# South Fork Snoqualmie River Gravel Removal Study

King County

Department of Natural Resources and Parks
King County Water and Land Resources Division
*River and Floodplain Management Section*
201 S. Jackson Street, Suite 600
Seattle, WA 98104

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King County Executive
Dow Constantine

Department of Natural Resources and Parks
Christine True, Director
Bob Burns, Deputy Director

Water and Land Resources Division
Mark Isaacson, Director
Joanna Richey, Assistant Director
Steve Bleifuhs, Manager, River and Floodplain Management Section

King County Council
Bob Ferguson, District 1
Larry Gossett, District 2
Kathy Lambert, District 3
Larry Phillips, District 4
Julia Patterson, District 5
Jane Hague, District 6
Pete von Reichbauer, District 7
Joe McDermott, District 8
Reagan Dunn, District 9

Primary Contributing Staff:
Terry Butler, P.E., L.G., Geologist and primary author, River and Floodplain Management Section
Robert Fuerstenberg, Former Senior Ecologist and contributing author, Watershed Ecology and Assessment Unit
Kyle Comanor, P.E., Engineer and hydraulic modeler, River and Floodplain Management Section

River and Floodplain Management Section Contributing Staff:
Clint Loper, P.E., Supervising Engineer, Snoqualmie River Basin
Jeanne Stypula, P.E., Supervising Engineer, Technical Services
Brian Murray, Countywide Programs and Policies Manager

Water and Land Resources Division Supporting Staff:
River and Floodplain Management Section:
Tom Bean, P.E., Supervising Engineer, Green River Basin
Chase Barton, P.E., L.G., Senior Engineer, Snoqualmie River Basin
John Bethel, L.E.G., Geologist, Technical Services
Priscilla Kaufmann, CFM, Program Manager, Countywide Programs and Policies
Deborah Scheibner, P.E., Senior Engineer, White River Basin
Ken Zweig, Project/Program Manager, Countywide Programs and Policies
Sylvia Aro, Administrative Specialist

GIS, Visual Communications and Web Unit:
Megann Devine, Visual Communications Specialist
Wendy Gable-Collins, Visual Communications Specialist
Ken Rauscher, GIS Analyst

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## Executive Summary—South Fork Snoqualmie River gravel removal study

This study of the South Fork Snoqualmie River characterizes the existing sediment accumulation and flooding conditions and evaluates the effectiveness of gravel removal for flood reduction in the South Fork Snoqualmie River from the North Bend Blvd (Bendigo) Bridge upstream approximately 1.6 river miles to near the I-90 Bridges. There is concern that sediment accumulation in this river reach has decreased the channel capacity and is causing increased flood hazards. King County monitors sediment levels in this part of the South Fork Snoqualmie River. If the monitoring data indicate that sediment accumulations are causing an adverse effect on flood hazards, then potential sediment management actions can be considered. Gravel removal is one such action.

Existing Conditions:

*Setting*

The South Fork Snoqualmie River in the North Bend area is confined along both banks by containment levees that generally have greater channel conveyance capacity in the upstream part of this study reach than the downstream and along the right bank (viewed looking downstream) than the left bank. The levees intentionally were built, in about 1964, with the right bank higher than the left bank. With this configuration, levee overtopping typically occurs along the left bank in the downstream area, affecting the Berry Estates and Shamrock Park subdivisions.

Available information indicates that the original channel capacity of the South Fork Snoqualmie River levees was 13,000 cubic feet per second (cfs) plus one foot of freeboard, although no levee design documents have been found that identify a specific channel capacity. The 2009 existing conditions have a channel conveyance capacity of 15,000 cfs (a 100-year flood) or more along both banks everywhere in the upstream part of the study reach, thereby exceeding the original channel conveyance capacity, except at one location. Existing conditions along the right bank in the downstream part of the study reach also continue to meet or exceed the original channel design capacity except near North Bend Blvd (Bendigo) Bridge, where containment is closer to 13,000 cfs (a 50-year flood). The left bank along most of the downstream part of the study reach does not presently contain 13,000 cfs plus one foot of freeboard, including two locations where the 2009 channel conveyance capacity is about 11,700 cfs (a 30-year flood): adjacent to the Shamrock Park subdivision and adjacent to the Berry Estates subdivision. Floods in November 1990, November 2006 and January 2009 overtopped the left bank in the downstream area and contributed to flooding of these residential neighborhoods.

*Sediment Trends*

This reach of the South Fork Snoqualmie River has natural conditions that favor sediment deposition, such as a decreasing channel gradient and a location at the downstream end of a basin with ample sediment sources. Some constructed features also enhance in-channel sediment deposition such as the containment levees themselves, which prevent the river from accessing and depositing some of its sediment on its floodplain, and the North Bend Blvd Bridge, which creates backwater conditions for a distance upstream.

Channel monitoring data from 1992/95 to 2009 show that sediment has accumulated on most of the nine gravel bars in this study reach, although there also are some locations that show erosion, and many locations without much net change in sediment levels through the 17-year study period. The average annual deposition rate for this study reach is an estimated 2,700 cubic yards per year, which translates to a reachwide average vertical increase in riverbed elevation of 0.4 feet per decade. These estimated rates of sedimentation are consistent with other studies on this river and with sedimentation observed in other rivers in this region.

Most of the factors that affect deposition rates in this study reach (e.g., channel gradient, confinement by the levees and North Bend Blvd Bridge, sediment supply from upstream) have been constant throughout this study period, so the primary factor affecting sediment deposition during shorter intervals within the full study period was the timing, magnitude and duration of high flow events. The following temporal trends in sedimentation were observed throughout the study reach: moderate to high increases in sediment levels during 1992/95 to 1999, negligible changes in 1999 to 2006, and moderate to high increases during 2006 to 2007 and 2007 to 2009.

*Floodwater level trends*

Hydraulic modeling of water level responses to the changes in channel conditions over the 17-year study period, and shorter periods within the full 17-year study period, indicates that there have been relatively minor (less than one-half foot) increases in modeled flood water surface elevations in the downstream part of this study reach, and that there have been moderate increases (one-half foot to one foot) increases in modeled flood water surface elevations in the upstream part of this reach. Trends in increases (and decreases) in water surface elevation changes appear to generally correspond to the trends of changes in sediment deposition (and erosion) throughout the full study reach and within the upstream and downstream subreaches. Temporal water surface trends also correspond closely to the temporal trends in sedimentation described in the paragraph above, both through the full study period and during shorter periods.

In the last two to three years, there have been noticeable increases in modeled flood water surface elevations at two key locations. One is adjacent to Berry Estates (River Mile [RM] 3.34 to 3.39), where there has been an increase of about 0.2 feet in the modeled flood water surface elevations since 2007. This is a minor increase but it is adjacent to the location of previous overtopping and damaging flood flows. The second is in the upstream area at the relatively large gravel bar 6 (RM 3.99 to RM 4.04), where there has been an increase of about one foot in the modeled flood water surface elevations since 2006. While this latter location has not seen previous overtopping flows and there is still adequate containment, this is a marked increase in modeled water levels over a short period of time. Both of these specific locations warrant continued close attention. Results described below focus on these two key locations.

The exception to these sediment and water surface trends is in the area upstream from the North Bend Blvd Bridge, where, even with increases in sediment levels, there were no corresponding increases in modeled water surface elevations through the full 17-year study period. This finding is consistent with that area's domination by backwater conditions due to bridge hydraulics, which appear to affect flood water surface elevations upstream about 1,000 feet (to RM 3.02) and possibly further.

Upstream of the backwater, reachwide increases in water surface elevations over the full study period are attributed to sediment accumulation during that period. Therefore, it is appropriate to consider gravel removal for flood hazard reduction purposes in this study.

*Salmonid habitat, endangered species*

No anadromous salmonids inhabit the South Fork Snoqualmie River, which is upstream of Snoqualmie Falls. This study reach supports two native salmonid species, the western cutthroat trout and the mountain whitefish, and two non-native salmonid species, the rainbow trout and Brook trout. Bull trout, which are listed as "threatened" under the Endangered Species Act, have not been detected in this part of the river. In-channel habitats through the study reach tend to be simple and lack variation in depth and structure. The main channel habitat is dominated by fast-moving water in the form of riffles and runs with only rare pools and very few still-water areas of any size.

Gravel Removal:

*Study approach*

Gravel removal can be conducted in a river by gravel bar scalping, which excavates the dry top of a gravel bar above the water, or by dredging, which includes excavation in the wetted channel. Three different bar scalping gravel removal scenarios were analyzed in order to consider a range of potential options in evaluating the effectiveness of gravel removal in reducing flood water surface elevations. A dredging scenario was considered but not analyzed in this study because present-day dredging likely would threaten the stability of the existing King County levees or North Bend Blvd Bridge and because it does not appear that dredging was done to create the original channel capacity when the levees were constructed.

The three bar scalping gravel removal scenarios were evaluated against criteria that are based on guidelines and goals of the adopted 2006 King County Flood Hazard Management Plan. Using these criteria, the evaluation process compared the flood hazard reduction effectiveness of each scenario to its potential adverse impacts and its long-term costs.

The reduction in flood water surface elevations computed by hydraulic modeling was used to indicate the flood hazard reduction effectiveness of each bar scalping scenario. Potential adverse impacts were described generally based on available information and reconnaissance-level field observations of the likely physical effects of each gravel scenario on existing habitat conditions, bridge and levee stability, and downstream flooding. Potential project costs were estimated using standard unit costs and assumed King County labor costs, or that a county contractor would conduct the gravel removal.

The longevity of flood hazard reduction benefits from gravel removal was estimated by dividing the excavation volume of each scenario by the average annual rates of sediment influx and sediment deposition in this study reach. The resulting values, in years, may suggest that the full flood hazard reduction benefits of gravel removal will persist throughout the full calculated period of longevity, but that is not the case. Channel capacity will diminish throughout this

calculated period at a rate dependent on the magnitude and duration of any flood events and the sediment they deliver, beginning with the first flow large enough to transport coarse sediment. A single large flood or a winter of large flows may move and deposit enough sediment to fill in areas of gravel excavation, thereby negating the benefits in a relatively short period of time.

*Gravel removal scenarios - results*

None of the three analyzed gravel removal scenarios would result in containment of the original estimated channel capacity of the levees (13,000 cfs plus one foot of freeboard), but each of the three scenarios would decrease flood levels by some amount at various locations. None of the three scenarios would decrease floodwater levels within the area dominated by North Bend Blvd Bridge backwater. Gravel removal by any of the three scalp scenarios would, to a greater or lesser extent, temporarily counteract the increases in the 13,000 cfs water surface elevation that have occurred since 1992/95 adjacent to Berry Estates. Two of the three scalp scenarios would have similar results along gravel bar 6.

Scalp Scenario 1 would affect five gravel bars spread throughout the study reach and is configured with a relatively limited depth, width and length of gravel extraction on each affected gravel bar, so as to minimize in-channel habitat impacts. Scalp Scenario 1 would decrease the water surface elevation of the 13,000 cfs (50-year) flood adjacent to Berry Estates by as little as 0.2 feet and as much as 0.5 feet, depending on the specific location. It also would decrease the 13,000 cfs flood water surface by as much as 1.6 feet along gravel bar 6. The longevity of these benefits is estimated at five to eight years. Scalp Scenario 1 would have the least impacts of the three scenarios and the lowest estimated cost, at $1.5 M.

Scalp Scenario 2 would include deeper excavation and would affect the full width and length of all nine gravel bars throughout the study reach. Scalp Scenario 2 would decrease the water surface elevation of the 13,000 cfs flood adjacent to Berry Estates by as little as 0.4 feet and by as much as 0.7 feet, depending on the specific location. It also would decrease the 13,000 cfs water surface elevation by as much as 2.1 feet along gravel bar 6. The longevity of Scalp Scenario 2 flood reductions is estimated at 12 to 19 years. Scalp Scenario 2 would cost more than twice as much as Scalp Scenario 1 or 3, at an estimated $3.6 M, and would have much greater impacts than the other scenarios due to a much larger areal extent and more pervasive effects on hydraulics and sediment movement through the study reach. With its deep and widespread excavation of a sediment volume far in excess of the average annual sediment influx to this reach, Scalp Scenario 2 likely would induce scour at the toe of existing levees and may threaten the stability of North Bend Blvd Bridge.

Scalp Scenarios 3 is configured identically to Scalp Scenario 2 in the downstream part of the study reach where previous overtopping flows have occurred. Scalp Scenario 3 also would excavate deeply and across the full width and length of each gravel bar it would affect, but it would affect only the four downstream gravel bars in the area. Scalp Scenario 3 would decrease the water surface elevation of the 13,000 cfs flood adjacent to Berry Estates by as little as 0.4 feet and by as much as 0.7 feet. Because it is focused on the downstream part of the study reach, Scalp Scenario 3 would not have any flood hazard reduction effect on the area along gravel bar 6. The longevity of Scalp Scenario 3 is estimated at six to nine years and its cost is estimated at $1.6 M.

*Evaluation of gravel removal scenarios*

Scalp Scenario 1 would have the least adverse impacts of the scenarios, but its inherently limited extent of scalping also minimizes its flood hazard reduction effectiveness, while its costs would be similar to Scalp Scenario 3. Scalp Scenario 2 and 3 would have identical flood reduction benefits in the downstream area where overtopping has occurred in the past, along Berry Estates. Either Scalp Scenario 2 or 3 would decrease the probability of overtopping adjacent to Berry Estates by about 1 percent in any given year. Scalp Scenario 2 would have much higher costs and appears likely to induce levee or bridge scour, and therefore does not appear to be a viable scenario.

When flood reduction benefits are compared to potential adverse impacts and long term costs, Scalp Scenario 3 would best meet all evaluation criteria regarding flood hazard reduction effectiveness, avoiding adverse impacts and minimizing estimated costs. However, the potential for the deep, extensive excavation on all four downstream gravel bars included in Scalp Scenario 3 to induce local scour and threaten levee or bridge stability is a real concern that would need to be addressed in a geotechnical analysis.

Next steps:

This study assessed the effectiveness of only one type of alternative—gravel removal—in reducing flood hazard along this study reach in the South Fork Snoqualmie River. A permanent or long-term solution to river flooding along this study reach will require measures beyond the gravel removal scenarios analyzed in this study. Other alternatives that could reduce flood risk, such as levee setbacks, increases in levee crest elevation, home acquisitions or elevations, or bridge modifications, were not considered here. Full consideration of a comprehensive strategy to reduce flood risks along this river channel is beyond the scope of this study but the results of this study will be used to inform the strategy and to develop viable project alternatives.

A comprehensive consideration of potential flood risk reduction projects is being coordinated for the South Fork Snoqualmie and Middle Fork Snoqualmie rivers through efforts of King County on behalf of the King County Flood Control District (KCFCD), and should include consideration of gravel removal. If a decision were made to further pursue a gravel removal project, it would be evaluated and rated for relative priority amongst all other flood risk reduction projects proposed by the KCFCD through a process that includes input by staff and elected officials from all King County jurisdictions. Whether or not a gravel removal project is pursued, channel monitoring of the South Fork Snoqualmie River will continue in this reach so as to inform the ongoing river and floodplain management program.

# 1. Introduction

## 1.1 Study purpose and scope

The South Fork Snoqualmie River flows from steep headwaters in the Cascades downstream through foothills and a widening valley to its confluence with the Snoqualmie River in the Three-Forks area upstream of Snoqualmie Falls. As sediment moves from source areas in steep headwaters to the lower gradient downstream channels, some of it deposits and accumulates, which can decrease channel capacity and aggravate flood levels.

The purpose of this study is twofold: (1) to characterize the existing sediment accumulation and its effect on river flooding conditions and (2) to evaluate the effectiveness of gravel removal for flood reduction in the South Fork Snoqualmie River near North Bend. This study is not intended to make a specific recommendation as to whether to pursue a gravel removal project. In accordance with the policies of the 2006 King County Flood Hazard Management Plan and the capital project prioritization approach of the King County Flood Control District (KCFCD), such a decision requires consideration of other alternatives for addressing flood hazards and risks in any given area. A capital project decision must reflect the relative effectiveness of a particular approach compared to other approaches to addressing flood hazards in that vicinity, as well as the priority of any project compared to other needs throughout the County. This report does provide enough information on the effects of gravel deposition in this reach, and the potential effectiveness of gravel removal, to allow for these comparisons to be made. It should be noted that a comprehensive evaluation of flood hazards along the South Fork Snoqualmie River, and development and prioritization of a broader suite of possible solutions, is currently being conducted by King County.

The specific study reach is the South Fork Snoqualmie River from North Bend Blvd (Bendigo) Bridge upstream to near I-90, which is about 1.6 River Miles (RM) (Figure 1-1). A more detailed description of existing conditions is provided in Section 5.

This study begins with an overview of riverine processes, with a description of the potential effects of gravel removal on those processes (Section 2). Gravel removal goals, objectives and evaluation criteria that are based on the goals of the adopted 2006 King County Flood Hazard Management Plan, plus a flood hazard reduction objective for the study area, are identified in Section 4. Existing patterns and trends in sediment accumulation, changes in water surface elevation over a period of about 15 years, and salmonid habitat and use in this study reach are described in Section 5.

The effectiveness of gravel removal in reducing flood hazards is determined primarily by hydraulic computer modeling of various gravel removal scenarios and comparing the results to existing conditions (Section 6). Potential adverse impacts of each gravel removal scenario are assessed generally in Section 7. The flood hazard reduction effectiveness of the gravel removal scenarios are evaluated against the criteria identified earlier, and compared to their adverse impacts and costs (Section 8). Summaries and conclusions are presented in Section 9.

For the purposes of this report, the evaluation of gravel removal effectiveness, costs and impacts assumes that any gravel removal action either would be conducted by King County staff and

crews— i.e., design and permitting staff, construction labor by crews experienced in conducting in-river construction, etc.—or by consultants and operators hired by King County. Although another party could be a project proponent and use the results of this evaluation to develop a specific project proposal, further refinement of project effectiveness, impacts and costs would need to be developed.

## 1.2 Background

Although river sediments can include a full range of sizes from silt and clay to gravel and cobble and boulders, the terms "gravel" or "gravel bar" are commonly used to refer to sediment accumulation. The term “gravel removal” generally includes excavation that can be done as gravel bar scalping (which excavates the top portion of a gravel bar above the ordinary water level) or dredging (which includes excavation across the full wetted channel). Only gravel bar scalping is formally evaluated in this study (as explained more in Section 4), so the terms gravel removal and gravel bar scalping are used interchangeably. While an in-channel dredging scenario was considered in the initial stages of working on this study, ultimately it was not fully developed and evaluated, for reasons described in Section 4.

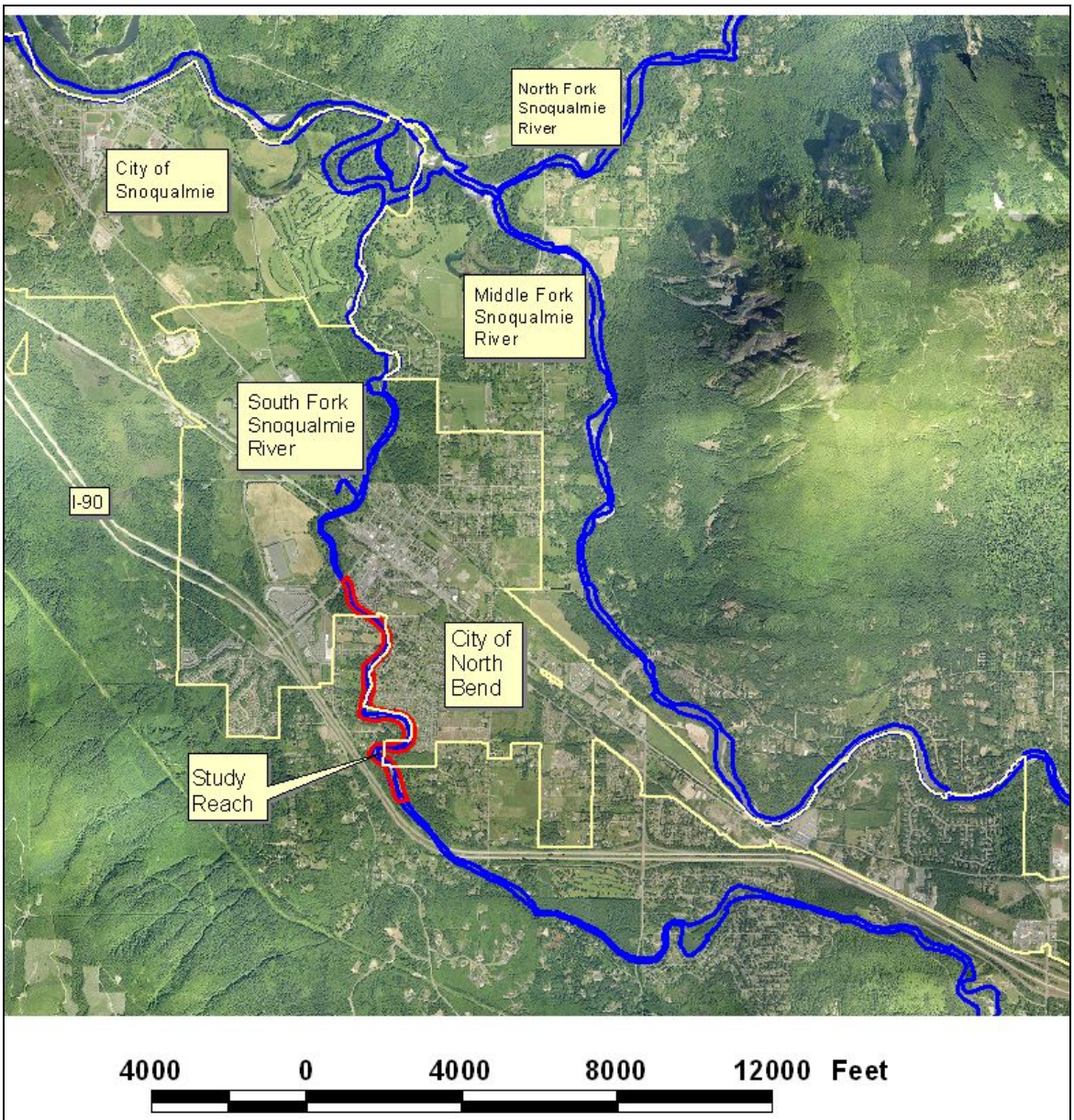



**Figure 1-1:**
**South Fork Snoqualmie River Study Reach location, in red. City limits in yellow. 2007 aerial photo.**

The King County River and Floodplain Management Section monitors channel conditions and sediment levels in a number of river channels, including the South Fork Snoqualmie River in North Bend in this same study reach. If the channel monitoring data indicate that sediment has accumulated and is causing an adverse effect on flood hazards then informed actions to decrease the flood hazards and flood risks can be identified, evaluated and implemented. Any permanent or longer-term solution to flood risks related to sediment accumulation will probably involve altering the existing bank armoring, removing structures that are at risk from the flood hazard, or both. Potential permanent or longer-term solutions include levee setbacks, floodplain reconnections, buyouts from willing sellers of affected structures, or a combination thereof. Gravel removal is another potential flood risk reduction action, but gravel removal would provide only a temporary remedy in an area of ongoing sediment accumulation. Gravel removal must be repeated on a periodic basis over time, in order to maintain the flood level reduction benefit as new sediments replace those that have been removed.

The historical response to sediment and gravel accumulation in some channels of the Snoqualmie River Basin has been gravel removal by dredging or gravel bar scalping, including in the South Fork Snoqualmie River. Gravel removal was conducted by the City of North Bend on the South Fork Snoqualmie River in the early 1990s (as described in more detail in subsequent sections). Gravel removal by King County for flood reduction purposes in the Snoqualmie River Basin was discontinued in the late 1960s due to dwindling flood control bond funds and a growing awareness of the adverse environmental impacts of in-channel dredging. Even with gravel removal largely discontinued, there has been continued interest in the potential of gravel removal for flood reduction through the years.

In the years since the last gravel removal operations, studies have documented the potential adverse effects of gravel removal on erosion and sediment transport processes, nearby and downstream flooding and aquatic habitat. Relevant literature is cited in Section 2. If gravel removal were to be pursued it would likely be required that the potential impacts of a project would be analyzed in greater detail than is done generally in this study (Section 7), as part of the permit application and approval process.

In recent years, fall chinook salmon (*Oncorhynchus tshawytscha*), bull trout (*Salvelinus confluentus*) and steelhead (*Oncorhynchus mykiss*) were listed as threatened under the Endangered Species Act (ESA). Because gravel removal can have significant adverse impacts on salmonid habitat and use, these ESA listings will affect the permit process required for a riverine gravel removal proposal. If a listed species is present, then it is likely that a consultation with the Federal fisheries services responsible for protection of these species, US Fish and Wildlife Services (USFWS) and National Oceanic and Atmospheric Administration/National Marine Fisheries Service (NOAA/NMFS), would be required as part of the requirements of a Section 404 permit from the US Army Corps of Engineers (USACE), which entails preparation of an extensive and detailed evaluation of potential adverse impacts of gravel removal on the species and their habitats. The presence or absence of ESA-listed species along this South Fork Snoqualmie River study reach will be addressed in this report.

It is consistent with King County policy (King County 1993; King County 2006) to evaluate gravel removal and other alternative flood strategies for flood risk reduction actions to be implemented by King County. This study assesses the effectiveness of only one alternative—

gravel removal—in reducing flood hazard along this study reach. Flood ***hazard*** reduction is the component of flood ***risk*** reduction that focuses on the potential decreases in flood water levels if gravel removal occurred. The other component of flood risk reduction is the effect of the flood hazard on areas of consequence such as public infrastructure or properties with residential or commercial structures on them. Other alternatives that could reduce flood risk to public infrastructure or residential or commercial structures, such as levee setbacks, increases in levee crest elevation, home acquisitions or elevations, or bridge modifications, are not considered here. Full consideration of a comprehensive strategy to reduce flood risks along this river channel is beyond the scope of this study but the results of this study will be used to inform the strategy and to develop viable project alternatives.

## 1.3 Problem statement

This subsection provides a brief description of the problem regarding sediment accumulation and river-based flooding problems in the South Fork Snoqualmie River along this study reach.

Reach Location:
Approximately 1.6 miles of river in North Bend area, running from North Bend Blvd Bridge (a.k.a. Bendigo Bridge or SR 202) upstream to near the I-90 Bridges.

Problem Description:
Accumulation of sediment in the channel appears to have reduced the channel conveyance capacity of the mainstem South Fork Snoqualmie River to the extent that it may be causing an increase in river flood levels and flood hazards. Flooding from other sources such as local tributaries, stormwater and high groundwater affect this area as well but are not addressed in this study.

Areas affected by flooding:
Flooding from the South Fork Snoqualmie River in this study reach affects residential areas of the City of North Bend, unincorporated King County and the North Bend business district.

A specific flood hazard reduction objective is identified in Section 4. Information on the physiographic setting of this study reach in the overall South Fork Snoqualmie River basin and basin-scale and reach-scale factors affecting the movement and deposition of sediment and the flooding characteristics is provided in Section 5 of this report.

## 1.4 Regulations, permits and policies affecting gravel removal from rivers

Regulations, permits and policies that would affect riverine gravel removal are described briefly in this subsection and summarized in Table 1-1. While every attempt has been made to provide a complete description and to characterize the regulatory environment, some details may have been omitted inadvertently. The information is described as it would apply to gravel removal being conducted by King County for flood risk reduction purposes.

