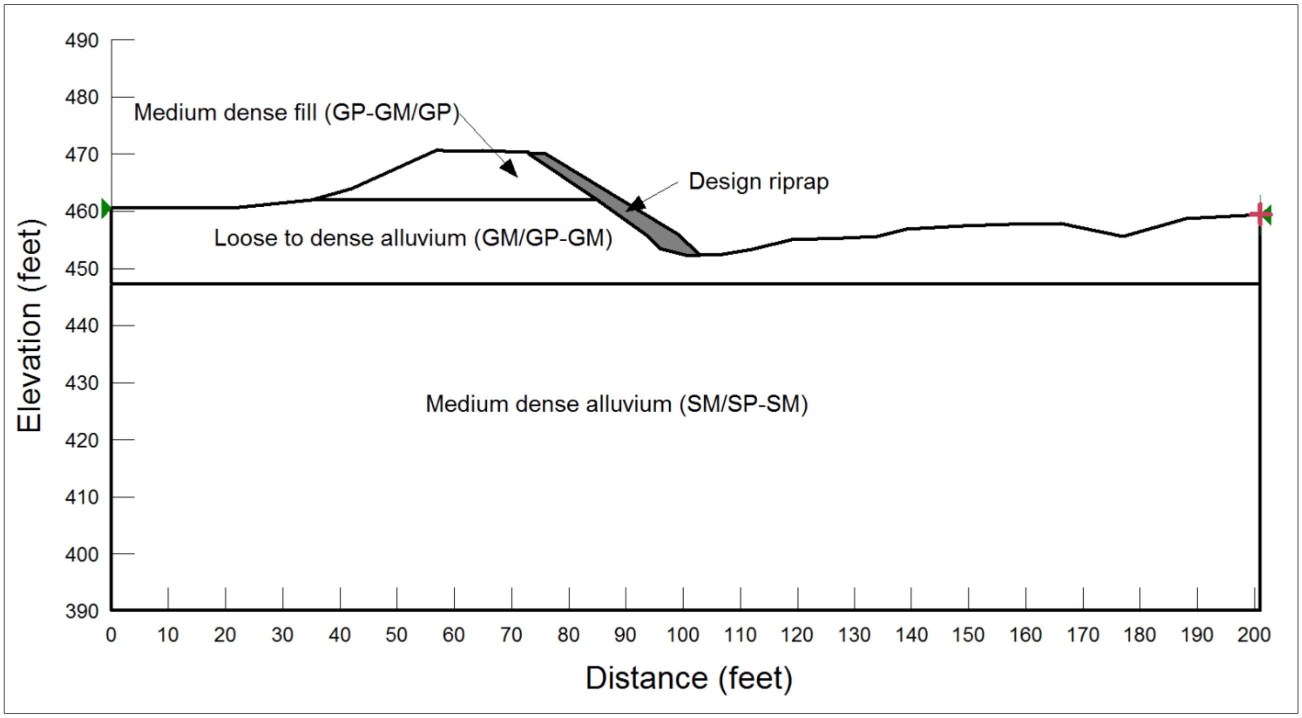


Figure 3-15. Levee Cross Section, Critical Section Location G-23

3.3 LEVEE PROTECTION

The presence and thickness of levee protection is a key element for the analysis of levee slope stability. A greater riprap thickness provides higher shear resistance to slope failure and therefore a higher factor of safety.

Historical plan documents for the levees show the design riprap protection having a 3-foot thickness at the toe of the riverside slope, tapering to a 2-foot thickness at the crest. However, detailed levee reconnaissance data (Shannon & Wilson 2009) indicates scattered to sparse riprap over more than two-thirds of the riverside slopes. The 2009 observations were made during multiple field reconnaissance visits accessing from the levee crest, and one from the river using a raft. Scattered to no riprap or toe erosion was noted in half of the top 20 potential geotechnical problem locations (G-1, G-2, G-3, G-4, G-5, G-9, G-11, G-17, G-20 and G-21).

Based on the documented design thickness and discussions with King County staff, the reported absence of riprap during previous reconnaissance may be incorrect, because it may have been obscured by an overlying layer of fluvial deposits and vegetation. To support this conclusion, King County completed three excavations in the riverside slope in July 2013 with the project team to evaluate the riprap thickness. Excavations were made where reconnaissance data indicated sparse to no riprap, in the vicinity of locations G-5, G-17, and G-21. The riverside slope was excavated from the levee crest with a track excavator owned and operated by King County. Two of the excavations were completed from the approximate mid-slope of the riverside slope and extended to about the levee crest (near location G-5 and G-17). The third excavation was located near location G-21 and was excavated from the midslope, extending down below the toe. The levee in this area is currently offset from the river where a sand bar separates the levee from the current channel location. A summary of the conditions encountered at these locations is presented in Table 3-6.

TABLE 3-6
EXCAVATIONS TO EVALUATE RIPRAP THICKNESS

River Mile/ Problem Area[a]	Description	Riprap Encountered
3.11, Left Bank, Near Location G-5	Excavated in middle portion of riverside slope	3-foot thickness encountered beneath silty sand cover. Riprap is 12 to 24 inches in size
3.19, Left Bank, Location G-17	Excavated in middle to upper portion of riverside slope	3-foot thickness of riprap encountered at midslope, 12- to 18-inch in size. 1½- to 2-foot thickness of quarry spalls with occasional cobbles encountered within the upper four feet of the slope
3.73, Left Bank, Location G-21	Excavated from riverside midslope to bottom of levee, levee is offset from river	Greater than 3-foot thickness encountered from midslope to approximately 3 feet below toe of slope. Rock is 2 to 3 feet in size. Also probing with steel rod through riverside slope detected riprap.

a. Excavated on July 16, 2013 with excavator owned and operated by King County

Based on the this data and discussions with King County, it appears that the rock thickness is in general accordance with the historical plan documents except where repairs or other maintenance have been performed. The riprap apparently is buried by alluvium and obscured by vegetative growth. The rock type differed in one of the explorations (the upper portion of the riverside slope near location G-17 encountered quarry spalls). This observation is based on a relatively small data sample so the presence of riprap cannot be confirmed with complete certainty. Uncertainty of the presence of riprap may be decreased by completing additional exploration in areas where sparse riprap was noted.

3.4 SUBSURFACE CONDITIONS

3.4.1 Field Explorations

Subsurface soil and groundwater conditions were evaluated by reviewing previous explorations and drilling six supplemental borings. Supplemental borings were drilled with a sonic Geoprobe 8140LS track rig owned and operated by Major Drilling. The explorations were continuously monitored by a geotechnical engineer who examined and classified the soils encountered, obtained representative soil samples, observed groundwater conditions, and prepared a detailed log of each boring. Locations of the explorations are shown on Figures 3-16 through 3-19.

Disturbed grab samples were obtained from the sonic cores, and standard penetration test samples were obtained at 5-foot intervals. The standard penetration test sampler was driven into the soil with a 140-pound hammer. The number of blows required to drive the sampler the last 12 inches or other indicated distance is recorded on the boring logs. Blow counts are likely overstated when the sampler was driven in samples with high gravel content. The logs are based on interpretation of the field and laboratory data and indicate the types of soils and groundwater conditions encountered. The logs also indicate depths at which these soils or their characteristics change, although the actual change may be gradual. The classification system and logs of the borings are presented in Appendix C.

Observations of groundwater conditions were made during drilling, and monitoring wells were installed in three of the borings (B-3-11, B-4-11, and B-5-11). Solinst Levellogger Gold series data loggers were placed in the wells to monitor long-term groundwater conditions at the site. Groundwater data and analyses are summarized in detail in Appendix C.

Figure 3-16. Borings, GPR Survey and Test Pit Locations RM 2.0 to RM 2.7

Figure 3-17. Borings, GPR Survey and Test Pit Locations RM 2.7 to RM 3.6

Figure 3-18. Borings, GPR Survey and Test Pit Locations RM 3.6 to RM 4.8

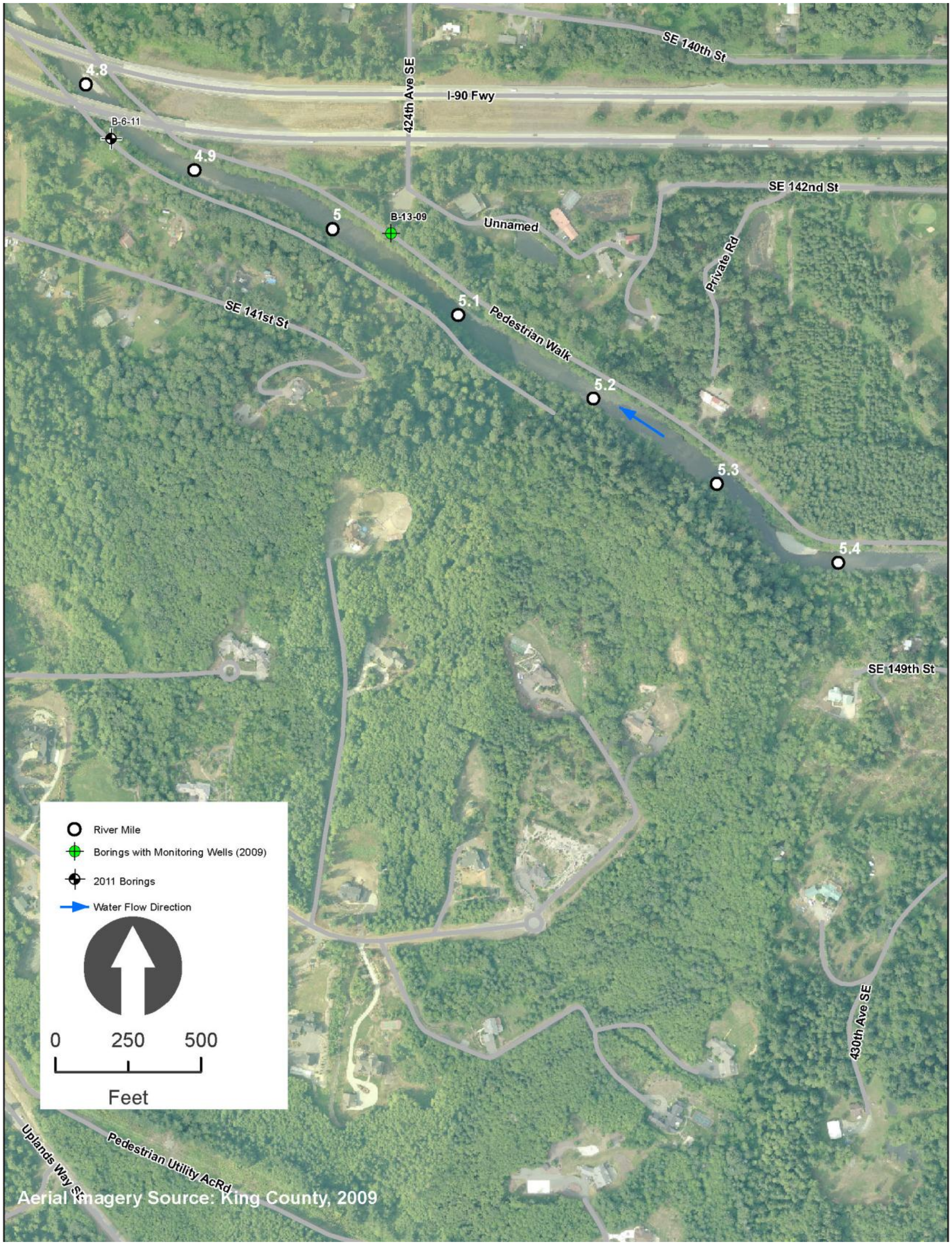


Figure 3-19. Borings, GPR Survey and Test Pit Locations RM 4.8 to RM 5.4

3.4.2 Soil Conditions

Subsurface soils are relatively consistent in the study area borings, consisting of mostly cohesionless soils with high permeability. Levee fill encountered in the current and previous borings consists primarily of medium dense to dense gravel with variable silt and sand. Occasional layers of silty sand with gravel were encountered in the fill. Foundation soils beneath the levee are generally more fine-grained (sand with variable silt or silt layers), grading into mostly gravel with sand and silt and occasional sand layers.

Both the levee fill and underlying soils encountered in the borings are representative of the native alluvial deposits in the North Bend area, containing coarse-grained deposits of moderate to high permeability. Typically, the levee fill soil type is medium dense, has an internal friction angle of 36 degrees or greater, and will remain stable at moderate to steep slopes (up to about 1.5H:1V) under static loading conditions. Slope failures are more likely to occur under rapid drawdown and seismic conditions.

Strength parameters for soils in the slope stability analyses were assumed based on parameters used in previous studies (Shannon & Wilson, 2009), soil classification, standard penetration test data, and the performance of the existing levee slopes. Triaxial strength tests were not performed because of the large particles in the samples and the inability to collect a relatively undisturbed sample. Results agree with the strength parameters developed by Shannon & Wilson, although a lower friction angle was used for soil layers that were very loose to medium dense. A summary of soil types encountered in the borings and strength parameters used in the analyses is shown in Table 3-7. Detailed laboratory test results and discussions of hydraulic conductivity are provided in Appendix C.

TABLE 3-7.
SUMMARY OF BORING SOILS AND STRENGTH PARAMETERS

Soil Layer and Classification	U.S. Soil Conservation Service Soil Classification[a]	Density (γ) (pounds per cubic foot)	Friction Angle (ϕ) (degrees)	Cohesion (c) (pounds per square foot)
Gravelly Soils				
Dense Gravel Fill	GP-GM/GP	130	36	0
Very Dense Alluvium	GP-GM	130	36	0
Medium Dense to Dense Alluvium/Fill	GP-GM/SP/GP	125	36	0
Very Loose to Medium Dense Fill	GP-GM	125	34	0
Loose to Dense Alluvium	GM/GP	125	34	0
Loose to Medium Dense Alluvium	GP-GM/GW-GM	125	32	0
Sandy Soils				
Dense to Very Dense Sand	SP-SM/SM	125	36	0
Medium Dense to Dense Alluvium	SP/SP-SM/ML/SM	120	34	0 to 50
Very Loose to Medium Dense Alluvium	SM/SP-SM	115	32	0
Very Loose Fill / Loose Alluvium	SM/SP-SM/ML	120	30	0 to 50

a. Soil classifications as follows:
- GW = Well graded gravels and gravel-sand mixtures, little or no fines
- GM = Silty gravels, gravel-sand-silt mixtures
- GP = Poorly graded gravels and gravel-sand mixtures, little or no fines
- ML = Inorganic silts, very fine sands, rock flour, silty or clayey fine sands
- SM = Silty sands, sand-silt mixtures
- SP = Poorly graded sands and gravelly sands, little or no fines.

3.4.3 Ground Penetrating Radar Survey

GPR studies were completed to evaluate the potential for stumps and logs in the levees, which present a significant risk to stability from piping failure. GPR testing was completed in 2008 by Shannon & Wilson and additional testing along the left bank of the South Fork Snoqualmie Levee was performed for this study in 2012. The locations of the GPR surveys are shown in Figures 3-16 through Figure 3-19.

The 2008 testing consisted of a GPR survey on a few hundred feet of the left bank levee, in the vicinity of RM 3.0. A subsequent backhoe test pit verification procedure included excavating four test pits within the GPR survey area, designated as TP-7 through TP-10. No obvious GPR targets were observed in test pits TP-7 and TP-8, and no debris was encountered during excavation. GPR targets were observed in TP-9 and TP-10, and large decayed wood pieces were encountered in one of the test pits (TP-10). Therefore the GPR results in three of the four test pits were accurate, or an approximate 75-percent success rate in identifying stumps.

GPR survey for this study included 9,000 feet on the left bank between RM 2.5 and RM 4.2. The left bank was selected because the levee heights are greater and therefore contain higher geotechnical and hydrogeologic risk, and because large stumps were previously found within this area. Anomalies identified by the GPR survey indicate a change in subsurface conditions, which typically represents extraneous matter. The most likely extraneous matter are tree stumps and logs; however, the anomalies may also represent other items such as below-grade pipes or structures. Backhoe excavation would be needed to explore the anomalies to confirm the presence or absence, and type of extraneous matter..

Results of the GPR survey noted that strong anomalous zones were observed in four general areas, and moderate anomalous zones were observed in more than 40 areas. The GPR stationing and approximate river mile locations of the strong anomalous zones, number and depth of the strong targets, and general comments relating to other site observations or conditions are summarized in Table 3-8.

TABLE 3-8.
SUMMARY OF STRONG ANOMALOUS ZONES

Location[a]	GPR Stationing (feet)	River Mile	Description of Observed Targets: No. of Strong Targets	Description of Observed Targets: Depth Below Levee Crest (feet)	Approx. Levee Height (feet)	Comments
1	4620 - 4640	3.41	5	2 to 5	< 2	4 depressions observed in vicinity, overtopping at 5 percent chance flood
2	5710 - 5750	3.60	7	5 to 7½	4 to 6	No reported depressions, protection provided for 1 percent chance flood
3	5860 - 5930	3.62	7	2½ to 5	4 to 6	No reported depressions, protection provided for 1 percent chance flood
4	7670 - 7730	4.04	7	2½ to 5	2 to 3	Sinkhole noted in King County Map dated 4/29/2008, 2009 Reif Road repair area, overtopping at 2 percent chance flood

a. All locations are on the left bank.

Two backhoe test pits were completed on July 16, 2013 by an excavator owned and operated by King County in an attempt to explain the anomalies at Locations 2 and 3. Additional excavations are recommended at Locations 1 and 4 to evaluate the anomalies at these locations. Test pits TP-1 and TP-2 were excavated at Locations 2 and 3 respectively, and are shown on Figure 3-18. Appendix C includes the logs of the explorations.

The test pit excavation at Locations 2 and 3 did not find the anomalies identified by the GPR. Large stumps were not encountered in the test pits. Occasional wood debris, with diameters of 1 to 8 inches, was encountered below a depth of 6 feet in both test pits. If additional GPR testing is completed, greater success may be achieved in finding anomalies by excavating test pits with the GPR equipment on site.

3.5 HYDROGEOLOGIC CONDITIONS

3.5.1 Groundwater Monitoring

The local hydrogeology of the project area was reviewed to develop a better understanding of the groundwater system in the North Bend aquifer. Groundwater levels were measured in monitoring wells installed through the levee and on the landward side of the levee at locations along both banks. Groundwater levels tended to follow river levels closely and rapidly, indicating that the shallow groundwater system is strongly connected to the South Fork Snoqualmie River level. Groundwater monitoring records are compared with river levels where the data is available during Water Years 2010, 2011 and 2012 in the comparative hydrographs provided in Appendix C.

3.5.2 Seepage Analyses Methods

Seepage analyses were completed at each critical section to examine the rates at which water loss can occur from the river, beneath and through the levee. Seepage analysis also helps to define pore pressure distributions used in the stability analyses and to assess potential critical exit gradients for seepage on the landward side of levees that could cause piping or instability at the landward toe.

Seepage analyses were completed using SEEP/W, a finite element computer model (GeoStudio, 2012). The model simulates seepage and groundwater flow by evaluating groundwater flow equations within finite elements across the domain defined for each model, and dependent on applied boundary conditions. The modeling process, assumptions and results are described in detail in Appendix C.

Table 3-9 includes estimated values for total and levee seepage flows (in cfs) if these conditions are uniform over a quarter-mile of levee length at each section location. Total seepage flow represents the loss from the South Fork Snoqualmie River and includes seepage through and beneath the levee only. Levee seepage represents the direct lateral seepage loss through the full height of the levee and does not include seepage beneath the levee. Piping flow and exit gradients at the landward toe were evaluated as shown in the table and discussed below.

SEEP/W also allows flows to be determined at other points by inspection. Groundwater discharge simulated at the seepage face set along the landward toe of the levee was evaluated by adding the nodal discharges at one or more nodes along the active seepage face. Since the SEEP/W model is nominally 1 foot deep (parallel to the levee axis), the seepage rates it calculates are equivalent to cubic feet per second (cfs) per lineal foot of levee. For low-lying areas behind the levee, toe seepage can be extrapolated over a case-specific levee length to estimate corresponding seepage contribution to surface water during flooding. In addition, piping flow was estimated for a partially developed soil pipe that is arbitrarily assumed to discharge at a point for all toe seepage developed over a levee length of 25 feet. This is an approximate estimate of piping flow, which could be substantially greater at discrete locations, such as through the action of rodents.

TABLE 3-9
SEEPAGE FLUX RATES FROM SEEP/W

Section Location[a]	Total Seepage[b]		Levee Seepage[c]		Toe Seepage[d]	Piping Flow (gallons/ minute)	Exit Gradient[e] (feet/feet)
	Flux ($feet^2/s$)	Flow (cfs)	Flux ($feet^2/s$)	Flow (cfs)	Flow (cfs)		
G-1	0.00203	2.68	0.000265	0.35	0.000778	8.7	0.07
G-2	0.01034	13.65	0.000686	0.91	0	0	0
G-3	0.00125	1.65	0.000022	0.03	0.000008	0.09	0.07
G-5	0.00938	12.38	0.000303	0.40	0.000171	1.9	0.05
G-8	0.00329	4.34	0.000130	0.17	0.000236	2.7	0.13
G-15	0.00193	2.55	0.000371	0.49	0.000930	10.4	0.13
G-23	0.00248	3.27	0.000111	0.15	0.000892	10.0	0.15

a. See Figure 3-5 through 3-8.
b. Includes seepage flow through and beneath levee.
c. Seepage flow through levee only.
d. Estimated volume of discharge flowing out of landward toe.
e. Average hydraulic gradient at the toe of the levee.

Seepage analyses of the seven critical sections indicate adequate factors of safety against piping. Exit gradients were determined from the SEEP/W simulations at each critical section to evaluate the risk of piping per U.S. Army Corps of Engineers (USACE) guidelines (ETL 1110-2-569). The risk of piping at the seven critical sections was determined to be low, based on the guideline that a light/no seepage condition is estimated for exit gradients of < 0.2. However, the seepage analyses described in this section are for the assumed uniform conditions extrapolated from the boring data. It is likely that more critical local areas of high permeability layers exist, where piping and internal erosion may occur.

3.5.3 Piping Risk

Generally seepage below and through the levee soils appears to be widespread. In some locations, rapid seepage occurs via discrete pathways along highly permeable gravel zones that lack a matrix of less-permeable sand or silt. In other locations, these layers result in seeps and springs during flood events. These layers create a risk of seepage forces facilitating piping and internal erosion, which could compromise the stability of the levees. The occurrence of seepage is consistent with the relatively high permeability of the levee materials and subgrade soils, and would represent a significant concern if accompanied by the continued discharge of sand or other fine-grained materials, such as in the form of sand boils or detrital fans adjacent to seepage exit points. The generally broad grain-size distributions for most soils sampled in the borings suggest that they offer some filter resistance to the development of piping, which is more of a problem in relatively uniform soils with low coefficients of uniformity.

There is photographic and anecdotal evidence of seeps or springs during high water conditions that may indicate piping or internal erosion at points along the levee (see Figure 3-20). Sand boils were observed following the January 2009 flood in the vicinity of RM 2.70 (problem location G-3; see Figure 3-21). Depressions are noted in many areas that may be caused by piping. However, based on available levee documentation, there is no history of failure that can be attributed to seepage and/or piping.

Figure 3-20. Seepage Observed During 2009 Flood Event

Figure 3-21. Sand Boil Near Problem G-3 Observed During 2009 Flood Event

Given the alluvial environment, there is the possibility of discrete zones of higher permeability that can result in higher exit gradients and the potential for internal erosion. It is therefore important that areas at the toe of the levees be inspected during major storm events to check for signs of water seepage through and beneath the levees. Active seeps and sand boils that are carrying and depositing sand would be indicative of piping and internal erosion, signaling elevated risk of levee failure and breach. In general, higher levee sections with smaller crest widths are more likely to exhibit seepage. Reaches on the outside of bends may be more at risk if scour on the riverside slope reduces seepage path lengths through the levee, which would increase exit gradients.

3.6 SLOPE STABILITY ANALYSES AT CRITICAL SECTIONS

Slope stability analyses were completed using the computer program SLOPE/W (GeoStudio, 2012). SLOPE/W evaluates the stability of numerous trial shear surfaces using a vertical slice limit-equilibrium method. This method compares forces and moments driving slope movement to forces and moments resisting slope movement for each trial shear surface. It presents the result as a factor of safety. SLOPE/W can model complex stratigraphic and slip surface geometry, and variable pore-water pressure conditions. The program sorts the trial shear surfaces and identifies the surface with the lowest factor of safety. All seven critical sections were analyzed for four cases recommended by USACE Design and Construction of Levees (EM 1110-2-1913):

- **End of Construction.** This case is based on the current condition of the levee or the post-construction condition of improved levees. The water level in the river is assumed to be at mean annual flow for this analysis.
- **Steady State Seepage.** The levee stability is evaluated under flood conditions assuming a river level at design flood stage condition. Full saturation of the embankment occurs and seepage through the levee achieves a steady state condition. Stability of both the riverside and landside slopes are considered.
- **Rapid or Sudden Drawdown.** The levee stability under a rapid drawdown condition represents a prolonged flood stage that falls faster than the soil can drain. Excess pore water pressures are developed in the embankment, which can lead to slope instability.
- **Seismic.** Seismic evaluation of the levee varies depending on the project requirements. Susceptibility to liquefaction is typically evaluated and a reduced soil strength profile is used for pseudostatic analysis where liquefaction occurs. Horizontal accelerations used in analyses typically include the peak ground acceleration for the 100-year return period earthquake, or the 10 percent in 50-year (475-year return period) earthquake with an applied coefficient. Both horizontal accelerations were considered for the seismic stability analyses in this study. The potential for liquefaction for this study is discussed in Appendix C.

As discussed in Section 3.3, the thickness of riprap on the slope and at the toe of the levee has an impact on the stability; a greater riprap thickness provides higher shear resistance and therefore a higher factor of safety. To evaluate the upper and lower bound of factors of safety at each critical section, the riprap thickness was varied for the analyses as follows:

- A worst-case condition was evaluated assuming no riprap was present on the slope.
- Analyses were completed for the design thickness of riprap (a 3-foot section at the toe with a gradual taper to 1 foot at the crest).
- A greater thickness of riprap was modeled for Problem Areas G-1, G-2, and G-23 to determine what level of protection was needed for seismic stability.

Table 3-10 provides a summary of the stability analyses.

TABLE 3-10.
SUMMARY OF SLOPE STABILITY ANALYSES

Analysis Case	Location	River Mile	Bank	Factor of Safety (FS): Long-Term or Low Stage Condition[b,c] Required FS = 1.3	Steady Seepage at High Stage[b,d] Required FS = 1.4	Rapid Drawdown[b] Required FS = 1.0 to 1.2	Seismic[b,e] Required FS = 1.0
Unprotected Slope (No Riprap)	G-1	2.27	Right	1.20	1.35	1.49	0.88
	G-2	2.51	Left	1.33	1.54	1.09	0.91
	G-3	2.70	Left	1.32	1.16	1.20	0.84
	G-5[h]	3.10	Left	1.17	1.28	0.8 to 1.0	0.81
	G-8	4.18	Left	1.37	1.52	1.19	0.98
	G-15	2.47	Right	1.34	1.62	1.23	0.98
	G-23	4.50	Left	1.24	1.10	1.05	0.90
Protected Slope (Design Thickness of Riprap or Greater)[a]	G-1	2.27	Right	1.33	1.52	>1.49	0.96, 1.03[f]
	G-2	2.51	Left	>1.33	>1.54	>1.09	1.02
	G-3	2.70	Left	>1.32	1.49	>1.20	0.94, 1.07[g]
	G-5[h]	3.10	Left	1.27	1.78	1.20	1.02
	G-8	4.18	Left	>1.37	>1.52	>1.19	1.05
	G-15	2.47	Right	>1.34	>1.62	>1.23	1.07
	G-23	4.50	Left	1.33	1.48	>1.05	0.98, 1.02[g]

a. Design thickness of armor included a 3-foot thickness at the toe tapering to 1 foot at crest. Greater riprap thickness modeled for seismic condition as noted in footnotes f and g.
b. Required factor of safety based on U.S. Army Corps of Engineers Design of Levees.
c. Long-Term or Low Stage Condition based on water level at 2,000 cfs.
d. Steady state water level based on water surface elevation at levee crest or 1-percent-annual-chance flood event, whichever lower.
e. The design earthquake does not consider the effects of liquefaction or lateral spreading of the alluvial soils below groundwater. Water level assumed as low stage condition at 2,000 cfs.
f. Lower factor of safety shown for design armor, higher factor of safety for 5-foot thickness.
g. Lower factor of safety shown for design armor, higher factor of safety for 4-foot thickness.
h. Stability analysis shown for levee section G-5 represents condition prior to recently completed repairs.

(Blue shading) **Does Not Meet Factor of Safety Criteria (without riprap)**
(Red shading) Does Not Meet Factor of Safety Even with Design Riprap

The stability analyses show that the majority of the cases analyzed at the seven critical sections have adequate factors of safety per USACE standards, provided that the design section of riprap protection is present on the riverside slope face. The analyses were completed on the seven critical sections with regard to slope stability and seepage conditions. The remaining levee sections have more favorable conditions and are therefore considered to also have adequate factors of safety per USACE standards, provided that the design section of riprap is present. However, this conclusion is based on visual observations and may not account for vulnerabilities within the levee.

One exception, where the factor of safety is below what is required under the long-term or low-stage condition, is at location G-5, where the riverside bank was over-steepened due to ongoing sloughing and erosion. However, this condition has been repaired since the stability analysis was completed.

Three other exceptions occurred, at locations G-1, G-3, and G-23, where shallow failures with inadequate factors of safety are indicated under seismic conditions, even if there is the design thickness of riprap protection. A greater thickness of riprap (more than 3 feet) on the riverside slope is required at these locations to obtain the specified factor of safety under seismic conditions. The riprap section was increased in the analyses until the seismic factor of safety was greater than 1.0. This required a 4-foot thickness at locations G-3 and G-23, and a 5-foot thickness at location G-1.

The results of the seismic analyses show the failure surfaces are typically on the riverside slope, extending from the toe of the slope upward and exiting on the riverside slope or at the levee crest. For example, Figures 3-22 and 3-23 show the failure surfaces analyzed for location G-1 for the seismic case. Figure 3-22 represents the case where the riprap is assumed to be equal to the design thickness, and Figure 3-23 shows the failure surface if a 5-foot thickness of riprap were constructed on the slope. The thickness of the failed soil mass varies from about 3 to 5 feet for the seismic analyses. Detailed figures showing the results for each critical section location and analysis case are provided in Appendix C.

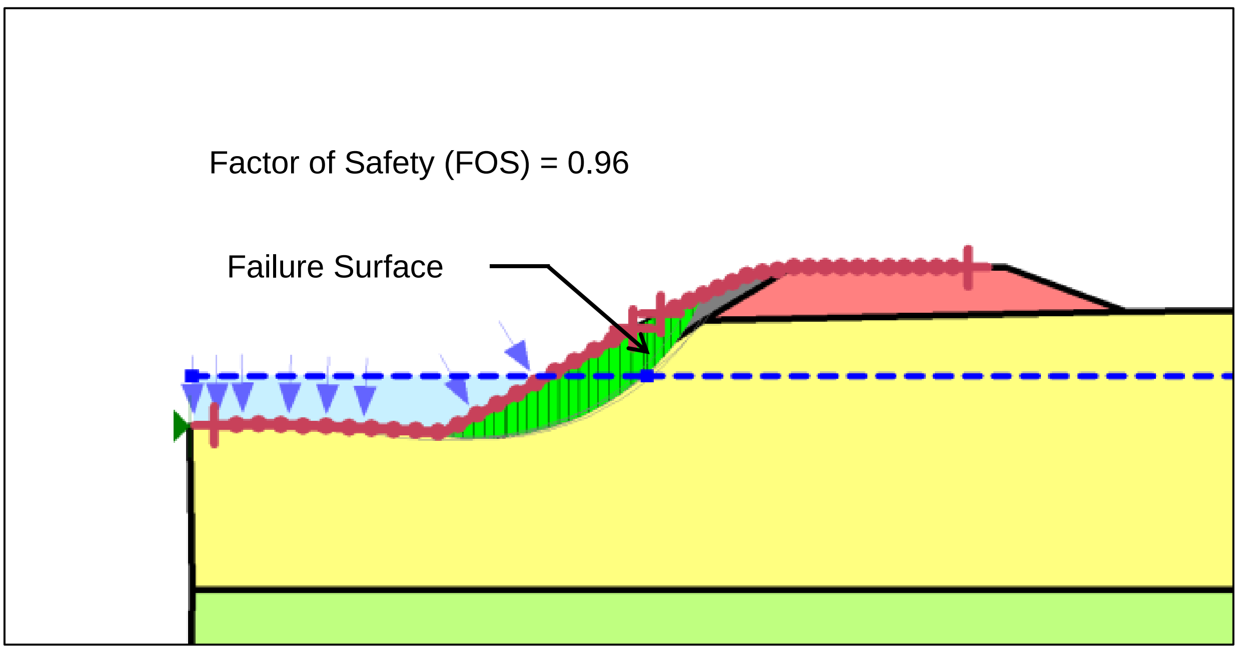


Figure 3-22. Location G-1, Seismic Results for Design Thickness of Riprap, Factor of Safety = 0.96

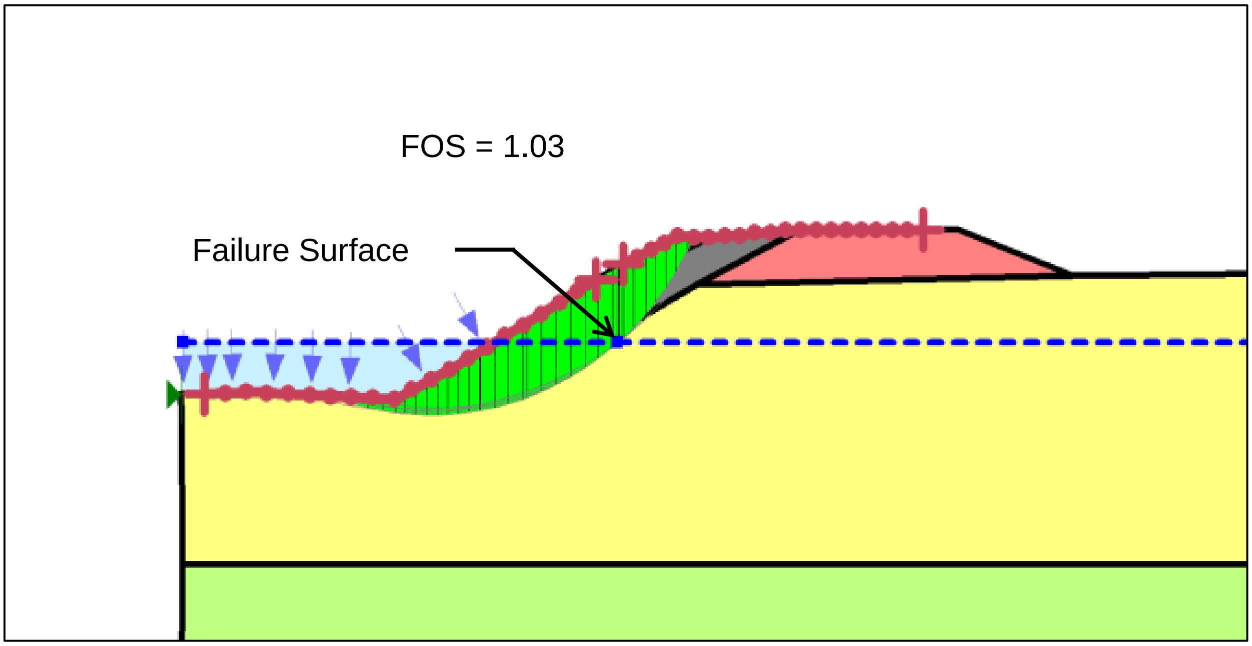


Figure 3-23. Location G-1, Seismic Results for 5-foot Thickness of Riprap, Factor of Safety = 1.03

3.7 SCOUR ANALYSES

3.7.1 Location Selection

The seven critical section locations and three other locations (G-4, G-11, and G-24) were considered selection of three locations for detailed scour analyses and stability analyses. The additional locations were included as potential scour analysis areas based on observed toe erosion and high velocity (G-4 and G-11) or based on proximity to the I-90 crossing (G-24). The project team and King County selected locations G-1, G-4, and G-24 for additional detailed scour and stability analyses.

3.7.2 Scour Analysis

Scour analyses were completed at locations G-1, G-4, and G-24 using the 1-percent-annual-chance peak flow hydraulic output of the FLO-2D model. Channel geometry was obtained from the HEC-RAS model used in the hydraulic analysis described in Chapter 2 and provided as station-elevation pairs for the in-channel portion of the wetted cross section. In all cases, the modeled water surface elevation was greater than the highest elevation of the cross section. The channel plan form used for bend radius measurements was derived from 1-foot LiDAR topography provided by King County. Sediment size estimates are based on the findings in the South Fork Snoqualmie River Gravel Removal Study (King County DNR, 2011). The results from the scour analysis are presented in Table 3-11.

Under the assumption that erodible material does extend to full scour depth (bedrock not present), bend and contraction scour were considered applicable to the project site and both conditions were evaluated. Several methods were used to evaluate potential scour depth, including equations by Thorne, Maynord, Laursen, Neil, Lacey and Blench. Detailed parameters used in the scour analyses are summarized in Appendix C.

TABLE 3-11
SUMMARY OF SCOUR CALCULATIONS FOR 1-PERCENT-ANNUAL-CHANCE FLOOD EVENT

Maximum Channel Flow Rate[a] (cfs)	Location[b]	Thalweg Elevation[c] (feet)	Potential Scour Depth			Potential Scour Elevation (NAVD88 feet)
			Contraction (feet)	Bend (feet)	Total (feet)	
13,650	G-1, RM 2.27	423.2	0.0	10.5	10.5	412.7
13,900	G-4, RM 2.87	425.3	1.5	10.0	11.5	413.8
14,450	G-24, RM 4.83	458.8	1.0	9.5	10.5	448.3

a. From FLO-2D analysis. Does not include floodplain flow or flow outside of the levee.
b. See Figures 3-5 through 3-8.
c. Assumes erodible material is deeper than potential scour depth.

After analysis and review of the results, bend scour was determined to be the primary mode of erosion occurring at all three project areas. Bend scour occurs on the outside of channel bends due to spiraling flow. It removes materials from the bank toe, precipitating toe erosion or mass failure. Contraction scour was calculated to be significant at two of three sites (G-4 and G-24). Contraction scour involves the removal of material from the riverbed across all or most of the channel width. This component of scour results from a contraction of the flow area, caused by a bridge or from natural narrowing of the stream channel. Scour is an aggregate process, so bend and contraction scour are summed to calculate total potential scour. The total calculated scour depth of 10.5 to 11.5 feet was incorporated into the ground surface profile of locations G-1, G-4, and G-24 for additional stability analyses. Although the degree of channel bend in each area was different, the calculated bend scour depth was similar. Based on these results and comparing the scour characteristics of the other site areas listed in Table 3-12, scour calculations in other areas are anticipated to be relatively similar.