### 1.4.1 Description of the permit process

Gravel removal for flood hazard reduction purposes would require a number of permits and approvals (Table 1-1). A Joint Aquatic Resources Permit Application (JARPA) can be filed to combine multiple permit applications and coordinate the permit review process between various agencies. Although a joint application can be made, some permits must be obtained before others can proceed. Available information indicates that a State Environmental Policy Act (SEPA) determination would be required before the permit process for a Hydraulic Project Approval (HPA) will be initiated, and that the USACE prefers to see the HPA granted before it will issue a determination on the 404 permit. Some permits can be processed in conjunction with others.

The estimated permit review timeframes indicated in Table 1-1 are gross estimates, with uncertainties indicated by the use of ranges of times for each permit review. While some permits may be reviewed concurrently, some of the timeframes in Table 1-1 will by necessity be cumulative, as the completion of certain permits or analyses is required prior to initiating the review of other permits. Actual times for the overall permit review process will vary greatly depending on the specific permits and supporting analyses that may be required. A rough estimate of the time necessary for permit review of the most straightforward of gravel removal proposals might be on the order of 12 months if the proposal were simple and unopposed and extensive analyses were not required. Regardless of the time for permit review, it should not be assumed that the necessary permits will be granted. More detailed information on other aspects of permit review, including permit timeframes, can be found at websites of the USACE and the Washington State Department of Ecology (Ecology) listed in the footnotes to Table 1-1.

Cost estimates are not included in Table 1-1 because the permit filing fee is negligible for many of the permits. However, for the Shoreline permit(s), the costs of permit review and processing could be on the order of tens of thousands of dollars. For SEPA review, King County presumably would develop the supporting information for the gravel removal proposal, which could consume considerable staff time and costs. Other costs associated with the permit process would be the staff time necessary to assemble information, submit the application and track it through the permit process. Potential costs of project design, project management and construction are described in Section 7.

### 1.4.2 Federal regulations and permits

Clean Water Act (CWA) Section 401:
Section 401 of the CWA requires that any activity that may result in excavation or discharge of dredged or fill material into surface waters be regulated by a Water Quality Certification permit (401 Certification). Ecology issues a 401 Certification, which is processed in conjunction with the USACE Section 10 or Section 404 permit applications.

CWA Section 402:
Section 402 of the CWA requires a National Pollutant Discharge Elimination System (NPDES) permit to ensure that erosion and sediment control measures be installed during construction or implementation of a project. Ecology issues the 402 permit, which is required for any activity that disturbs an area of one acre or more, or which may discharge stormwater to surface waters of the state.

**Table 1-1: Permits and regulations relevant to riverine gravel removal for flood reduction purposes**

| PERMIT OR REGULATION | LEAD AGENCY | ESTIMATED PERMIT REVIEW TIMEFRAME | ADDITIONAL INFORMATION |
|---|---|---|---|
| Clean Water Act Section 404 permit | US Army Corps of Engineers (USACE) | Nationwide permit: 3 to 6 months [B]. Individual permit: 6 to 24 months [B] | Applicable in all waters of the U.S. [A] Permit timeframe will depend on complexity of impacts and other factors. |
| U.S. Rivers and Harbors Act, Section 10 permit | USACE | Same timeframe as for Section 404 permit | Applicable to navigable waters. [A] Permit timeframe will depend on complexity, etc. |
| Clean Water Act Section 401 Water Quality Certification | Department of Ecology | Nationwide: 30 to 180 days Individual: 3 to 12 months [B] | Ecology will not conduct a 401 review until a 404 permit is issued. |
| Clean Water Act Section 402 | Department of Ecology | Minimum 38 days after complete application [B] | Permit requires water quality standards be met during implementation of project. |
| Endangered Species Act (ESA) Section 7 Consultation | USACE, in consultation with US Fish and Wildlife Service and National Oceanic and Atmospheric Admin. | Estimated 3 to12 months. | The ESA consultation process has the potential to affect the length and outcome of the permit process substantially. |
| National Historic Preservation Act Section 106 | USACE, WA Dept of Archaeology and Historic Preservation (DAHP), affected Tribes | Processed in conjunction with USACE permits. | |
| National Environmental Policy Act (NEPA) | If there is a federal action involved, the appropriate federal agency would be lead. | Concurrent with Section 404 or Sect. 10 process if USACE is lead | If there is no federal action involved, then NEPA is not required. |
| Washington State Environmental Policy Act (SEPA) determination and checklist or Environmental Impact Statement (EIS) | The county department sponsoring a county project is lead agency on SEPA (KCC 20.44.020.A). Assume for this study it would be KC Dept of Natural Resources and Parks (DNRP). | If Mitigated Determination of Non-Significance, assume 2 to 3 months. If EIS required, assume 9 to 18 months. | When King County is lead agency, SEPA review likely would be conducted during planning and design process, before permit applications. |
| Hydraulic Project Approval (HPA) | WA Department of Fisheries and Wildlife (WDFW) | Up to 45 days after SEPA review and receipt of a complete permit application. | SEPA must be completed before HPA will be issued. |
| Coastal Zone Management Certification | WA Department of Ecology | 60 to 180 days [B] | Processed concurrently with Section 401 permit |
| Aquatic Lands Use Authorization | WA State Department of Natural Resources | 6 to 12 months after complete application is received [B] | Other permits must be obtained first. [B] |
| Clearing and grading permit | King County Dept of Development and Environmental Services (DDES) | Within 90 days after a complete application (KCC 20.20.100) | |
| Compliance with Critical Areas Ordinance (CAO) | King County DDES | Concurrent with clearing and grading permit | No CAO permit; CAO compliance determined during county permit review. |
| WA State Shoreline Management Act (SMA); local Shoreline permit(s) | King County DDES | Concurrent with clearing and grading permit | A Shoreline permit indicates compliance with SMA provisions, but all applicable local permits still must be obtained. |
| City(s): CAO, grading, SEPA | Applicable city(s) | | A city might not conduct SEPA review if King County does it. |
| Easements, rights of way | King County or city(s) | | Depends on landowner willingness. |

**Table 1-1 footnotes:**
A: USACE website regarding permits:
http://www.nws.usace.army.mil/PublicMenu/Menu.cfm?sitename=REG&pagename=PermitGuidebook

B: Washington State Department of Ecology website regarding permits:
http://apps.ecy.wa.gov/permithandbook/handbook.asp

CWA Section 404:
The purpose of Section 404 of the CWA is to restore and maintain the chemical, physical, and biological integrity of the waters of the nation. A Section 404 permit is required for the discharge of dredged or fill material into all waters of the United States, including wetlands. "Discharge of dredged or fill material" includes disturbance of a water body or wetland, mechanized clearing, grading or excavation. The USACE regulates all such activities through issuance of a Section 404 permit (as described by 33 CFR 323).

The 404 permit application could be reviewed for possible issuance of a nationwide permit, which would be appropriate if the proposed activities are routine in nature and would cause only minimal environmental impacts. If a nationwide permit is not appropriate, then the application would be considered for issuance of an individual permit, wherein the proposal is evaluated on a case-by-case basis.

Further information with regard to the 404 permit process that was gleaned from discussion with USACE - Seattle District X staff (personal communication Maryann Baird, Amy Klein, September 2008) includes the following. There would be an emphasis placed on adherence to an approach that would avoid, minimize and mitigate adverse impacts. The provisions of 404(b)1, which require a thorough consideration of alternatives and demonstration that the least damaging alternative was selected, would be an important part of any individual application. USACE staff stated that it should be recognized that gravel removal is a temporary solution and therefore is generally not a preferred alternative. An individual 404 permit requires consideration of cultural resources. It would be necessary to demonstrate that sediment deposition is a cause of increased flood hazard or flood damage, and to demonstrate the effectiveness of gravel removal on decreasing flood hazard or flood damage. Review of a gravel removal application by the USACE is distinct from other state and local reviews in that the USACE is required to evaluate impacts on navigation, threatened and endangered species, and treaty rights.

Section 10 of the U.S. Rivers and Harbors Act:
The purpose of the Section 10 permit is to protect the integrity of navigation and water quality in waters of the United States. A Section 10 permit is required for any structures or work in navigable waters, including construction of piers, etc., and for dredging. Section 10 permits are issued by the USACE.

A key issue is the determination as to whether the USACE would have regulatory jurisdiction under Section 10, which depends upon the project site's location relative to the waters of the United States, sometimes referred to as navigable waters. Available information suggests that the South Fork Snoqualmie River would not be considered to be navigable waters. However, a

definitive decision on whether the USACE has jurisdiction under Section 10 would not be made until a permit application is submitted to the USACE for gravel removal.

Endangered Species Act (ESA):
The ESA does not, itself, require a direct permit to carry on a gravel removal activity. If species are present that are listed or are proposed to be listed under the ESA, the ESA requires any federal agency that does issue a permit, or provide funding for such an activity, or act as a partner with a local agency in such a project (called the "nexus"), to consult with the federal resource agency that has jurisdiction for the listed species that could be affected by the activity. The federal resource agency(s) with such jurisdiction are the USFWS and NMFS. The federal agency that would constitute a nexus for the activity of gravel removal likely would be the USACE, via its Section 10 or 404 permit process. The project proponent (King County) would likely prepare a Biological Assessment (BA) which considers the effects of the proposed action on listed or proposed species, and submit the BA to the USACE for consultation with the services. The ESA Section 7 consultation process allows any affected native American Tribe(s) to be involved in review and comment on a proposed gravel removal project. Overall, the ESA consultation process has the potential to increase the length and change the outcome of the permit process substantially.

U.S. Coastal Zone Management (CZM) Act:
A Coastal Zone Management (CZM) Certification (or Determination) is required of federal activities in order to determine if the activity is consistent with the Coastal Zone Management Program. Application is made to the USACE within one of 15 coastal counties in Washington, which includes King County. The CZM Determination was originally authorized under the U.S. CZM Act. Permits are administered by Ecology.

National Environmental Policy Act (NEPA):
NEPA requires federal agencies to consider the environmental consequences of a federal action prior to making a decision on that action. A federal action may include federal projects, federal funding, and federal permits. The agency must evaluate environmental impacts, consider project alternatives and identify mitigation for the project as appropriate. The federal agency documents the decision-making process by determining whether the federal action is categorically exempt, or if an environmental assessment or an environmental impact statement needs to be prepared. If there were a federal permit required for gravel removal such as a Section 404 or Section 10 permit, then the USACE likely would be the lead agency for review under NEPA. In previous river-oriented projects implemented by King County, the county has provided information and materials for use by the lead agency in addressing the requirements of NEPA. It also is possible for a federal agency to delegate NEPA lead agency status to a local agency.

National Historic Preservation Act of 1966 Section 106:
This act requires that all federal agencies take into account the effect of its actions on archaeological and cultural resources and historic properties. Therefore, the USACE would conduct a consultation with the Washington State Department of Archaeology and Historic Preservation (DAHP) and affected Tribe(s) in conjunction with its permit process.

### 1.4.3 State regulations and permits

Hydraulic Project Approval (HPA):
An HPA is required for work that uses, diverts, obstructs, or changes the natural flow or bed of state waters. It is intended to protect fish life in waters of the state. The HPA is administered and issued by the Washington State Department of Fish and Wildlife (WDFW). It can be assumed that an HPA would be required for gravel bar scalping for flood hazard reduction purposes.

Discussions with the WDFW staff provided the following information (personal communication Alex Uber, Stewart Reinbold, August 2008). Gravel removal is not a preferred approach for flood reduction, and there would be an emphasis on an approach to avoid, minimize and mitigate adverse impacts. Because of the temporary nature of its flood hazard reduction benefits, a long-term strategy for flood reduction would need to be provided along with an application for gravel removal, and a thorough analysis of alternatives would be needed. The WDFW review of an HPA application for gravel removal would focus on the potential for impacts on salmonid species, including (non-anadromous, non-listed) species such as rainbow trout above Snoqualmie Falls.

Aquatic Land Use Authorization (WAC 332-30-122):
Use of state-owned aquatic lands (including harbors, state tidelands, shorelands, and beds of navigable waters) requires approval from the Washington State Department of Natural Resources (WDNR). Such approval may result in royalties being due to the state for gravel removal, based on the volume extracted. In regards to the 1991 gravel bar scalping, WDNR advised that they did not consider the South Fork Snoqualmie River to be navigable, based on available information, and therefore did not need to issue an authorization or require royalty payments. As with the USACE 404 permit, it may not be possible to get an actual determination without submitting a proposal.

State Environmental Policy Act (SEPA):
The SEPA ensures that environmental values are considered by state and local government officials when making decisions about projects. For a gravel removal proposal in a river channel located solely within unincorporated King County, the local lead agency would be King County. If a King County department was proposing the project (as assumed in Section 1.1 of this report), that department would be the lead agency under SEPA (King County Code 20.44.020.A). For a gravel removal project, the lead agency for SEPA review likely would be the Department of Natural Resources and Parks (DNRP). If the channel where gravel removal would occur flows through both incorporated and unincorporated areas, or along their boundary (such as is the case with this reach of the South Fork Snoqualmie River), King County or that city would be the local lead agency (see also North Bend permits and regulations, below).

SEPA is intended to allow for evaluation of a broad range of potential environmental impacts associated with a particular action. If, through the SEPA process, a determination is made that gravel removal would not have significant adverse impacts, then a Determination of Non-Significance (DNS) could be issued. If a determination is made that such impacts could be mitigated, a Mitigated Determination of Non-Significance (MDNS) could be issued. If a

determination is made that the project will have probable significant adverse impacts, a Determination of Significance is issued and an Environmental Impact Statement (EIS) would be required in order to evaluate a range of alternatives, choose a preferred alternative, and fully identify impacts and measures to mitigate those impacts.

Shoreline Management Act (SMA):
The SMA requires that activities that take place in water, associated wetlands, floodways, floodplains, or within 200 feet of the ordinary high water mark of a water body or floodway obtain a Shoreline permit. While state law sets the framework for SMA requirements, each local government has a local Shorelines Management Program (SMP). Shoreline permits are issued by the local agency, which would be the Department of Development and Environmental Services (DDES) for channels in unincorporated King County. The King County SMP is in the process of being updated as of late 2010.

Discussions in 2008 with King County DDES staff that implement the SMP provided the following information that pertained to gravel removal and the SMP at that time (personal communication, Randy Sandin, Pesha Klein, Steve Bottheim, August 2008). In 2008 there were four environmental designations under Shorelines regulations: Urban, Rural, Conservancy, and Natural. The South Fork Snoqualmie River in the study reach is designated as Conservancy. A Shorelines permit review of gravel removal would focus on the primary purpose of the excavation. Gravel removal for purely commercial purposes would not be allowed, so it would be critical to demonstrate the flood hazard reduction benefits of the proposed gravel removal. Dredging in the wetted channel would not be allowed in Conservancy areas unless it is needed to mitigate conditions that endanger public safety or fisheries resources (K.C.C. 25.24.140). The 1991 and 1994 South Fork Snoqualmie River bar scalping operations were conducted within a Conservancy designation.

The 2010 update to the King County SMP establishes eight Shorelines designations. Ordinance 16985, which would implement the SMP, identifies “Excavation, dredging, dredge material disposal” as a shoreline modification that is allowed within all eight Shorelines designations, subject to conditional use review procedures, consistent with standards specified in K.C.C. 25.16.190 as amended in Ordinance 16985. (Note that this ordinance will be recodified upon final adoption of the SMP following approval by Ecology, so the code section number cited here will be changed.) The standards vary depending on the proposed use and the location relative to the Ordinary High Water Mark. A few excerpted standards that are particularly relevant to this current study include the following:

> Dredging and dredge material disposal below the ordinary high water mark shall be permitted only:
>
> - When necessary to mitigate conditions that endanger public safety or fisheries resources;
> - For flood risk reduction projects conducted in accordance with Policy RCM-3 of the King County Flood Hazard Management Plan.

There are other updated King County SMP standards that must be met that are not listed here. Policy RCM-3 is provided below.

Washington Administrative Code (WAC) provisions that apply to shoreline areas identify specific requirements of gravel removal for flood reduction purposes (WAC 173-26-221(3) c (v)):

> Require that the removal of gravel for flood management purposes be consistent with an adopted flood hazard reduction plan and with this chapter and allowed only after a biological and geomorphological study shows that extraction has a long-term benefit to flood hazard reduction, does not result in a net loss of ecological functions, and is part of a comprehensive flood management solution.

These WAC provisions would continue to apply to gravel removal activities regulated by an updated King County SMP.

### 1.4.4 King County regulations, permits and policies

Critical Areas Ordinance (CAO):
The state Growth Management Act requires identification of Critical Areas and regulation of activities therein by local government. Critical areas include flood hazard areas such as floodways, floodplains and channel migration zones. Floodplains and channel migration zones include river channels and gravel bars, so gravel removal for flood reduction purposes must meet be an allowable use under the CAO.

The King County CAO (K.C.C. 21A.24.045.C) identifies "flood risk reduction gravel removal" as an allowable use, subject to the following conditions:

> Allowed if sponsored or cosponsored by the countywide flood control zone district and the department [DDES] determines that the project and its location:
> a. is the best flood risk reduction alternative practicable;
> b. is part of a comprehensive, long-term flood management strategy;
> c. is consistent with the King County Flood Hazard Management Plan policies;
> d. will have the least adverse impact on the ecological functions of the critical area or its buffer, including fish habitat for fish and wildlife that are identified for protection in the King County Comprehensive Plan; and
> e. has been subject to public notice in accordance with KCC 20.44.060.

Clearing and Grading Ordinance:
Activities that remove existing woody vegetation by mechanized means, or that excavate or move soil or rock materials within a critical area require a clearing and grading permit, which is administered by the local government agency. A grading permit application would need to specify areas and volumes of excavation, excavation methods and access routes and demonstrate adequate protection of critical areas and erosion control measures are in place. A clearing and grading permit would not be issued until after SEPA and CAO requirements are met.

King County policy regarding gravel removal:
The King County policy regarding gravel removal by King County for flood reduction purposes is stated in the King County Flood Hazard Management Plan (King County 2006):

> Policy RCM-3: Gravel Removal
> King County should remove gravel from rivers and streams for flood hazard management purposes only when:
>
> a. It can be demonstrated that gravel accumulation poses a flood risk, as defined in Policy G-2 of this Plan,
> b. Hydraulic and geomorphic studies conclude gravel removal has a long-term benefit of flood risk reduction,
> c. Biologic studies determine it does not, with appropriate mitigation, result in a net loss of ecological function,
> d. It is part of a comprehensive, long-term flood management strategy,
> e. It is consistent with the best available science, the provisions of this Plan, and state and federal guidelines and regulations, including the Endangered Species Act, and
> f. It is determined to be the best flood risk reduction alternative available, based on criteria in this Plan.

### 1.4.5 North Bend permits and regulations

Preliminary discussion with City of North Bend staff (personal communication, Duncan Wilson, August 2008) suggests that City of North Bend permits that would be required for a gravel removal operation in the South Fork Snoqualmie River include a clearing and grading permit, demonstration of consistency with the North Bend CAO, and compliance with SEPA, and that the City of North Bend likely would not conduct SEPA review if King County was conducting SEPA review.

### 1.4.6 Summary

Information on existing regulations and discussions with permit agency staff suggests that permit application and review of riverine a gravel removal proposal for flood reduction purposes probably would entail a relatively long and involved process, and permit approval is not guaranteed. Alternatives to gravel removal would need to be fully considered and all impacts would need to be identified and mitigated. However, none of the regulations reviewed place an outright prohibition on gravel removal for flood reduction. If details regarding application requirements, jurisdiction or likelihood of obtaining a permit for gravel removal seem vague, permit agency staff consistently indicated that definitive details on project viability, permit requirements, etc., could not be provided until an actual application for gravel removal is submitted.

# 2. Overview of riverine processes and the effect of gravel removal on them

This section provides a brief overview of physical and biological processes in the riverine setting relevant to this study, including sediment transport and deposition, salmonid habitat and use, and the potential effects of gravel removal on them. More comprehensive discussions of these topics are provided by Collins and Dunne (1990), Kondolf (1993), Spence et al. (1996), Collins (1997), Norman et al. (1998), Sear and Archer (1998), Kondolf et al. (2001) and NOAA (2004).

## 2.1 Sediment transport and deposition

Coarse sand, gravel, and larger sediment moves as *bedload* by rolling, sliding, and bouncing along the riverbed during moderate and high flows. Medium and fine sand and silt are transported in suspension with water flow as *suspended load*, which typically constitutes 90 percent or more of the total sediment yield from a drainage basin (Leopold, Wolman, and Maddock 1963; Dunne and Leopold 1978; Booth et al. 1991). Suspended load and bedload are not entirely distinct, as some of the coarser suspended load can settle out on riverbeds during recession of high flows. *Bed material* is the sediment mixture of which the streambed is composed (Simons and Senturk 1977), and so can be a combination of sediment deposited from suspended load and bedload. But to a very large degree, the material visible on the channel bed and bars is composed of bedload (Klingeman and Emmet 1982; Parker et al. 1982). Bedload is the part of total sediment load that is of main concern for this study because it constitutes most of the in-channel sediment accumulations and defines the channel form in the study reaches.

*Sediment transport* refers to the movement of sediment past a given point on a river, whether in suspension or along the bed. Sediment transport occurs primarily as a function of the slope of the water surface and the depth of water, so high flows transport proportionately greater sediment loads than moderate flows. On rivers with a wide range of water discharge, such as the South Fork Snoqualmie River, there is high variability of sediment transport and deposition between different floods and different years and most sediment is moved episodically during high flows that occur infrequently. Accordingly, rates of transport and deposition can vary greatly from year to year and reference to an average annual rate of sediment transport and deposition is more of a statistical construct than the actual amount of sediment movement that occurs in any given year (Kondolf and Matthews 1993). Still, an average annual deposition rate is calculated herein, and deposition during extreme flow years also is estimated.

When, over a long period of time, more sediment is carried into a river reach from upstream than the river can transport downstream out of the reach, the bed builds up or *aggrades*. If bed material is not removed from a depositional reach, either by erosion or by extraction, the riverbed will build up. If bed material is removed at a rate in excess of the long-term deposition rate, either by erosion or by extraction, the bed will be lowered, or *degrade*.

A *sediment budget* is "an accounting of the sources and deposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin" (Reid and Dunne 1996). The

primary components of a sediment budget are sediment input, sediment output, and change in sediment storage, which are not unlike the components of a bank account. A sediment budget for the entire river basin was not done for this study, but elements of a sediment budget were calculated or estimated for the river channel within the study reach.

The *change in storage* volume is the net change in sediment volume that has occurred within a study reach channel during a certain time period as a result of all erosion, deposition, and extraction. If there has been no extraction, then the change in storage is identical to the net deposition, or the net erosion, whichever happened, in a river reach during the period of interest. The period of interest in this study is the time elapsed between repeated cross section surveys. The *sediment input* of interest to this study will be the total bedload transport entering the study reach in a given period of time, also referred to as *bedload flux* or *influx* herein.

*Gravel bar scalping* removes sand and gravel from the tops of gravel bars, usually during low flow periods, without excavation or equipment entering the wetted channel. *Dredging* includes the lowering of the channel bottom by excavation, taken both from gravel bars and within the wetted channel, and often across the entire channel width.

The *thalweg* is the flow path connecting the deepest points along the channel. By convention, the *left bank* and *right bank* are as viewed looking downstream.

A decrease in channel gradient often is a natural cause of long-term sediment deposition, such as where a channel emerges from steeper foothills and flows across a flatter valley floor. The backwater effect present at the confluence of rivers also causes water surface slope to decrease, as does backwater due to flow constrictions at levees or bridges. All of these conditions can result in sediment deposition, and most of these conditions exist in the present study reach.

## 2.2 Salmonid habitat and use of gravel bedded rivers

This report focuses on an evaluation of impacts to salmonid habitat due to the status of several salmonid species under the ESA, as well as the emphasis on salmon conservation and recovery in many regional and local planning efforts. Potential impacts to salmonids and their habitat tend to be important considerations in many federal, state, and local permitting processes. It should be noted, however, that the South Fork Snoqualmie River provides aquatic and riparian habitat not only for salmonids, but for a broad array of species, and if a gravel removal action were to be pursued it would be appropriate and likely necessary to evaluate impacts for other aquatic species and habitat types as well.

The range and distribution of anadromous salmonids:

The range of Pacific salmon (members of the genus *Oncorhynchus*) extends along the west coast of North America from the northern Bering Sea southward to Monterey, California, and inland to the Great Basin and to the upper Snake River in the United States, penetrating inland to the Rocky Mountains and the upper Yukon. All together, there are nine species in the genus: chinook, coho, chum, pink, and sockeye are the five most recognizable species on the west coast of the US and Canada; masu and amago are two species common only in Asia; and the cutthroat and rainbow/steelhead complexes were added to this genus (from the genus *Salmo*) in 1989.

In the Snoqualmie River, anadromous salmon occupy the mainstem river to Snoqualmie Falls and can be found in all accessible tributaries as adults or juveniles. Above Snoqualmie Falls, only resident (non-anadromous) cutthroat and rainbow are found, together with non-native Brook trout that were planted to enhance the fishery. Distribution maps for each species can be found in the WRIA7 Limiting Factors Report (WA State Conservation Commission 2001) and in the Snohomish Basin Salmon Recovery Forum (2005). A fourth salmonid, the mountain whitefish is also a native resident of the forks above Snoqualmie Falls.

Two other species of salmonid, members of the genus *Salvelinus*, are also present across much of this range and in the rivers of Puget Sound. Bull trout (*Salvelinus confluentus*) and Dolly Varden (*Salvelinus malma*) are called chars, a group that includes Lake Trout in the east and Arctic char throughout the far north. Of these two species, Dolly Varden have the most restricted range in Puget Sound, found mainly from Lake Washington north while Bull trout (though rarer) are found in all drainages of Puget Sound (Wydoski and Whitney 2003). Bull trout was listed under the ESA as “threatened” in 1999.

Habitat preferences in Pacific salmon:

Although there are some slight variations (like lake-spawning sockeye, for example), all members of the Pacific salmon genus *Oncorhynchus* lay their eggs in nests (called redds) excavated into the gravel beds of cold, clear streams and rivers. After hatching, the young remain in these gravel nests for up to two months, living on reserves stored in the egg. They then work their way upward, through the gravel spaces, into the free-flowing stream where some species will spend a year or more before moving to the estuary and the ocean. Each species has its preferred combination of place in the river, flow depth and velocity, and size of gravel. In general, the larger the species, the faster water and larger gravel it prefers. Tables 2-1, 2-2 and 2-3 provide some values for habitat preferences of several salmonid species.

If extensive gravel beds for spawning were the only requirement for successful survival, there would be little concern for salmon populations in the Northwest. Our generally gravel-rich rivers provide extensive spawning habitat for all species of salmon. Once the juveniles emerge from the gravel, however, they must seek out both food for growth and cover for refuge from predators. For species that will remain in the river for some or all of their life history, pools are the preferred habitats for food and cover. In the gravel-bedded rivers of the Northwest, the erosive and depositional processes of the river tend to result in complex channel forms both across and down the river (Benda et al. 1992). These variations in depth and slope create variations in hydraulic conditions that are exploited by the juveniles of various salmonid species.

**Table 2-1: Important components of freshwater habitat for salmonids**

| Category | Component | Elements |
|---|---|---|
| Physical | Flow Regime | - Depth<br>- Velocity<br>- Seasonality |
| | Habitat Structure | - Substrate material, size and distribution<br>- Channel Morphology (channel slope, width depth, bedforms, such as pools, riffles)<br>- Large wood<br>- Cover (escape, feeding, resting)<br>- Riparian structure (stand composition, age)<br>- Temperature |
| Chemical | Water Quality | - Dissolved oxygen<br>- Anions and cations (pH)<br>- Dissolved nutrients<br>- Pollutants<br>- Turbidity |
| Biological | Interaction among species and life histories | - Competition<br>- Predation<br>- Biological modification (e.g., redd building) |

**Table 2-2: Tolerance and preferred temperature ranges for adult salmonid migration and spawning (after Spence et al. 1996)**

| Species (Resident) | Migration (Tolerance) ($^{o}$C) | Spawning (Preferred) ($^{o}$C) |
|---|---|---|
| Cutthroat | 5.0 – 10.0 | 4.4 – 15.5 |
| Rainbow | | 2.2 – 20.0 |
| Bull Trout | | 4.5 – 9.0 |

**Table 2-3: A sample of water depths and velocities used by salmonids for spawning (after Spence et al. 1996)**

| Species | Depth (inches) | Velocity (feet per second) |
|---|---|---|
| Coho | > 7.2 | 0.5 to 3.0 |
| Cutthroat | > 3 | 0.3 to 2.3 |
| Bull Trout | > 10 | 1.3 to 3.0 |

## 2.3 Potential effects of gravel removal

The eight studies listed at the start of Section 2 describe potential effects of gravel removal, which are summarized in this subsection. Kondolf and Matthews (1993) depict physical impacts and resource impacts, including some that would affect salmonid habitat, in Figure 2-1. NOAA

(2004) summarizes physical effects of gravel bar mining and possible consequences for salmonid habitat in Table 2-4.

### 2.3.1 Potential effects of gravel removal on sediment transport, erosion and deposition

Gravel removal from a gravel bar or river reach interrupts the movement of bed material, which can alter the sediment supply downstream of that location (Collins and Dunne 1987). If the transport capacity remains the same entering the area downstream but sediment supply has been depleted due to gravel removal, there can be erosion downstream of the gravel removal as the river regains its sediment load by scouring the riverbed or banks. This increased erosion can reduce the size and number of downstream gravel bars (Dunne et al. 1981). It can also result in an increase in the downstream bed material grain size (Lane 1955; Kondolf 1997; NOAA 2004).

In a channel in which the sediment transport into a reach is naturally greater than the transport out of it, gravel removal can reduce aggradation. However, extraction of bed material in excess of replenishment from upstream results in bed degradation (Dunne et al. 1981; Collins and Dunne 1987; Kondolf and Matthews 1993; Oregon Water Resources Research Institute [OWRRI] 1995; NMFS 2004). Bed degradation resulting from either dredging or bar scalping can extend upstream and downstream of the removal site, often at great distances (Collins and Dunne 1990; Kondolf 1994; OWRRI 1995; Kondolf et al. 2001). It can undermine bridge supports, pipelines, and other structures (Collins and Dunne 1990) such as levees and revetments. Bed degradation can change the morphology of the channel (Collins and Dunne 1990; Kondolf 1994; OWRRI 1995). Bed degradation can deplete gravel beds, which in turn can affect aquatic habitat and salmonid spawning sites (Section 2.3.3). Rapid bed degradation may induce lateral bank erosion by increasing the heights of banks, which would then be more prone to undercutting and failure (Collins and Dunne 1990).

Gravel removal alters the local channel gradient and therefore the water surface slope and sediment transport capacity. This is particularly apparent in channel dredging where the water slope is locally increased at the upstream end and locally decreased at the downstream end of a gravel removal site. With locally increased slope, the channel bottom can incise upstream or downstream of the area of extraction, resulting in knickpoint migration (Kondolf and Matthews 1993; Norman et al. 1998). A decreased local slope within the dredged area would favor sedimentation.

While outright channel incision or knickpoint migration may not result from bar scalping, it can cause scour of riffles upstream or downstream of the bar scalping site (Collins 1997; NOAA 2004). Bar scalping lowers the overall elevation of the bar surface, which increases the local water surface slope at the upstream end, and may reduce the flow threshold at which sediment transport occurs (OWRRI 1995). Bar scalping leaves a wide, flat gravel bar surface that changes the confinement of the flow, altering the flow hydraulics around the bar at moderate and larger flows (Kondolf 1994). If bar scalping results in a significantly wider and shallower channel for a given flow, then sediment transport capacity is decreased and conditions favoring sediment deposition are enhanced (Kondolf et al. 2001; NOAA 2004). Such enhanced deposition can result in the infilling of pools (Kondolf and Matthews 1993; NOAA 2004).

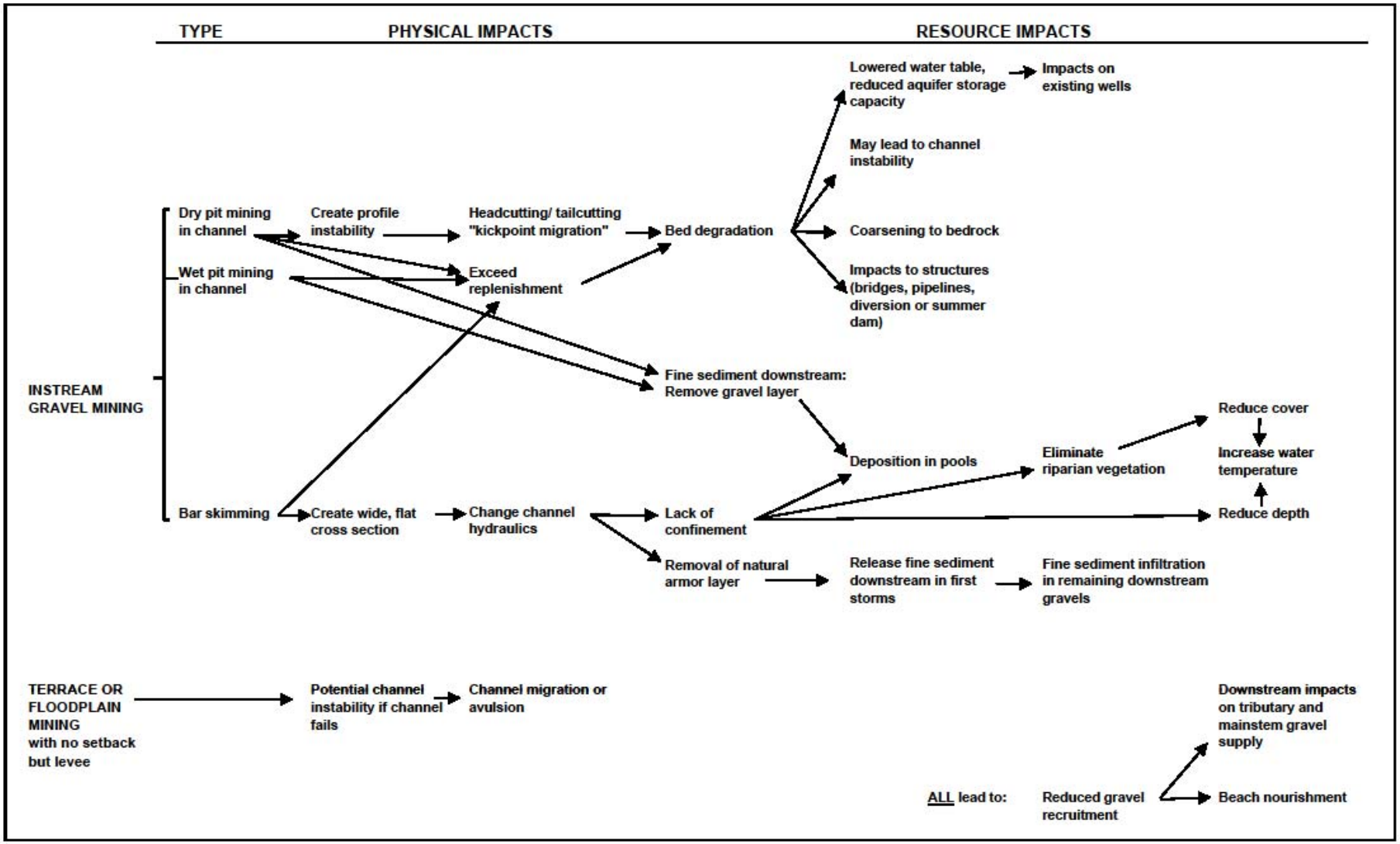



**Figure 2-1: Diagram illustrating the effects of instream gravel mining on channel processes and aquatic habitat (Kondolf and Matthews 1993)**

**Table 2-4: Summary of effects: instream sediment removal and implications for salmonid habitat (NOAA 2004)**

| Element of Instream Sediment Removal | Physical Effect | Possible Consequences for Salmonid Habitat |
|---|---|---|
| Removal of sand and gravel from a location or from a limited reach. | Propagate stream degradation both upstream and downstream from removal site. | Loss or reduction in quality of pool and riffle habitats. |
| | Scour of upstream riffles. | Lower success of spawning redds. |
| | Reduced pool areas. | Loss of spawning and rearing habitat. |
| | Scour or burial of armor layer. | Lower quality of spawning and rearing habitat; changes to invertebrate community. |
| | Surface caking or pore clogging. | |
| Removal of sand and gravel from a bar. | Loss of sand and gravel from neighboring bars. | Possible loss of riffle and pool habitats. |
| | Wider more uniform channel section, less lateral variation in depth, reduced prominence of the pool-riffle sequence. | More difficult adult and juvenile migration. Reduced trophic food production. Lower quality of rearing habitat. |
| | Surface caking or pore clogging. | |
| Removal of sediment in excess of the input. | Channel degradation. | Deeper, narrower channel. Dewatered back channels and wetlands. |
| | Lower groundwater table. | Possible reduction of summer low flows; possible reduction of water recharge to off-channel habitat. |
| | Complex channels regress to single thread channels. | Less habitat complexity. |
| | Armoring of channel bed, may lead to erosion of banks and bars. | Less spawning area. Reduced water quality. Prompt new bank protection works – reducing habitat. |
| | Or, scour or burial of armor layer. | |
| Reduced sediment supply to downstream. | Induced meandering of stream to reduce gradient. Erosion on alternate banks downstream. | Reduced riparian vegetation. Increased local sedimentation. Prompt new bank protection works. Propagate river management and habitat losses downstream. |
| | Armoring of bed, or scour of armor layer. | |
| Removal of vegetation and woody debris from bar and bank. | Reduce shade. | Increased water temperature in inland, narrow rivers. |
| | Decrease channel structure from wood. | Possibly reduce cover; reduce number and depth of pools; reduce area of spawning gravel; limit channel stability. |
| | Decrease drop-in food, nutrient input. | Decrease stream productivity. |

When bar scalping scrapes off the coarse surface layer, or the armor or pavement layer that occurs on many gravel bars, finer subsurface material is exposed and can be more easily transported. Those fine sediments will be transported in the first few moderate flows and

deposited in areas downstream (Kondolf and Matthews 1993). Because the pavement layer appears to regulate rates of bedload transport (Parker et al. 1982; Parker and Klingeman 1982), its removal could affect bedload transport, at least until a pavement layer is re-established.

Potential effects on flood protection facilities or other existing infrastructure:

Ongoing sediment accumulation on a point bar can force the main current towards the opposite bank, which can cause undermining or erosion of the opposite bank. Reduction in the size or height of gravel bars can cause either the erosion or stabilization of upstream and downstream riverbanks (Collins and Dunne 1990). Dunne et al. (1981) note that "careful scalping" of the annual accumulation of sediment on a point bar may be useful in stabilizing the eroding outer bank or channel, but "excessive harvesting" can result in high flows taking a more direct flow path over the point bar than the longer path around the bar. With a shorter flow path, the local slope increases and with it transport capacity. The gravel bar may be scoured and cut off, the channel may be realigned, or other less predictable consequences may ensue (Dunne et al. 1981). Such consequences can include erosion of the opposite riverbank or levee, or the channel at the downstream end of the shortened flow path.

Levee undermining would be a primary concern if gravel were removed to an elevation deeper than or close to the bottom elevation of the toe of the existing levee. The actual depth of the levee toe may not be known with certainty due to the age and undocumented construction methods used on many older levees. Localized scour during high flows also can extend deeper than the low flow river bottom (which typically is the elevation measured in channel surveys) and thereby threaten the stability of existing levees, riverbanks, and public facilities such as bridge piers. While channel dredging is the main gravel removal method that might cause undermining, bar scalping that is an "excessive harvest" could result in overall channel degradation (downcutting) to the extent that the stability of levees, banks, or facilities could be compromised.

Kondolf and Matthews (1993) identify numerous examples of channel incision from instream gravel mining in California, most of which had associated damage to bridge supports. Kondolf et al. (2001) expand the listing of mining-induced incision to Washington State and to other countries, again with examples of damage, sometimes catastrophic, to infrastructure such as bridges, pipelines, and riverbanks. A locally relevant study of gravel removal in the Pilchuck River (Collins 1991) documents long-term excavation by channel pit mining and bar scalping far in excess of the estimated natural deposition rate with resulting degradation of the channel. While structural damage did not occur, the potential for bridge undermining and undercutting of bank protection was identified as a concern (Collins 1991). Most of the examples from these studies involve in-channel excavation beyond bar scalping, but the principal remains consistent: excavation far in excess of the annual deposition rate results in channel incision that can destabilize existing infrastructure including levees and bridges.

### 2.3.2 Potential effects of gravel removal on nearby flooding

Gravel removal can lower bed elevations and decrease flood heights, which can reduce overbank flooding and reduce the hazard for human occupancy of the floodplains and the chance of flood

damage to bridge spans (Collins and Dunne 1987). Gravel removal will be most effective in reducing the frequency and magnitude of overbank flooding along confined (e.g., leveed) channels where most of the flow is conveyed within the channel. However, in situations where most of the floodwater is conveyed on the valley floodplain, flood levels will not be significantly affected by gravel removal in the channel because such a small fraction of the total water volume being conveyed would be affected (Booth et al. 1991). If overbank flooding occurs due to backwater effects upstream of a constriction or confluence, even large-scale gravel removal would be ineffective and irrelevant (Booth et al. 1991; Kondolf et al. 2001; NMFS 2004).

The intent of gravel removal for flood reduction purposes is to increase containment of flood flows. But containment of flood flows in the channel that would otherwise overtop the channel banks and temporarily be stored in floodplain areas results in increased in-channel flood conveyance to downstream areas. Improved in-channel conveyance of floodwater that result in benefits to the area adjacent to gravel removal can cause increased flooding to areas downstream, either as increased volumes or more rapid arrival of floodwater.

### 2.3.3 Potential effects of gravel removal on salmonids and their habitats

In general, the removal of gravel from river and stream channels has the potential to produce significant adverse effects to salmonids and their habitats. These effects may be local and short-lived or they may extend beyond the project reach and have long-lived effects on habitat and population viability depending on the type, magnitude, and location of gravel removal (bar scalping or in-channel dredging). The effects may be categorized as follows:

- Modification of riffle substrates
- Reduction in pool depth, frequency, and number of pools
- Reduction in overall channel complexity
- Reduction in riparian vegetation

For salmonids, the biological outcomes of these effects can include changes in spawning and rearing distributions, decreased population productivity, loss of diversity, and decreased abundance if the effects are widespread and persistent enough. Another important effect includes decreases in benthic macro-invertebrate production and diversity as a result of stream bed disturbance.

Modification of riffle substrates:

The removal or surface disturbance of gravel bars by scalping or even by staging of equipment has been shown to affect spawning areas in at least two ways. First, the removal of bars can result in elevated shear stresses across the channel that may erode adjacent areas or prevent new deposits from forming. If the eroded areas are spawning habitats, the increase in shear stress effectively lowers the flow at which adjacent or nearby gravels may be scoured. This increases the probability that any salmonid redds in the area will be scoured during subsequent years. Pauly et al. (1989) observed scouring of incubating eggs from riffles following a bar scalping

project and concluded that the increased shear stress that resulted from the decreased bar height was responsible for the scouring effect.

A second, and opposite, effect can occur if the surface material on a bar is larger than the material directly beneath. Bar scalping removes the surface armor layer and exposes the smaller material below, which is more easily eroded than the surface armor layer. Once eroded, this material may come to rest atop downstream spawning areas or, if fine enough, may infiltrate the interstitial spaces of spawning beds. McDowell-Boyer (1986) described two mechanisms by which porous substrates can become clogged with fine particles. The first is particle straining, where fine particles move through the substrate until they encounter spaces too small to pass through and are effectively "strained," filling the substrate from the bottom upward. The second mechanism, surface caking, occurs when a large amount of sediment is deposited on the surface of the streambed and fine particles settle to the boundary with the original surface. This newly deposited material may cake on the bed and effectively seal the surface from infiltration and penetration by spawning salmonids. If caking occurs after egg deposition, egg mortality will increase significantly due to decreased oxygen exchange through the sediments (Kondolf and Williams 1999). Wickett (1954) demonstrated that sediment intrusion is most damaging to embryos during the first 30 days of development when the embryos are inefficient at oxygen uptake. Hatching fry may be prevented from moving to the surface if the caked layer is thick enough (Tappel and Bjornn 1983).

Sediment intrusion from bar scalping and excavation is likely a short-lived effect that occurs at the first flows capable of mobilizing the sediment exposed by the operation. The potential for harm to habitats and to certain salmonid embryos is high because of the timing of bar scalping, the spawning and incubation timing of some South Fork Snoqualmie River species, and the onset of winter rains with their higher flows. Winter season rains may be sufficient to mobilize exposed sediment on scalped gravel bars during November and December, exposing the embryos of Brook trout and Mountain whitefish (both of which spawn from August or September through December) to the fine material eroded from these bars. The embryos of cutthroat and rainbow trout, on the other hand, which spawn between February and June, have a lower likelihood of direct exposure. The intrusion of sediment into gravels used for spawning can reduce the rate of intra-gravel flow that brings dissolved oxygen to embryos and carries away waste products. This effect can be cumulative as fine gravel builds in the sediment over time. According to Alderdice et al. (1958), even temporary episodes can exceed the tolerance of embryos to reduced oxygen concentrations. According to NOAA (2004), the least desirable situation would be a large disturbed area adjacent to or immediately upstream from spawning habitat.

Reduction in pool depth, frequency, and number of pools:

The effect of sediment removal on the shape and form of gravel-bedded rivers has been well-documented, especially the effect on pool features. Pool habitats provide deep, low velocity areas critical to salmonid survival (Brown and Moyle 1991). Pools are essential habitat elements that provide cover, winter habitat, and thermal refuge. The removal or scalping of alternate bars affects fundamental hydraulic and sediment transport processes related to pool maintenance. In undisturbed systems, flows tend to converge at pools, increasing the scour process as flows increase. Altering in-channel bars by skimming reduces the convergence of flows through pools

by increasing the width to depth ratio of the channel, sometimes by an order of magnitude or more. As a result, pool depths decrease and the spacing between pools increases throughout the altered reach. The result is a decline in available rearing and refuge space for salmonids and a potential decrease in productivity.

Reduction in overall channel complexity:

Overall channel complexity is affected by gravel removal as well. In general, the channel becomes wider and more uniform, with less lateral variation in depth and velocity, and the normal pool-riffle sequence is lost (Collins and Dunne 1990). Complex channels tend to degenerate toward less sinuous, single thread channels with a concomitant reduction in habitat diversity. Juvenile salmonids of all species tend to prefer heterogeneous stream environments with a complex blend of deep and shallow pools, side channels, streambank vegetation, and in-stream woody debris, all elements that tend to be removed by gravel removal. The production of juvenile salmonids can be directly related to habitat complexity and the reduction in habitat complexity should be expected to cause a decline in juvenile survival (Fausch and Northcote 1992).

Cumulative alterations in riffle substrates, pools and channel complexity can result in an effect on the intra-gravel flow patterns in the channel. In gravel bedded rivers, considerable movement of water occurs within the bed of the channel, below the obvious surface flow. It is this flow through the interstitial spaces in the gravel bed that is critical to survival of salmonid eggs and young that hatch and rear in the gravel nest. Variations in channel depth, width and substrate type all influence the volume and rate of flow through the salmon redd. In fact, female salmon choose the site for the redd by probing the bed for signs of upwelling from intra-gravel flow. Infiltration of fines, a reduction in deep pools through the reach, and a dramatic change in channel uniformity would be likely to cause a reduction or re-distribution of intra-gravel flow. Together, or separately if the single effect is large enough, the effect on habitat suitability could be significant. Spawning locations would likely be affected and embryo survival would probably decline in some areas if intra-gravel flows were to decline as a result of physical effects.

Reduction in riparian vegetation:

Bar scalping often results in the loss or modification of riparian vegetation that would otherwise colonize river bars. The presence of riparian vegetation on gravel bars adjacent to the low flow channel contributes to channel stability, habitat complexity, and streamside cover in a variety of ways. Mature vegetation provides root structure that consolidates and stabilizes substrate material, making it more resistant to erosion (Beschta 1991). In the absence of anthropogenic disturbance, this vegetation would grow and pass through several successional stages, providing streamside cover, leaf and woody litter to the channel, and eventually, large woody debris that creates habitat complexity in Pacific Northwest rivers. Furthermore, riparian vegetation in the form of tall trees provides considerable shade to many rivers, reducing the potential for heat gain to the river.

# 3. Methods

## 3.1 Study approach

This study follows this approach:

1. Identify flood hazard reduction goals and objectives;
2. Characterize existing conditions of the system for flood capacity, gravel movement and deposition, and environmental and ecological attributes, including endangered species;
3. Identify the effect of gravel accumulation on water surface elevations;
4. Characterize the likely effectiveness of gravel removal on flood hazard reduction;
5. Estimate the costs and describe the likely adverse effects of gravel removal; and
6. Evaluate the effectiveness of gravel removal in meeting the flood hazard reduction objective.

This approach is consistent with previous documents that discuss freshwater gravel removal (Collins and Dunne 1990; Kondolf et al 2001; and NOAA 2004). It is also the approach used in the King County sediment monitoring program described and adopted in the 2006 King County Flood Hazard Management Plan (King County 2006). The South Fork Snoqualmie River in this area is a channel monitored by King County.

Collins (1997) listed the following questions to consider in planning and assessment of riverine gravel removal for flood control purposes.

- What are the planning objectives for flood hazard management?
- What flood heights, for floods of what recurrence, are specific planning targets?
- What will the efficacy be of gravel removal in meeting those objectives?
- With what frequency must gravel be removed to maintain the planned bed elevations? What are the average annual deposition and the extreme annual deposition rates? What are the sources of sediment deposition, and are recent rates higher or lower than under future conditions?
- What are the potential undesirable effects to river gravel bars?

Other pertinent questions have been identified for this study, including:

- Where is gravel removal likely to have long-term flood hazard reduction benefits?
- What permits would be involved in gravel removal for flood reduction purposes?
- What impacts would gravel removal have on nearby levees, downstream flooding, and salmonid habitat?

The approach for this study is intended to address the questions listed here.

## 3.2 Sediment accumulation: patterns and rates

It is necessary to describe sediment movement and deposition in enough detail to characterize the effect of gravel accumulation on flood hazards under existing conditions. It is also necessary to estimate a rate of gravel flux into and gravel deposition within the study reach. The average annual rates, or volumes per year, of flux and deposition will be compared to the volume of gravel proposed for extraction in each gravel removal scenario, both as a way to estimate how long the flood reduction effectiveness of gravel removal would persist and as a way to assess the

potential adverse impacts of gravel removal. While this study reach is depositional on the whole and over the long term, sediment movement and deposition is highly episodic and variable from year to year. Consequently, some indication of the range of gravel flux and gravel deposition is needed for both the average annual basis and for large individual floods.

Surveyed cross sections:

The primary method by which sediment levels in the South Fork Snoqualmie River channel are monitored is by repeated survey of channel cross sections at specific locations, most of which were established in the early 1990s. Cross sections surveyed in 1999, 2006, 2007, 2009, and a combination of 1992 and 1995 (explained in the next paragraph) were used in this analysis. Channel monitoring survey data collected by or for King County in 1993, 1996, 2005 and earlier surveys by others were consulted but are not included explicitly in this analysis.

Cross sections surveyed in 1992 in the downstream part of the study reach and 1995 in the upstream part of the study reach were combined into a 1992/1995 timeframe in order to characterize conditions that likely reflect the greatest channel conveyance capacity in the last two decades because they immediately followed gravel removal by bar scalping that occurred in 1991 in the downstream part and 1994 in the upstream part of the study reach. These 1992 and 1995 cross sections also are, in most locations, the earliest, most clearly established and repeatable set of surveyed cross sections available in this study reach.

Resurveying cross sections allows for quantitative measurement of measures the change in riverbed and gravel bar sediment levels that has occurred in the period between surveys at a specific, marked location. It also allows determination of the change in cross sectional area at each cross section. The (mean) average of changes in cross sectional area at two adjacent cross sections are multiplied by the channel length between those cross sections to calculate changes in sediment volume between cross sections during the time period since the previous survey. Volumetric changes between cross sections are summed in order to determine the cumulative change in sediment volume through the entire study reach during that period. Any sediment volumes extracted by excavation during that period also were considered in order to determine the volume of sediment actually deposited during that time period.

The control elevations at all cross section endpoint markers were resurveyed in late 2008. There were discrepancies on the order of one-half foot between the 2008 control elevations and the previously surveyed control elevations at a number of the cross section survey markers. However, no attempt was made in this study to adjust cross section elevations or to resolve the discrepancies, and the previous control elevations were retained for use in this study. This approach was taken because the main purpose of ongoing channel monitoring surveys is to determine relative in-channel changes through time, which would not be affected by absolute changes in the control elevations, as long as a consistent reference elevation is used throughout. However, to the extent that absolute elevations at cross sections are relied on for hydraulic modeling purposes, these elevation discrepancies introduce another source of uncertainty to hydraulic modeling results in this report. Any subsequent studies or analyses in this reach that use these survey data should recognize these control survey elevation differences and decide the appropriate approach for that effort.

The existing South Fork Snoqualmie River Flood Insurance Study (FIS) hydraulic model (FEMA 2005) has 13 surveyed channel cross sections within the 1.6 river mile length of this study reach from RM 2.85 to RM 4.46. Eight additional cross sections were surveyed in 2007 and 2009 in order to better represent the gravel bars within this same river length, both for sediment monitoring and hydraulic modeling purposes. Comparisons were extended into the past at the eight newly added cross sections for which there is no previous survey data typically by using elevation information from a nearby cross section that was surveyed on the same gravel bar at that earlier time.

Topographic surfaces:

The topographic surfaces of the gravel bars in this study reach were compared using topographic maps prepared from standard aerial photography flown in March 1995 and December 2006. A comparison also was made between the topographic surfaces of the December 2006 photography and a February 2009 LiDAR topographic surface. These comparisons provide a graphic image that maps the changes in out-of-water elevation of the gravel bar tops through the years between aerial images, as well as a calculation of the change in sediment volume in the gravel bars through the same period.