3.7.3 Stability Analysis of Scour-Impacted Profile

Scour depths analyzed at the three locations were incorporated into the ground surface profile assuming two conditions. Condition 1 assumes that the scour depth occurs offset from the toe of the slope and infilling of bed material occurs at the toe. Condition 2 assumes that the full scour depth occurs at the toe of the existing riverside slope in a near vertical configuration. Figures 3-24 and 3-25 illustrate the assumed channel bottom for both scour configurations.

The two scour conditions were analyzed for slope stability at the three locations (G-1, G-4 and G-24) using both a high and low water condition. The results of the stability analyses indicate factors of safety less than the USACE standards for both scour conditions described above. For Condition 1, where infilling occurs, the analysis indicates a factor of safety slightly greater than 1.0, and loss of an approximate 3- to 5-foot thick section of the riverside slope that projects roughly to the riverside edge of the levee crest. Figures 3-26 and 3-27 present the results for this condition at location G-1.

The results of the stability analyses for Condition 2 indicate that factors of safety are less than 1.0. Factors of safety are as low as 0.5 indicating removal of about the outer 10 feet of the riverside slope; factors of safety near 1.0 indicate loss of about one-half of the levee crest width. The stability analysis results for location G-1 for Condition 2 are shown in Figure 3-28 and 3-29. The shape and size of the failure surfaces for the other two locations (G-4 and G-24) are similar, and results are provided in Appendix C.

TABLE 3-12
SUMMARY OF POTENTIAL SCOUR ANALYSES AREAS

	Scour Characteristic						
Location[a]	Observed Toe Erosion/Scour	Reported or Observed Seepage through Levee	Riverside Slope	Outside Bend or Contraction	Max. Average Channel Velocity[b] (feet/s)	Max. Channel Depth[b] (feet)	Soil Type[c]
G-1	Observed erosion at crest, sparse to no riprap	Yes	M	Outside Bend	7.65	14.7	GP, GM
G-2	Sparse riprap	Yes	M	Outside Bend	5.47	17.4	GP-GM, GM
G-3	Sparse riprap	Yes/Piping	M	No	9.98	15.0	SM, GW
G-4	Observed toe erosion	No	M	Contraction	9.01	22.0	GM, GP, SM
G-5	Observed erosion, scoured rills	Yes	S	No	7.72	14.1	GP-GM, GP
G-8	No	Yes	M	Outside Bend	7.45	18.0	GP-GM
G-11	Severe toe erosion	No	S	No	7.67	16.2	GW-GM, SM
G-15	No	Yes	S	No	5.64	16.1	SM, SP/SM
G-23	Scour and undercutting of riverside toe	No	S	Slight Outside Bend	8.5	17.5	GP-GM assumed
G-24	No	No	M	Slight Outside Bend	9.65	17.2	GM, GW, SP-SM

a. See Figures 3-5 through 3-8.
b. 1-percent-annual-chance-flood-event from FLO-2D analysis, see Chapter 2.
c. See Table 3-7 for description of soil type.

Lower Risk
Moderate Risk
High Risk

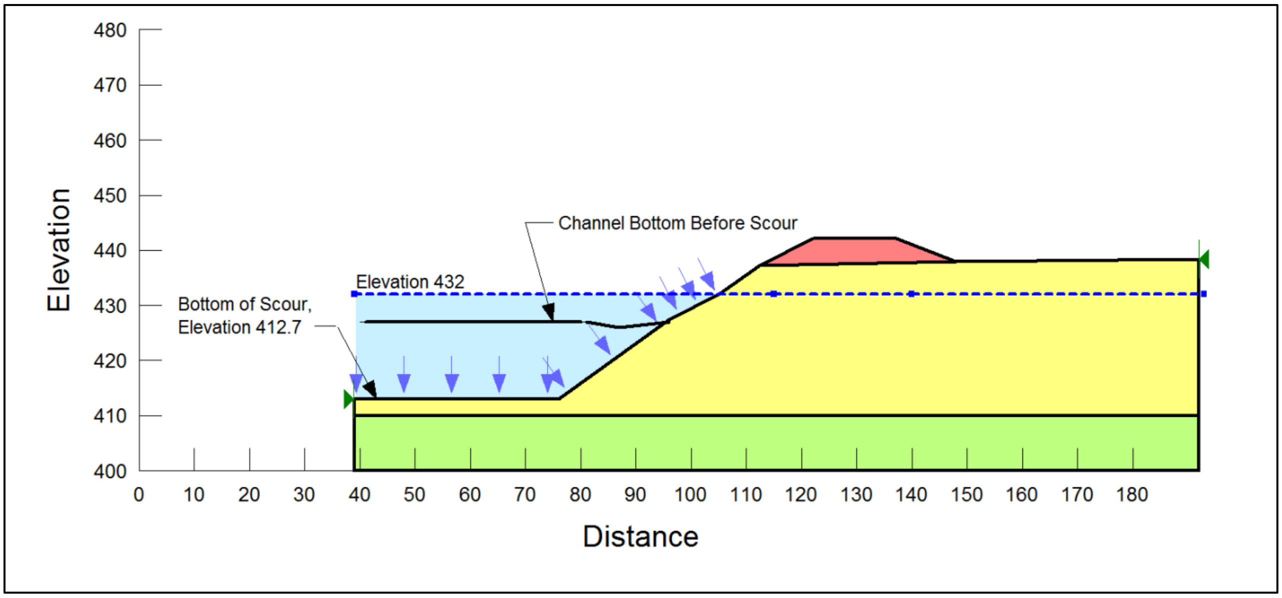


Figure 3-24. Condition 1, Infilling Occurs, Full Depth Scour is Offset from Original Toe of Riverside Slope

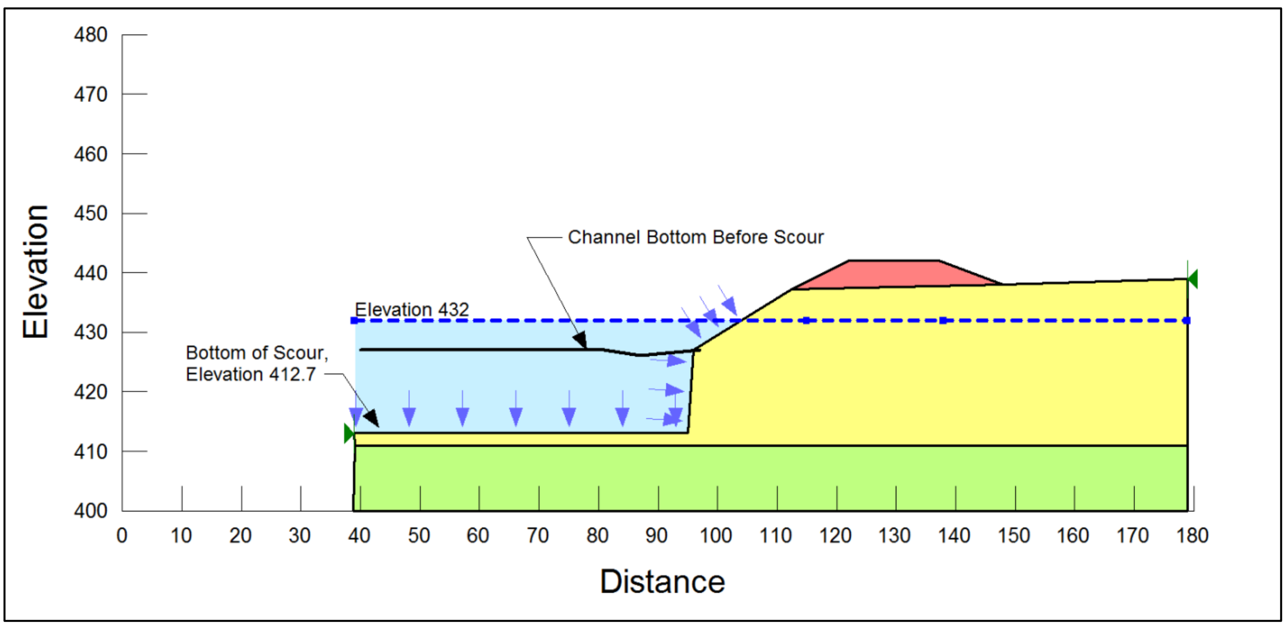


Figure 3-25. Condition 2, No Infilling, Full Depth Scour Occurs Below Original Toe of Riverside Slope

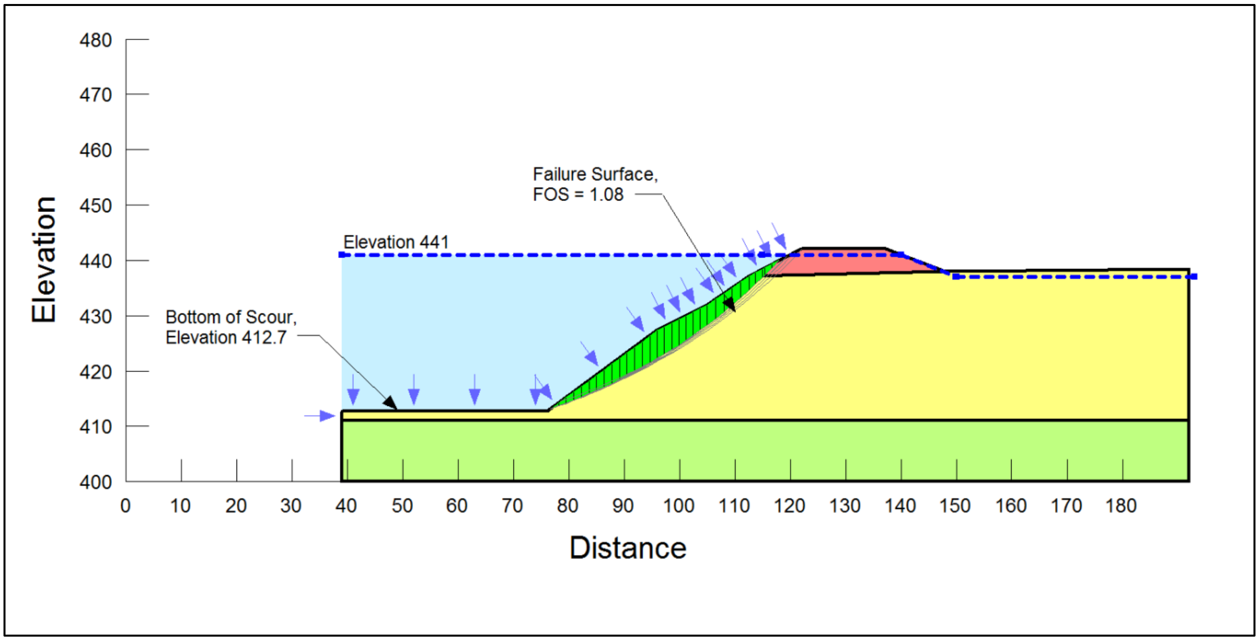


Figure 3-26. Stability Analyses Results, Scour Condition 1 at Location G-1, Water Level at 1 Percent Chance Flood Elevation; Failure Surface Results in Loss of About 5-foot Thick Section of Riverside Slope

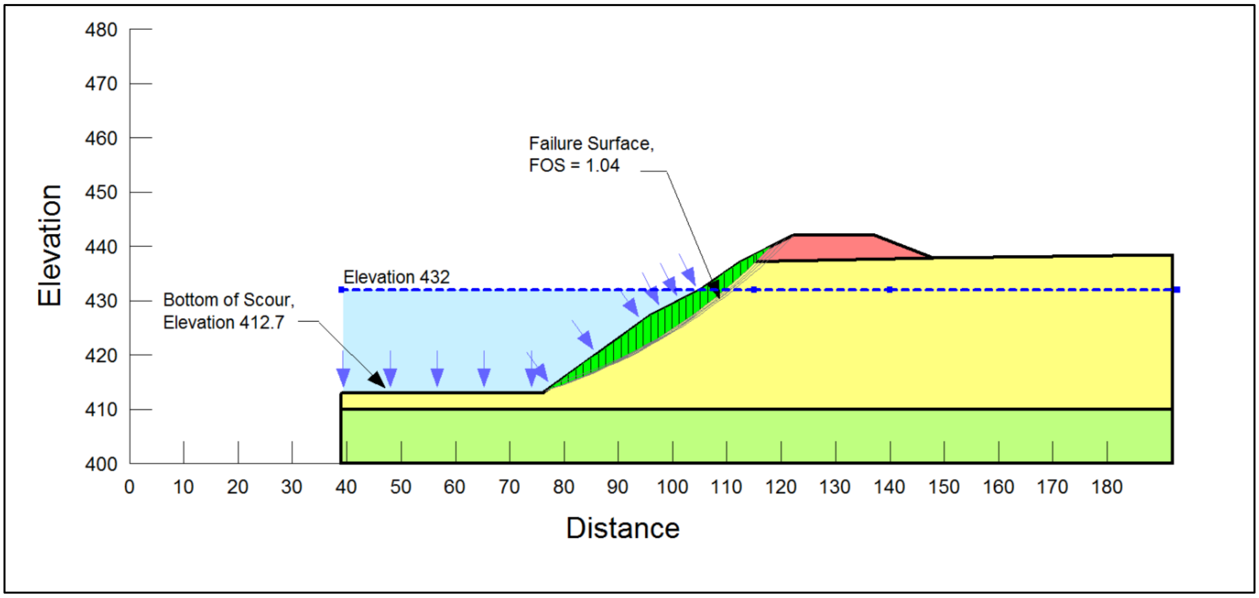


Figure 3-27. Stability Analyses Results, Scour Condition 1 at Location G-1, Low Water Condition (about 2,000 cfs); Failure Surface Results in Loss of about 5-Foot Thick Section of Riverside Slope

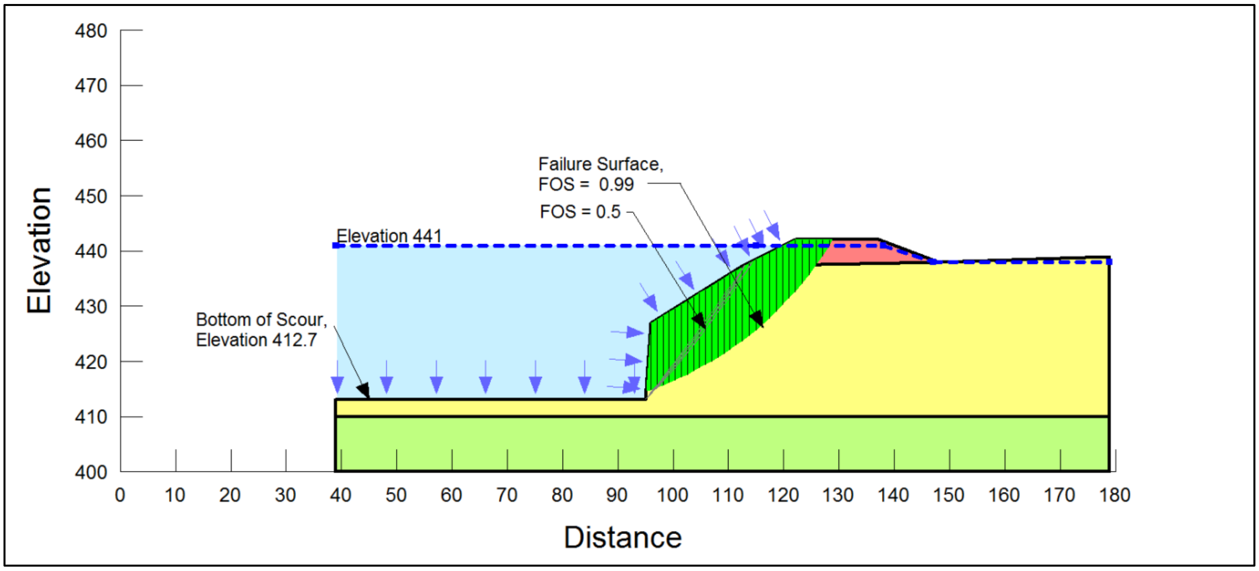


Figure 3-28. Stability Analyses Results, Scour Condition 2 at Location G-1, Water Level at 1 Percent Chance Flood Elevation; Failure Surface Results in Loss of a Portion of the Levee Crest Width

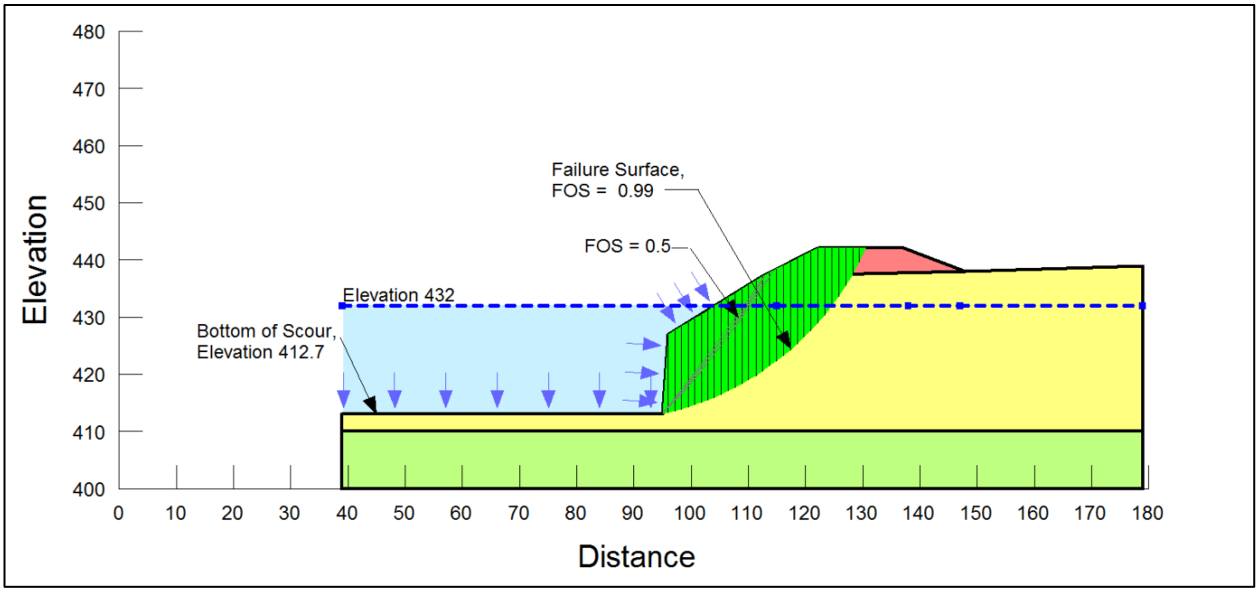


Figure 3-29. Stability Analyses Results, Scour Condition 2 at Location G-1, Low Water Condition (about 2,000 cfs); Failure Surface Results in Loss of a Portion of the Levee Crest Width

The results of the scour analyses indicate that loss of a few feet of the levee crest width is possible if the full depth scour occurs in a near-vertical configuration at the location of the existing riverside toe. The failure can occur both at the 1-percent chance flood and at a low-water condition where no riprap is present. The results of the scour analysis were discussed in a meeting with the project team. Interim action measures were discussed to include detailed levee inspections throughout the levee system after significant events to evaluate potential loss of the levee embankment.

Because the scour analysis indicates a high potential for failure due to scour, additional geomorphic and hydraulic analyses of the potential for the scour to occur in a near vertical configuration (Condition 2) should be performed to assess the scour risks along the levee system.