Bedload transport modeling:

A bedload transport model computes the transport capacity at a location along a river usually using an empirical bedload transport equation (e.g., Bagnold 1980). Deposition or erosion is calculated as the difference in transport capacities from one location to the next. The results of previous bedload transport modeling by others were used in this study as another means to estimate gravel flux and deposition volumes in this study reach (Booth et al. 1991; and Shannon & Wilson 1993).

## 3.3 Hydrology and hydraulics

Hydrology:

The flood frequency analyses prepared as part of the South Fork Snoqualmie River FIS (FEMA 2005) identified the flood magnitude (discharge, in cfs) at recurrence intervals of the 10-, 50-, 100-, and 500-year events and the flood of November 1990. The same flood frequency analysis from the South Fork Snoqualmie River FIS was used here to identify the flood magnitudes for the 20-year, 30-year and 40-year recurrence interval events.

Hydraulics, existing conditions:

HEC-RAS is a one-dimensional hydraulic model that uses field-based inputs such as channel geometry and channel roughness along with a selected instantaneous discharge to calculate hydraulic conditions such as water surface elevation, maximum depth, and mean velocity for that discharge. When available, the elevations of high water marks from actual floods are used to calibrate the hydraulic model.

Water surface elevations and other hydraulic conditions are computed in the existing steady state HEC-RAS hydraulic model of the South Fork Snoqualmie River prepared for the South Fork Snoqualmie FIS (FEMA 2005). That model is based on cross sections surveyed mostly in 1999. Eight additional cross sections were inserted into the existing HEC-RAS model in order to better represent the existing gravel bars in this study area. The models (actually referred to as "Plans" in HEC-RAS) created for this study use these same 21 cross sections—13 existing and eight additional—for 1992/95, 1999, 2006, 2007 and 2009 channel conditions. Comparison of the hydraulic modeling results from the HEC-RAS models representing the various years' surveyed cross sections model is the primary method used in this study to characterize the effect of channel changes on flood levels during the intervening period. Comparison of water surfaces computed with the 1992/95 and the 2009 channel conditions are used to indicate the effect of longer-term channel changes on water surface elevations.

The HEC-RAS model created for this study makes use of a "Raised Levee" condition, which inserts a frictionless and infinitely tall wall at the top of both levees and artificially contains all flows above the top of bank through the entire study length. This was done in order to eliminate the need to account for flow splits if overbank flow occurs. These artificially modeled walls also mean that water surface elevations for those flows that exceed the top of bank will be overstated; i.e., the modeling results will report higher water surface elevations than would be expected if overbank flow were to occur. Regardless, this simplification is a useful modeling approach for indicating where and at what discharge floodwaters would be expected to overtop the channel banks.

Water surface elevations upstream of bridges can differ significantly depending on the hydraulic conditions present at the bridge (e.g. low flow conditions versus high flow conditions). HEC-RAS has several different computational methods to model low flow and high flow conditions. Internal triggers in the model are used to identify which hydraulic equation will be used. The bridge computational method used in the existing South Fork Snoqualmie River HEC-RAS model (FEMA 2005), and therefore in the 1999 condition model for this study, resulted in the water surface elevations for the 13,000 cfs (50-year) flood being calculated at and upstream of the North Bend Blvd (Bendigo) Bridge using an equation for pressure flow conditions because the energy grade elevation came into contact with the bottom chord of the bridge at that flow. The 1992/95, 2006, 2007 and 2009 models calculated the 13,000 cfs water surface elevations upstream of the North Bend Blvd Bridge using a different equation (the energy equation) because the energy grade elevation did not come in contact with the bottom chord of the bridge. However, in each model the computed energy grade elevations upstream of the bridge were nearly equal. Because the intent of this study is to compare changes in water surface elevations due to changes in channel conditions, the hydraulic model trigger for the North Bend Blvd Bridge was set to the water surface elevation rather than the energy grade elevation for the North Bend Blvd Bridge to ensure that computational methods used for all models were relevant and consistent. No changes were made to other bridges in the model. This modification affected only the 13,000 cfs flood.

Hydraulics, gravel removal simulation

Cross sections surveyed in 2009 were modified to simulate channel geometries that would result from gravel removal by gravel bar scalping to evaluate their effect on water surface elevations and other hydraulic conditions over a range of flood discharges.

Hydraulic modeling results are presented in tables and figures in the body of this report. The HEC-RAS model created to represent existing conditions and to simulate gravel removal scenarios in this study can be provided upon request.

Limitations to hydraulic modeling:

HEC-RAS is a useful tool in analyzing and comparing the effect of different channel configurations on hydraulic conditions, but HEC-RAS has limitations in its application to this study's purposes that should be recognized. HEC-RAS is a one-dimensional model that calculates channel-averaged conditions, so it will not address issues such as flow deflection by existing gravel bars or changes in flow direction due to gravel removal. The channel bed is assumed to be a fixed boundary in HEC-RAS, so potential changes in the gravel-bedded channel of this study reach due to erosion, deposition, or channel responses to gravel removal will not be indicated. Localized scour is not calculated by HEC-RAS.

The HEC-RAS model created for a flood study is calibrated to available high water marks with the main intent of modeling the water surface elevation of the 100-year flood, where agreement between the modeled water surface elevation and observed flood levels to within plus or minus one-half foot is assumed to be adequate accuracy for a flood study (FEMA 1993). The inherent uncertainty of plus or minus one-half foot for the calibrated flood study hydraulic model flood that focuses on the 100-year flood should be recognized in general, and in particular with the focus in this study on smaller floods such as the 20-year and 30-year flood events. Also, the one dimensional HEC-RAS model does not consider superelevation of water surfaces at river bends, which can be considerable.

Due to these inherent hydraulic modeling uncertainties and limitations, it is best to use the hydraulic modeling results as a tool for relative comparison of the effects of gravel deposition over the timeframe of this study, as well as of different gravel removal scenarios, rather than as a technique to determine the absolute water surface elevations at any given point under any given scenario. Furthermore, the computed water surface elevations in this study are not intended for use in determining the areas of inundation or determining floodplain or floodway boundaries resulting under the various conditions or scenarios. Notwithstanding these limitations, hydraulic modeling with the HEC program has been used successfully to evaluate different gravel removal and restoration alternatives (e.g., Booth et al. 1991; Phillip Williams and Associates 1995; Morris 1996; Parametrix 2004) and therefore is considered adequate for the purposes of this study.

## 3.4 Salmonid habitat

Ecological conditions were derived and evaluated based on information contained in the following documents: *A Catalog of Washington Streams and Salmon Utilization* (WDFW 1975); *Snoqualmie Watershed Aquatic Habitat Conditions Report* (Solomon and Boles 2002); the *Snohomish Watershed Salmon Recovery Plan* (Shared Strategy 2007), *A synthesis of existing data for resident fishes in the Snoqualmie River above Snoqualmie Falls* (Overman 2008). Salmonid composition and distribution, known spawning areas, habitat conditions, and restoration and protection objectives for salmon conservation are contained in these plans. The Snohomish Watershed Recovery Plan is a chapter in the Puget Sound chinook Recovery Plan that was approved by the NOAA in January 2007 and is now the framework for salmon protection in the Snoqualmie River system. That plan addresses primarily chinook salmon that occur below the falls and does not address the species of salmonids that occur above the falls. Nevertheless, the plan does recognize the system-wide issues confronting salmon in the Snohomish watershed and provides some recommendations for almost all areas within the watershed.

## 3.5 Potential adverse impacts of gravel removal

General descriptions of potential adverse impacts on local flooding, erosion, and salmonid habitat and use due to gravel removal are provided in this study, based on the assumption that more detailed impact assessments would be required as part of the permit process if a gravel removal operation were to be pursued. In particular, the presence of any species listed under the ESA likely would require a consultation with USFWS/NMFS, in which case a much more detailed assessment of impacts would be prepared. Three main sources of information were used to characterize adverse impacts: descriptions in the literature of likely adverse effects of gravel removal (as summarized in Section 2 of this report); available existing information, including data and modeling results; and reconnaissance-level field observations.

Reconnaissance-level field observations were made during the summer of 2008. Field observations were made on the following attributes: gravel bar type, aspect, and position; vegetation type, age, and extent; presence and general extent of woody debris; bar-associated habitat types; and other conditions such as invasive plants, animal species and general extent of human use. These observations, though largely qualitative, provided a quick and repeatable method for assessing important features of the channel and its associated riparian area relevant to salmonid habitat condition and function. They also provided information on existing hydraulic and sediment conditions as well as on the potential configuration of gravel bar scalping scenarios.

A general evaluation of likely adverse impacts of the gravel removal scenarios analyzed in this study is presented in Section 7.

# 4. Gravel removal goals, objectives, criteria and scenarios

## 4.1 Gravel removal goals and objectives

A set of goals and objectives is established in this section to help frame potential gravel removal projects in this study. The goals and objectives focus on the purpose of reducing flood hazard in the affected river reach. Goals describe overarching or long-term desired outcomes and objectives should be specific management actions with measurable results that lead to achieving the identified goals. Evaluation criteria are posed as questions that ask whether a specific objective has been met, or the extent to which it has been met. The evaluation criteria are used to evaluate each gravel removal scenario in Section 8.

Gravel removal goals must remain consistent with the goals of the 2006 adopted King County Flood Hazard Management Plan (FHMP), which are:

1. To reduce the risks from flood and channel migration hazards.
2. To avoid or minimize the environmental impacts of flood hazard management.
3. To reduce the long-term costs of flood hazard management.

Gravel removal goals and objectives are based on these FHMP goals but are customized to apply to gravel removal as a flood hazard reduction alternative, as listed and described below.

**Goal 1: Reduce flood hazards attributable to gravel accumulation.**

Objectives:

1.1 Meet a specified flood hazard reduction objective.

1.2 Produce a significant increase in the channel conveyance capacity within the study reach.

1.3 Produce a significant decrease in flood water surface elevations.

1.4 Produce flood hazard reduction that remains effective over a long time period.

**Goal 2: Avoid or minimize adverse impacts of gravel removal.**

Objectives:

2.1 Avoid adverse erosion impacts to the stability of existing King County flood protection facilities and public infrastructure.

2.2 Avoid or minimize adverse impacts due to increased flooding of public or private property**.**

2.3 Avoid or minimize adverse impacts to salmonid habitat.

**Goal 3: Minimize the long-term costs of flood hazard management**

Objective:

3.1 Minimize the long-term costs of flood hazard management.

Goal 1 states the main purpose of a potential gravel removal project, which is to reduce flood hazards attributable to gravel accumulation in this study reach. The flood hazards attributable to gravel accumulation are determined primarily by comparing changes through time in modeled flood water surface elevations to changes in the measured in-channel sediment levels.

In this study, increases or decreases in the water surface elevations within the South Fork Snoqualmie River channel are taken to be synonymous with increases or decreases in flood hazard. As described in Section 3.3, there is no attempt in this report to translate changes in water surface elevation to potential corresponding changes in area of inundation, so this definition of flood hazard also is not translated to the plan view (floodplain) area that may be affected by any changes in water surface elevation. For this part of the South Fork Snoqualmie River, this definition further limits the consideration of flood hazard because inundation from sources other than overtopping of the South Fork Snoqualmie River channel are a significant component of overall flood hazard along this study area. In particular, flooding from stormwater sources, groundwater sources, levee seepage, and overbank flows from the Clough Creek, Ribary Creek and Gardiner Creek commonly affects the left bank area along the South Fork Snoqualmie River. Flooding from some of those sources has been evaluated separately (Northwest Hydraulic Consultants 2001). The collective flood hazard from all sources is being considered as part of King County's ongoing coordinated flood risk reduction efforts, in conjunction with other agencies. This report addresses only the flood hazard due to flooding from the South Fork Snoqualmie River channel and considers that flood hazard to be represented by the water surface elevations during specific flood events. The flood hazard reduction that gravel removal could accomplish is described only as in-channel flood hazard reduction in this report.

Gravel removal Goal 1 is based on FHMP Goal 1 but differs from it in a specific aspect. Gravel removal Goal 1 is to reduce flood hazard, which would manifest as reduced water surface elevations resulting from gravel removal. FHMP Goal 1 is to reduce flood risk, where flood risk considers flood hazard reduction but also considers the consequences of flooding on adjacent properties and structures, etc. Consideration of the consequences of flooding is beyond the scope of this gravel removal study, so this study addresses only the in-channel flood hazard reduction that could be achieved by gravel removal.

Objective 1.1 recognizes the importance of identifying a specific flood reduction objective that a gravel removal operation must meet, and identifying that objective before a project is initiated. This approach is consistent with existing documents and policies on gravel removal for flood reduction purposes (Collins and Dunne 1990; Kondolf et al. 2001; King County 2006). The flood reduction objective for the South Fork Snoqualmie River is identified in Section 4.3.

Objectives 1.2 and 1.3 recognize that different amounts of flood reduction may occur at different locations in the study reach whether or not the flood reduction Objective 1.1 is met. Gravel removal Objective 1.2 is to produce a significant increase in the channel conveyance capacity relative to existing conditions. Gravel removal Objective 1.3 is to produce a significant decrease in flood water surface elevations. It should be informative to evaluate Objectives 1.2 and 1.3 adjacent to locations of previous overtopping and potential flood damage.

Objective 1.4 recognizes that gravel will continue to be conveyed into the area in which gravel removal has occurred such that the flood reduction effectiveness of gravel removal will decrease over time, and that therefore gravel removal provides only temporary flood hazard reduction benefits. Meeting this objective calls for a gravel removal operation that would reduce flood

hazard over a relatively long period of time. The longevity of flood hazard reduction, and timeframes involved, are discussed more in Section 6.

Gravel removal Goal 2 states the intent to avoid or minimize adverse impacts due to gravel removal, consistent with FHMP Goal 2. For this study, three types of impacts are specified. Objective 2.1 is to avoid or minimize potential riverbed or bank erosion that could destabilize the levees or public infrastructure. Objective 2.2 recognizes that improved flood protection along one area of a river, e.g., due to gravel removal, can increase in-channel containment and thereby convey floodwaters to downstream areas in greater amounts or rapidity. Objective 2.2 is to avoid or minimize those potential downstream flooding impacts. Objective 2.3 is to avoid or minimize the adverse impacts of gravel removal on salmonid habitat.

Gravel removal Goal 3 and Objective 3.1 is to minimize the long-term cost of flood hazard management; both are based directly on FHMP Goal 3. Although detailed costs of the gravel removal scenarios cannot be estimated precisely at this level of study, a rough cost estimate of each gravel removal scenario is provided for comparison purposes.

## 4.2 Evaluation criteria

Criteria mirror the objectives identified above and are posed as a questions as to whether or to what extent each objective has been met. The response to that question is based on the results of analyses conducted in this study (e.g., hydraulic modeling of gravel removal scenarios), the consideration of available information and literature on the topic, or reconnaissance-level field observations, or some combination thereof. The application of these criteria is the main way that each scenario is evaluated for its potential as a gravel removal project for King County to conduct.

The criteria are used to evaluate each gravel removal scenario for its effectiveness in flood hazard reduction for its likely avoidance of adverse impacts and for its minimization of costs. Effectiveness of flood hazard reduction is described in terms of whether the flood reduction objective is met, the maximum level of containment achieved and an estimated period through which the flood hazard reduction will persist (i.e., its longevity). Avoidance of gravel removal adverse impacts are described using a range of Low, Moderate, and High ratings (with intermediate ratings of Low-Moderate and Moderate-High), where “Low” indicates a less favorable rating and “High” indicates a more favorable rating**.** The protocols for assigning low, moderate, high and intermediate ratings are listed in Table 4-1.

**Table 4-1: Description of evaluation ratings used evaluating avoidance of adverse impacts of gravel removal**

| Avoidance of impacts | Description |
|---|---|
| Low | Very likely to have major and measureable effects throughout the reach and possibly beyond; effects likely to persist for a long duration. |
| Low-Moderate | Between Low and Moderate |
| Moderate | Likely to have measureable effects that would be of moderate to possibly major magnitude, but would be short duration or not affect the entire reach. |
| Moderate-High | Between Moderate and High |
| High | Likely to be difficult to detect any measurable effects; if so, they would have relatively minor magnitude, duration and extent. |

Each gravel removal scenario is evaluated in Section 8 against the flood hazard reduction criteria of Table 4-2 and the adverse impacts and costs criteria of Table 4-3.

**Table 4-2 Criteria to evaluate flood hazard reduction**

| Obj. No. | Objective | Crit. No. | Evaluation Criteria | Response, Range |
|---|---|---|---|---|
| 1.1 | Meet the specified flood hazard reduction objective. | 1.1 | Does the proposed gravel removal meet the specified flood hazard reduction objective? | Y/N |
| 1.2 | Produce a significant increase channel conveyance capacity . | 1.2 | What is the channel conveyance capacity relative to existing conditions? | Maximum discharge (cfs) |
| 1.3 | Produce a significant decrease in water surface elevations. | 1.3 | Does the proposed gravel removal cause a significant decrease in water surface elevations? | Change in water surface elevations (feet) |
| 1.4 | Produce flood hazard reduction that remains effective over a long time period. | 1.4 | What is the estimated longevity of flood hazard reduction effectiveness, in years? | Estimated longevity (years) |

**Table 4-3: Criteria to evaluate adverse impacts and costs**

| Obj. No. | Objective | Crit. No. | Evaluation Criteria | Response, Range |
|---|---|---|---|---|
| 2.1 | Avoid destabilizing existing King County flood protection facilities or public infrastructure. | 2.1 | Extent to which the proposed gravel removal would avoid destabilizing existing King County flood facilities and public infrastructure | L/M/H |
| 2.2 | Avoid or minimize adverse impacts due to increased flooding of public or private property. | 2.2 | Extent to which the proposed gravel removal would avoid or minimize adverse impacts due to increased flooding of public or private property due to altered flood characteristics. | L/M/H |
| 2.3 | Avoid or minimize adverse impacts to salmonid habitat. | 2.3 | Extent to which the proposed gravel removal would avoid or minimize adverse impacts to salmonid habitat. | L/M/H |
| 3.1 | Minimize the long-term cost of flood hazard management. | 3.1 | Extent to which the proposed gravel removal would minimize the long-term cost of gravel removal. | 2010 dollars |

The evaluation can be used to determine the viability of any given scenario unto itself or to compare different gravel removal scenarios. For example, one scenario may provide a high level of flood hazard reduction but also incur major impacts and high costs, whereas another scenario may reduce flood hazard adequately but have much lesser impacts and costs. Gravel removal scenarios are evaluated in Section 8.

## 4.3 Flood hazard reduction objective for the South Fork Snoqualmie River

The preferred approach would be to identify a flood reduction objective equal to the original design capacity of the leveed channel as it was built in circa 1964, because the South Fork Snoqualmie River levees are flood containment facilities. It also would be preferred to express the objective in terms of a maximum discharge contained, because units of discharge (cfs) do not change through time whereas the calculated recurrence interval of that maximum discharge may change through time (see Section 5.2.1). Research into available information used in design of the levees in 1964 has not revealed a specific maximum design capacity discharge, but there is sufficient information available to estimate the original channel capacity, as built, and use that as a flood reduction objective for this study.

A 1969 letter written by the King County Engineer of the Flood Control Division in the Department of Public Works stated that Shamrock Park was expected to be protected from the greatest flood of record to that time plus one foot of freeboard, which, the letter said, would give protection from a flood greater than the 100-year flood. The largest flood of record when the levees were built in about 1964 and also when the 1969 letter was written was an estimated 13,000 cfs in 1959 at U.S. Geological Survey (USGS) gage 12144000 in North Bend (Figure 5-3). Although the 1969 letter does not identify it explicitly, the discharge of the 100-year flood in

1964 would have been 11,900 cfs as calculated by a flood frequency analysis using the period of record available through Water Year 1964 (Table 5-2). A channel capacity of 13,000 cfs plus one foot of freeboard therefore would have given protection from a flood greater than the 100-year flood at the time when the 1969 King County Engineer letter was written.

Other relevant pieces of information include a 1971 flood study by the USACE, which calculates the 100-year flood on the South Fork Snoqualmie River as 12,200 cfs, and depicts the 12,200 cfs flow as being fully contained by the levees along both banks of this study reach through North Bend (USACE 1971). Also, a peak flow of 12,400 cfs was contained throughout the study reach in 1977, although no details are available regarding that containment or its freeboard.

Based on the available information, it appears reasonable to assume that the original design channel capacity for the South Fork Snoqualmie River levees through this study reach was 13,000 cfs plus one foot of freeboard. It is appropriate to use the original channel capacity as a present-day flood reduction objective. The flood reduction objective for the purposes of this study is 13,000 cfs plus one foot of freeboard.

## 4.4 Gravel removal scenarios

Three bar scalping scenarios were selected to span a range of potential gravel removal projects, and to suggest the level of flood hazard reduction benefit and adverse impacts associated with projects across that range. These scenarios were not intended to be specific design proposals, or to allow comparison of the details of various design proposals. The results of this study are intended to provide guidance to decision makers on the costs, benefits, and impacts for a range of projects. A design team could use the analyses and results presented in this report as a starting point for project design.

A schematic diagram shows the typical depth and configuration of the three gravel bar scalping scenarios in cross section view in Figure 4-1. The length and width of the gravel bars that would be affected by each scenario is shown in plan view and more detail on extent of simulated extraction is provided in Section 6.

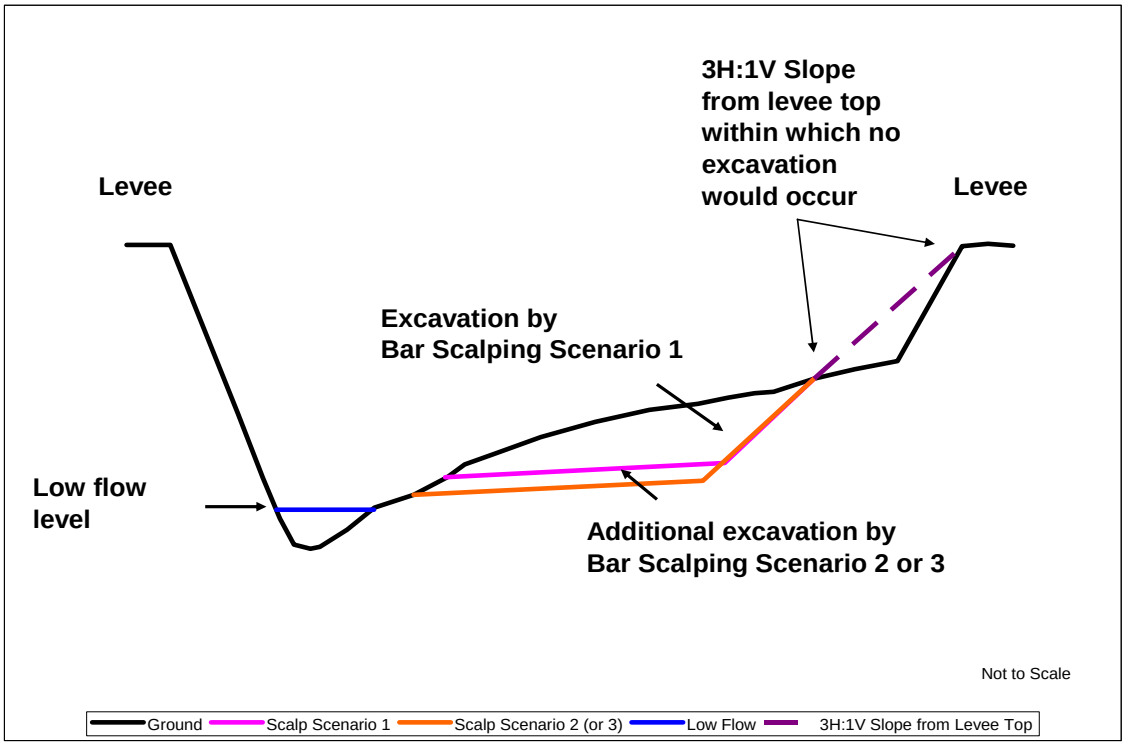



**Figure 4-1: Typical cross section view of the three bar scalping scenarios analyzed in this study. Note that Scalp Scenario 2 and Scalp Scenario 3 are identical in cross section view.**

Existing Conditions:

Changes in the existing conditions of the channel in this study reach due to sediment accumulation or erosion and without any simulated gravel removal are examined in detail in Section 5, where water surface elevations over a range of flood flows are modeled for the years 1992/95, 1999, 2006, 2007 and 2009.

For the purposes of evaluating the effect of gravel removal scenarios on flood water levels, the 2009 channel topography is used as the existing condition to compare to all gravel removal scenarios. Note that all elevations of modeled water surfaces and the changes in water surface elevations that occur above the top of the river bank may be overstated because all of the hydraulic modeling herein was done using the "Raised Levee" condition (explained in Section 3).

Bar Scalping Scenario 1:

Scalp Scenario 1 is intended to adhere to potential conditions for a permit from WDFW based on conditions suggested by WDFW staff circa 1997, as well as existing regulatory provisions in WAC 220-110-140. The lowest point of simulated bar scalping would go down to within two (2) vertical feet of the low flow water surface. The scalping surface would slant upward at 2 percent away from the river and toward the bank or levee. No excavation would occur where live, woody vegetation is present. No extraction would occur in the area within a 3H:1V slope of

the riverward top of levee, and no extraction would occur from the upstream one third of the gravel bar.

Bar Scalping Scenario 2:

Scalp Scenario 2 would be a more extensive gravel removal option. Its lowest point of gravel extraction would go to within one (1) vertical foot of low flow. The scalping surface would slant upward at 2 percent away from the river toward the levee. Extraction is simulated regardless of presence of live, woody vegetation. No extraction would occur in the area within a 3:1 slope of the riverward top of levee. Actual full implementation of this scenario may not be realistic due to regulatory constraints, but it is modeled to illustrate the potential effect of extensive gravel extraction while still staying out of the water during low flow.

Bar Scalping Scenario 3:

Scalp Scenario 3 simulates gravel removal in the area that hydraulic modeling and past actual flooding indicates that overtopping is most likely to occur. Within that area of simulated extraction, Scalp Scenario 3 is identical to Scalp Scenario 2 in its depth, configuration and standards. This scalp scenario is intended to see if gravel removal at specific critical sites would lower water surface elevations enough to adequately reduce flood hazard.

Dredge scenario (not analyzed in this study):

An in-channel dredging scenario was considered but not analyzed in this study, for two reasons. The first reason is that it does not appear that dredging was used to construct the channel and levees in circa 1964.

A 1964 design graphic that includes the full-channel cross section (Figure 4-2) shows that a gravel bar was to be removed (by in-channel dredging) down to an elevation approximately as deep as the low point of the wetted channel. However, a 1964 aerial photo of this river reach (Figure 4-3), taken during levee construction or just thereafter, shows most of the same gravel bars as today with their top surfaces located above the water surface during a summer flow of 620 cfs. This evidence suggests that the gravel bars were scalped and that dredging within the wetted channel did not occur, which is consistent with the interpretation by Shannon & Wilson (1993). The difference between the proposed 1964 design and the estimated As-Built conditions at this same cross section is depicted in Figure 4-4. Note that the proposed 1964 design in both Figures 4-2 and 4-4 indicate a left bank levee top elevation that is approximately equal to the right bank levee top elevation (looking downstream), but the As-Built condition in Figure 4-4 show actual conditions which include left bank levee top elevations lower than on the right bank.