3.8 RELATIVE RISK, UNCERTAINTY AND ADDITIONAL INVESTIGATIONS

Considerable effort was expended to quantify the stability of the South Fork Snoqualmie River levee system in terms of slope stability, seepage and scour. Based on these analyses, the levee system was found to meet USACE guidelines and satisfy conventional seepage analysis, assuming uniform soil conditions. The stability analysis also assumes the design riprap is present throughout the entire levee system. Adequate factors of safety were identified for all stability analysis except seismic, and the seepage analysis found the risk of piping to be low. However, the presence of riprap was only partially confirmed, and additional investigation is required to reduce the uncertainty that riprap at the original design quantity actually exists on the levee face throughout the full length of the system. This investigation should be completed as soon as possible.

Even though the levee system is relatively stable, numerous problems were identified with potential to worsen stability in the levee system. Piping was noted at one location and seepage with depression in the levee surface was noted at numerous other locations. Additionally, toe erosion and culvert penetrations were found throughout the levee system. Remediation measures should be developed for these problems to improve the safety of the levee.

Geomorphic and hydraulic analyses to evaluate the potential for scour to occur in a near vertical configuration may be appropriate to assess the scour risks along the levee system.

3.9 KEY GEOTECHNICAL AND HYDROGEOLOGIC CONCLUSIONS

The following are key findings of the geotechnical and hydrogeologic review and analyses.

- The levees are old and were constructed without material or compaction control. Evidence of organic matter including large tree stumps has been encountered in explorations of the levees.
- The scour analysis results indicate a relatively deep scour depth that increases the risk of riverside failures. Loss of a portion of the levee crest is possible if the full depth scour occurs in a near-vertical configuration at the location of the existing riverside toe. The failure can occur during both a full flood stage and at a low-water condition where no riprap is present. Geomorphic and hydraulic analyses to evaluate the potential for the scour to occur in a near vertical configuration at the riverside toe is appropriate to assess the scour risks along the levee system.
- An adequate thickness of riprap is required to meet the USACE factor of safety requirements in areas with steeper riverbank slopes. While previous investigations (Shannon and Wilson, 2009) indicated significant areas where riprap is missing, it is possible that the riprap is covered by a layer of silt. A cursory test pit investigation of the presence of the riprap indicated that riprap is present below the silt layer. A more extensive survey of the riprap continuity and thickness would need to be completed to address safety concerns posed by levee breaching due to slope failure.
- Sand boils were observed following the January 2009 flood in the vicinity of RM 2.70 (potential problem area G-3). Observations of the levee performance during and after flood events should continue and appropriate repairs should be completed as soon as possible (e.g.

construction of anti-seepage devices such as a sand drainage blanket on the landside toe to increase the factor of safety against piping).

- Small localized areas of subsidence/depressions were observed in several areas along the levee facility. Depressions may be the result of surface traffic, degradation of subsurface organic matter, or piping. These areas should be monitored over time to observe changes, and repairs should be completed as necessary. Excavations to explore the presence of large organic debris should be scheduled based on the monitoring results.
- Based on the rapid response of piezometers on the landward side of the levee to changes in river level, the subsurface soils are concluded to be very permeable.
- Penetrations through the levee (e.g. pipe culverts) pose a higher risk of piping. These areas should be carefully monitored during annual levee inspections to document changes. Appropriate repairs should be completed as required (excavation and replacement with seepage risk reduction devices).
- The risk of piping at the seven critical sections was determined to be low, based on the guideline that a light/no seepage condition is estimated for exit gradients of < 0.2. However, there is the possibility of discrete zones of higher permeability that can result in higher exit gradients and the potential for internal erosion. It is therefore important that areas at the toe of the levees be inspected during major storm events to check for signs of water seepage through and beneath the levees.
- Based on the limited reported visual observations of slope instability, sand boils and seepage during flood events, the levees appear to be performing satisfactorily; however, the character of levees is that they include heterogeneities (presence of organic matter, loose soils, discrete zones of high permeable material, rodent burrowing) that can lead to failures.
- All the potential geotechnical and hydrogeological problem areas identified during the review of previous studies and investigations conducted as part of this study should be monitored on a regular basis. Remedial repair measures should be developed that address the identified geotechnical and hydrogeological problems where actual damage to the levee was noted (e.g. seepage, erosion, depressions). This includes design and construction of a pervious toe trench to mitigate seepage at location G-3, and confirmation of the riprap thickness throughout the levee system
- Continued levee monitoring and inspection should occur during and after major flood events per USACE guidelines.

3.10 CATEGORIZATION OF GEOTECHNICAL PROBLEMS FOR RISK EVALUATION

The full list of geotechnical and hydrogeological problems presented in Section 3.2 was reviewed to determine the problems types that warrant additional consideration of risk and priority during the risk evaluation in Chapter 5. Generally, the problems identified in Section 3.2 that are associated with active damage failure potential (e.g. observed seepage, piping, depression) were included in this list and are shown in Table 3-13.

Potential problems identified as culvert penetration, vegetation on the levee, or problems where no active failure mode was observed were not selected for additional consideration. However, the South Fork Snoqualmie River is a dynamic river system and levee conditions may change during peak flood events. For this reason, the potential problem locations described in Table 3-14 should be included in a monitoring program in case conditions change in the future.

TABLE 3-13
SCREENED LIST OF GEOTECHNICAL PROBLEMS

Location ID[a]	RM/ Reach	Problem Description	General Problem Type
G-1	2.27 / BR-A	Outside bend, moderate slopes, sparse to no riprap observed within upper 5 feet of riverside slope, riprap observed at toe, nearby bridge abutment, erosion at levee crest	Erosion
G-2	2.51 / CL-B	Outside bend to straight, seepage observed from river to landside Jan 09, moderate slopes, severe depression, sparse riprap, nearby bridge abutment	Seepage
G-3	2.70 / CL-A	Piping and sand boil observed Jan 09, depression, moderate slopes, sparse riprap	Piping
G-4	2.87 / DR-A	Toe erosion on riverside slope, outside bend, sparse riprap, nearby bridge abutment	Erosion
G-8	4.18 / GL-A	Outside bend, narrow crest, moderate slopes, reported seepage during Jan 2009 flood	Seepage
G-9	4.47 / GR-B	Toe erosion, moderate slopes, narrow crest, sparse riprap observed, bar protects levee toe	Erosion
G-10	5.03 / IR-B	Moderate slopes, locally 1.4H:1V, sags, depressions in crest 6 to 10 inches deep, I-90 nearby	Depression
G-11	2.04 to 2.11 / AR-A	Severe toe erosion, 50 to 400 feet upstream of pedestrian bridge, some large trees midslope, levee protection is offset from current toe	Erosion
G-13	2.28 / BL-B	Depression, 2 feet by 4 feet with two interior circles, probe depth 18 inches to 3 feet, moderate to severe riverside slope	Depression
G-14	2.39 / BR-A	Small 14-inch Dia. sinkhole, probe depth 15 inches to 3 feet	Depression
G-15	2.47 / CR-A	Culvert penetrations at levee bend, severe riverside slopes in subreach, water ponding behind pier, seepage noted during January 2009 flood	Seepage
G-23	4.5 to 4.6 / HL-A,B	Side channel developing and undercutting riverside toe, severe riverside slope, evidence of slope movement	Erosion
G-25	2.13 to 2.23 AR-A	Toe erosion, no riprap observed, subsurface conditions unknown	Erosion
G-27	2.3 to 2.5 / BR-A	Toe erosion and oversteepened toe	Erosion
G-29	~2.7 / CR-A	Toe erosion, severe slopes	Erosion
G-36	4.48 to 4.72 / HR-A	Numerous alder trees on slope, Toe erosion and scattered riprap	Erosion
G-42	~5.08 / IL-C	Toe erosion, little to no riprap observed during river reconnaissance, subsurface conditions unknown	Erosion
G-44	5.21 / JR-A	Drainage collecting on landside / riverside toe erosion, abundant trees midslope	Erosion

a. See Figure 3-5 to 3-8 for problem locations.

TABLE 3-14
GEOTECHNICAL PROBLEMS REMOVED FROM RISK CONSIDERATION

Location ID[a]	RM/ Reach	Problem Description	Rationale for Removal
G-5	3.10 / DL-E	Recent repair completed (issues included seepage from landside to river, scoured rills and soft areas, near vertical face, rubber tires, nearby flap gate	Problem area repaired in 2012
G-6	3.54 / DL-A/EL-A	Outside bend to straight, undulating crest surface, moderate slopes, telephone crossing with boulder protection in river	Potential problem only
G-12	2.11 / AR-A	48-inch diameter culvert penetration	Culvert penetration
G-17	3.19 / DL-D	Channel split, gravel bar in center. Left channel lower than right, rapid water on left. Soft crest (12 to 14 inch probe). Riprap slope protection observed in July 2013 excavation.	Potential problem only
G-18	3.26 / DR-F	Outside bend with severe riverside slopes	Potential problem only
G-20	3.68 / EL-A	Oversteepened slope, recent riprap placement on riverside slope	Potential problem only
G-21	3.73 / EL-A	End of large bar, riprap covered by vegetation and recent alluvium	Potential problem only
G-24	4.83 / IL-A	Slight outside bend approaching I-90 abutment	Potential problem only
G-26	2.24 / AR-A	Outflow through levee, levee penetration	Culvert penetration
G-28	2.45 / BR-A	Dense tree growth at levee toe, North Bend Way Bridge abutment	Vegetation
G-30	2.5 to 2.9 / CR-A	Numerous 1- to 2-foot diameter trees along riverside slope, severe slopes	Vegetation
G-31	2.87 / DL-F	No riprap observed subsurface conditions unknown, potential toe erosion near Bendigo Boulevard bridge abutment	Potential problem only
G-32	3.12 to 3.19 / DR-D	Moderate to severe slopes, outside bend	Potential problem only
G-33	4.03 / FR-C	Two 48-inch diameter culverts with flap gates	Culvert penetration
G-34	4.2 to 4.4 / GR-A	Numerous trees near toe of slope	Vegetation
G-35	4.4 to 4.5 / GL-B/-C	Moderate to severe slopes	Potential problem only
G-37	4.53 / HL-A	Culvert with missing flap gate	Culvert
G-38	4.72 to 4.44 / HR-B	Moderate to severe slopes	Potential problem only
G-39	4.72 / HR-B	Culvert with flap gate	Culvert penetration
G-40	5.01 to 5.19 / IR-B	Moderate to severe slopes	Potential problem only

TABLE 3-14
GEOTECHNICAL PROBLEMS REMOVED FROM RISK CONSIDERATION

Location ID[a]	RM/ Reach	Problem Description	Rationale for Removal
G-41	5.05 to 5.12 / IL-C	Moderate to severe slopes	Potential problem only
G-43	~5.08 / IL-C	5-foot diameter maple growing on landside crest	Vegetation
G-45	5.58 / JR-C	Soft ground/depression at crest / 20-inch probe depth	Zero height levee
G-46	5.6 / JR-C	Soft ground/depression at crest / 14-inch probe depth	Zero height levee

a. See Figure 3-5 to 3-8 for problem locations.

CHAPTER 4.
ECOLOGICAL ASSESSMENT

The ecological assessment evaluated past aerial mapping, reviewed recent studies, and rated existing conditions along the South Fork Snoqualmie River for streambank velocity refuge, floodplain connectivity, riparian condition, and instream natural cover. Aerial mapping was used to review changes to the channel morphology starting in 1944. Pertinent recent studies reviewed include: the Snoqualmie River Game Fish Enhancement Plan that assessed current habitat conditions in the South Fork Snoqualmie River and associated tributaries. The Snoqualmie Watershed Water Quality Synthesis Report, Snoqualmie River Basin Fecal Coliform Bacteria, Dissolved Oxygen, Ammonia-Nitrogen, and pH Total Maximum Daily Load Water Quality Effectiveness Monitoring Report, and Snoqualmie River Basin Temperature Total Maximum Daily Load Water Quality Improvement Reports and Implementation Plan, all provided data on existing water quality issues and recommendations to improve water quality in the South Fork Snoqualmie River. Additional detail related to the ecological assessment is provided in Appendix B – Ecological Characterization.

4.1 FISH AND WILDLIFE HABITAT

A variety of fish and wildlife species use the South Fork Snoqualmie River, its tributaries, and adjacent riparian habitats. The river supports resident fish populations of cutthroat and rainbow trout, both state priority species, as well as mountain whitefish and sculpin, among others. Tributaries support cutthroat trout and rainbow trout (City of North Bend, 2001; WDFW, 2008).

Snoqualmie Falls is an upstream migration barrier for anadromous salmonids, including Chinook salmon and Puget Sound steelhead, which are listed under the federal Endangered Species Act. The falls also block upstream migration of other anadromous salmonids that use the Snoqualmie River below the falls, including coho, chum, pink, and coastal cutthroat trout. Bull trout or other native char have not been found in several surveys of the South Fork Snoqualmie basin (City of North Bend, 2001; King County 2001; and WDFW 2008). Nevertheless, bull trout could still be present in the upper Snoqualmie River system.

Historically the South Fork Snoqualmie River has been constrained by construction of levees in the City of North Bend area. The levees have altered the dynamics of downed wood entering the river from riparian areas, thereby reducing large woody debris and log jams that would increase the quality of instream habitat. The channelization of the South Fork Snoqualmie River by levees has also affected instream habitat by increasing flow velocities, reducing channel complexity, and removing channel connectivity to floodplains and side channels. The levees have resulted in removal of trees and other vegetation to armor the levees immediately adjacent to the South Fork Snoqualmie River.

Stands of mature trees exist behind the levee through the North Bend Reach. However, land uses, including agricultural, residential, commercial, and transportation uses, have fragmented the riparian areas along the river in many places. Levees along the South Fork Snoqualmie River prevent riparian areas from normal flooding during high flows along the river corridor. Dominant trees typical of the riparian zone include cottonwood, Douglas fir, western red cedar, big leaf maple, and alder. Understory plants observed by project biologists include sword fern, salmonberry, red-twig dogwood, and snowberry. This riparian zone along the South Fork Snoqualmie River provides habitat support for a variety of native wildlife species typical of the area. In some areas, riparian habitats are degraded by invasive species, such

as Himalayan blackberry and English ivy. A program of ivy removal is ongoing in the riparian area near the Bendigo Boulevard South bridge.

Riparian wetlands along the South Fork Snoqualmie River in the study area include forested, scrub/shrub, and emergent vegetation classifications (City of North Bend, 2001). Some of these forested and scrub/shrub wetlands, particularly in and adjacent to intact riparian forest areas, maintain relatively high functional values. Emergent wetlands in pastures tend to have been degraded as a result of agricultural and grazing activities. Reed canary grass is present in many wetland areas, particularly where wetland communities have been disturbed. Forested and scrub/shrub wetlands have been cut off from direct river hydrologic connections by levees with consequent reductions in functional values, especially related to floodplain functions (City of North Bend, 2012). Figure 4-1 shows National Wetland Inventory wetland mapping. The study did not confirm the presence or absence of wetlands in the study area.

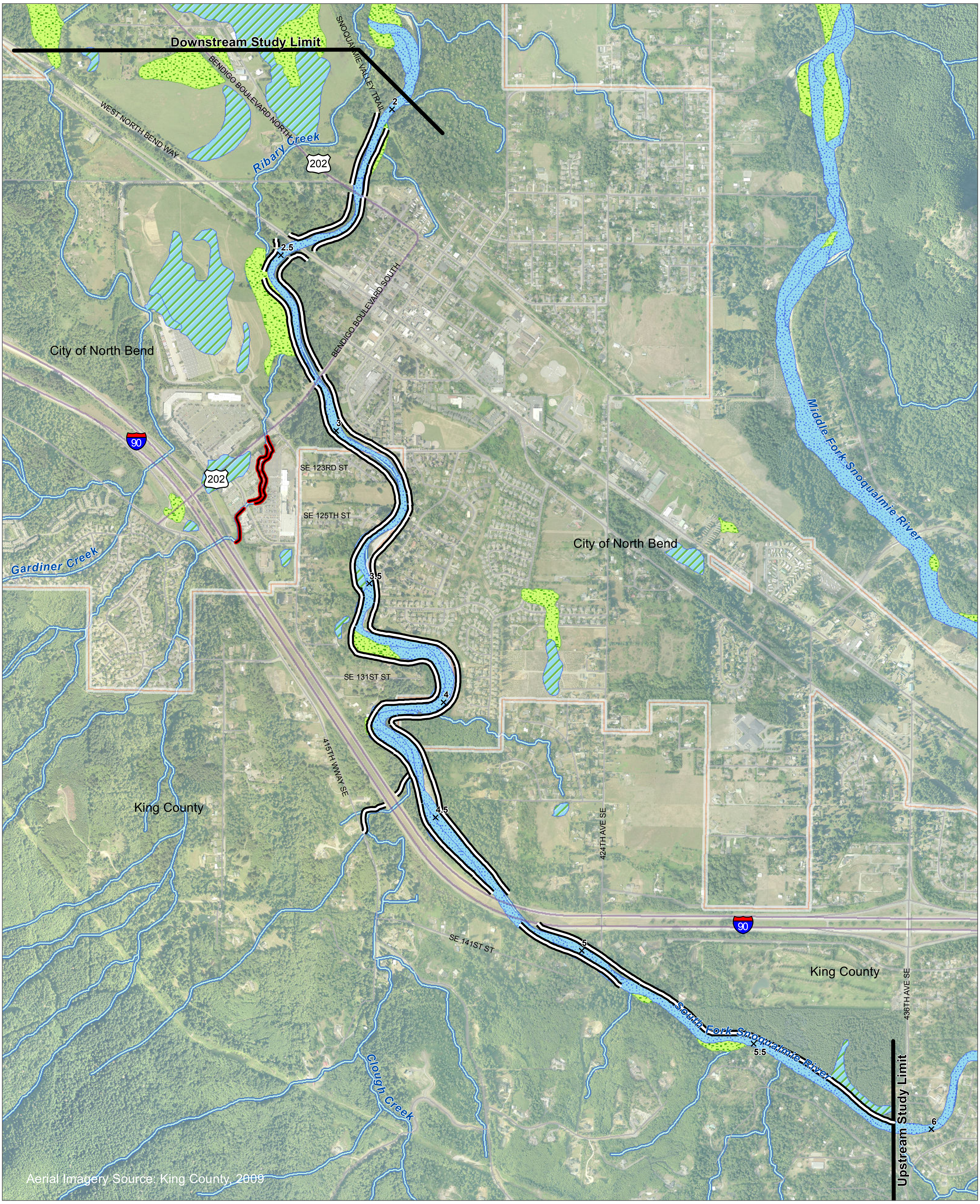
Residential and commercial development and levees have reduced the scale and overall quality of the riparian habitats along the river, with less accumulated downed wood and snags, resulting in fewer places for mammals, birds, and amphibians to find cover or suitable nesting and rearing sites.