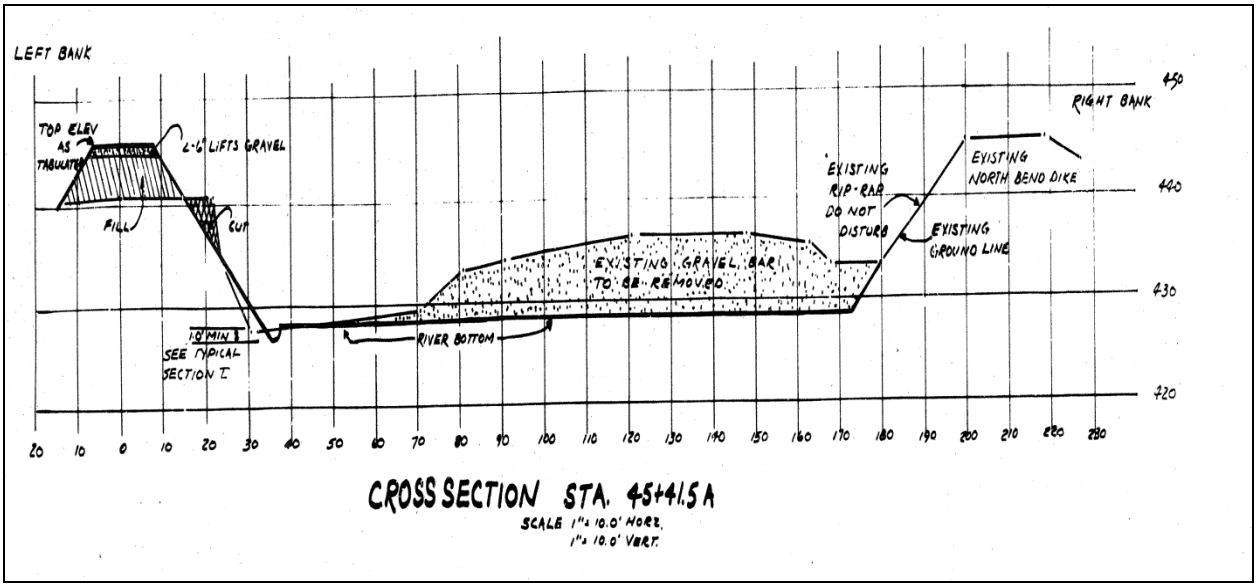



**Figure 4-2: Excerpt from the 1964 South Fork Snoqualmie River levee plans (for Reif Road levee) showing a cross section with existing conditions and proposed levee design, including removal of a gravel bar. This 1964 location (Sta. 45+41.5 A) is equivalent to present-day River Mile 2.97.**

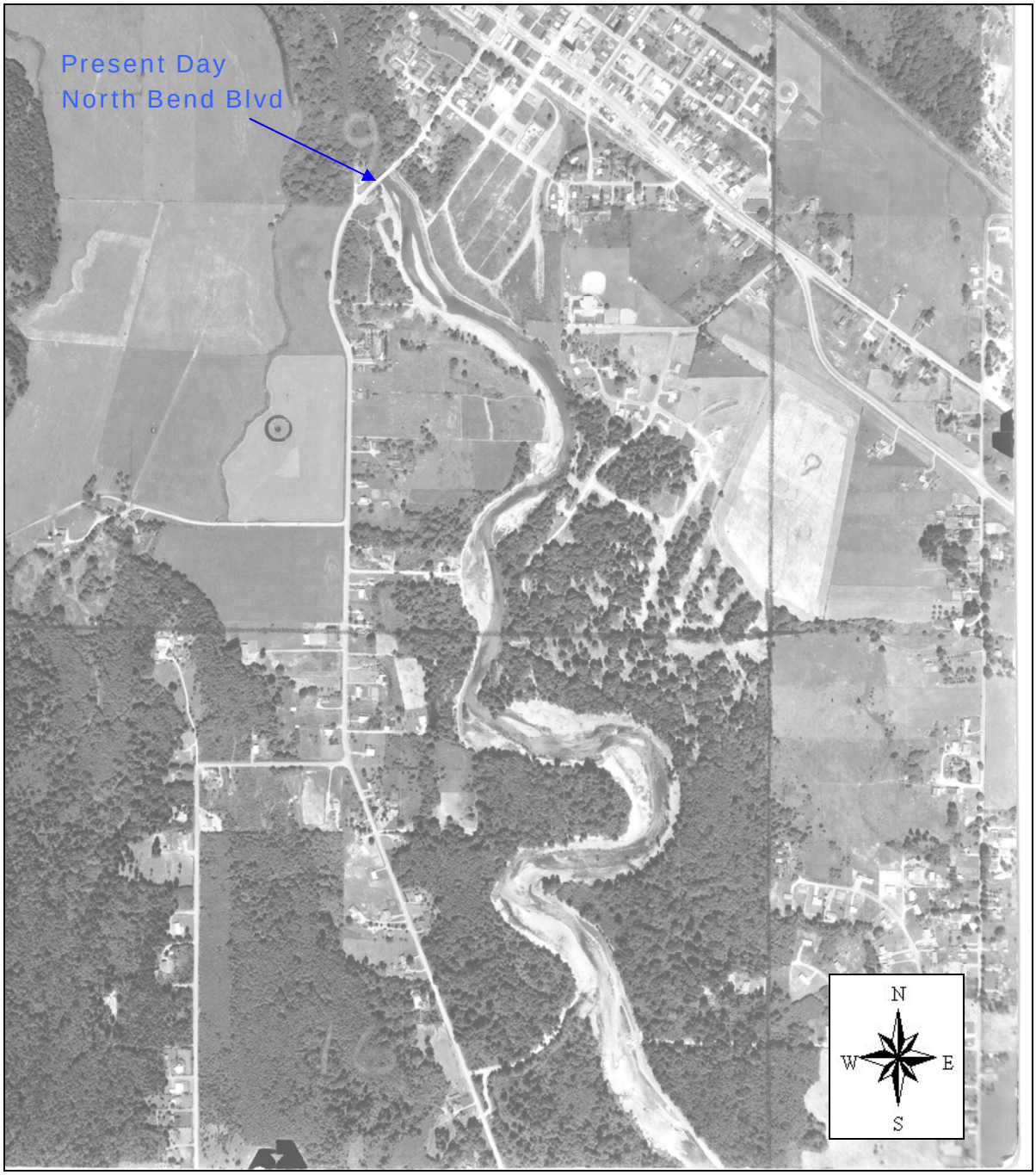



**Figure 4-3: 1964 aerial photo of South Fork Snoqualmie River through the present study reach, with bare gravel bars above the water surface. Mean daily flow was 620 cfs on date of photo (7/25/64).**

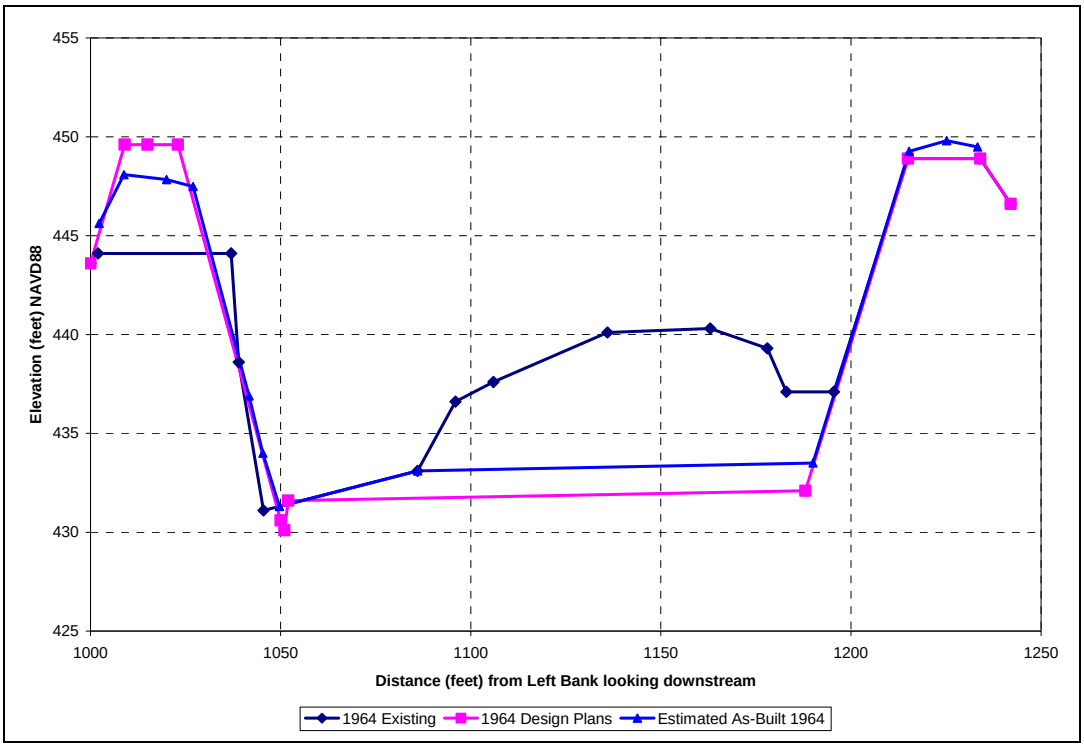



**Figure 4-4: South Fork Snoqualmie River cross section at present-day RM 2.97 showing 1964 existing conditions, and 1964 proposed levee design and estimated 1964 As-Built conditions**

The second reason for not analyzing a dredge scenario is that in-channel dredging today would threaten the stability of the present-day levees.

Information from 1964 As-Built sketches indicates that the South Fork Snoqualmie River levee toes along both banks were constructed to an elevation that is higher than the present-day channel thalweg in many places in this study reach. This means that today's river channel bottom is lower than the lowest point of the levee toe of slope in many places. There also is geotechnical documentation that the present-day South Fork Snoqualmie River levees are structurally deficient in several places (Shannon & Wilson 1993, 2009). This condition results from outdated construction methods, including oversteepened banks built at a slope of 1.5H:1V, inconsistent or unknown construction materials and ongoing flood damages sustained over a 45-year lifespan. In-channel dredging either would excavate to an elevation lower than the present-day thalweg or would excavate in-channel sediment adjacent to levee toes that presently provides some buttressing effect to the levees, thereby threatening levee stability. Because of these reasons, in-channel dredging should not be further considered for implementation as a flood hazard reduction measure along this part of the South Fork Snoqualmie River and no dredge scenario was analyzed in this study. More information on potential erosion of the existing levees is provided in Section 7.1.2.2.

## 4.5 Other approaches than the gravel removal scenarios analyzed in this study

As described above, if it is determined that gravel removal should be pursued for flood hazard reduction purposes, a configuration of gravel removal that is a variation or combination of the three gravel bar scalping scenarios may be appropriate. The specific extent and configuration would be determined in the design process of such a project.

Another approach that differs from a specific single project with a defined start and finish date would take more of a maintenance approach to gravel removal. This "replenishment rate" approach (Kondolf et al. 2001) would extract gravel at an annual or other appropriate frequency at a rate based on the average annual volume of influx, or some fraction thereof, as a "safe yield." This approach would limit extraction to a volume that is scaled to the annual bedload flux into this study reach, which should avoid some of the impacts associated with the "excessive harvest" that would occur with excavation far in excess of the annual influx of coarse sediment (Section 2) (Kondolf et al. 2001). A variation on this approach would be to conduct an initial project to reestablish some identified channel conveyance capacity and then carry out a replenishment rate regimen thereafter.

The replenishment rate to be extracted would be determined adaptively and on an ongoing basis, using information from regular channel monitoring, because the average influx and the corresponding appropriate extraction amount, location and frequency may change through time. Such adaptive management should avoid potential downstream incision that could result, for example, if an equilibrium had been established but extraction continued at the previously estimated replenishment rate. The replenishment rate approach was not analyzed here mainly because it does not lend itself to analysis by steady state 1-dimensional hydraulic modeling. Its effectiveness may not be apparent immediately (as it would be with the gravel removal scenarios in this study) and probably would manifest as a lack of continued aggradation with possibly a minor amount of riverbed or bank erosion at and downstream of the extraction site(s) if the extraction volume, location and frequency is refined adaptively.

Alternatives to gravel removal:

This study does not conduct an alternatives analysis for evaluating flood risk reduction. This study focuses on a variety of versions of one alternative, gravel removal, for reducing flood hazards. If this study finds that gravel removal reduces flood hazards attributable to sediment accumulation and that a gravel removal project may be warranted, it is likely that an alternatives analysis will be required under various regulations (e.g., NEPA, SEPA, CWA) and consistent with King County flood management policy (King County 1993, 2006).

# 5. Existing Conditions

Existing conditions in the present and recent past are described in this section. Channel geomorphology and sediment levels are described from existing information and from ongoing channel monitoring efforts in the South Fork Snoqualmie River. Water surface elevations associated with each channel condition are calculated using hydraulic computer modeling analyses. Information from existing studies and data plus reconnaissance-level field observations are used to describe salmonid habitat and use in the study reach.

## 5.1 Physiographic setting

The South Fork Snoqualmie River drains an area of about 82 square miles, with 3,300 feet of relief, from headwaters in the central Cascades to the North Bend area. The upper watershed drains steep, deeply incised, forested slopes that have thin discontinuous soils developed on sedimentary and volcanic bedrock geology. Recessional glacial outwash that was deposited when glaciers retreated from the region some 14,000 years ago is draped upon the middle elevations of the watershed and contributes sand and gravel for fluvial transport. As the South Fork Snoqualmie River emerges from the mountain front, it deposits its coarse sediment load on the broad, gently-sloping valley floor upstream of Snoqualmie Falls (Booth et al. 1991). Sediment deposited by the South Fork Snoqualmie and the Middle Fork Snoqualmie rivers has combined to fill the valley at and upstream of North Bend with coarse alluvium (Shannon & Wilson 1993), and built a depositional fan down which both rivers flow (Figure 5-1). Almost the entire floor of the upper Snoqualmie Valley, including this study area, is composed of alluvium (Perkins 1996).

The South Fork Snoqualmie River flows through a leveed channel in the City of North Bend area (Figure 1-1), where the river channel forms a boundary between incorporated North Bend and unincorporated King County for part of its length. The downstream end of the study reach at North Bend Blvd (Bendigo) Bridge is about 2.8 river miles upstream of the confluence of the South Fork Snoqualmie and the mainstem Snoqualmie rivers. The study reach includes about 1.6 river miles, with nine gravel bars, from North Bend Blvd (Bendigo) Bridge upstream to near I-90 (Figure 5-2).

## 5.2 Recent history of river flooding and gravel removal within the study reach

### 5.2.1 Basin hydrology, flood events

The USGS gage 12144000 is located at the North Bend Blvd Bridge. Its flow record runs from 1909 to present with some periods of interruption and the gage itself was moved to its present location from about a half mile upstream after 1974. The USGS characterizes this record as “good,” which means that 95 percent of their reported discharge estimates are within 10 percent of the actual values. The historic record of annual peak flows at this gage is shown in Figure 5-3.

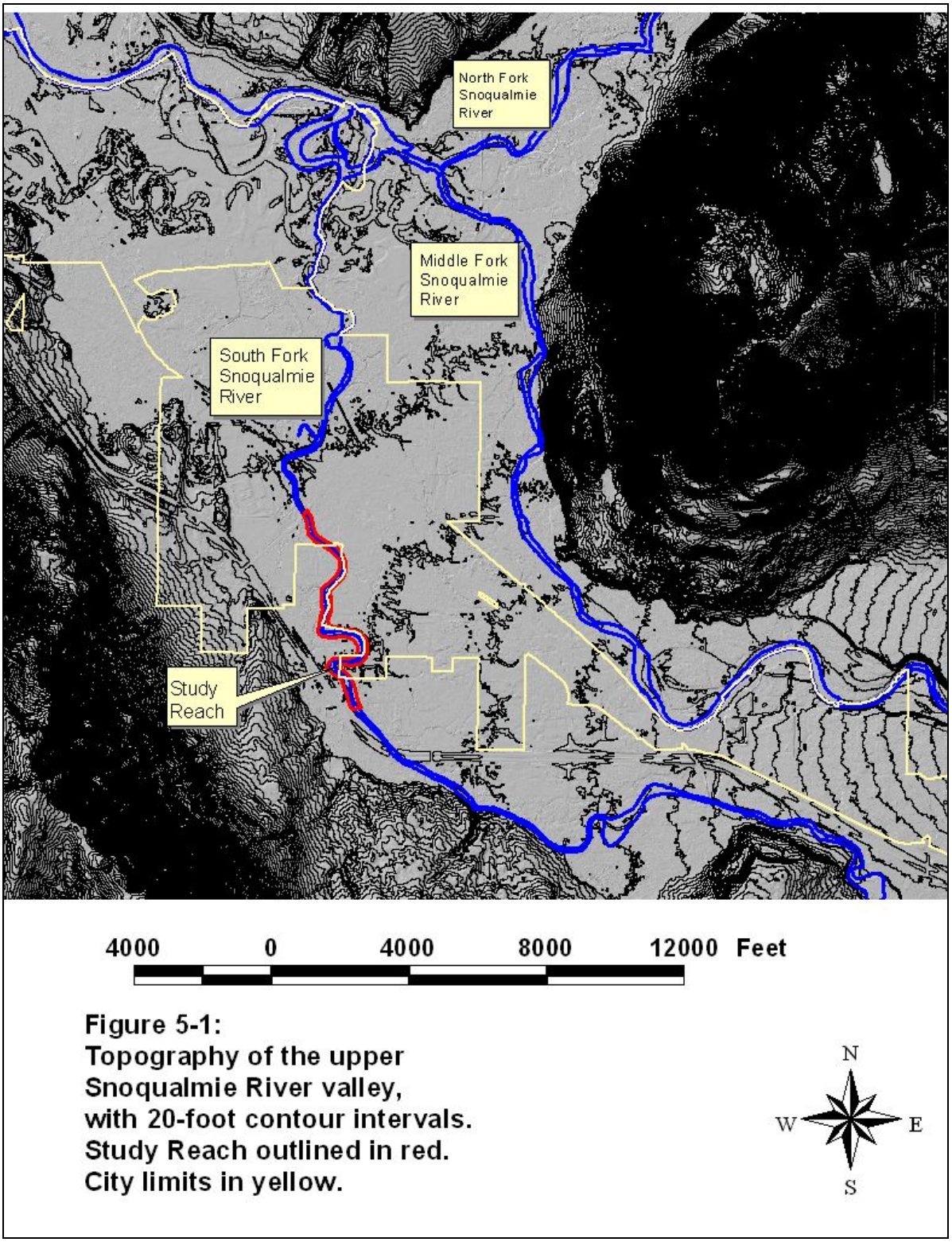
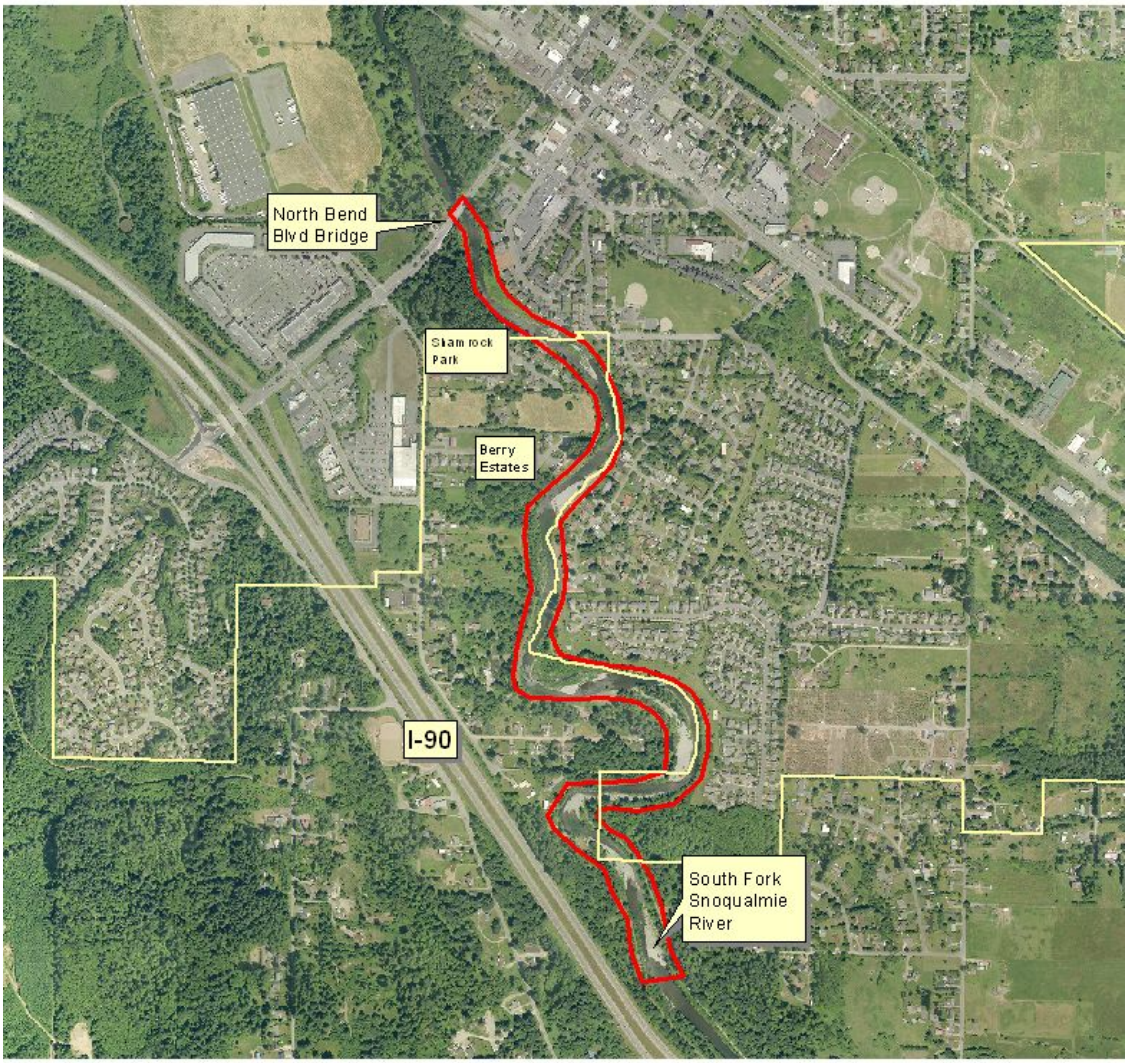



**Figure 5-1:**
**Topography of the upper Snoqualmie River valley, with 20-foot contour intervals. Study Reach outlined in red. City limits in yellow.**




1000 0 1000 2000 3000 Feet

**Figure 5-2:**
**South Fork Snoqualmie River Study Reach boundary, in red. City limits in yellow. 2007 aerial photo.**

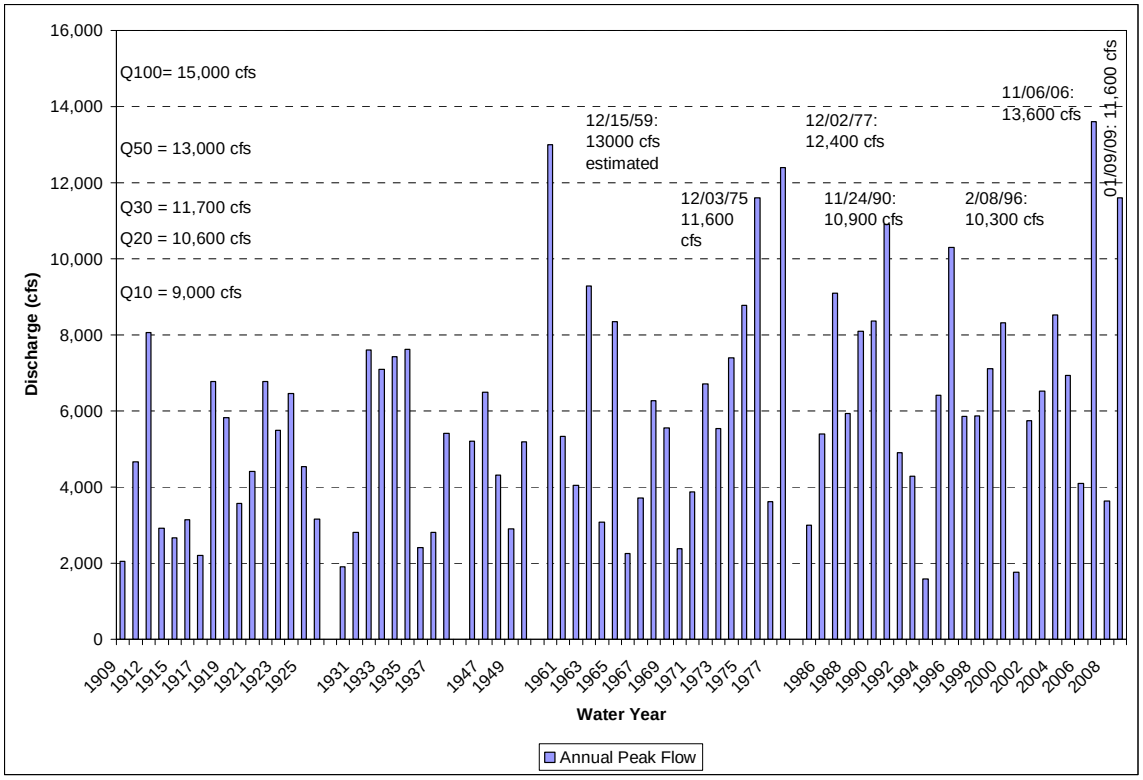



**Figure 5-3: South Fork Snoqualmie River annual peak flows at USGS Gage 12144000**

To provide consistency with other published flood reports, the flood frequency analysis at USGS gage 12144000 that was prepared for the South Fork Snoqualmie River Flood Insurance Study ([FIS]; FEMA 2005) is used in this study. Flood flow magnitudes, exceedance probabilities and recurrence intervals reported by FEMA (2005), as well as others that were calculated using the same flood frequency analysis, are summarized in Table 5-1. The period of record for this flood frequency analysis is Water Year 1909 to 1991; it includes 56 annual peak flood events (there are gaps in the record). The period of record for the South Fork Snoqualmie FIS flood frequency analysis was current when it was conducted in the early 1990s; it is cited as FEMA (2005) because that is when a regional compilation of the then best-available flood studies was completed and published. As such, this particular flood frequency analysis and its period of record are still considered the effective hydrologic information for flood insurance and regulatory purposes.

**Table 5-1: South Fork Snoqualmie River flood frequency analysis at USGS gage 1214400 as per FEMA (2005), using data from Water Year 1909 through 1991**

| Flow (cfs) | Exceedance probability (percent) | Recurrence Interval (years) | Note |
|---|---|---|---|
| 9,000 | 10 | 10 | A |
| 10,800 | 5 | 20 | B |
| 11,700 | 3.33 | 30 | B |
| 12,500 | 2.5 | 40 | B |
| 13,000 | 2 | 50 | A |
| 15,000 | 1 | 100 | A |
| 19,700 | 0.2 | 500 | A |
| Notes: | | | |
| A: Values reported by FEMA (2005) | | | |
| B: Values calculated by the same flood frequency analysis as FEMA (2005) | | | |

A flood frequency analysis based on the period of record from Water Year 1909 through 1964, the approximate date of levee construction, includes 34 annual peak flood events (there are gaps in the record) and results in lower flood magnitudes at all recurrence intervals (Table 5-2) than in the FEMA (2005) flood frequency analysis (Table 5-1). This flood frequency analysis, based on an earlier period of record, is of interest as it corresponds to the data available at the time of levee design and construction in the study reach. Because flood frequency analyses can change through time, flood events are expressed in this study in terms of discharge (cfs) primarily, and recurrence intervals (years) secondarily; when recurrence intervals are used, they will refer to the FEMA (2005) flood frequency analysis (Table 5-1) unless otherwise noted.

**Table 5-2: South Fork Snoqualmie River flood frequency analysis at USGS gage 1214400 using data from Water Year 1909 through 1964**

| Flow (cfs) | Exceedance probability (percent) | Recurrence Interval (years) |
|---|---|---|
| 7,720 | 10 | 10 |
| 9,000 | 5 | 20 |
| 10,700 | 2 | 50 |
| 11,900 | 1 | 100 |
| 14,900 | 0.2 | 500 |

Factors that affect basin hydrology, and flood frequency analyses, can change through time, such as land use and land cover percentages of forested, vegetated and impervious surfaces, in addition to the natural variability of climate. The majority of the land use in the upper basin is forest production and wilderness areas; therefore any effects of urbanization in the South Fork Snoqualmie River basin are expected to be rather modest. Another basin-scale modification to the hydrologic regime is the presence of any large water impoundments. There are no major water impoundments or other flood control structures in the upper watershed. The Twin Falls hydropower facility is located on the South Fork Snoqualmie River upstream of this study reach but its impoundments are not significant enough to affect flood flows in the study reach. In addition, it is not unusual for flood frequency results to shift as time passes and more data are

available for a flood frequency analysis. Larger data sets improve the statistical confidence of such estimates.

To provide a context that incorporates the observed data from recent large flood events, the flood frequency analysis for the South Fork Snoqualmie River at USGS gage 12144000 was recalculated using annual peak flows from 1909 through 2009. This analysis, based on data through the most current Water Year, indicates that a 10-year flood would have a discharge of 9,700 cfs, a 50-year flood would be 13,500 cfs, a 100-year flood would be 15,100 cfs, and a 500-year flood would be 18,800 cfs. These discharge values are within minus 4 percent to 7 percent of the discharge values for the South Fork Snoqualmie River FIS (FEMA 2005) at the same location.

Climate change also may affect basin hydrology. A separate, county-wide analysis of climate change impacts on river flooding (King County 2010) found no statistically significant trend in annual maximum flows on the South Fork Snoqualmie River above Alice Creek (USGS gage 12143400) for the 10-year, 50-year or 100-year flood through the 47-year period of record from Water Years 1961 through 2008. The Alice Creek gage is located several river miles upstream of the study area. Given the findings of King County (2010) that no long-term statistically significant increase in annual maximum flows in the South Fork Snoqualmie River above Alice Creek have occurred, it is likely that no long-term increasing trend in maximum flows would be evident in the South Snoqualmie in North Bend either.

Taken together, all of the above suggests that the 1909-1964 flood frequency analysis (Table 5-2) is likely a good indicator of available hydrologic data as of the time of levee construction, and that the FEMA 1909-1991 flood frequency analysis (Table 5-1) remains a reasonable approximation of flood flows for the purposes of discussion in this report. Regardless, as stated above, this report will primarily compare flood conveyance capacity and flood reduction results in terms of the absolute discharge in cfs.

The magnitude of large flows on the South Fork Snoqualmie River and the location of overtopping within this study reach are summarized in Table 5-3. The extent of overtopping during the December 1959 flood, with an estimated discharge of 13,000 cfs, is undocumented but assumed to be widespread because it predates the 1964 levee construction. The floods of 1975 (11,600 cfs) and 1977 (12,400 cfs) did not overtop the levees, but a smaller flow (10,900 cfs) that occurred 12 to 15 years later, in November 1990, overtopped the left bank at RM 3.39 to RM 3.35 along the Berry Estates subdivision. Flows in November 1995 (10,000 cfs) and February 1996 (10,300 cfs) came close but did not overtop the left bank near Berry Estates. The 1991 and 1994 gravel removal operations on the South Fork Snoqualmie River occurred between 1990 and 1995/96. The November 2006 flow of 13,600 cfs, about a 65-year flood, is the largest flow on record for the South Fork Snoqualmie River at gage 12144000. It overtopped the left bank at RM 3.39 to RM 3.35 along Berry Estates, the left bank from RM 2.97 to RM 3.02 near the Shamrock Park subdivision, and the right bank near North Bend Blvd Bridge. The November 2006 flows also threatened to overtop the left bank further upstream at a sharp right bend at RM 4.17. The November 2008 flood of 9,900 cfs did not overtop anywhere in this reach but came close to the left bank levee top at RM 3.34. The January 2009 flood had a peak discharge of 11,600 cfs (provisional USGS data as of this writing), which is almost exactly a 30-

year flood. It overtopped along Berry Estates (RM 3.34 to RM 3.35) but not elsewhere. See Figure 5-4 for cross section RM locations and gravel bar numbers.

**Table 5-3: South Fork Snoqualmie River – Summary of high flow events at USGS gage 12144000**

| Date(s) | Maximum discharge at USGS 12144000 (cfs) | Overtopping (yes or no). If so, the location(s) of overtopping within study reach (River Miles) |
|---|---|---|
| December 1959 | 13,000 estimated | Overtopping is assumed widespread, because this predates 1964 levee construction. |
| 1975; 1977 | 11,600; 12,400 | Did not overtop. |
| November 1990 | 10,900 | Overtopped left bank RM 3.35 to RM 3.39 (Berry Estates). |
| November1995; February 1996 | 10,000; 10,300 | Did not overtop, but came close along the left bank at Berry Estates. |
| November 2006 | 13,600 (flood of record) | Overtopped left bank RM 3.35 to RM 3.39 (Berry Estates) and RM 2.97 to RM 3.02 (Shamrock Park), and right bank RM 2.97 near North Bend Blvd Bridge. Same flood threatened overtopping at left bank RM 4.17. |
| November 2008 | 9,900 | Did not overtop, but came close along the left bank at Berry Estates. |
| January 2009 | 11,600 | Overtopped left bank RM 3.34 to RM 3.35 (Berry Estates). |

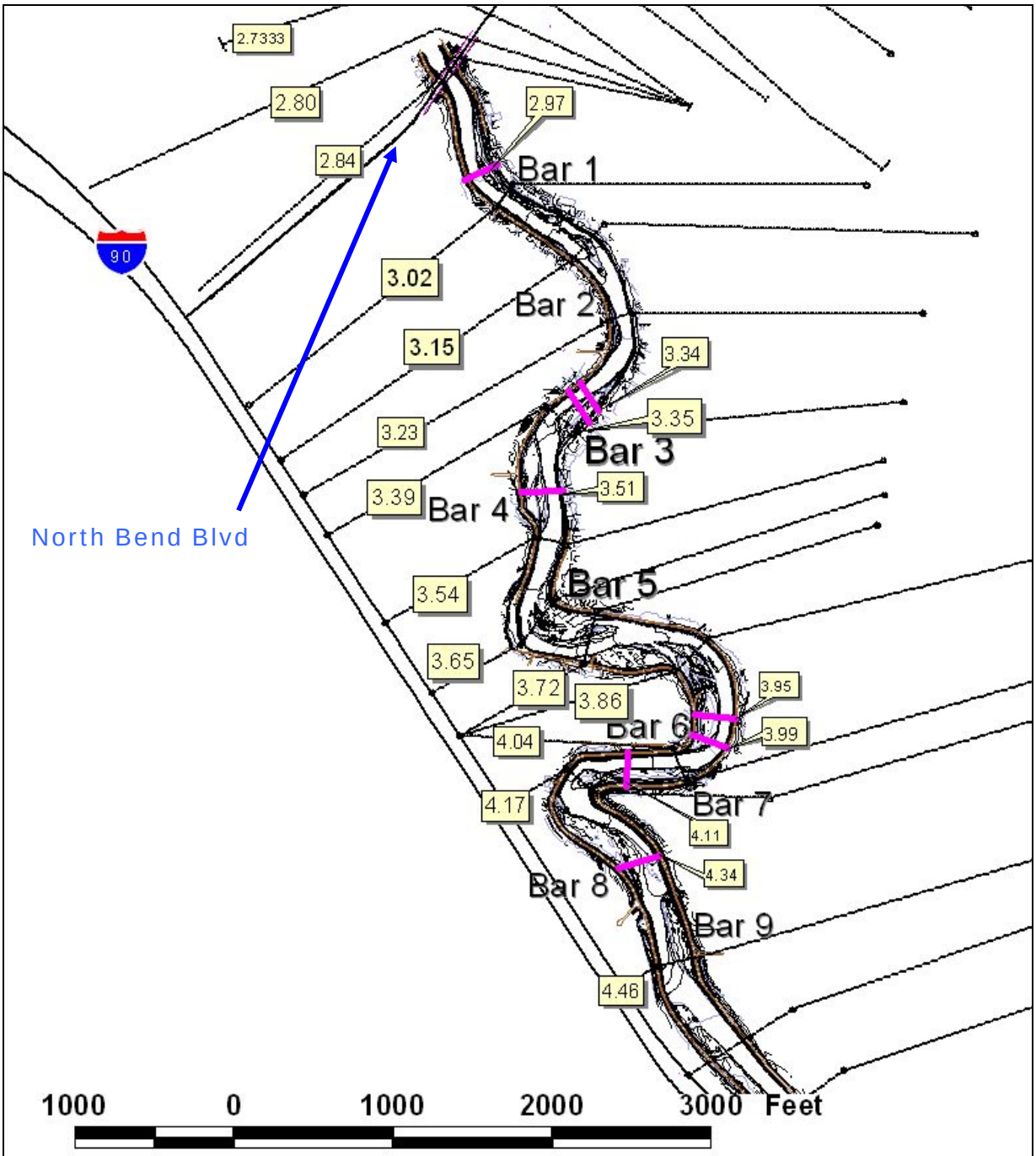



**Figure 5 - 4:**
**SF Snoqualmie River**
**Cross Section and**
**Gravel Bar Numbers**
**Black= Flood study cross sections**
**Pink = Added cross sections**

From these examples it is possible to identify that flow discharges in the range of 11,000 cfs to 12,000 cfs, or about a 20-year to 30-year flood event (Table 5-1), are of sufficient magnitude to overtop the left bank at or near RM 3.39 (Berry Estates) and the left bank at RM 2.97 (Shamrock Park), and to threaten overtopping at other places in this reach.

### 5.2.2 History of gravel removal

Available information and historical aerial photos indicate that the containment levees along both sides of the river in this study reach were constructed in the mid-1960s using river gravel excavated from the South Fork Snoqualmie River gravel bars. It appears that gravel was excavated by scalping most of the gravel bars in the reach (bar numbers 1, 2, 4, 6, 8 and 9), not by in-channel dredging (Figure 4-3 and Shannon & Wilson 1993). Based on the planview area of the gravel bars and assuming a four foot depth of excavation, an estimated 63,000 cubic yards of river gravel was excavated for levee construction (Shannon & Wilson 1993).

Sediment has accumulated in parts of the channel since construction of the levees. Gravel bar scalping was conducted for flood reduction purposes at specific locations in the early-1990s, after the overtopping flood of November 1990. Gravel bar scalping on gravel bars 1 through 4 (RM 2.85 through RM 3.54) removed approximately 27,000 cubic yards in 1991. Gravel bar scalping on gravel bar 5 (approximate RM 3.65) and bar 7 (RM 4.04 to RM 4.17) for flood reduction purposes removed about 5,200 cubic yards in 1994. In addition, there was a commercial operation that removed about 1,000 cubic yards at gravel bar 6 (approximately RM 3.86 through RM 3.99) annually, from 1956 through 1998. The total annual amount removed from gravel bar 6 varied and the gravel was removed at various times over the course of the year. This annual operation was discontinued in 1999 (Mr. Rod Churchill, personal communication, 1999).

A plot of water level (or stage) measured at a specific discharge of 500 cfs at USGS gage 12144000 shows a drop of approximately 2.5 feet in the stage between 1964 and 1965 (Figure 5-5). This USGS gage was located at approximate RM 3.3, between gravel bar 2 and 3, during the period in this plot. This plot was not extended further in time because this USGS gage was relocated to its current location at North Bend Blvd (Bendigo) Bridge sometime after 1974. Because the large drop in stage coincides with 1964 levee construction, which used river gravel as levee prism fill, Figure 5-5 suggests that extraction from gravel bars near the gage affected water levels at the gage. To the extent that similar excavation occurred throughout much of this reach during the same timeframe as a result of levee construction, Figure 5-5 may infer similar lowering of water levels throughout the reach, but there are no specific data to support that inference.

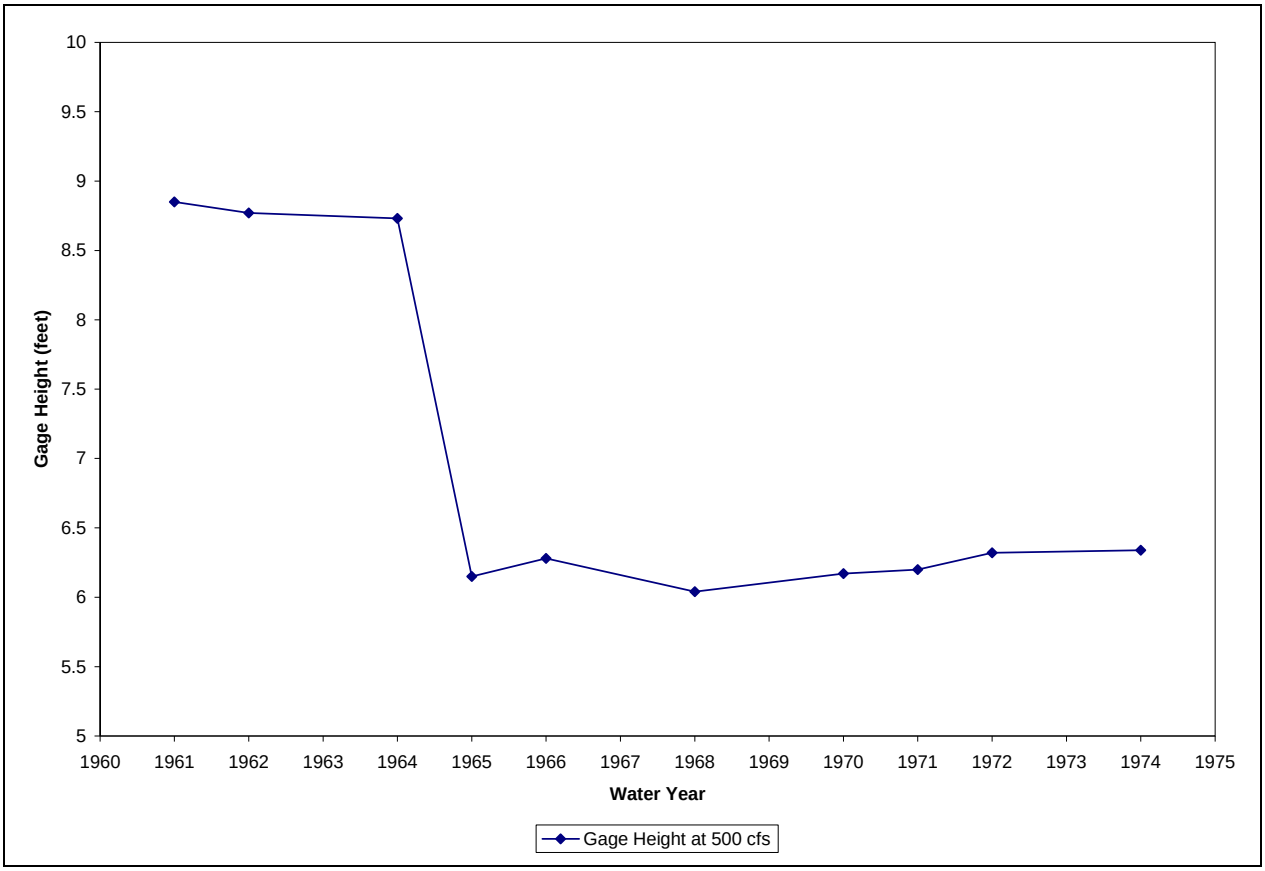



**Figure 5-5: South Fork Snoqualmie River USGS Gage 12144000 gage height at 500 cfs, Water Years 1961 to 1974**

## 5.3 Geomorphic and sediment conditions

### 5.3.1 Basin-scale influences

The South Fork Snoqualmie River exhibits some distinct river segments based on channel gradient through its lower 20.5 miles: the upper 7 river miles has an average gradient of 1 percent; the central 4.3 river miles has an average gradient of 3 percent and the lowest 9.2 river miles has an average gradient of 0.4 percent (Shannon & Wilson 1993). The longitudinal profile of part of the South Fork Snoqualmie River is plotted in Figure 5-6, with this study reach identified. The channel gradient in this study reach averages 0.4 percent in its upper part and 0.3 percent in the lower part (Shannon & Wilson 1993; survey data from this study).

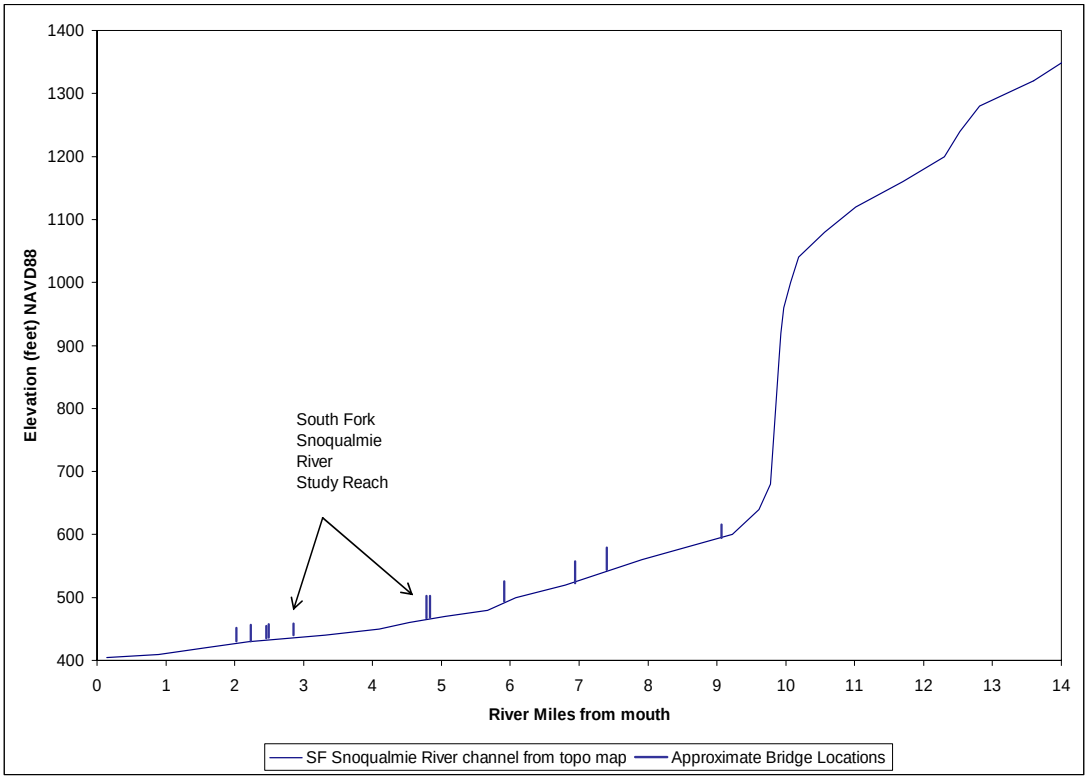



**Figure 5-6: Longitudinal profile of South Fork Snoqualmie River from its mouth to RM 14**

The drop in channel gradient from mountainous headwaters to the study reach area has resulted in both the South Fork and Middle Fork Snoqualmie Rivers depositing coarse alluvium in a depositional fan that underlies the North Bend area, as illustrated in Figure 5-1. The continued drop in channel gradient within this study reach is consistent with a depositional fan environment.

Sediment deposition is not a new phenomenon in the upper Snoqualmie Valley. The 2003 City of North Bend Floodplain Management Plan (City of North Bend 2003) reported that during drilling for a water well in North Bend, wood was encountered at a depth of 495 feet. The wood was radiocarbon dated at 8,000 years before present, suggesting an average burial rate of six feet per century at that site.

The South Fork Snoqualmie Watershed Analysis (U.S. Department of Agriculture [USDA] Forest Service 1995) describes avalanches as the dominant source of natural sediment delivery to the upper reaches of the South Fork Snoqualmie River. Other sediment contributions come from road failures, stream bank erosion and dam-break floods. While the incidence of landslides in the historic condition appears to be low, land management activities appear to have increased the sediment contribution to the stream channels (USDA Forest Service 1995). In particular, "The trend in sediment delivery to the South Fork Snoqualmie River and its tributaries is expected to continue at the same rate for several decades and then decrease gradually. This is based on the assumption that natural (or geologic) slope forming processes, such as soil creep, surface erosion and mass wasting, will occur at a continuous level. In addition, the elevated rates of surface

erosion and mass wasting are anticipated to continue from management activities, which include ski areas, timber harvest and roads" (USDA Forest Service 1995).

The same study states that present rates of sediment production in the upper South Fork Snoqualmie watershed probably are elevated over historical rates (USDA Forest Service 1995). Findings by Nelson (1971) based on samples taken in 1967 and 1968 suggest that the South Fork Snoqualmie River had a relatively high rate of suspended sediment production per square mile compared to similar tributary rivers in the Snohomish Basin. Though these are limited and 40-year old data on suspended sediment, not bedload, there is some context provided.

With the application of forest practices intended to prevent erosion and decrease sediment delivery to river channels, as prescribed by the South Fork Snoqualmie Watershed Analysis, coarse sediment flux into and deposition in this study reach should decrease over the long term, although the rate of this decrease is not known. For the purposes of this study, it is assumed that this study reach is not sediment supply limited, that the present rate of coarse sediment delivery to the study reach is elevated over historical rates, and that the present trend in sediment delivery will continue for several decades.

### 5.3.2 Reach-scale geomorphic conditions

This South Fork Snoqualmie River study reach was a depositional reach before the levees were constructed. The natural conditions of being located 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 upstream areas all favor deposition.

Historical maps and aerial photos provide information on reach-specific conditions before the levees were completed. A similar planform meander configuration as today is shown in the 1913 USGS Cedar Lake topographic quad map (Figure 5-7). In addition, locations of split flow around islands, indicating multiple channels even at the small scale of the 1913 map, suggest a more heterogeneous channel geomorphology than at present. The 1913 channel features can be compared to the present-day channel planform, gravel bar locations and configuration in Figures 5-2 and 5-4.

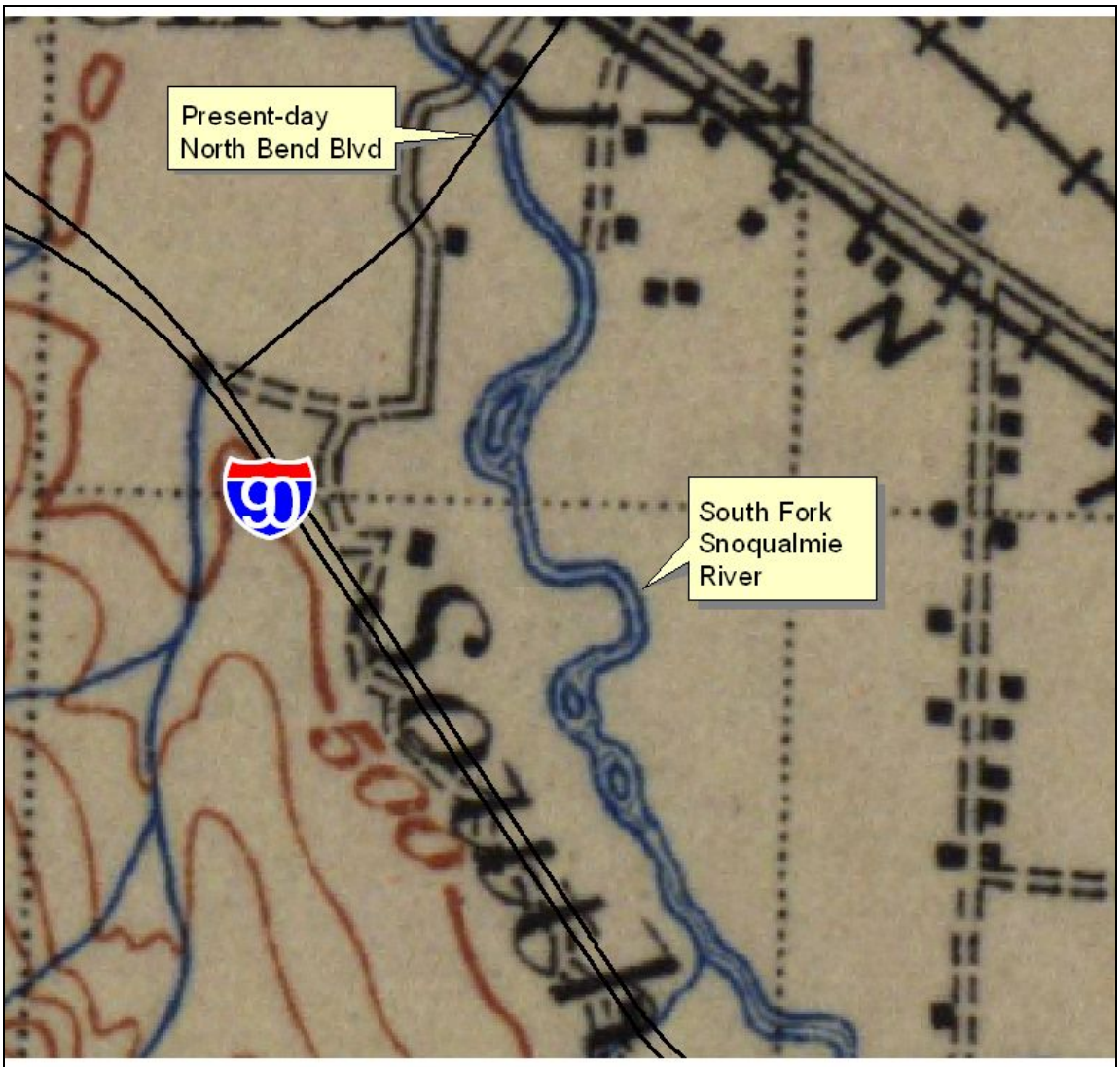
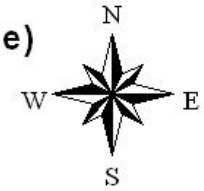



**Figure 5-7:**
**1913 USGS Cedar Lake Quad Map (1:125,000 scale) showing South Fork Snoqualmie River through study reach, with present-day roads for context**




The basic planform meander configuration of 1913 remained the same in 1958 (Figure 5-8), but there appears to be a transition underway between pre- and post-levee conditions. Levees are either under construction or in place in the downstream part of the reach (e.g., from present-day

RM 3.51 downstream) and the downstream bars (gravel bars 1, 2, 3) appear freshly graded and bare of vegetation. From RM 3.54 upstream, there appear to be more areas of bank erosion and multiple or braided channels, which would be consistent with a channel of decreasing gradient on a depositional fan.