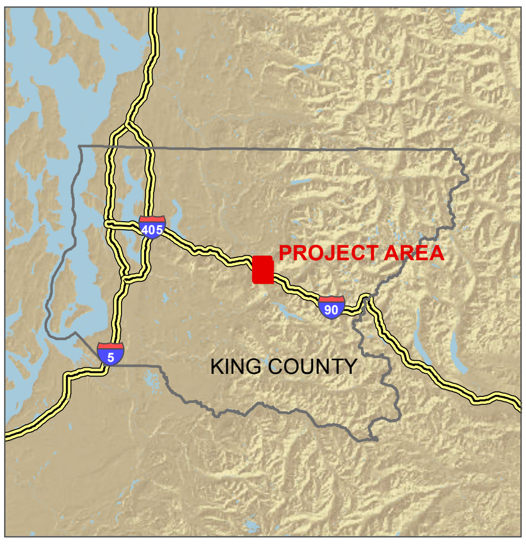
No federally listed threatened or endangered wildlife species are known to use habitats in the project area; however, rainbow trout are genetically identical to steelhead trout. The WDFW Priority Habitats and Species program identified the western toad (*Anaxyrus boreas*) as having been mapped within a riparian area associated with the South Fork Snoqualmie River. This species is a Washington State Candidate species and a federal species of concern. Elk is another state priority species that uses habitats in the general locality of the study area. It is possible that marbled murrelets, a threatened species under the federal Endangered Species Act, use the South Fork Snoqualmie River as a corridor to fly to old-growth nesting areas in the upper parts of the watershed. King County associates the North Fork and Middle Fork Snoqualmie Rivers with such use (King County 2011).

The North Bend foothills are home to a large herd of resident elk (WSDOT 2012). Movements of elk occur between the north and south sides of Interstate 90 and like many wildlife species use riparian corridors for migration pathways. Elk have been observed crossing under the Interstate 90 bridge along the left bank of the South Fork Snoqualmie River to move to habitat areas west of North Bend. The space under the Interstate 90 Bridge is not high enough above the streambank to be considered an optimal wildlife crossing for the Interstate 90 corridor and conflicts between elk and vehicle traffic on Interstate 90 have occurred, including a fatal collision killing four passengers on Interstate 90 near North Bend in 2004, as reported in a Seattle Times newspaper article (December 23, 2008). The Upper Snoqualmie Elk Management Group reported increased property damage in the area from the growing elk herd and 35 known collisions in 2009 on area highways, including Interstate 90 (Elk Management Group 2010).

4.2 HISTORICAL AERIAL PHOTOGRAPHY

Historical aerial photographs were obtained from 1944, and 1958 are shown in Figures 4-2 and 4-3. By 1944, much of the study area had been cleared and was either part of the City of North Bend or in agricultural uses. Generally, the same stands of trees that were present in 1944 are still present today. Also in 1944, side channels appear to be present from RM 4.7 to RM 5.5, and it appears the channel had more complexity then than in later years, with more gravel bars and associated braiding of the main channel.





× Rivermile

Municipal Boundary

Streams

King County Levee

North Bend Levee

Wetland Type (National Wetland Inventory)

Freshwater Emergent Wetland

Freshwater Forested/Shrub Wetland

Riverine

0 400 800 1,200

Feet

1 inch = 1,200 feet

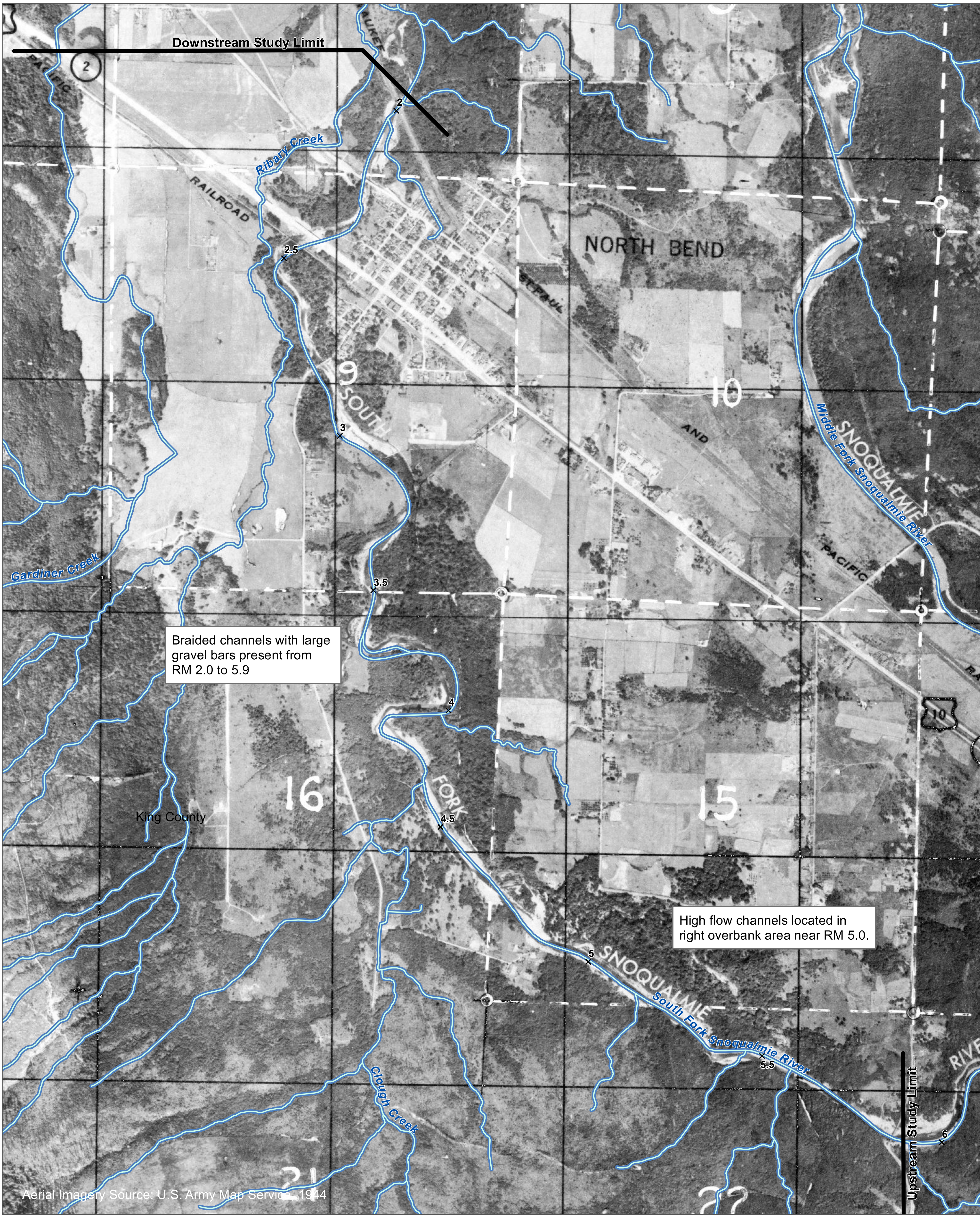
July 02, 2014

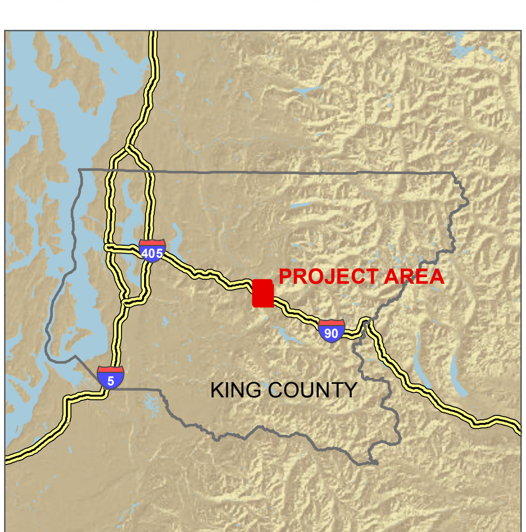
King County
Department of Natural Resources and Parks
Water and Land Resources Division

Prepared for King County by **Tetra Tech**

Figure 4-1. 2009 Aerial Photography and NWI Weltands

South Fork Snoqualmie River Levee Characteization Report, RM 2.0 - 5.9





× Rivermile
═ Streams

0 400 800 1,200
Feet

1 inch = 1,200 feet

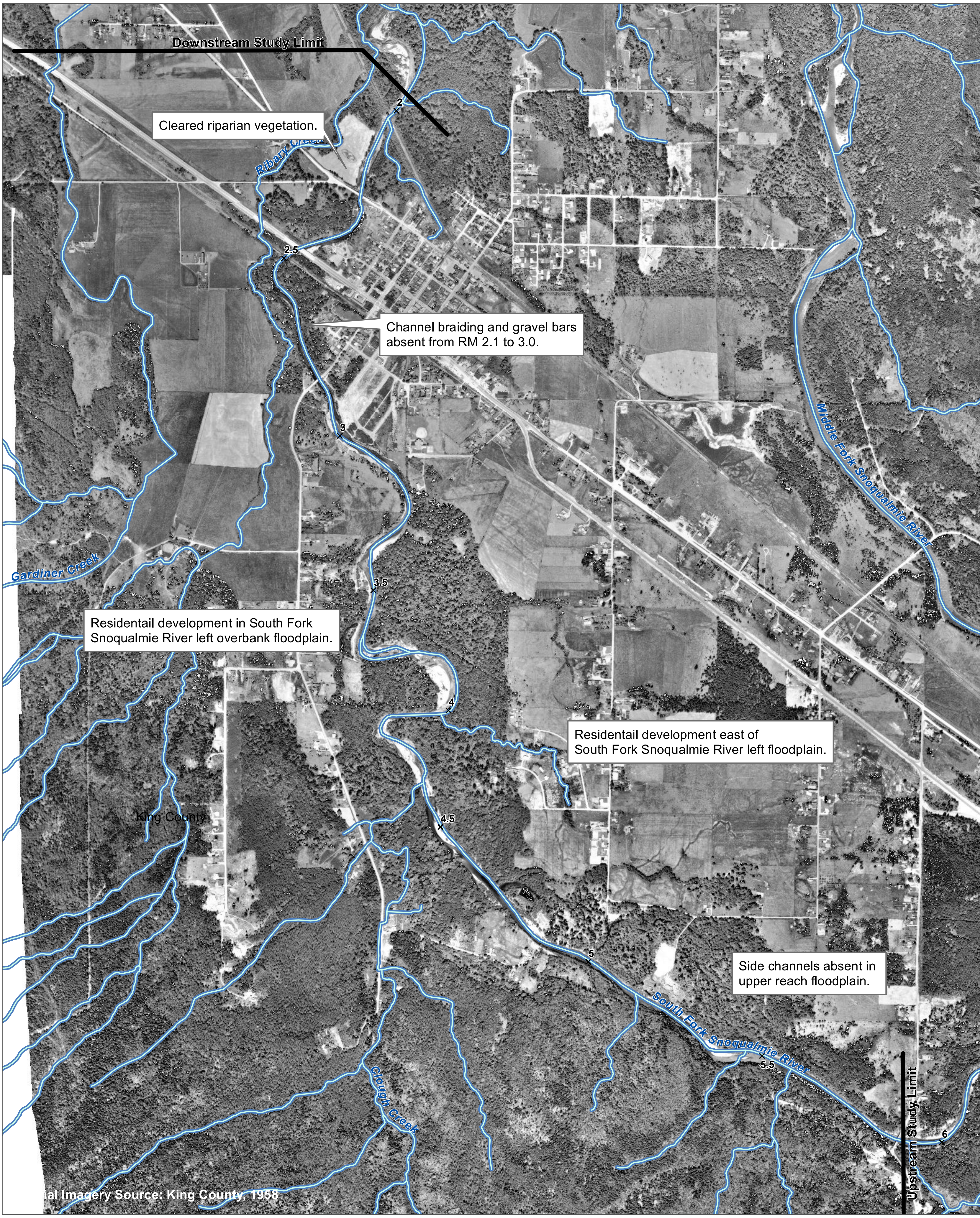
July 02, 2014

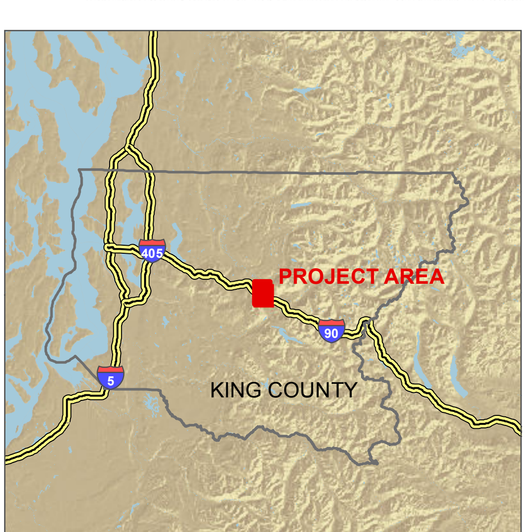
King County
Department of Natural Resources and Parks
Water and Land Resources Division

Prepared for King County by **Tetra Tech**

Figure 4-2. 1944 Aerial Photography

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9





× Rivermile

Streams

0 400 800 1,200
Feet

1 inch = 1,200 feet

July 02, 2014

King County
Department of Natural Resources and Parks
Water and Land Resources Division

Prepared for King County by **Tetra Tech**

Figure 4-3. 1958 Aerial Photography

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9

The side channels along the reach from RM 4.7 to RM 5.5 observed on the 1944 aerial photos do not appear on the 1958 aerial photos. A backwater channel is still present in 1958 at RM 4.7, adjacent to the future Interstate 90 alignment. Gravel bars are no longer visible in the 1958 aerial photograph from RM 2.1 to about RM 3.2 in the vicinity of North Bend, resulting in a loss of channel complexity. Rural residential developments were constructed along South Fork Avenue W. Additional residential developments were constructed east of the South Fork Snoqualmie River on previous agricultural lands. A large forested area (as much as 17 acres) was cleared along the left bank around RM 2.0 to 2.2.

Current mapping (Figure 4-1) shows a loss of braided channels and continued deforestation and development. Interstate 90 runs through the site, and it construction resulted in additional deforestation. Records of construction of the flood control levees indicate that construction of the current levee system started in the early 1960s. Some construction of levees may have occurred before this, but design and construction methods are unknown**.**

4.3 EXISTING CONDITIONS

The South Fork Snoqualmie River study area was divided into three reaches for discussion purposes. The lower reach is from the Snoqualmie Valley Trail to Bendigo Boulevard South (RM 2.0 to RM 2.85), the middle reach is from Bendigo Boulevard South to Interstate 90 (RM 2.85 to 4.85), and the upper reach from Interstate 90 to 436th Avenue SE (RM 4.85 to 5.9). These reaches were generally aligned with study reaches used in the hydraulic condition assessment.

The lower reach (RM 2.0 to RM 2.85) of the South Fork Snoqualmie River has a few bends in the lower reach located primarily between RM 2.3 and RM 2.6. Substrates are composed of sand and gravel deposits are present in the lower reach. Riparian conditions are forested riparian for much of the reach, generally ranging from 100 to 300 feet in width, although a few areas have been cleared to the levee. Land use adjacent to the South Fork Snoqualmie River includes single-family homes within the City of North Bend along the right bank and rural residential and pasture along the left bank. The levees are generally vegetated with shrubs and small trees.

Ribary Creek parallels the lower South Fork Snoqualmie River on the north and west and enters the South Fork Snoqualmie River just below the study area at RM 1.65. Channel gradients in Ribary Creek are low, and the channel becomes less defined as it enters forested areas by the Snoqualmie Valley Trail. Wetlands present in this area are hydraulically connected to Ribary Creek. There are many relic overflow swales and channels located adjacent to Ribary Creek along the lower reaches of the study area.

The City of North Bend operates a wastewater treatment plant on the right bank just downstream from the Bendigo Boulevard North (SR 202) bridge at about RM 2.2. The wastewater treatment plant is subject to discharge requirements under its National Pollutant Discharge Elimination System permit. This essential public facility is at risk of flooding under some conditions, as described in Chapters 2 and 5.

The middle reach (RM 2.85 to 4.85) of the South Fork Snoqualmie River has greater channel complexity than the upper or lower reaches. Substrates in the middle reach are sand and gravel, with gravel bars alternating from the left bank to the right bank throughout the reach. Several high flow secondary channels are present between the streambank and gravel bars. Clough Creek enters the Snoqualmie River at RM 4.4 through two corrugated metal pipes under the levee. Land use along the right bank of the South Fork Snoqualmie River is primarily a built environment through the City of North Bend. Riparian areas are degraded and fragmented, with isolated stands of trees. Riparian habitat within the left and right bank levee footprint is also fragmented, with isolated patches of shrubs growing over the bank armoring. The left bank is rural residential with more vegetation coverage than the right bank. The upper part of the reach has more continuous forested habitat and vegetation between the levees and the river channel.

The upper reach of the South Fork Snoqualmie River (RM 4.85 to RM 5.9) has a higher gradient, as indicated by its coarse gravel and cobble substrate. A few large boulders are present in the stream. This is the straightest reach in the study area, with a few minor bends. Riparian habitat in the upper reach is mostly forested, interspersed with rural residential areas. The levees are vegetate, with some sparse trees and shrubs along the right bank. The left bank has stretches with less armoring and more mature vegetation in spots. Some properties contain landscaping down to the water's edge along the left bank.

All three reaches have been maintained by King County for reduction of invasive species. The City of North Bend has actively removed English ivy from some of the riparian areas; however, some English ivy that was untreated along the left bank has grown into the crowns of some of the mature trees. The lower reach also has extensive areas of Himalayan blackberry along Ribary Creek where it passes along agricultural areas. Other areas of patchy Himalayan blackberries are present throughout the study area along the edge of forested areas. Japanese knotweed is being aggressively controlled along the levees by King County. No large stands of Japanese knotweeds were noted during the site reconnaissance, but stray patches of this invasive species were present along the levees.

4.4 ECOLOGICAL FUNCTION ASSESSMENT

Habitat conditions along the South Fork Snoqualmie River levees were qualitatively evaluated for streambank velocity refuge, floodplain connectivity, riparian condition, and instream natural cover habitat. Figure 4-4 and Table 4-1 summarize the ecological function assessment. These and other instream habitat conditions are also presented in more detail in Appendix B – Ecological Characterization.

4.4.1 Streambank Velocity Refuge

An upper velocity threshold of 1.5 feet per second was used to evaluate instream functional conditions for velocity. Juvenile salmonids usually occupy relatively shallow and low-velocity areas. These areas are typically found in edge habitats along banks, bars, and backwater areas. Beechie et al. (2005) found that most fish occupy areas with a velocity less than 0.49 feet per second. The upper velocity threshold is exceeded during flood events in areas normally occupied by most juvenile salmon. It is assumed during usual yearly high flow events that woody vegetation, such as trees and mature shrubs, can provide temporary refuge from high flows. A hydro-modified edge is used to describe armored stream banks that provide little to no high flow refuge. To rate the functions of velocity in the study area, the following ratings were used:

- Reaches that have only hydro-modified edge were rated low.
- Reaches that have a hydro modified edge but also have some small trees and mature shrubs that can withstand high flows were rated low plus because they are still low functioning but have some streamside function.
- Reaches with good edge habitat, but containing some modification, such as cleared vegetation for access to the water's edge, but no armoring, were assigned a medium value.
- Reaches with abundant edge habitat with assumed velocity refuge below 1.5 feet per second, because of vegetation or other refuge with low flows, such as benches and floodplains, were rated high.

The entire study area has stream banks that are confined by levees, with the exception of the left bank from RM 5.1 to 5.9, which has a natural slope. Much of the streambank along levees has scattered areas of shrubs and small trees and was rated with low functions, but may have some functions because of mature shrubs and small trees growing on the levees. These vegetated areas provide only minimal refuge during higher flows, although they may provide more refuge than streambank sections with emergent vegetation, small shrubs, and riprap, which provide no substantial refuge from high flows.