Channel configuration and gravel bar conditions showed little change from 1958 to 1964 (Figure 4-3), with completion of the South Fork Snoqualmie River levees. Gravel bar 1 appears as a mid-channel bar in 1964. The surfaces of most 1964 gravel bars appear almost entirely bare, presumably due to bar scalping for levee construction. There is less channel heterogeneity in the upstream part of the study reach in 1964 than in 1958 as levees line both banks.

The location of most of the gravel bars is the same as today but there have been a few changes since the 1958 and 1964 aerial photos. Gravel bar 1 is now established on the right bank. Gravel bar 2, a long left bank point bar in 1958 and 1964, now has split off into a mid-channel bar. Land seen in earlier photos along the left bank at RM 3.65 has eroded away and the present-day gravel bar 5 has deposited along the right bank. The location and size of gravel bars 3, 4, 6, 7, 8, and 9 are generally similar now to conditions in 1958 (Shannon & Wilson 1993) and 1964. The eroding and shifting character of the channel and bars in 1958 and 1964 around RM 3.65 through RM 3.72 persists to this day.

Overall, there have not been significant or widespread changes in the planform meander configuration of the South Fork Snoqualmie River channel from 1913 to the present. Within that configuration, the channel geomorphology has simplified through nearly the past century from split channels to a single thread, with some of the transition within the reach captured in the 1958 and 1964 images.

The meandering planform geometry of this gravel bedded river with alternating gravel bars might suggest a pool-riffle channel classification (Montgomery and Buffington 1998), but few deep areas are present in this reach. There is one pool at RM 3.23, which is also where the channel narrows down considerably. All other deep areas are along outside bends where they likely were formed by scour along the toe of the armored banks. The majority of the river channel in this reach has relatively shallow geomorphic/habitat units with faster moving water, i.e., riffles and runs, so there probably are not enough pools to be called a pool-riffle channel. This channel therefore likely would be a plane-bed channel under the Montgomery-Buffington classification. Also, the river is no longer unconfined and the river banks are no longer alluvial, both of which are attributes of a pool-riffle channel. Lastly, there is little or no large wood in the low flow wetted channel and few pieces on gravel bar tops, indicating a lack of pool-forming structure. In general, the channel morphology is relatively uniform and lacking complexity.

Most of the gravel bars support vegetation ranging from grass to emergent shrubs to riparian deciduous trees. Large areas of dense and established vegetation suggest that the processes of erosion and channel migration have been diminished or are relatively static in those areas. Similarly, gravel bars stabilized by vegetation do not appear to be a significant part of the active

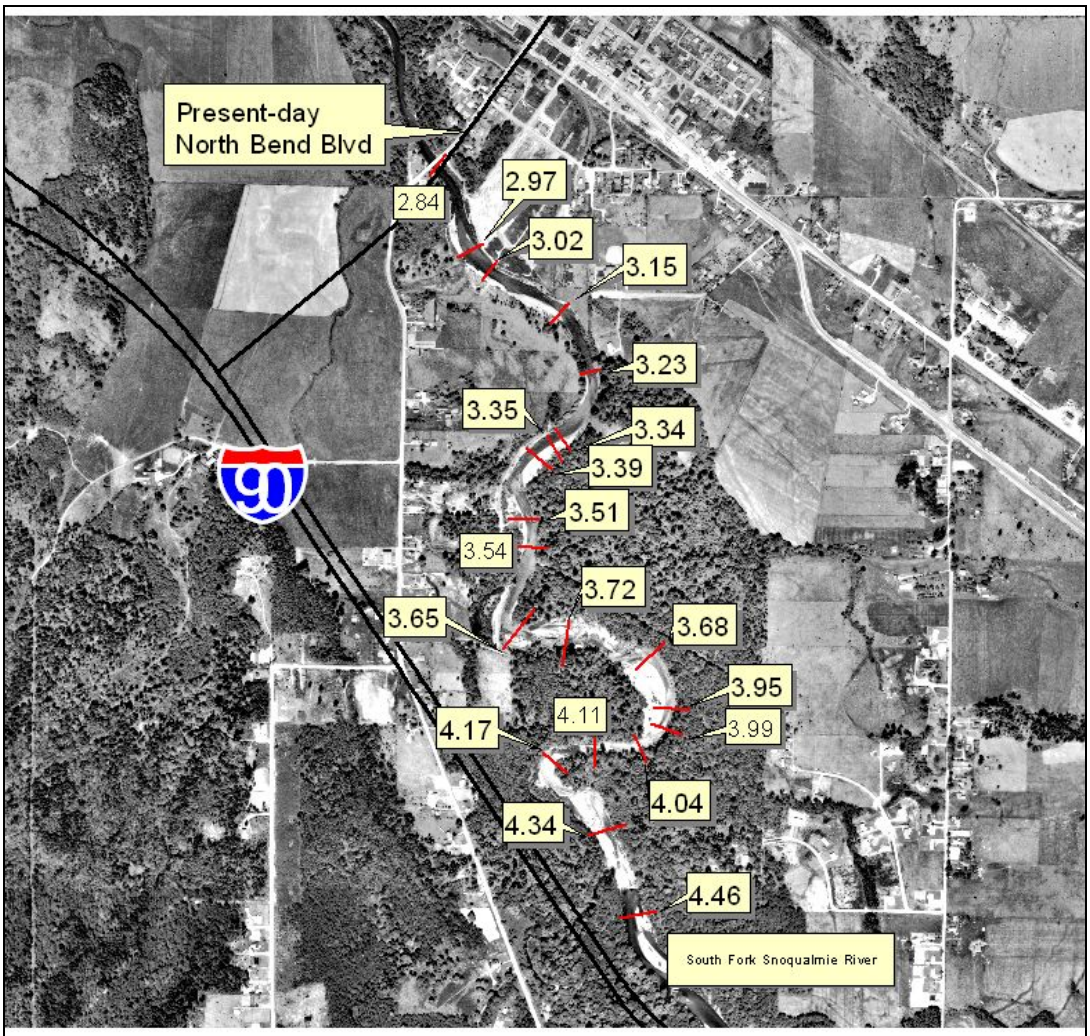



**Figure 5-8:**
**1958 Aerial Photo of South Fork Snoqualmie River through this Study Reach, with present-day roads and cross sections**

routing of gravel through the channel. Notable exceptions are the areas around RM 3.15 and RM 3.72 that have recently formed mid-channel bars and exhibit active channel or bank erosion.

While natural conditions favor deposition in this study reach, some of the constructed conditions may further enhance depositional tendencies. For example, the widespread combination of uniform conditions and stabilized gravel bars may reflect the influence of the channel being

constrained to its current configuration by the levees along both of its banks. The levees have locked the historic channel configuration in place, such that the natural channel response to accommodate sediment deposition—bank erosion and channel migration—is not an option. With little or no horizontal movement available, sediment that deposits in this study reach results primarily in the vertical growth of gravel bars.

Another constructed feature also affects hydraulic conditions and therefore sediment movement and deposition in this reach. The North Bend Blvd (Bendigo) Bridge appears to have been designed with an opening that would convey 10,900 cfs, estimated to be a 50-year flood calculated for bridge designs in 1976 but which is about a 20-year flood event today; this discrepancy between historic and present-day peak flow estimates may imply that the bridge opening is under-designed (Kato and Warren, Inc 2000). Hydraulic modeling results in this present study indicate backwater effects clearly exist to RM 3.02 (Section 5.4). Kato and Warren, Inc (2000) state that the North Bend Blvd Bridge would not have freeboard for the present-day 50-year (13,000 cfs) and greater floods, and that the associated backwater conditions would propagate upriver to about RM 3.23. Backwater conditions decrease the water surface slope, which decreases sediment transport capacity and favors sediment deposition.

Some generalizations can be made about sediment movement and deposition within this study reach. Three areas, or subreaches, within this study reach have generally distinct channel gradients and channel widths (Shannon & Wilson 1993). An upper part (RM 4.46 to RM 4.17) is relatively steeper with moderate channel widths and most sediment appears to be conveyed downstream through this subreach. A middle area or subreach (RM 4.17 to RM 3.3) has generally wider channel widths as channel gradient decreases. This is a depositional area with large and active gravel bars including deposition mid-channel. A downstream part (RM 3.3 to RM 2.85) narrows down and retains its gradient, which favors sediment transport and less deposition (although the backwater conditions from the North Bend Blvd Bridge may locally enhance deposition within this downstream subreach).

All of the coarse sediment delivered from the upstream basin deposits in the lower nine miles of the South Fork Snoqualmie River channel (Dunne 1984), which includes this study reach. However, not all of the coarse sediment delivered from upstream deposits in this study reach; about half is conveyed further downstream (Booth et al. 1991), as described in more detail below. Historical aerial photos and maps indicate that the South Fork Snoqualmie River downstream of this study reach to its mouth exhibits multiple and braided channels that migrate across the floodplain (Perkins 1996), which are characteristics common to a depositional channel particularly on a depositional fan.

### 5.3.3 Sediment movement and deposition

#### 5.3.3.1 Surveyed cross sections

King County monitors certain river channels for sediment accumulation and its effects on flood hazard; the South Fork Snoqualmie River in the North Bend area is one such channel. Data on

channel conditions gathered by this monitoring program, plus data from previous studies, are used to characterize changes in the in-channel sediment levels under existing conditions over the past 17 years in this subsection. Cross section locations are shown in Figure 5-4. Surveyed channel cross sections from 1992/95, 1999, 2006, 2007 and 2009 are plotted in Appendix A, where all cross sections used in this study, their origins and dates of survey also are listed.

Channel monitoring data from these five years or timeframes were selected for this study for the following reasons. The 1992/95 timeframe immediately follows gravel removal in 1991 (downstream part of the study reach) and 1994 (upstream part) and includes some of the earliest survey data that are well documented. The 1999 sections were the basis of the South Fork Snoqualmie Flood Insurance Study (FEMA 2005) and allow ample time since the 1992/95 data set for an informative comparison of channel changes. The 2006 data set includes additional cross sections that were added to better represent gravel bars, also with ample time elapsed since the previous data set. Comparison of 2006 to 2007 cross sections should represent the effects of the November 2006 flood event. The 2009 data are the most recent available; comparison to 2007 should represent changes associated with high flows in November 2008 and January 2009. Channel survey data from other years were consulted but not analyzed quantitatively in this report, including a few cross sections from 1989/90, all of the reach in 1993 (same cross sections as 1992), 1995 (upper part of the reach), 1996 (all), and 2005 (lower part of the reach).

Survey results at a few cross sections in Figure 5-9 illustrate the range of channel changes during the study period from 1992/95 to 2009. The cross section at RM 3.15 (Figure 5-9A) shows erosion of a gravel bar on the left of the channel and deposition of a mid-channel bar. The cross section at RM 3.39 (Figure 5-9B) shows a low and flat gravel bar in 1992 after bar scalping in 1991; since then, deposition is evident across much of the scalped surface in 1999, 2006 2007, and 2009, while there is also some erosion in the channel. The pattern and sequence of deposition at RM 3.39 is typical for those sections in this study that have had net deposition on a gravel bar after scalping. The cross section at RM 3.54 (Figure 5-9C) shows little change through the entire study period, which is also seen at some of the other cross sections in the study reach. Conversely, there has been about 110 feet of lateral erosion of the left bank at RM 3.72 (Figure 5-9D) from 1992 to 2009, during which time deposition also occurred to form a gravel bar in the middle of the channel. Deposition over the relatively wide gravel bar at RM 4.17 (Figure 5-9E) is fairly typical of conditions near the upstream end of the study reach.

The changes in sediment levels at each cross section and the net reachwide changes in sediment deposition for each period of 1992/95 to 1999, 1999 to 2006, 2006 to 2007 and 2007 to 2009 are calculated in tables in Appendix A and summarized in Table 5-4. The estimated volume of net sediment deposition over the entire study reach is 20,400 cubic yards from 1992/95 to 1999, with 1,600 cubic yards from 1999 to 2006, with 6,600 cubic yards from 2006 to 2007, and 17,500 cubic yards from 2007 to 2009 for a total deposition of about 46,000 cubic yards from 1992/95 to 2009. The average annual rates of deposition are calculated simply by dividing the total deposition by the intervening years and are provided for comparison purposes. Actual rates of deposition or erosion in any given year may vary greatly due to the episodic nature of sediment movement.

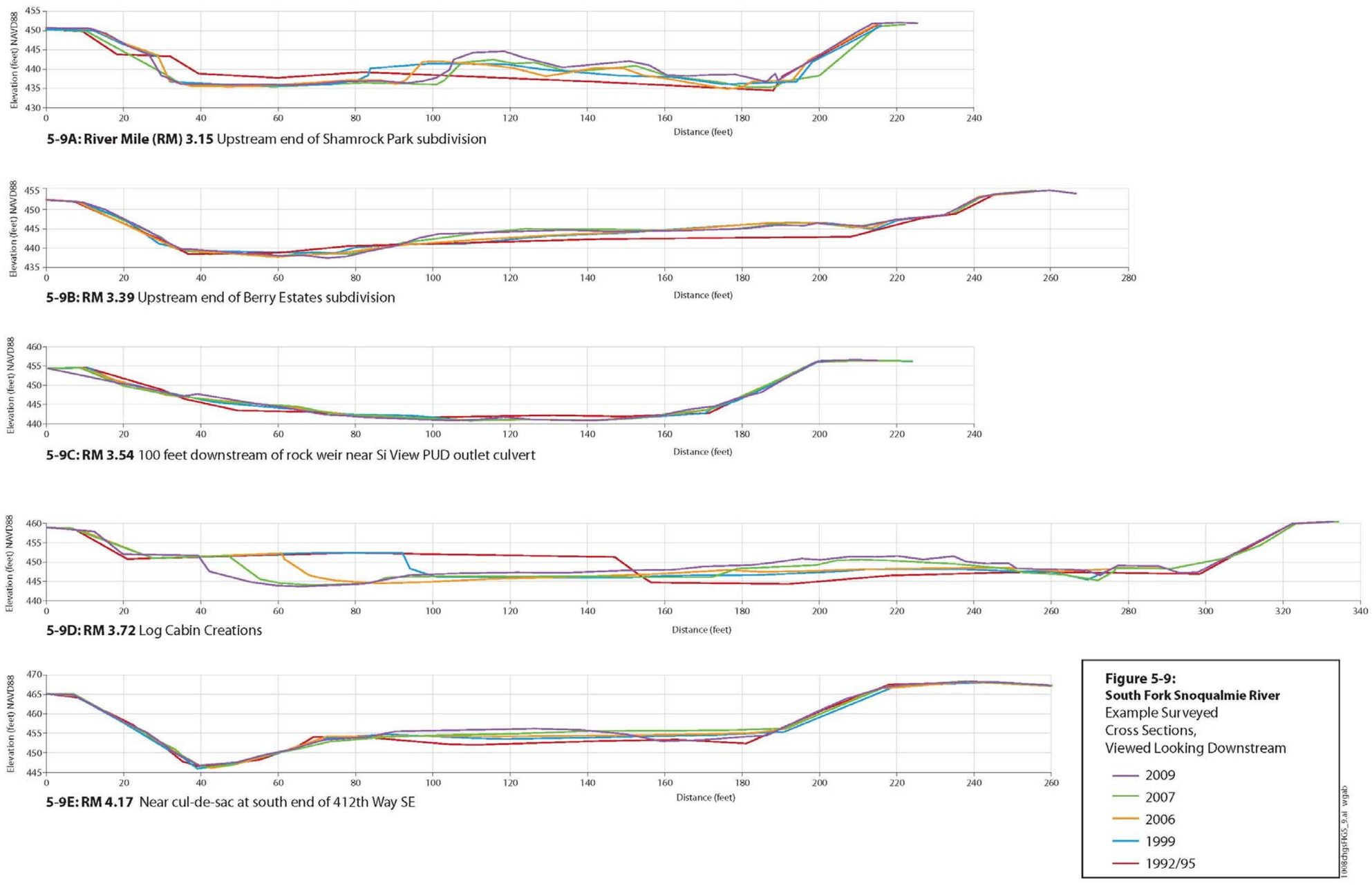



**Figure 5-9**: South Fork Snoqualmie River example surveyed cross sections showing channel topography in 1992/95, 1999, 2006, 2007 and 2009

**Table 5-4: Estimated sediment deposition in the South Fork Snoqualmie River study reach**

| Time Period | Estimated Volume of Sediment Deposition (cubic yards) | Estimated Average Rate of Sediment Deposition (cu yds/year) |
|---|---|---|
| 1992/95 to 1999 | 20,400 | 2,900 |
| 1999 to 2006 | 1,600 | 200 |
| 2006 to 2007 | 6,600 | 6,600 |
| 2007 to 2009 | 17,500 | 8,800 |
| **TOTAL (1992/95 to 2009)** | 46,100 | 2,700 |

The calculated sediment deposition volumes and rates in Table 5-4 illustrate the variability that can occur in sediment movement and deposition during different periods, where variations by orders of magnitude are not uncommon (Kondolf and Matthews 1993). These reachwide values are compared to values from previous studies for this same study reach, below.

#### 5.3.3.2 Longitudinal profiles

The longitudinal profiles of thalweg elevations through the study reach for the five timeframes focused on in this study, plus a few others since circa 1990, are plotted in Figure 5-10. The change in thalweg elevation at each cross section relative to 1992/95 is plotted in Figure 5-11. Based on this information, the following observations can be made. There appears to be ongoing downcutting of the thalweg at the North Bend Blvd (Bendigo) Bridge. From the bridge upstream to about RM 3.2 (gravel bar 2), consistent aggradation is apparent. There have been variable changes in thalweg elevations from RM 3.2 to RM 3.54, most of which tended to be positive (aggradational). There is distinct downcutting at RM 3.65. This is the location of a left bank riprap repair project from about 1997, so a scour hole probably developed at its toe. From RM 3.72 upstream to about RM 4.17, there have been variable changes, generally tending negative (degradational). The downcutting of as much as two feet at RM 3.96 is probably associated with the scour hole at the outside bend adjacent to gravel bar 6. Upstream of RM 4.17 there has been variability over the years but the net changes from 1992/95 to 2009 appear to approximate zero or are within one foot (positive or negative) of net zero.

In summary, these data are interpreted to indicate the following for the thalweg in this study area from 1992/95 through 2009. There has been scour at the bridge and thalweg aggradation in the backwater area. The remainder of the downstream part of the study reach has seen variable changes in thalweg elevations with local examples of aggradation. In the upstream part of the study reach, there are two locations of distinct degradation likely due to scour holes along armored toes at outside bends. The remainder of the upstream area has seen variable changes in thalweg elevations with local examples of degradation. Overall, if the local examples of changes that may have been induced by imposed conditions (e.g., scour at the bridge, deposition in the backwater area, and the prominent scour hole adjacent to riprap repair at RM 3.65) are excluded,

the net change in thalweg elevations through the remainder of the study reach for the full study period does not appear to exhibit a significantly aggradational or degradational trend.

#### 5.3.3.3 Sediment changes measured by topographic surfaces

Reachwide changes in the elevation of gravel bar surfaces (for the out-of-water only portion only) and the resulting volumes of erosion and deposition also were estimated by comparison of topographic surfaces using photogrammetric methods.

From March 1995 and December 2006, full study reach:

Topographic surfaces were created from aerial photographs taken in March 1995 and December 2006 and differences in the elevations of gravel bar surface were determined digitally. The results are shown as a map of elevation change in Figure 5-12A and 5-12B. Deposition in this period ranged from maximum heights of to 2.5 to 4 feet (red) and greater than 4 feet (pink), e.g., on gravel bar 6 and gravel bar 4, to more average heights of deposition in the 0.5 to 1.5 foot range (orange) seen on many of the gravel bars. The color white signifies no significant change and light green through blue colors indicate erosion. Occurrence of erosion and deposition on the same gravel bar was common (e.g., gravel bar 4).