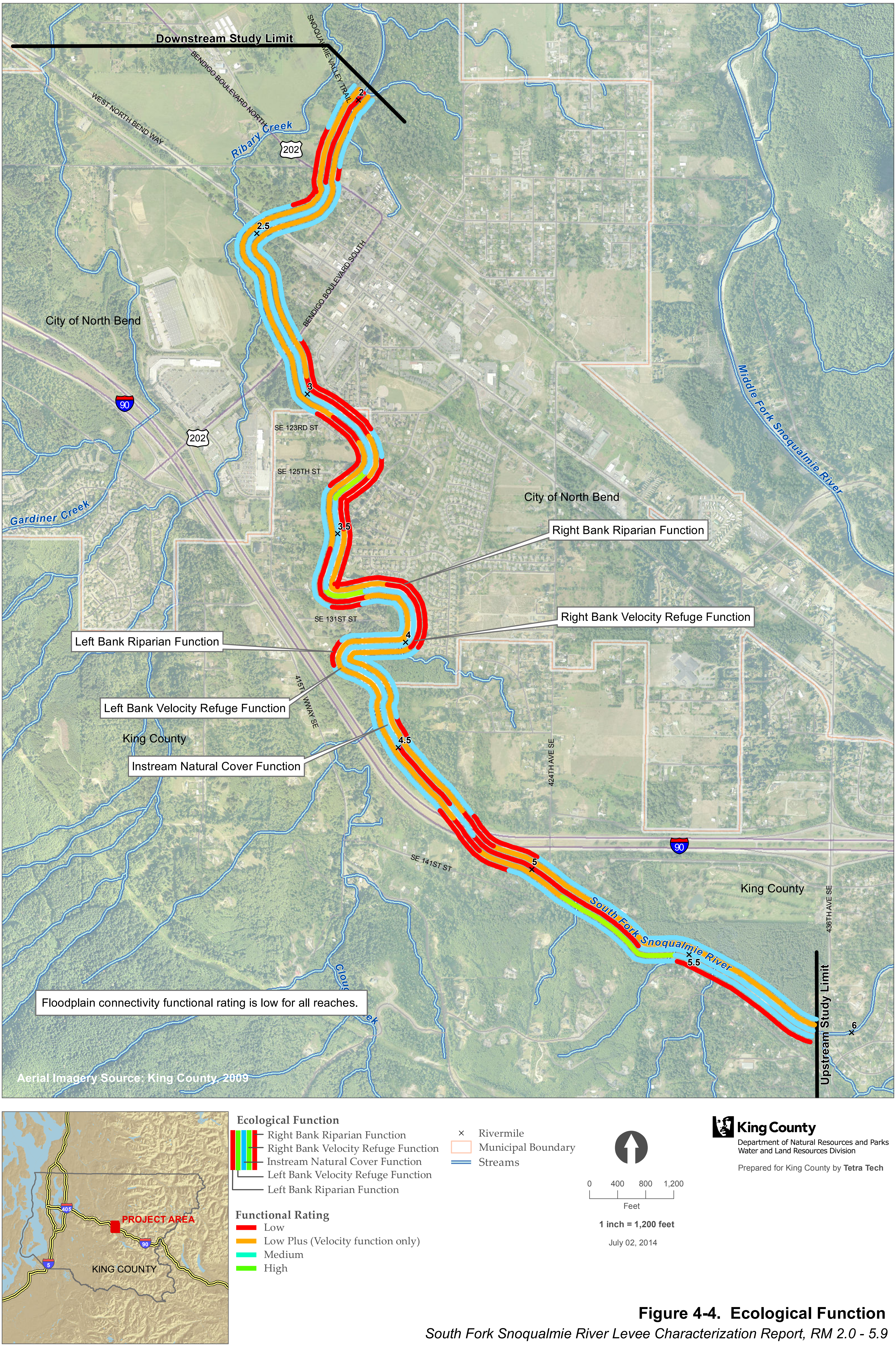


Figure 4-4. Ecological Function

South Fork Snoqualmie River Levee Characterization Report, RM 2.0 - 5.9

TABLE 4-1.
ECOLOGICAL FUNCTION OF THE SOUTH FORK SNOQUALMIE RIVER RIPARIAN AREA

Functional Rating [a]	Ecological Function (percent of total reach length) Streambank Velocity Refuge	Floodplain Connectivity	Riparian Condition	Instream Natural Cover
Lower Reach - Snoqualmie Valley Trail to Bendigo Boulevard South (RM 2.0 – 2.85)				
Low	0	100	21	29
Low Plus[b]	100	n/a	n/a	n/a
Medium	0	0	79	71
High	0	0	0	0
Middle Reach - Bendigo Boulevard South to Interstate 90 (RM 2.85 – 4.85)				
Low	29	100	50	13
Low Plus	71	n/a	n/a	n/a
Medium	0	0	50	77
High	0	0	0	10
Upper Reach - Interstate 90 to 436th Avenue SE (RM 4.85 – 5.9)				
Low	0	100	33	48
Low Plus	62	n/a	n/a	n/a
Medium	21	0	67	52
High	17	0	0	0
Combined South Fork Snoqualmie River (RM 2.0 – RM 5.9)				
Low	15	100	39	26
Low Plus	75	n/a	n/a	n/a
Medium	6	0	61	69
High	5	0	0	5

a. Functional ratings (low, low plus, medium, and high) are defined in sections 4.4 for each of the ecological functions (streambank velocity refuge, floodplain connectivity, riparian condition, and instream natural cover).
b. Low Plus functional rating applies to velocity refuge function only. Low Plus recognizes the slightly improved function provided by vegetation on armored streambanks.

An approximately 0.8-mile stretch along the left bank in the upper reach where no levees have been constructed has medium and high functions. The areas rated medium have patches of woody vegetation along the shoreline, but sometimes have manicured lawns that approach the water's edge. A short stretch of streambank from about RM 5.1 to 5.45 along an undeveloped area adjacent to a steep slope has high potential functions. This area has taller trees up to the stream edge and a small, vegetated bench area with willows and emergent vegetation.

Stohr et al. (2009) recommended levee setbacks as an option for areas needing channel restoration that are currently hardened by levees. This option is currently being applied near the mouth of the Tolt River and it is anticipated that the levee setback project will reconnect the Tolt River to existing wetlands and floodplain, improving habitat conditions along the channel while still providing flood protection.

4.4.2 Floodplain Connectivity

Floodplain connectivity to off-channel habitats, such as side channels, sloughs, ponds and seasonally flooded wetlands, can provide important refuge areas for fish (juvenile and adults) during high flows. These areas also can provide important salmonid juvenile rearing habitat. Seasonal flood pulses allow fish to leave the channel and exploit inundated floodplain habitats (Junk et al., 1989). Fish may seek refuge from winter floods in tributaries and floodplain sloughs, then re-emerge in spring (Tschaplinski and Hartman, 1983). To measure the functions of floodplain connectivity in the study area, the following ratings were used:

- Reaches without floodplain or side channel connections were rated low.
- Reaches with some connections and some disconnections were rated medium.
- Reaches without disconnections to side channels and floodplains were rated high.

The entire study area lacks floodplain connectivity with off channel habitat during the 50-percent-annual-chance flood event (2-year return period) with the exception of Clough Creek, which has a direct connection to the South Fork Snoqualmie River through an open culvert. The levee prevents overtopping during these usual flooding events. The Clough Creek reach, above its confluence with the South Fork Snoqualmie River, is short between the levee and a long culvert that passes under Interstate 90.

Many wetlands and side channels that may have been present along the South Fork Snoqualmie River have been isolated from flood flows and no longer function as wetlands. Habitat functions in the South Fork Snoqualmie River in the vicinity of the City of North Bend have been severely compromised as banks have been modified for flood protection, lessening interaction with the floodplain. However, the South Fork Snoqualmie River remains connected to Clough Creek, which is used by all life stages of trout and supported the highest amount of spawning during a recent study (Thompson et al., 2011). Conditions in downstream reaches of other South Fork tributaries near North Bend appear to be suitable for trout. However, land use and development have diminished the floodplain connectivity between upper and lower portions of tributaries, such as Ribary Creek.

4.4.3 Riparian Condition

Riparian refers to biological communities along the shores of streams, rivers, lakes, ponds, and some wetlands (Naiman et al. 2000). Riparian buffer zones are strongly influenced by the adjacent aquatic features and, in turn, strongly influence the characteristics of the adjacent aquatic ecosystem. Riparian areas contribute to the health of rivers by influencing functions such as temperature regulation, water quality, flood conveyance, bank stabilization, large-wood recruitment, and wildlife habitat. Riparian condition influences the condition of the aquatic communities through various dynamic interactions.

Flooding of adjacent floodplains contributes nutrients to the riparian zone contributing to plant communities and food chain support for wildlife. The combination of water, nutrients, and light available along the shores promote high levels of plant community productivity. Biological materials, such as insects and leaves, enter the aquatic system from the adjacent riparian zone contributing to aquatic productivity where the detritus is used by organisms that may lead to food for fish or other aquatic animals.

High flood flows may undercut streambanks resulting in trees falling into the stream or river. This large wood in the channel from the riparian zone may result in geomorphic changes in the river channel, such as pools and overhanging structures, that provide shelter and resting locations for resident and migrating fish.

Riparian zones also provide habitats for a variety of wildlife. Their high productivity may provide berries and seeds for a variety of songbirds, nesting sites, shelter for larger mammals, and migration corridors, such as elk that use the South Fork Snoqualmie riparian corridor. The importance of riparian zones for wildlife is emphasized by the fact that together nearly 30 percent of amphibian, reptile, bird, and mammal species in the Pacific Coast Ecoregion are considered to be obligate riparian species (Naiman et al. 2000). Their populations may decrease when riparian communities are removed. Additional species may also use both upland and riparian communities and move between them and may be vulnerable for some part of their life support needs if riparian communities are removed.

A notable function of the riparian buffer zone is to provide shading to maintain cooler instream temperatures that are important to all life stages of native fish. Temperature plays an important role in life history requirements for salmonids. High summer water temperatures can has been shown to negatively affect salmonids species by decreasing dissolved oxygen and preferable food sources, and increasing metabolic rates, vulnerability to disease and toxins, and rates of predation. Stream temperatures exceed water quality standards (16ºC or 15.5ºC) in the study area during the summer months (Stohr et al., 2011).

The total maximum daily load for temperature (TMDL) in the Snoqualmie River temperature TMDL implementation plan, which applies to the South Fork Snoqualmie River, calls for maintaining or reestablishing mature intact buffers 150 feet tall and 150 feet wide with native vegetation (Stohr et al., 2011). For tributaries such as Clough Creek and Ribary Creek, the total maximum daily load calls for total shading. To rate the functions of riparian habitat in the study area, the following values were used:

- Reaches without buffers 150 feet wide and 150 feet tall were rated low.
- Reaches with areas having 150 wide buffers or 150 tall trees were rated medium.
- Reaches with buffers meeting the total maximum daily load standard were rated high.

The entire study area lacks mature stands greater than 150 feet tall. However, there are 150-foot-wide riparian areas in a patchwork through the middle reach, and the lower and upper reaches have significant stands of riparian vegetation that is 150 feet wide. About 70 percent of the left bank has forested vegetation and 60 percent of the right bank. However, the highest rating assigned to the riparian function was medium due to a gap of about 30 feet between the water's edge and riparian forested areas where trees have not been able to grow on the levee, probably due to poor soil conditions or continued maintenance of the levee roads. This gap also prevents large wood from entering the South Fork Snoqualmie River further degrading instream habitat conditions. Low riparian function is primarily found near developed residential areas of North Bend, Berry Estates and Shamrock neighborhoods, and Interstate 90.

Many lowland forests within the floodplain of the Snoqualmie River and along its tributaries were logged in the mid- to late 1800s and during the first half of the 20th century. In areas that now feature agricultural, urban and rural residential land uses, the loss of forests along streams and rivers likely has had a profound effect on water quality (Kaje, 2009). Other impairment of riparian function, such as decreased large woody debris generation, may take 40 to 50 years post-harvest to be fully expressed (Scrivener and Brown, 1993) and 75 to 150 years subsequently to recover (Koski, 1992).

Stohr et al. (2011) state that establishing 150-foot-wide buffers with 150-foot-tall trees along the Snoqualmie River could result in significant reductions in incident solar radiation, lowering of localized air temperatures (microclimate), and reductions in water temperatures. Their modeling predicts that with such buffers, water temperatures at the mouth of the Snoqualmie River would be reduced by 2.2ºC during the warmest week in a typical year and by 2.8ºC during the warmest conditions that occur once every 10 years.

Kaje (2009) identifies several water quality priority actions that apply to the study area. These include enhancing riparian habitat along tributaries such as Clough Creek and Ribary Creek. Stohr et al. (2011) concludes that restoration of riparian conditions is essential to reducing summer water temperature and that channel restoration should consider levee setback as an option in areas that have levees.

4.4.4 Instream Natural Cover

Instream natural cover is an important habitat element for salmon recovery. Instream natural cover includes submerged and overhanging large wood, log jams, beaver dams, aquatic vegetation, large rocks and boulders, side channels, and undercut banks. To measure the functions of the instream natural cover in the study area, the following ratings were used:

- Reaches with minimal complexity were rated low.
- Reaches having some periodic cover, but lacking complexity, were rated medium.
- Reaches with a high degree of complexity and cover, such as ample large woody debris, pools, and boulders, were rated high.

The study reach was characterized by riffle and run habitat but lacked deep pools associated with large wood accumulation and channel braiding associated with gravel bar formation. Despite the loss of floodplain connectivity with a natural floodplain and side channels, the instream natural cover generally is rated medium for most of the study area. The lower reach generally lacks boulders, wood, and vegetation within the channel, but several scour pools were observed and overhanging vegetation is present along several areas. The middle reach has several gravel bars with established willows and other persistent vegetation that have collected some large woody debris and many woody debris piles that rated high and provided the best instream natural cover for the study area. However, the relatively straight confined reach downstream of Interstate 90 was rated low. The low rating continued upstream of Interstate 90 into the upper reach. Above the low rated segment, the upper reach has some large woody debris and large boulders in the channel which improve function to a medium rating. No barriers to fish movement in the South Fork Snoqualmie River were identified in the project area.

Thompson (2011) found that the North Bend area has the least amount of trout over any areas upstream or downstream of the study area and noted that this may be because of the constrained channel caused by construction of the levees. The greatest amount of trout productivity below Twin Falls was found in Clough Creek. The high spawning concentration in Clough Creek could be due to the lack of other good spawning habitat in the North Bend reach.

4.5 SUMMARY OF ECOLOGICAL ASSESSMENT

The following are key findings of the ecological assessment:

- Ninety percent of the South Fork Snoqualmie River streambanks have been degraded by armoring and result in low function for velocity refuge. However, the low velocity refuge function due to bank armoring is slightly improved over a significant length of streambank where mature shrubs and small trees are growing in the levee. Vegetated areas help reduce velocities during flooding events and provide a small amount of refuge from high stream flows during flood events.
- Connectivity to floodplain habitats (side channels and wetlands) is non-existent throughout the entire study area due to levees blocking channel refuge and rearing areas for salmonids within the study area.
- Areas with low riparian function are primarily associated with residential areas in North Bend and the Berry Estates/ Shamrock Park neighborhood and Interstate 90.

- A patchwork of mature riparian areas is present through the study area. These areas lack the average stand height needed to provide ample shading to reduce summer temperatures.
- The highest rating assigned to the riparian function was medium due to a gap of about 30 feet between the water's edge and riparian forested areas. This gap further hinders the cooling effect these areas may have and reduces overhanging vegetation in many areas.
- Because riparian habitat is setback from the South Fork Snoqualmie River by levees, large wood recruitment is lacking throughout the study area.
- Wildlife movement through the area relies on the connectivity of riparian habitat. The riparian habitat is patchy and movement of large animals such as elk are hindered by residential and commercial development in the riparian corridor and Interstate 90.
- Instream natural cover is generally rated medium for most of the study area. Low function is found in the lower reach generally due to a lack boulders, wood, and vegetation within the channel. High functioning instream natural cover is found in the middle reach where several gravel bars with established willows and other persistent vegetation have collected some large woody debris and many woody debris piles. This area provided the best instream natural cover for the study area. The relatively straight confined reach downstream and upstream of Interstate 90 was rated low. Above the low rated segment, the upper reach has some large woody debris and large boulders in the channel which improve function to a medium rating.
- The South Fork Snoqualmie River in the study area is lacking in suitable spawning areas for salmonids. Ribary Creek and Clough Creek are the only areas that provide suitable spawning areas and connections to Clough Creek may be hampered by culverts under the levee and Interstate 90.
- No barriers to fish movement in the South Fork Snoqualmie River were identified in the project area.
- Habitats within the South Fork Snoqualmie River in the study area are generally characterized as riffle run habitat and lacking deep pools.
- Thompson (2011) observed that trout numbers decreased in the North Bend segment where the channel is extensively constrained by bank armoring and levees. The reach generally lack large wood accumulation that would create higher channel complexity. However, some areas still have some lateral pools and side channels within the levee system.

CHAPTER 5.
PROBLEM IDENTIFICATION AND GROUPING

Hydraulic, geotechnical and ecological problems were identified within the study area levee system based on the findings presented in their respective chapter. This chapter provides a concise summary of the problems and consequences for each problem type. A qualitative risk assessment is applied to the hydraulic and geotechnical problems to identify reaches in the South Fork Snoqualmie river with the most critical problems. A problem numbering system was developed to identify the hydraulic and ecological problem areas. The geotechnical problems retained the numbering assigned in Chapter 3.

5.1 IDENTIFICATION OF PROBLEMS

5.1.1 Hydraulic Problems

The identified hydraulic problems are generally based on existing-conditions model results for 2- through 0.2-percent-annual-chance flood events. However, extensive levee overtopping occurs for the 0.2-percent-annual-chance flood event so that many of the individual problem areas are connected. Hydraulic problem area H12, representing overtopping of the levee on the right bank immediately upstream of the Bendigo Boulevard South bridge was not predicted by the model. Anecdotal observations indicated this overtopping during the November 2006 flood event, but calibration of the hydraulic model was not able to duplicate overtopping without making flood conditions substantially worse upstream. The problem is included due to its being observed during an historical event, but the hydraulic model does not predict flooding at this location until the 0.2-percent-annual-chance flood event.

5.1.2 Geotechnical Problems

Geotechnical problem areas were identified based on previous geotechnical analysis, augmented by the new geotechnical investigations. Eighteen geotechnical and hydrogeologic levee problems were selected from a list of 46 potential problems for inclusion in the plan. Problem areas were identified in the 2009 South Fork Snoqualmie Levee Geotechnical Studies, by subsurface borings or monitoring wells, and additional reconnaissance, data review, and analysis performed for this study. The selected geotechnical problems were limited to those with active damage or failure activities. The selection of a subset of geotechnical problem from a larger set also results in non-consecutive numbering. The selection of the geotechnical problems are documented in Section 3.10.

A previous visual investigation (Shannon and Wilson, 2009) noted sparse or missing riprap at numerous locations on the riverside levee face. These observations were made primarily during a river reconnaissance and were not based on subsurface exploration. A limited field investigation performed for this study showed riprap to be present at locations previously noted as missing, but is obscured by a layer of alluvium and vegetation suggesting riprap is present in the system. For our analysis, it was assumed that riprap is present in the levee system and is therefore not considered to be a system-wide problem at this time. However, a more thorough investigation of riprap should be performed to confirm the presence of riprap throughout the system.

A scour analysis performed for this study identified the potential for scour to be a system-wide problem in the South Fork Snoqualmie River. The analysis showed that scour depths of 10 feet or more are possible resulting in a potential loss of a significant portion of the levee. However, the scour analysis was limited in scope so there is uncertainty in the conclusions drawn from this analysis. A more rigorous analysis of

scour potential would need to be performed to reduce the uncertainty and improve the understanding of scour potential in the river channel especially at outside bends and significant channel constrictions.

5.1.3 Ecological Problems

Reaches with low ecological function for floodplain connectivity, riparian, streambank velocity refuge and instream cover were identified as having impaired function. Floodplain connectivity, riparian and streambank velocity refuge functions have obvious left and right bank components. Instream cover relates to in-channel conditions in the South Fork Snoqualmie River but is documented as a left bank problem as a convenience in the tabulation.

5.1.4 Summary of Hydraulic, Geotechnical, and Ecological Problems

Each of the identified problems documented in the previous chapters have been compiled in Table 5-1 shown below. This table describes the problems and lists potential consequences of failure. Problems are grouped by reaches generally defined by road crossings. Locations of the problems are shown in Figure 5-1.

5.2 PROBLEM ASSESSMENT AND RISK SCORE

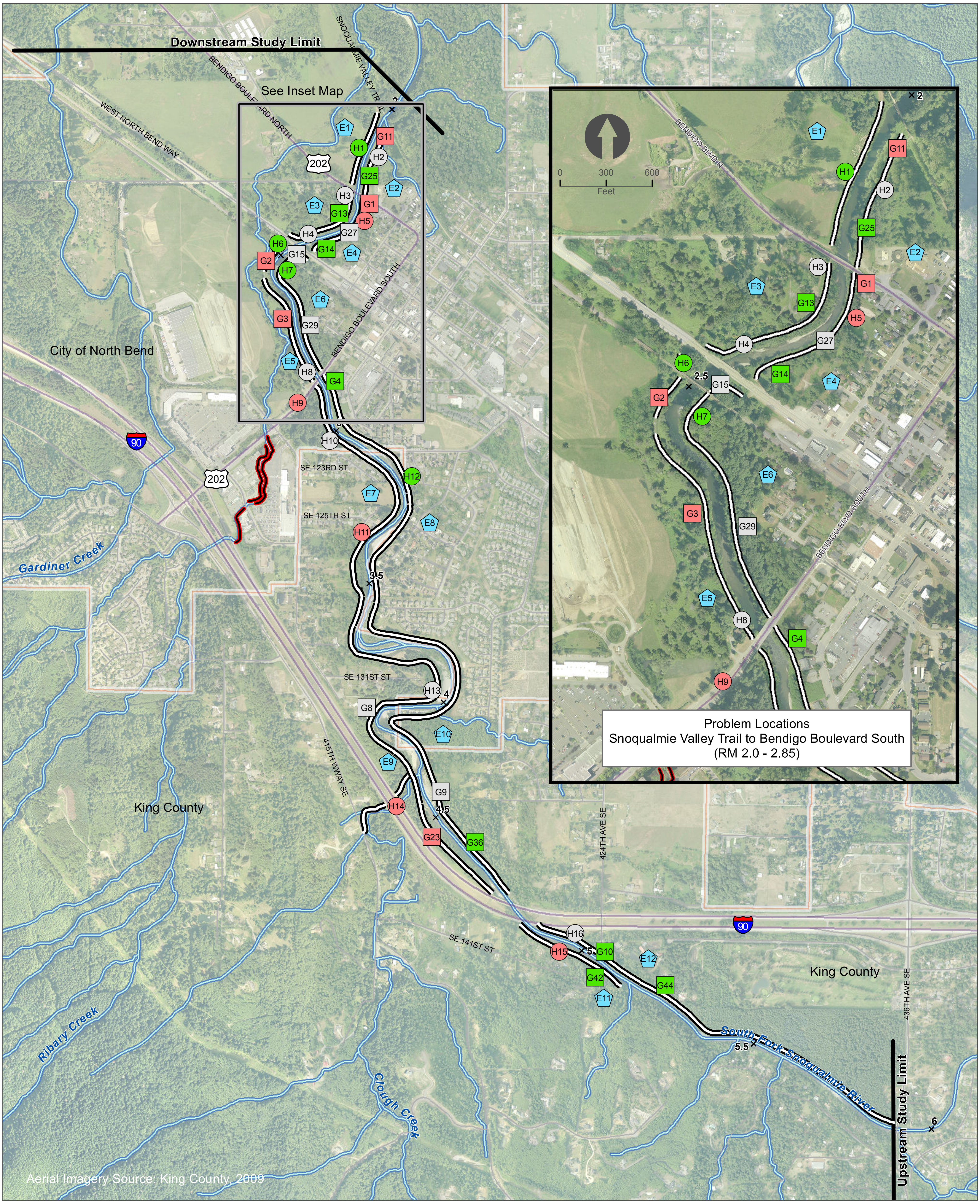
Each of the hydraulic and geotechnical problems presented in the previous section were assessed and assigned a “risk score” to determine the relative severity and importance of each of the reported problems. Ecological problem areas were not prioritized but addressing these problems would need to be considered when developing solutions to the hydraulic and geotechnical problems.

Hydraulic and geotechnical problems are sorted into high, medium, and low risk problems which can be used to determine priorities when developing project mitigation and repair action priorities. For the hydraulic problems, the process of assigning risk scores was adapted from project prioritization criteria used by the King County Flood Control District (FCD) to prioritize projects and actions based on flood risk and vulnerability. Assigning risk scores for the geotechnical problems was based on the likelihood of failure ratings assignment used to establish the initial analytical priority described in Chapter 3. The risk process presented in this report is qualitative and represents a relative difference in severity between identified problems. The relative ranking and quasi-qualitative assessment used to develop risk scores differs from the more qualitative risk assessment process developed by the USACE as part of its levee safety program.

5.2.1 Hydraulic Problem Risk Score Assignment

Project prioritization criteria developed by the King County FCD (King County, 2008) and used in the risk scoring identify four evaluation categories that evaluate the consequences of failure and likelihood of failure. The categories include current land use, hazard, extent, and timing of the potential impact. Points are assigned for each category based on the scale of the impact or failure likelihood with higher points assigned to problems with more severe impacts or a higher likelihood of failure.

Current land use considers the degree of development within the affected area and evaluates the consequences of failure. The range of land use considered, from low to high, includes undeveloped land, agricultural land, recreational land, commercial property, residential development, and critical facilities. Each of these land uses are contained within the South Fork Snoqualmie River study area. Land use is generally described in section 1.3.8. The point assignment ranges from 1 – 12 reflecting the relative high level of importance the King County FCD has placed on this category.



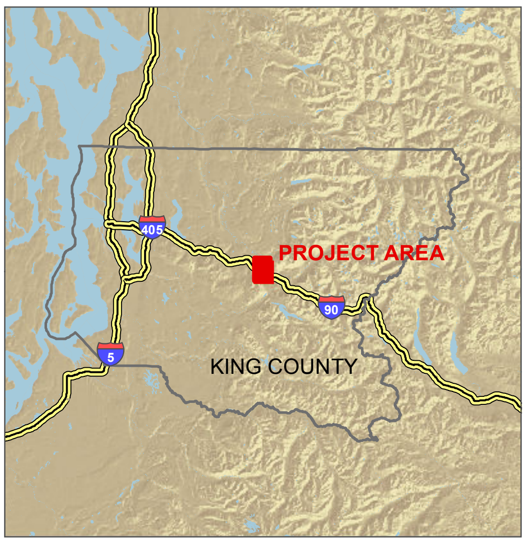


Figure 5-1. Hydraulic, Geotechnical, and Ecological Problem Areas

South Fork Snoqualmie River Levee Characterization Report

TABLE 5-1.
SUMMARY OF HYDRAULIC, GEOTECHNICAL AND ECOLOGICAL PROBLEM AREAS

Prob. Id[a]	River Mile	Problem Description	Consequence Description
Left Bank, Snoqualmie Valley Trail to Bendigo Boulevard North, (RM 2.0 – RM 2.25)			
H1	2.05 to 2.21	• Levee overtopping, 5-percent-annual-chance event. • Large backwater effect, Snoqualmie River Trail bridge. • Flooding from upstream locations, 2-percent-annual-chance and larger flood events. See problem IDs H3, H4, H6, H8 – H11, H13 – H15.	• Forested area flooded, 5-percent-annual-chance flood event.. • Overtopping at Snoqualmie Valley Trail, 5-percent-annual-chance flood event. • Increased potential for backside scour and headcut through the levee. Levee height 5 feet, crest width 15 to 20 feet, moderate landside slopes.
E1	2.1 to 2.25	• Impaired floodplain connectivity.	• Eliminates off-channel refugia during high flow events for all fish life stages.
		• Impaired streambank velocity refuge.	• High stream edge velocity detrimental to juvenile fish use.
		• Impaired instream cover function.	• Reduces in-channel complexity and habitat diversity.
	2.1 to 2.25	• Impaired riparian function.	• High water temperatures in excess of TMDL limits, interferes with recruitment of large wood.
Right Bank, Snoqualmie Valley Trail to Bendigo Boulevard North, (RM 2.0 – RM 2.25)			
H2	2.05 to 2.25	• Levee overtopping, 5-percent-annual-chance flood event. • Large backwater effect, Snoqualmie River Trail bridge. • Flooding from upstream locations, 0.2-percent-annual-chance flood event. See problem IDs H12 and H16.	• Forested area flooded, 5-percent-annual-chance flood event. • Overtopping at Snoqualmie Valley Trail, 5-percent-annual-chance flood event. • Overtopping contributes to flooding at the Wastewater treatment plant, 1-percent-annual-chance flood event. • Flooding in downtown North Bend from upstream sources, 0.2-percent-annual-chance flood event. • Increased potential for backside scour and headcut through the levee. Levee height 5 to 10 feet, crest width 15 to 17 feet, moderate landside slopes.
G11	2.04 to 2.11	• Severe toe erosion, 50 to 400 feet upstream of pedestrian bridge • Large trees mid-slope. • High shear stress from backwater at Snoqualmie River Trail bridge, 5-percent-annual-chance and larger.	• Potential to compromise levee stability, repeated maintenance and repair.
G25[b]	2.13 to 2.23	• Toe erosion, no riprap observed, subsurface conditions unknown.	• Potential to compromise levee stability, repeated maintenance and repair.
E2	2.0 - 2.25	• Impaired floodplain connectivity.	• Eliminates off-channel refugia during high flow events for all fish life stages
		• Impaired streambank velocity refuge.	• High stream edge velocity detrimental to juvenile fish use
	2.25	• Impaired riparian function.	• High water temperatures in excess of TMDL limits, interferes with recruitment of large wood.

TABLE 5-1.
SUMMARY OF HYDRAULIC, GEOTECHNICAL AND ECOLOGICAL PROBLEM AREAS

Prob. Id[a]	River Mile	Problem Description	Consequence Description
Left Bank, Bendigo Boulevard North to West North Bend Way (RM 2.25 – RM 2.45)			
H3 H4	2.25 to 2.28 2.38 to 2.45	• Levee overtopping, 1-percent-annual-chance flood event. • Levee overtopping, 2-percent-annual-chance flood event. • Flooding from upstream locations, 2-percent-annual-chance and larger flood event. See problem IDs H6, H8 – H11, H13 – H15.	• 4 structures inundated, 2-percent-annual-chance flood event. • NW 8th Street flooded, 2-percent-annual-chance flood event. • Overflow to Ribary Creek, 2-percent-annual-chance flood event contributes to downstream flooding. • Increased potential for backside scour and headcut through the levee. Levee height 4 to 6 feet, crest width 15 to 20 feet, moderate landside slopes.
G13	2.28	• Depression, 2 feet by 4 feet, probe depth 1.5 inches to 3 feet.	• Potential to compromise levee stability, repeated maintenance and repair.
E3	2.25 to 2.4 2.25 to 2.45	• Impaired riparian function. • Impaired floodplain connectivity. • Impaired streambank velocity refuge.	• High water temperatures in excess of TMDL limits, interferes with recruitment of large wood. • Eliminates off-channel refugia during high flow events for all fish life stages. • High stream edge velocity detrimental to juvenile fish use.
Right Bank, Bendigo Boulevard North to West North Bend Way (RM 2.25 – RM 2.45)			
G1[b]	2.27	• Seepage reported at outside bend with moderate slopes, sparse to no riprap.	• Potential to compromise levee stability, repeated maintenance and repair. • Five structures and forested area flooded due to seepage, 5-percent-annual-chance flood event.
H5	2.26 to 2.44	• Levee overtopping, 1-percent-annual-chance flood event. • Flooding from upstream locations, 0.2-percent-annual-chance flood event. See problem ID H15.	• 21 structures inundated, 1-percent-annual-chance flood event. • Low level flooding at wastewater treatment plant, 1-percent-annual-chance flood. • 35 structures inundated and widespread road flooding in downtown North Bend, 0.2%-annual-chance-flood event. • Increased potential for backside scour and headcut through the levee. Levee height 4 to 8 feet, crest width 15 to 20 feet, moderate landside slopes.
G14	2.39	• 14-inch-diameter sinkhole, probe depth 15 inches to 3 feet.	• Potential to compromise levee stability, repeated maintenance and repair.
G27	2.3 to 2.5	• Toe erosion and oversteepened toe	• Potential to compromise levee stability, repeated maintenance and repair.
E4	2.25 to 2.45	• Impaired floodplain connectivity. • Impaired streambank velocity refuge.	• Eliminates off-channel refugia during high flow events for all fish life stages • High stream edge velocity detrimental to juvenile fish use

**TABLE 5-1.
SUMMARY OF HYDRAULIC, GEOTECHNICAL AND ECOLOGICAL PROBLEM AREAS**

Prob. Id[a]	River Mile	Problem Description	Consequence Description
Left Bank, West North Bend Way to Bendigo Boulevard South, (RM 2.45 – RM 2.85)			
G2[b]	2.51	• Seepage observed from river to landside January 2009, moderate slopes. • Severe depression. • Sparse riprap, subsurface conditions unknown.	• Potential to compromise levee stability, repeated maintenance and repair.
G3[b]	2.70	• Piping and sand boil observed January 2009, moderate slopes. • Depression in levee crest. • Sparse riprap subsurface conditions unknown.	• Potential to compromise levee stability, repeated maintenance and repair.
H6	2.47 to 2.52	• Levee overtopping, 5-percent-annual-chance flood event. • Flooding from upstream locations, 2-percent-annual-chance and larger flood events. See problem IDs H8 – H 11, H13 – H15.	• Flooding within the West North Bend Way and Historic Railroad embankment, 5-percent-annual-chance flood event • Overflow to Ribary Creek, 2-percent-annual-chance flood event contributes to downstream flooding. • Increased potential for backside scour and headcut through the levee. Levee height 5 to 10 feet, crest width 20 to 30 feet, moderate landside slopes.
H8	2.81	• Levee overtopping, 2-percent-annual-chance event. • Levee overtopping at upstream locations contribute to flooding, 5-percent-annual-chance and larger flood events. See problem IDs H9 – H11, H13 – H15.	• One structure inundated, 2-percent-annual-chance and larger flood events. • Overtopping at South Fork Avenue, 5-percent-annual-chance flood event. • Overflow to Ribary Creek, 2-percent-annual-chance flood event contributes to downstream flooding. • Increased potential for backside scour and headcut through the levee. Levee eight 5 to 10 feet high, crest width 20 to 30 feet wide, moderate landside slopes.
E5	2.45 to 2.85	• Impaired floodplain connectivity. • Impaired streambank velocity refuge function.	• Eliminates off-channel refugia during high flow events for all fish life stages. • High stream edge velocity detrimental to juvenile fish use.

**TABLE 5-1.
SUMMARY OF HYDRAULIC, GEOTECHNICAL AND ECOLOGICAL PROBLEM AREAS**

Prob. Id[a]	River Mile	Problem Description	Consequence Description
Right Bank, West North Bend Way to Bendigo Boulevard South (RM 2.45 – RM 2.85)			
G15	2.47	• Seepage noted during 2009 flood event, water ponding behind pier. • Culvert penetrations at levee bend, severe riverside slopes.	• Potential to compromise levee stability, repeated maintenance and repair.
G29	~2.7	• Toe erosion and severe riverside slopes	• Potential to compromise levee stability, repeated maintenance and repair.
H7	2.85	• Levee overtopping, 2006 flood event • Levee overtopping predicted by model, 0.2-percent-annual-chance flood event. • Bendigo Boulevard South bridge restricts flow, 0.2-percent-annual-chance flood event.	• Minor flooding, no structure damage, 2006 flood event. • 15 structure inundated, 0.2-percent-annual-chance flood event. • Increased potential for backside scour and headcut through the levee. Levee height 5 to 10 feet, crest width 15 to 20 feet with flatter landside slopes.
E6	2.45 to 2.85	• Impaired floodplain connectivity • Impaired streambank velocity refuge function.	• Eliminates off-channel refugia during high flow events for all fish life stages • High stream edge velocity detrimental to juvenile fish use
Left Bank, Bendigo Boulevard South to RM 3.55 (RM 2.85 – RM 3.55)			
H9	2.85	• Bendigo Boulevard South overtopping from upstream sources, 5-percent-annual-chance flood event. See problem IDs H10, H11, H13 – H15. • Bendigo Boulevard South bridge restricts flows, 0.2-percent-annual-chance flood event.	• Arterial road flooding, 5-percent-annual-chance flood event. • Increased potential for erosion and scour on the downstream side of the roadway embankment.
H10	2.85 to 3.13	• Levee overtopping, 2-percent-annual-chance flood event.	• Inundation of undeveloped forested area, 2-percent-annual-chance flood event • 13 structures inundated in the Shamrock Park neighborhood, 1- and 0.2-percent-annual-chance flood event. • Overflow to Ribary Creek contributes to flooding in commercial area. • Increased potential for backside scour and headcut through the levee. Levee height 2 to 4 feet, crest width 15 to 20 feet, with flatter landside slope.

**TABLE 5-1.
SUMMARY OF HYDRAULIC, GEOTECHNICAL AND ECOLOGICAL PROBLEM AREAS**

Prob. Id[a]	River Mile	Problem Description	Consequence Description
H11	3.33 to 3.48	• Levee overtopping, 5-percent-annual-chance event. • Upstream levee overtopping contributes to flooding, 5-percent-annual-chance and larger flood events. See problem IDs H13 – H15.	• 26 structures inundated in the Shamrock Park and Berry Estates neighborhoods, 5-percent-annual-chance flood event. • 37 structures inundated, 5-percent-annual-chance-flood event. • 43 structures inundated, inundation extends into commercial area, 1-percent-annual-chance flood event. • 45 structures inundated, 0.2-percent-annual-chance flood event. • Overtopping contributes to downstream flooding of arterial roadway. • Limited potential for backside erosion and scour through the levee, zero height levee.
E7	3.05 to 3.4 2.85 to 3.40	• Impaired riparian function. • Impaired floodplain connectivity function • Impaired streambank velocity refuge function.	• High water temperatures in excess of TMDL limits, interferes with recruitment of large wood • Eliminates off-channel refugia during high flow events for all fish life stages • High stream edge velocity detrimental to juvenile fish use
Right Bank, Bendigo Boulevard South to RM 3.55 (RM 2.85 – RM 3.55)			
G4[b]	2.87	• Toe erosion at outside bend • High shear stress predicted, 0.2-percent –annual-chance flood event.	• Potential to compromise levee stability, repeated maintenance and repair. • Potential scour at bridge
H12	3.2	• Levee overtopping, 1-percent-annual-chance flood event.	• Inundation of area near Meadow Drive SE. • 176 structures inundated and widespread road flooding in North Bend, 0.2-percent-annual-chance flood event. • Low potential for backside erosion, 2 foot levee height.
E8	2.85 to 3.55	• Impaired riparian function • Impaired floodplain connectivity • Impaired streambank velocity refuge function.	• High water temperatures in excess of TMDL limits, interferes with recruitment of large wood. • Eliminates off-channel refugia during high flow events for all fish life stages. • High stream edge velocity detrimental to juvenile fish use.

TABLE 5-1.
SUMMARY OF HYDRAULIC, GEOTECHNICAL AND ECOLOGICAL PROBLEM AREAS

Prob. Id[a]	River Mile	Problem Description	Consequence Description
Left Bank, RM 3.55 to Interstate 90 (RM 3.55 – RM 4.85)			
H13	3.92 to 4.13	• Levee overtopping, 2-percent-annual-chance flood event.	• 10 structures inundated along SE 131st Street, 2-percent-annual-chance flood event. • 25 structures inundated, 1-percent-annual-chance flood event. • Overtopping at this location contributes to flooding in Berry Estates, Shamrock Park and downstream locations. • Increased potential for backside scour and headcut through the levee. Levee height 2 to 8 feet, crest width 15 to 20 feet, moderate landside slopes.
G8	4.18	• Outside bend, less than 12-foot-wide crest, moderate slopes, • Seepage reported during January 2009 flood event.	• Potential to compromise levee stability, repeated maintenance and repair. • 7 structures inundated due to seepage, SE 131st Street, 5-percent-annual-chance flood event.
G23	4.5 to 4.6	• Side channel developing and undercutting riverside toe, severe riverside slope. Evidence of slope movement (observed tension cracks in levee crest, leaning conifer on riverside slope).	• Potential to compromise levee stability, repeated maintenance and repair.
E9	3.7 and 4.2	• Riparian function is rated low.	• High water temperatures in excess of TMDL limits, interferes with recruitment of large wood.
	3.55 to 4.85	• Impaired floodplain connectivity	• Eliminates off-channel refugia during high flow events for all fish life stages.
		• Impaired streambank velocity refuge.	• High stream edge velocity detrimental to juvenile fish use
	4.50 to 4.80	• Impaired instream cover function.	• Reduces in-channel complexity and habitat diversity
Right Bank, RM 3.55 to Interstate 90 (RM 3.55 – RM 4.85)			
G9[b]	4.47	• Toe erosion, moderate slopes, • Sparse riprap, subsurface conditions unknown.. • High shear stresses near this location.	• Potential to compromise levee stability, repeated maintenance and repair.
G36[b]	4.48 to 4.72	• Toe erosion • Numerous alder trees on slope • Scattered riprap, subsurface conditions unknown.	• Potential to compromise levee stability, repeated maintenance and repair.
E10	3.55 to 4.0, 4.5, 4.85	• Impaired riparian function.	• High water temperatures in excess of TMDL limits, interferes with recruitment of large wood
	3.55 to 4.85	• Impaired floodplain connectivity	• Eliminates off-channel refugia during high flow events for all fish life stages.
		• Impaired streambank velocity refuge	• High stream edge velocity detrimental to juvenile fish use.

TABLE 5-1.
SUMMARY OF HYDRAULIC, GEOTECHNICAL AND ECOLOGICAL PROBLEM AREAS

Prob. Id[a]	River Mile	Problem Description	Consequence Description
Left Bank, Interstate 90 to 436th Avenue SE (RM 4.85 – RM 5.90)			
H14	Left Floodplain	• Flooding due to backwater from South Fork Snoqualmie River and Clough Creek, 5-percent-annual-chance flood event. • Interstate 90 overtopping occurs between 5- and 1-percent-annual flood event. • Flooding from upstream sources, 2-percent-annual-chance flood event. See problem H15.	• Interstate 90 overtopping, flood depths 0.5 foot depth, velocity 1 to 3 fps, 1-percent-annual-chance flood event. • 12 structures inundated along 415th Way SE, 5-percent-annual-chance flood event. • 20 structures inundated, 2-, 1-, and 0.2-percent-annual-chance flood events. • Increased potential for erosion and scour on the downstream side Interstate 90 roadway embankment, damage to subgrade and pavement section.
H15	4.85 to 5.08	• Levee overtopping, 2-percent-annual-chance event. • 4-foot backwater effect at Interstate 90 bridges, 1-percent-annual-chance flood event.	• 7 structures inundated along SE 141st Street, 2-percent-annual-chance flood event. • 13 structures inundated, 1-percent-annual-chance flood event. • 15 structures inundated, 0.2-percent-annual-chance flood event. • Overtopping at this location contributes to structure flooding in the Clough Creek floodplain area, Interstate 90, SE 131st Street, Berry Estates, Shamrock Park and other downstream locations. • Increased potential for backside scour and headcut through the levee. Levee height 3 to 7 feet, crest width 15 to 20 feet, moderate landside slopes.
G42[b]	5.08	• Toe erosion • Little to no riprap observed, subsurface conditions unknown.	• Potential to compromise levee stability, repeated maintenance and repair.
E-11	4.85 – 5.90	• Impaired floodplain connectivity.	• Eliminates off-channel refugia during high flow events for all fish life stages.
	4.85 - 4.95, 5.45 - 5.90	• Impaired riparian function.	• High water temperatures in excess of TMDL limits, interferes with recruitment of large wood
	4.85 - 5.10	• Impaired streambank velocity refuge	• High stream edge velocity detrimental to juvenile fish use.
	4.85 – 5.35	• Impaired instream cover function.	• Reduces in-channel complexity and habitat diversity

TABLE 5-1.
SUMMARY OF HYDRAULIC, GEOTECHNICAL AND ECOLOGICAL PROBLEM AREAS

Prob. Id[a]	River Mile	Problem Description	Consequence Description
Right Bank, Interstate 90 to 436th Avenue SE (RM 4.85 – RM 5.9)			
H16	4.96	• Levee overtopping, 1-percent-annual-chance flood event. • 4-foot backwater effect, Interstate 90 bridges, 1-percent-annual-chance flood event.	• 424th Street SE inundated, 1-percent-annual-chance flood event. • 5 structures inundated along 424th Street SE, 1-percent-annual-chance flood event. • Over 300 structures inundated in North Bend neighborhoods, 0.2-percent-annual-chance flood event. • Increased potential for backside scour and headcut through the levee. Levee height 0 to 5 feet high, crest width 15 to 25 feet, flatter landside slope.
G10	5.03	• Sags and depressions in crest 6 to 10 inches deep. • High shear stress due to Interstate 90 bridges, all flood events.	• Potential to compromise levee stability, repeated maintenance and repair.
G44	5.21	• Drainage collecting on landside of levee, riverside toe erosion, abundant trees midslope.	• Potential to compromise levee stability, repeated maintenance and repair.
E-12	4.85 – 5.9	• Impaired floodplain connectivity. • Impaired streambank velocity refuge.	• Eliminates off-channel refugia during high flow events for all fish life stages. • High stream edge velocity detrimental to juvenile fish use.
	4.85 – 5.0	• Impaired riparian function.	• High water temperatures in excess of TMDL limits, interferes with recruitment of large wood

a. See Figure 5-1 for location of problem area. H prefix indicates hydraulic problem, G indicates geotechnical problem, E indicates ecological problems.
b. Sparse and missing riprap is based on descriptions provided in the levee rating tables (Shannon & Wilson, 2009) which may have incorrectly reported the absence of riprap. Limited excavation of test pits indicated the presence of riprap at three locations but obscured by an overlying layer of fluvial deposits and vegetation (see Section 3.2).

The hazard of the potential impact evaluates public safety and the nature and severity of the impact on human activity. Potential hazards range from nuisance flooding with little interruption of human activity, land and property loss or damage, to more severe impacts such as injury and loss of life. The point assignment ranges from 1 – 12 reflecting the relative high level of importance the King County FCD has placed on this category.

The extent of the impact describes the scale of the problem. Problems are evaluated locally, on a larger neighborhood or city level, or regionally extending well outside the problem area. The point assignment ranges from 1 – 8 reflecting a relatively moderate level of importance placed on this category by the King County FCD.

The timing of the impact describes the likelihood of failure and provides information of the urgency needed to address the risk. For this study, likelihood of failure for hydraulic problems is described in terms of the probability of occurrence with higher probability events scoring higher than events with

lower probability. The point assignment ranges from 1 – 6 reflecting a relatively lower level of importance placed on this category by the King County FCD.

Scores for each of the risk categories were summed to define the total risk score for each of the identified problems. The problems were then sorted into high, medium, and low risk priority. High risk priority problems scored 25 or above, medium risk priority problems scoring between 11 and 24, and low risk priority problems scoring less 10 or lower. Risk scores are shown in Table 5-2. The process used to assign risk scores and priority is documented in Appendix D.

TABLE 5-2.
GEOTECHNICAL AND HYDRAULIC PROBLEM RISK

Prob. ID[a]	Description	Hyd. Risk Score[b]	Geo. Risk Score[b]	Risk Priority
	Left Bank, Snoqualmie Valley Trail to Bendigo Boulevard North (RM 2.0 – 2.25)			
H1	Levee overtopping RM 2.05 – 2.21	6		L
	Right Bank, Snoqualmie Valley Trail to Bendigo Boulevard North (RM 2.0 – 2.25)			
H2	Levee overtopping RM 2.05 – 2.25	21		M
G11	Toe erosion at RM 2.04 – 2.11		6	H
G25	Toe erosion at RM 2.13 to 2.23		2	L
	Left Bank, Bendigo Boulevard North to West North Bend Way (RM 2.25 – 2.45)			
H3	Levee overtopping RM 2.25 – 2.28	19		M
H4	Levee overtopping RM 2.38 – 2.45	19		M
G13	Depression in levee RM 2.28		1	L
	Right Bank, Bendigo Boulevard North to West North Bend Way (RM 2.25 – 2.45)			
G1	Seepage at RM 2.27		4	M
H5	Levee overtopping RM 2.26 – 2.44	26		H
G14	Small sinkhole right bank levee RM 2.39		1	L
G27	Toe erosion RM 2.3 to 2.5		3	M
	Left Bank, West North Bend Way to Bendigo Boulevard South (RM 2.45 – 2.85)			
G2	Depression, seepage and steep riverside levee slope RM 2.51		7	H
G3	Piping observed, depression, moderate riverside levee slopes RM 2.70		8	H
H6	Levee overtopping RM 2.47 – 2.52	8		L
H8	Levee overtopping RM 2.81	18		M
	Right Bank, West North Bend Way to Bendigo Boulevard South (RM 2.45 – 2.85)			
G15	Seepage, culvert penetration, severe riverside levee slope at RM 2.47		5	M
G29	Toe erosion and severe riverside levee slopes RM 2.7		3	M
H7	Levee overtopping RM 2.85	9		L

TABLE 5-2.
GEOTECHNICAL AND HYDRAULIC PROBLEM RISK

Prob. ID[a]	Description	Hyd. Risk Score[b]	Geo. Risk Score[b]	Risk Priority
	Left Bank, Bendigo Boulevard South to RM 3.55 (RM 2.85 – 3.55)			
H9	Flooding at Bendigo Boulevard South	25		H
H10	Levee overtopping RM 2.85 – 3.13	21		M
H11	Levee overtopping RM 3.33 – 3.48	25		H
	Right Bank, Bendigo Boulevard South to RM 3.55 (RM 2.85 – 3.55)			
G4	Toe erosion RM 2.87		2	L
H12	Right bank levee overtopping RM 3.2	8		L
	Left Bank, RM 3.55 to Interstate 90 (RM 3.55 – 4.85)			
H13	Levee overtopping RM 3.92 – 4.13	21		M
G8	Seepage and moderate riverside levee slopes RM 4.18		5	M
G23	Toe erosion and unstable slope left bank levee RM 4.5 – 4.6		6	H
	Right Bank, RM 3.55 to Interstate 90 (RM 3.55 – 4.85)			
G9	Toe erosion and moderate riverside levee slopes RM 4.47		3	M
G36	Toe erosion RM 4.48 to 4.72		2	L
	Left Bank, Interstate 90 to 436th Avenue SE (RM 4.85 – 5.90)			
H14	Clough Creek floodplain inundation and flooding on Interstate 90	32		H
H15	Levee overtopping RM 4.85 – 5.08	32		H
G42	Toe erosion RM 5.08		2	L
	Right Bank, Interstate 90 to 436th Avenue SE (RM 4.85 – 5.90)			
H16	Levee overtopping RM 4.96	23		M
G10	Depression in levee crest, moderate to steep slopes RM 5.03		1	L
G44	Interior drainage, toe erosion RM 5.21		2	L

a. H prefix indicates hydraulic problem, G indicates geotechnical problem.
b. Risk scores assigned to hydraulic problems cover a wider range than the geotechnical problems so a direct comparison between scores is not possible between the problem types.

5.2.2 Geotechnical Problem Risk Score Assignment

Risk scores were assigned based on the likelihood of failure ratings described in Chapter 3. Initially, the King County FCD process outlined in the previous section was applied to the geotechnical problems but it was found that the higher weighting tied to consequences of failure under-emphasize the likelihood of failure and did not adequately consider levee stability in prioritizing risk. Also, the nature of the geotechnical problems were typical of the type of problem addressed through localized maintenance or remedial actions likely implemented over the short term rather than as reach scale levee improvement projects.

The screened list of geotechnical problems from Chapter 3 and included in Table 5-1 are comprised of problems exhibiting active damage or failure. These problems were assigned risk scores based on the likelihood of failure ratings outlined in Table 3-3 but modified to cover the range of identified problem types. Geotechnical problems were grouped as follows as having high, medium or low risk priority:

- High risk priority (risk score of 6 to 10)—Piping, seepage combined with a surface depression, or severe toe erosion with slope instability.
- Moderate risk priority (risk score of 3 to 5)—toe erosion or seepage with narrow crest, seepage with pipe penetration or erosion.
- Low risk priority (risk score less than 3)—toe or crest erosion, depression on levee crest.

Because the risk scores for the geotechnical problems only cover likelihood of failure, the risk scores listed above cover a narrower range of values compared to the risk scoring for the hydraulic problems so a direct comparison between scores is not possible. Instead, the risk priority should be used to evaluate relative priority between the two problem types. Risk scores and priority for geotechnical problems are shown in Table 5-2. The process used to assign risk scores is documented in Appendix D.

5.2.3 Reach Summary

The overall risk priority of each reach was qualitatively assessed based on the risk priority of the hydraulic and geotechnical problems in that reach. Generally, high risk reach segments are associated with reaches with at least one high risk geotechnical and/or hydraulic problem, moderate risk reaches with moderate problems and low risk reaches with low risk problems.

Snoqualmie Valley Trail to Bendigo Boulevard North (RM 2.0 – 2.25)

Left bank - This reach would be considered to have a **low** risk. The single hydraulic problem in this reach (H1) causes flooding starting with the 5-percent-annual-chance flood event in an undeveloped park located in the right overbank area.

Right bank – Severe toe erosion (G11) causes this reach to have a **high** risk. Toe erosion is also reported upstream (G25) near the Bendigo Boulevard North bridge. Levee overtopping occurs in the reach (H2) for the 5-percent-annual-chance flood event but only inundates undeveloped park land adjacent to the levee. However, during the 1-percent-annual-chance flood event, overtopping at this location contributes to flooding at the North Bend Wastewater Treatment plant and also downtown North Bend during the 0.2-percent-annual-chance flood event.

Bendigo Boulevard North to West North Bend Way (RM 2.25 – 2.45)

Left bank – The left bank of this reach would be considered to have a **moderate** risk due the moderate risk levee overtopping problem along the full length of this reach (H3 and H4). Overtopping at this location causes flooding in the forested area but also inundates NW 8th Street and residential properties during the 2-percent-annual-chance flood event. A depression in the levee crest (G13) near Bendigo Boulevard North is also found in this reach.

Right bank – This reach would be considered to have a **high** risk. The hydraulic problem in this was determined to have a high risk priority due to the levee overtopping that occurs along the entire length of the levee during the 1-percent-annual-chance flood event which inundates the North Bend Wastewater Treatment Plant. Toe erosion with seepage (G1), toe erosion (G27), and a sinkhole (G14) are also found in this reach.

West North Bend Way to Bendigo Boulevard South (RM 2.45 – 2.85)

Left bank – The left bank is considered to have a **high** risk due to the presence of two high risk priority geotechnical problems in the reach. Seepage through the levee with depression in the levee were observed during the 2009 flood event (G2). Piping and a depression (G3) were also observed during the same flood event. The presence of two high risk geotechnical problems would suggest this reach is the highest risk priority for geotechnical issues. Levee overtopping also occurs at this location (H6 and H8), starting with the 5-percent-annual-chance flood event, inundating the undeveloped Ribary Creek floodplain, However, one structure is inundated starting with the 2-percent-annual-chance flood event.

Right bank – This reach is considered to have a **moderate** risk due to seepage near a culvert penetration (G15) near West North Bend Way, and toe erosion mid-reach (G29). Levee overtopping (H7) was also reported near Bendigo Boulevard South during the 2006 flood event.

Bendigo Boulevard South to RM 3.55 (RM 2.85 – 3.55)

Left Bank – Levee overtopping near Berry Estates (H11) and flooding on Bendigo Boulevard South (H10) cause this reach to have a **high** risk. Levee overtopping near Berry Estates inundates the residential and commercial area in the overbank floodplain starting with the 5-percent-annual-chance flood event. Levee overtopping also occurs upstream of Bendigo Boulevard South (H10) and contributes to flooding in this area starting with 2-percent-annual-chance flood event. Levee overtopping from both locations contribute to flooding over Bendigo Boulevard South (H9) and other downstream locations. Levee overtopping near Berry Estates and flooding on Bendigo Boulevard South are considered to be high risk priority problems. There are no geotechnical problems in this reach.

Right bank – This reach is considered to have a **low** risk due to two low risk priority problems. Levee overtopping occurs in this reach (H12) during the 1-percent-annual-chance-flood event inundating a small undeveloped area on the landward side of the levee. Toe erosion (G4) upstream of Bendigo boulevard South also found in this reach.

RM 3.55 to Interstate 90 (RM 3.55 – 4.85)

Left bank – Toe erosion and an unstable slope (G23) downstream of Interstate 90 cause this reach to have a **high** risk. Seepage (G8) was also reported during the 2009 flood event near SE 131st Street. Levee overtopping occurs at the same location (H13) starting with the 2-percent-annual-chance flood event.

Right bank – This reach is considered to have **moderate** risk due to toe erosion over an extended length at a levee segment with a narrow crest (G9 and G36) downstream of Interstate 90. There are no hydraulic problems in this reach.

Interstate 90 to 436th Avenue SE

Left bank – Levee overtopping upstream of Interstate 90 (H15) and backwater in the South Fork Snoqualmie River result in deep and widespread flooding in the Clough Creek overbank area (H14) ultimately causing floodwaters to overtop Interstate 90. Overtopping of Interstate 90 starts with the 1-percent annual-chance flood event and contributes to downstream flooding in Berry Estates, Shamrock Park, the commercial area along Bendigo Boulevard South, and Bendigo Boulevard South. This reach contains the two highest scoring problems which would be make this the **highest** risk reach for hydraulic issues. A single geotechnical problem is located in this reach where toe erosion is occurring near SE 436th Avenue SE (G42)

Right bank – This reach would be considered to have **moderate** risk due to levee overtopping that occurs upstream of Interstate 90 (H16). Overtopping occurs starting with the 1-percent-annual-chance flood

event and inundates a forested area and several residences. However, during the 0.2 percent-annual-chance flood event, floodwaters travel under Interstate 90 at 424th Street SE to downtown North Bend where widespread flooding occurs. Two low risk priority geotechnical problems, depression in the levee crest (G10) and toe erosion (G44), are also located in this reach.

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