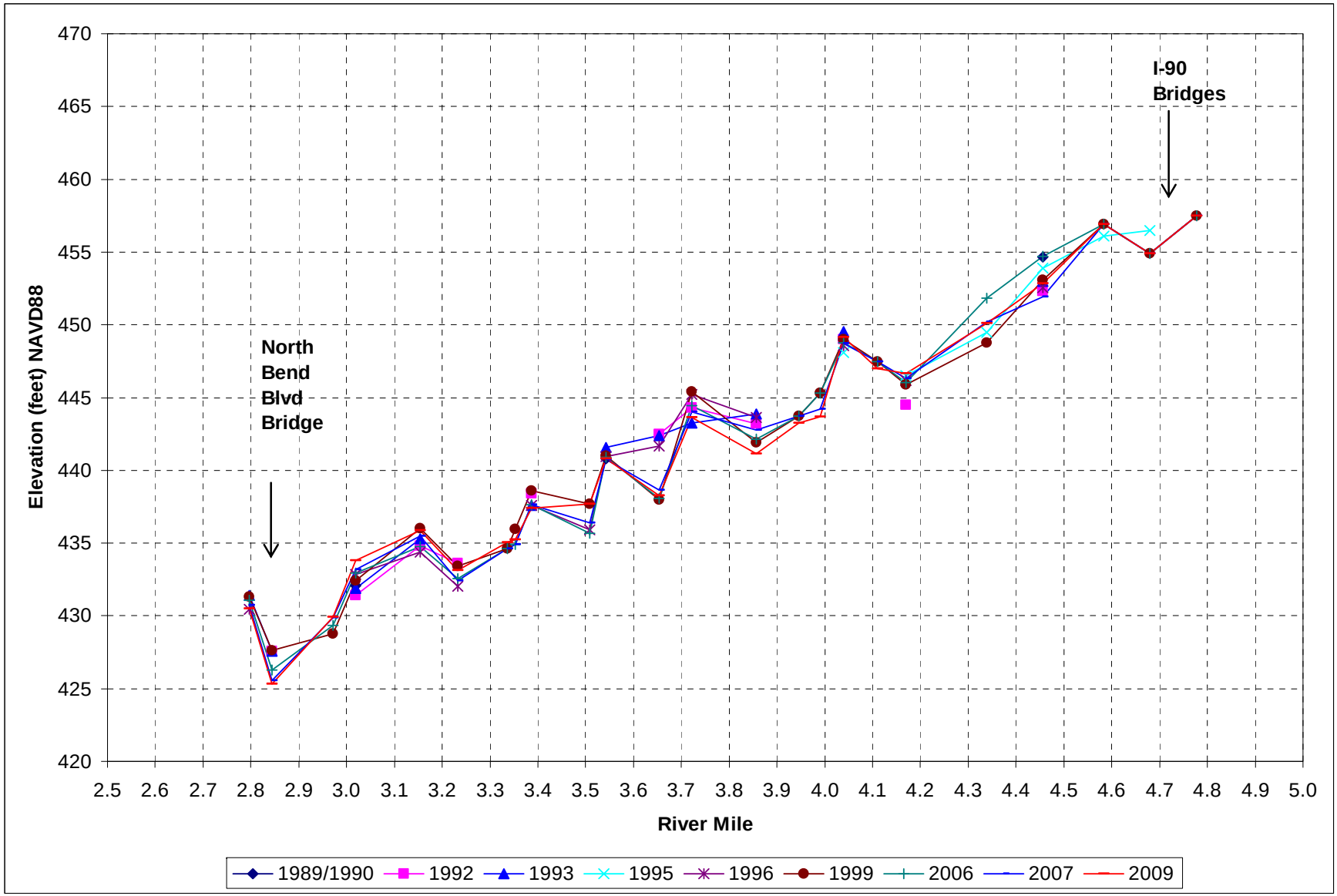



**Figure 5-10: South Fork Snoqualmie River longitudinal profile of thalweg elevations through the study reach**

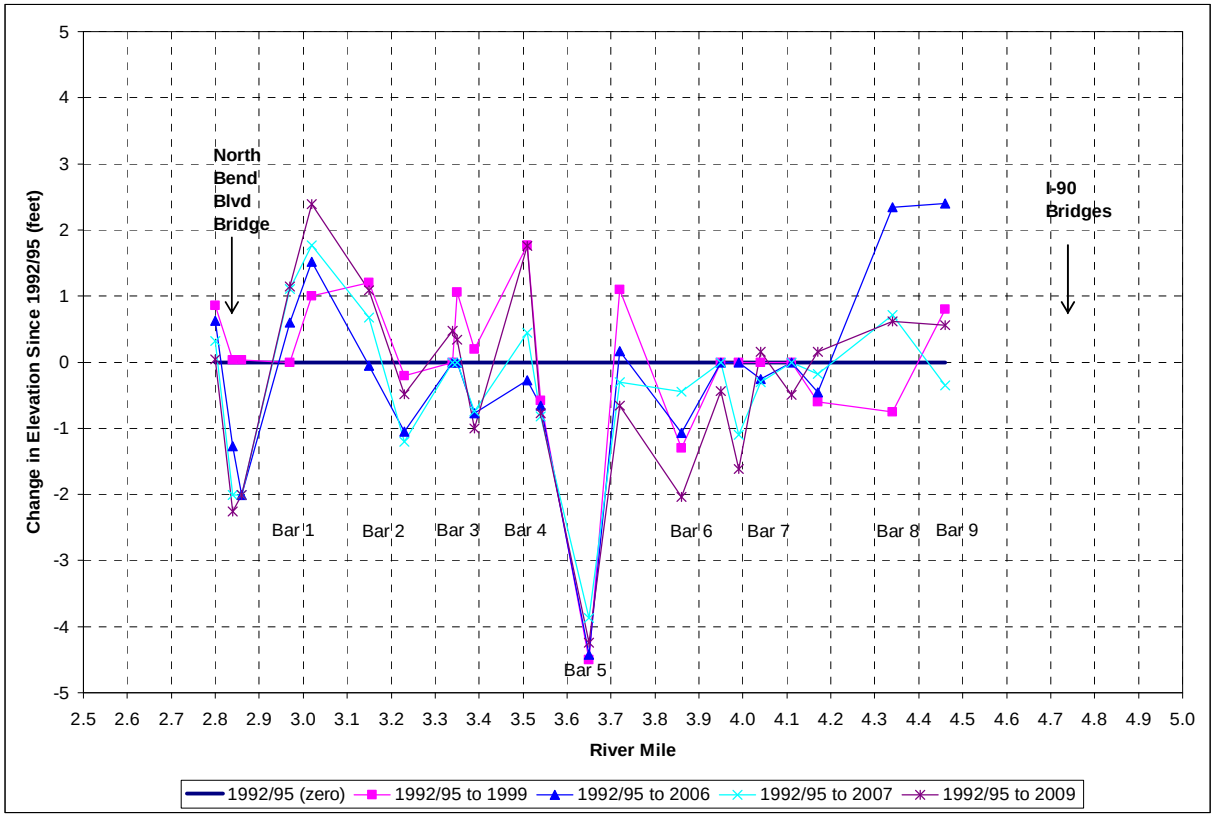



**Figure 5-11: South Fork Snoqualmie River change in thalweg elevations relative to 1992/95**

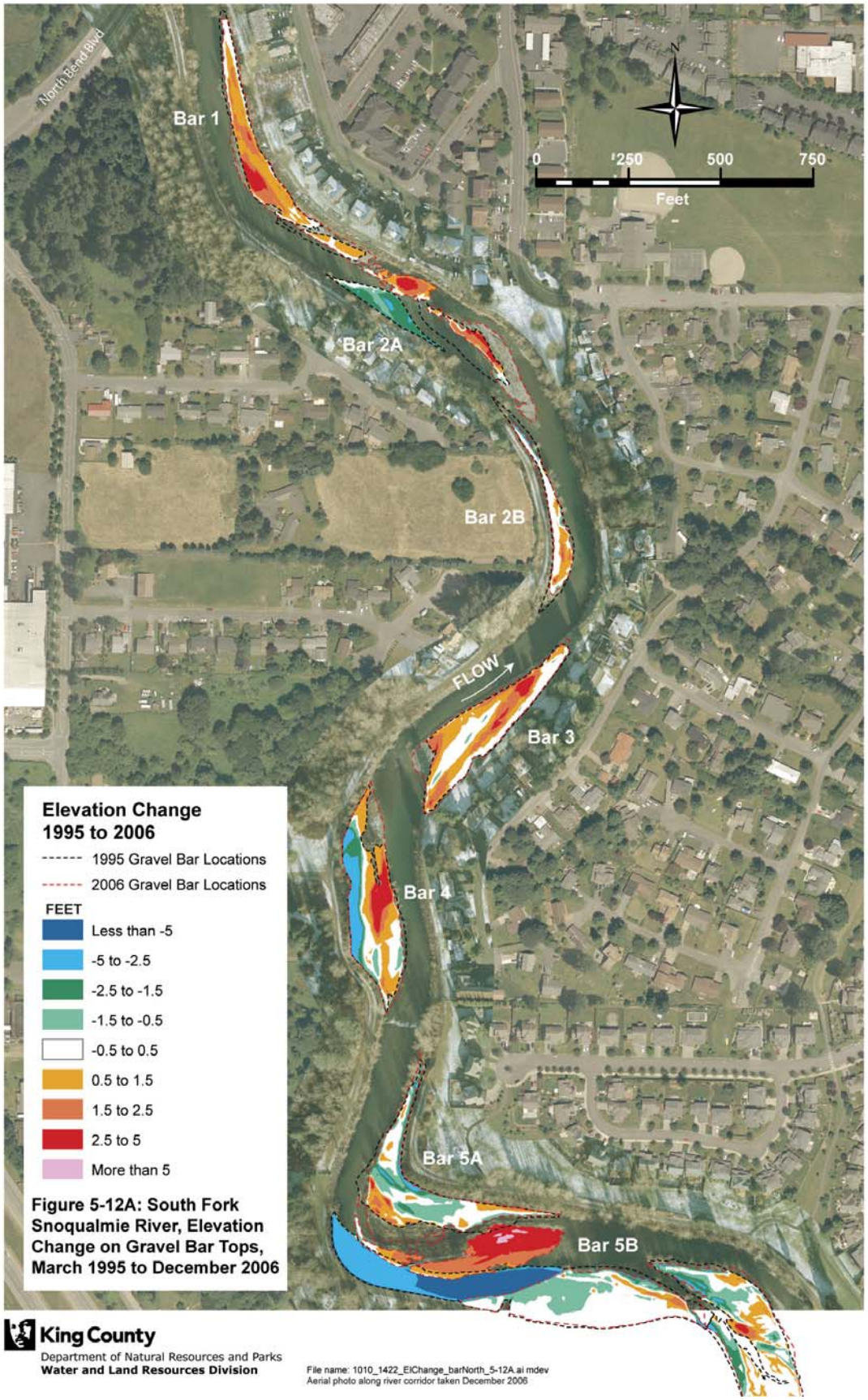



**Figure 5-12A: South Fork Snoqualmie River, Elevation Change on Gravel Bar Tops, March 1995 to December 2006**

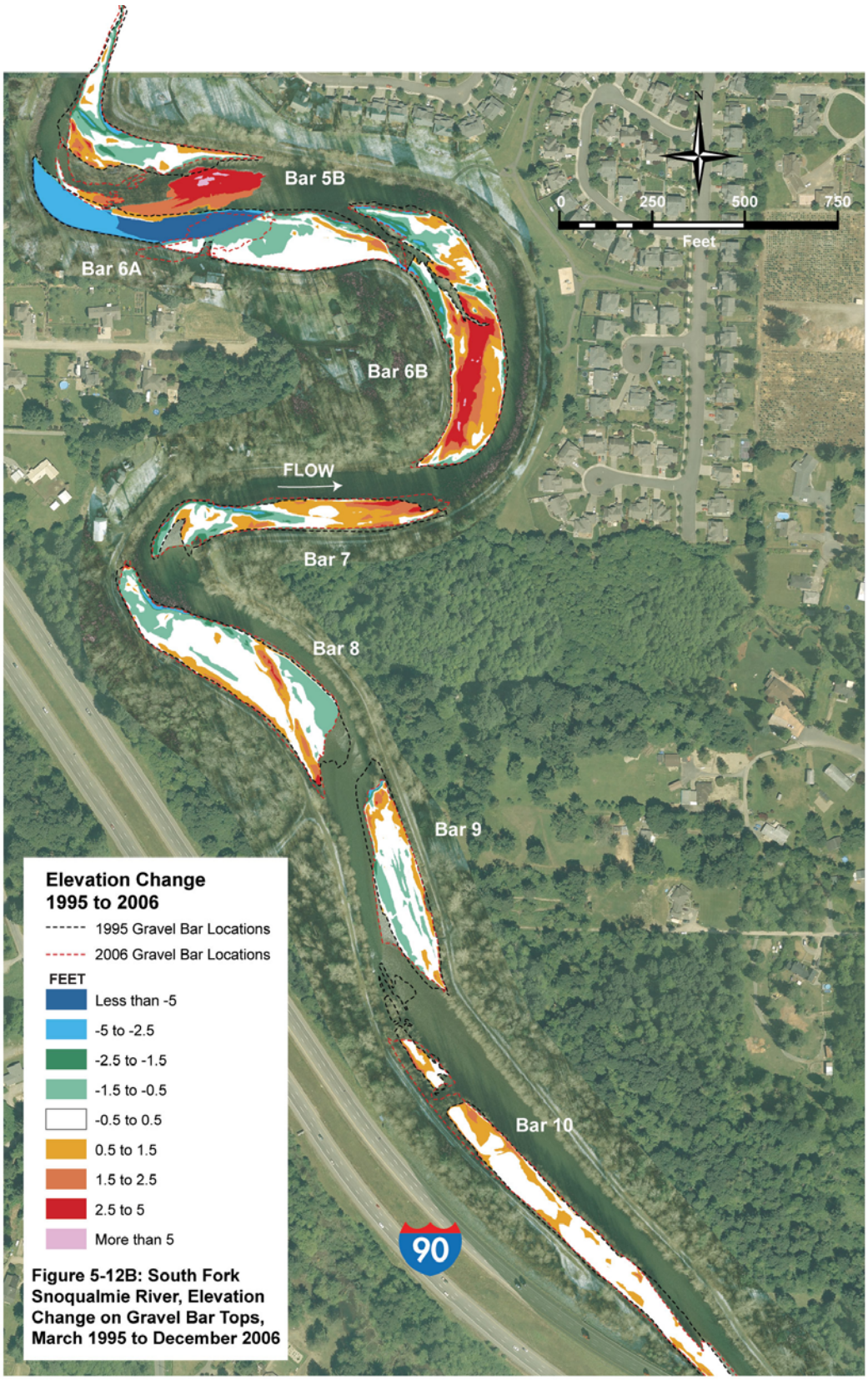



**Figure 5-12B: South Fork Snoqualmie River, Elevation Change on Gravel Bar Tops, March 1995 to December 2006**

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

File name: 1010_1422_ElChange_barSouth_5-12B.ai mdev
Aerial photo along river corridor taken December 2006

In places where the 1995 surface was eroded away entirely as of December 2006, or where a new surface had been deposited as of December 2006 that did not exist in 1995, assumptions were made about the elevation of the (earlier or later) changed surface based on surrounding or adjacent surfaces in order to produce the map of elevation changes. Examples of such changes include the deposition of gravel bar 5B and the erosion of gravel bars 2A and 6A during this period.

Calculated changes in volume between the two topographic surfaces indicate that there was a net reachwide deposition of approximately 28,300 cubic yards for this period, which corresponds to an average annual deposition of about 2,600 cubic yards/year. This out-of-water average annual deposition rate calculated by comparison of topographic surfaces from March 1995 to December 2006 is essentially identical to the average annual deposition rate (2,700 cubic yards/ year) calculated by cross section analysis for the full 1992/95-2009 study period. Information from cross section surveys suggests that the long-term reachwide change in thalweg elevations may exhibit no obvious net trend (Section 5.3.3.2). To the extent that there has been little net reachwide change in underwater portions of the channel, the results of the topographic surface analysis appears to corroborate the long-term average annual deposition rate of about 2,700 cubic yards/ year calculated from cross section surveys.

From September 2006 to December 2006 at gravel bar 3 only:

A similar comparison of topographic surfaces was made at gravel bar 3 (RM 3.35) only (adjacent to the Berry Estates), using sufficiently dense ground survey data from September 2006 and the photogrammetric data from December 2006 to produce a map of elevation changes on gravel bar 3 during this three month period (Figure 5-13). It is assumed that the elevation changes depicted by Figure 5-13 show the effects of the November 2006 flood event at this particular gravel bar. Deposition occurred in a swath along the river side of the gravel bar (orange, red, pink**)**, to a height of 0.5 feet to more than 3.5 feet. There is also an area of erosion in the landward part of the gravel bar (green and blue), with 0.5 feet to 1.5 feet and greater depths of erosion. Other parts of the bar had little change (white). An estimated net volume of about 700 cubic yards deposited on this gravel bar during this period, which likely all resulted from the November 2006 flood.

From December 2006 to February 2009, full study reach:

Aerial imagery collected in February 2009 again produced a topographic surface of the South Fork Snoqualmie River gravel bars in this study area on that date. The changes in elevation of the out-of-water gravel bar surfaces from December 2006 to February 2009 are shown in Figure 5-14, using the same color scheme as in previous figures. Portions of gravel bar 4 and gravel bar 6 appear to exhibit the greatest areas of sediment accumulation (orange and red colors), with minor to moderate sedimentation (white and yellow colors) indicated on most of the gravel bars.

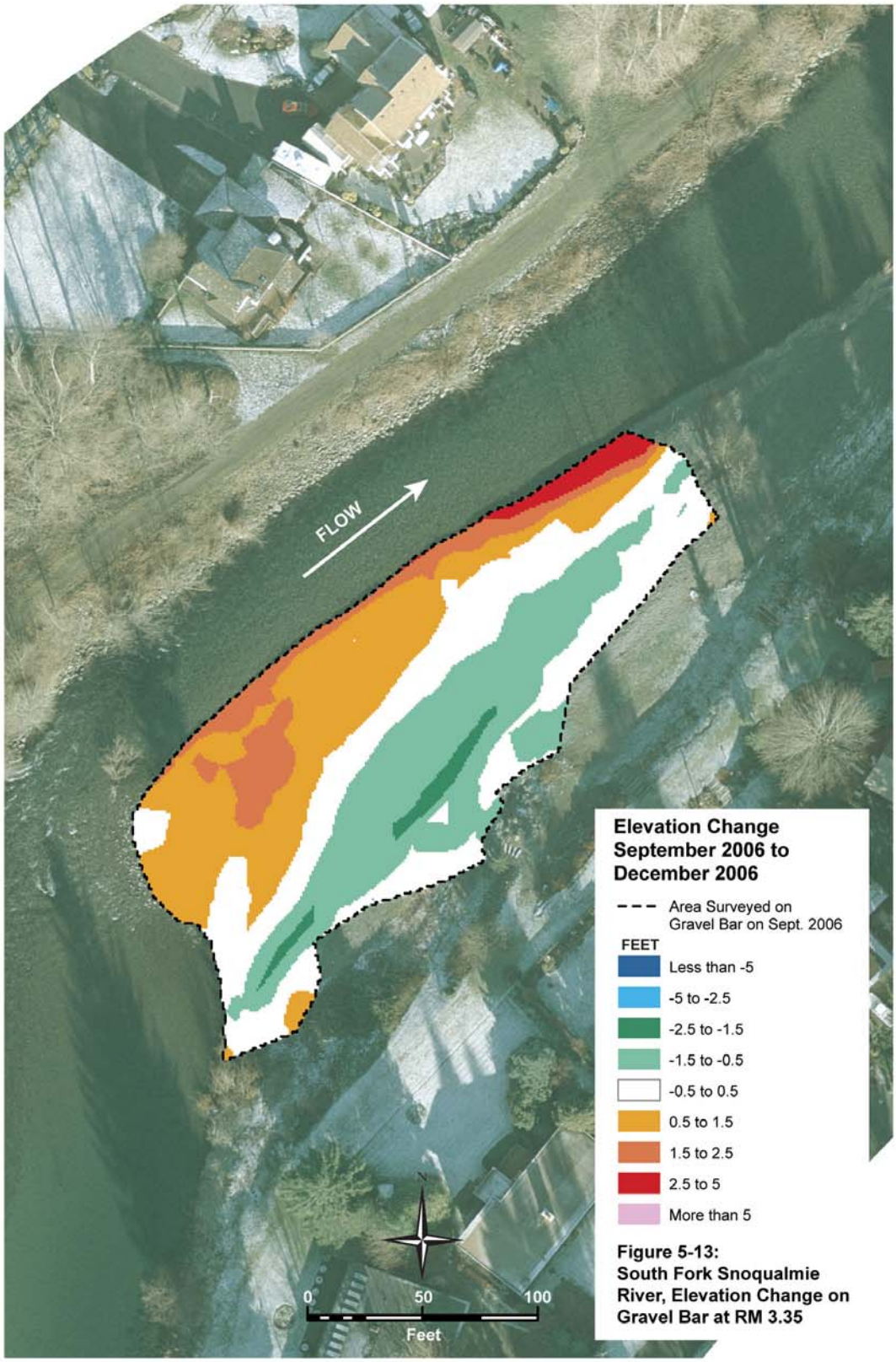



**Figure 5-13: South Fork Snoqualmie River, Elevation Change on Gravel Bar at RM 3.35**

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

File name: 1010_1422_ElChange_5-13A.ai mdev
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Aerial photo along river corridor taken December 2006

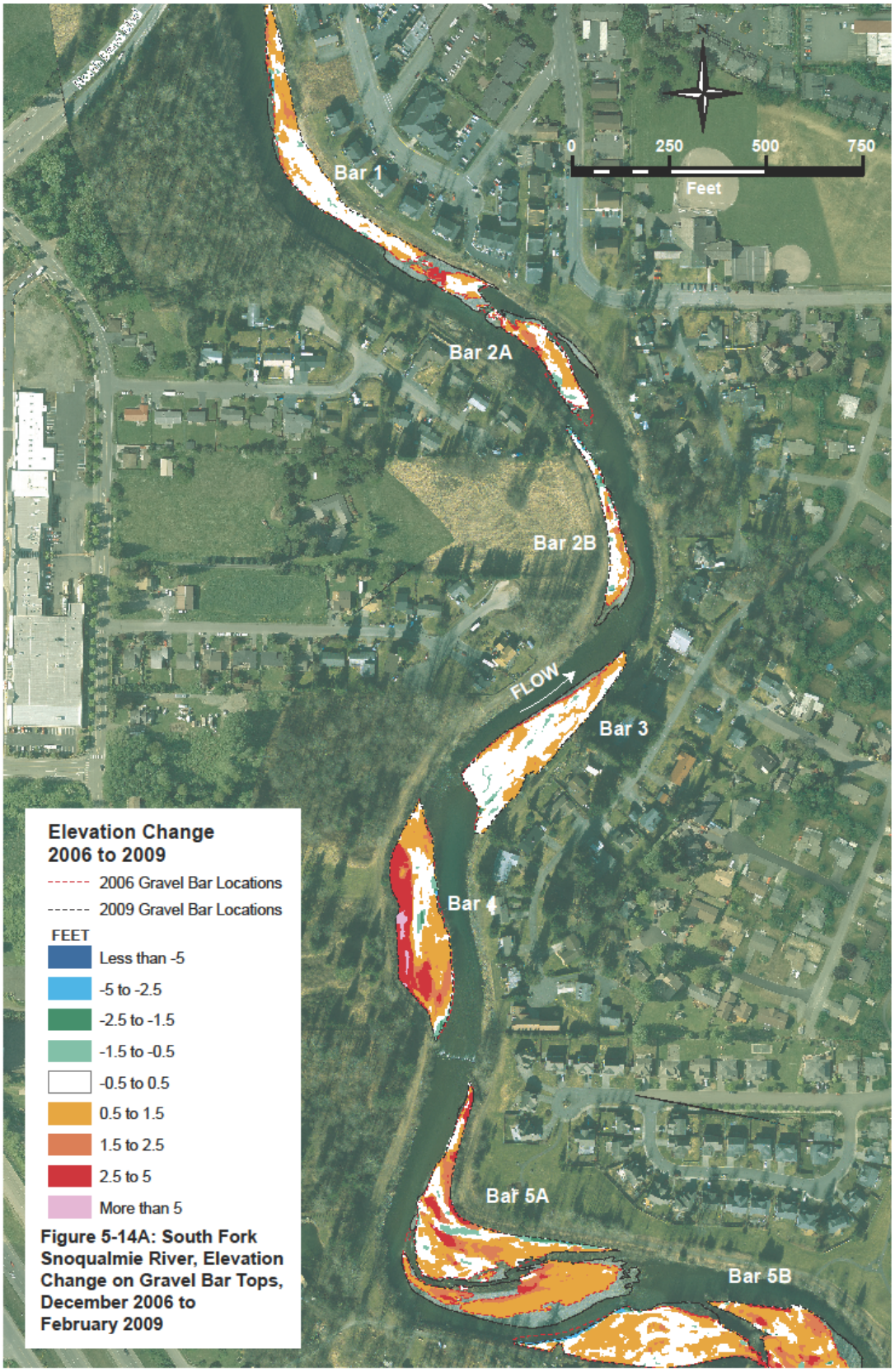


**Figure 5-14A: South Fork Snoqualmie River, Elevation Change on Gravel Bar Tops, December 2006 to February 2009**

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

File name: 1010_1422_ElChange_5-14A.al mdev
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Aerial photo along river corridor taken February 2009

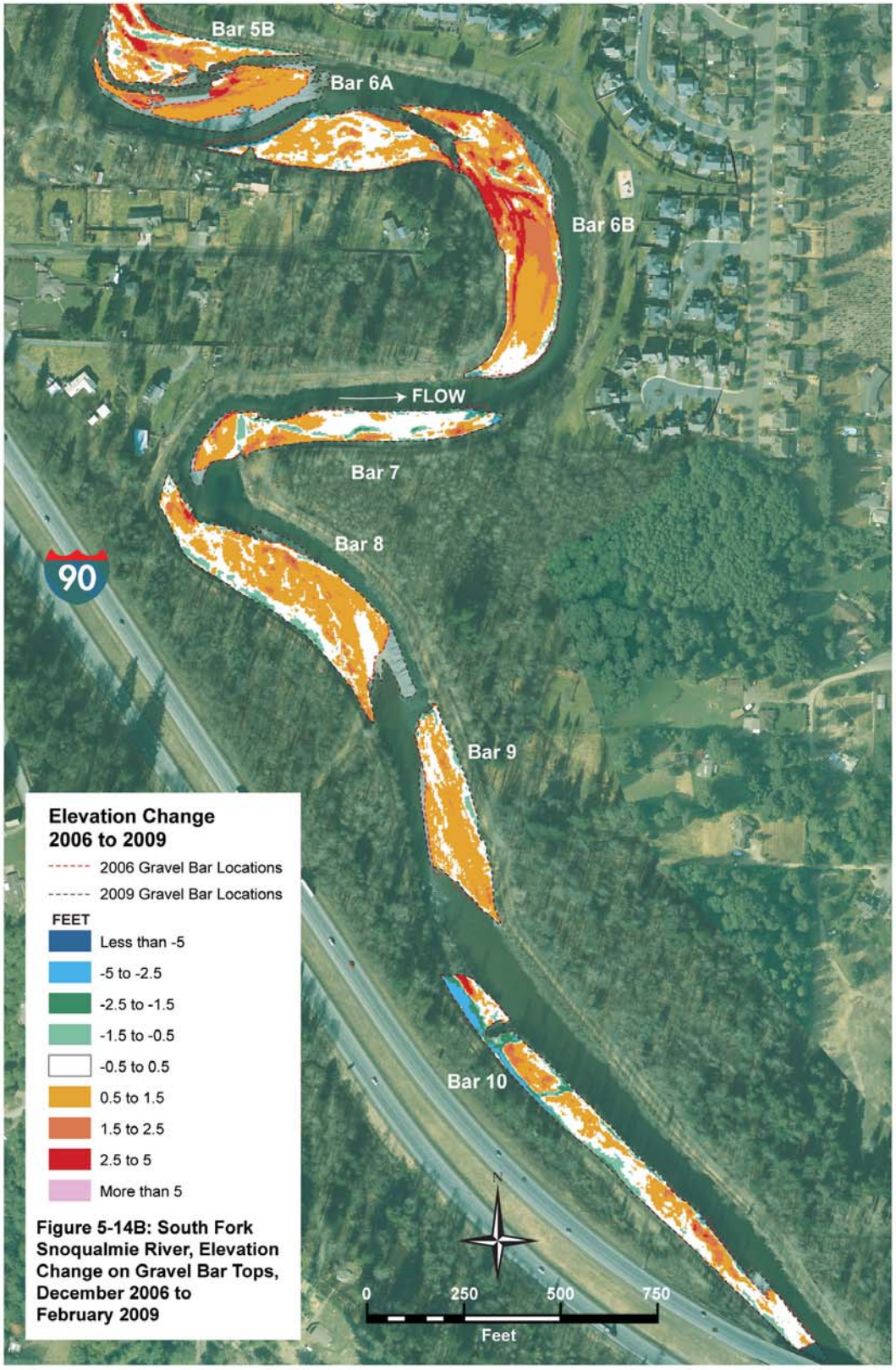


**Figure 5-14B: South Fork Snoqualmie River, Elevation Change on Gravel Bar Tops, December 2006 to February 2009**

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

File name: 1010_1422_ElChange_5-14B.ai mdev
10044\MapDocs\Elev_difference.mxd KR
Aerial photo along river corridor taken February 2009

The calculated change in volume between the two topographic surfaces is 20,700 cubic yards. If it is assumed that the period represented between these two aerial images is two years (because there were no significant floods during the winter of 2006-07 after December 2006), then the deposition is higher than, but similar to, the values calculated by comparison of cross sections (17,500 cu yd deposition; 8,800 cu yd/year rate) for this same interval. The discrepancy suggests that there is bar top aggradation not captured by the cross section analysis, assuming little net change underwater. Regardless, the sedimentation values calculated by the two methods are within about 15 percent, which generally would be considered consistent results in sediment budgeting calculations.

#### 5.3.3.4 Comparison to findings of previous studies

Previous studies of the South Fork Snoqualmie River estimate the average annual sediment deposition rate in this study reach at less than 1,000 up to about 6,000 cubic yards/year (Table 5-5). A range this large is not uncommon when characterizing sediment transport and deposition (e.g., Gomez and Church 1989). Some of these previous studies also estimate the annual bedload flux and the total (i.e., suspended and bedload) annual sediment flux along with annual deposition volumes.

The previous studies used a variety of analytical methods, including bedload transport estimated as a percentage of suspended load (Nelson 1971), a sediment budget (Dunne 1984), bedload transport modeling (Booth et al. 1991; Shannon & Wilson 1993), and estimates of the gravel excavated in the mid 1960s to construct the levees, one assuming that the gravel bars were scalped and one assuming that the river was dredged (Shannon & Wilson 1993). Most volumes and rates of deposition calculated in this study are within the range of estimates from previous studies, though values in this study during individual time intervals match or exceed the high end of values in previous studies on the South Fork Snoqualmie River. Calculations from this study also are consistent with, though toward the higher end of, regional estimates of sediment production observed in other drainage basins of this size in this region (Nelson 1971). For comparison, the average annual rate of deposition in the 1.7 mile leveed reach of the lower Tolt River from 1994 to 2000 was about 3,800 cubic yards per year (Parametrix 2001).

**Table 5-5: Previous studies; values for bedload flux and deposition in South Fork Snoqualmie River study reach**

| Study | Bedload flux into reach (cu yd/year) | Bedload deposition in study reach (cu yd/year) | Method; assumptions |
|---|---|---|---|
| Nelson (1971) | 1,900 to 4,600 | 950 to 2,300 | Nelson reported suspended sediment flux. Assume bedload flux = 5% to 12% of suspended sediment; assume 50% of bedload flux deposits. |
| Dunne (1984) | 1,450 | 300 | Sediment budget. |
| Booth et al. (1991) | 4,400 transport capacity | 2,000 | Bedload transport model. |
| Shannon & Wilson (1993) | | 700 to 3,200 | Bedload transport model; average to high estimate for average annual rate. |
| Shannon & Wilson (1993) | | 4,100 to 6,200 | Estimate of gravel volumes excavated to build levees (low value assumes scalped bars; high value assumes channel dredged). |

### 5.3.3.5 Reachwide estimated average annual deposition rates

Based on the variety of values in previous studies and this study, an annual deposition volume for "average" years in this study reach might range from less than 1,000 cubic yards to over 3,000 cubic yards. Such a range would reflect the variability inherent in reachwide calculations, the actual physical variation in erosion and deposition observed within this study reach, plus the natural year to year variability in sediment transport and deposition.

For the purposes of this study, it is assumed that the reachwide deposition average annual rate is 2,700 cubic yards/year, though a high variability also should be assumed. This estimated average annual rate is consistent with the longer term 1992/95 to 2009 annual deposition rate calculated for this reach by various methods and with the range of estimates provided by previous studies. An annual deposition value of 6,000 to 9,000 cubic yards/year is assumed to represent a high rate of deposition that could occur during as a result of a major flood or an entire winter season with high flows, as witnessed in recent study intervals. With basin sediment yield elevated above historic rates (Section 5.3.1), the present estimated annual deposition rate for this study reach may also be elevated above historic rates.

### 5.3.3.6 Spatial patterns and temporal trends in sediment deposition

Variability in erosion and deposition is evident within the study reach as well as on the reach-scale, described above. The change in cross sectional area through a time interval times the river distance between cross sections provides the change in sediment storage in that length of channel in the period between successive cross section surveys. A plot of the change in sediment storage from cross section to cross section during each individual study period depicts the spatial patterns and temporal trends in sediment deposition or erosion within this study reach (Figure 5-15). The "change in sediment storage" is identical to the volume of deposition or erosion if there

was no gravel extraction during the period (see Section 2.1). Because there was some gravel extraction during the period 1992/95 to 1999 (an estimated total 7,000 cubic yards at gravel bar 6), the change in sediment storage volume in Figure 5-15 is somewhat less than the actual deposition/erosion that occurred during that period. Even so, Figure 5-15 suggests certain spatial patterns of sediment erosion or deposition in this reach through the full study period. There has been minor to moderate deposition or erosion in the downstream area (RM 2.85 through RM 3.23; gravel bars 1 and 2); moderate to high changes, whether depositional or erosional, in the middle part of the study reach (RM 3.34 through RM 3.99; gravel bars 3-6); and moderate to locally high deposition in the upstream part of the study reach (RM 4.04 to RM 4.46; gravel bars 7-9).

The change in cross-sectional area at each cross section, divided by channel width, provides a measure of vertical change in sediment level at the location during that period. This value is normalized to an annual rate of change in elevation at each cross section in Figure 5-16.

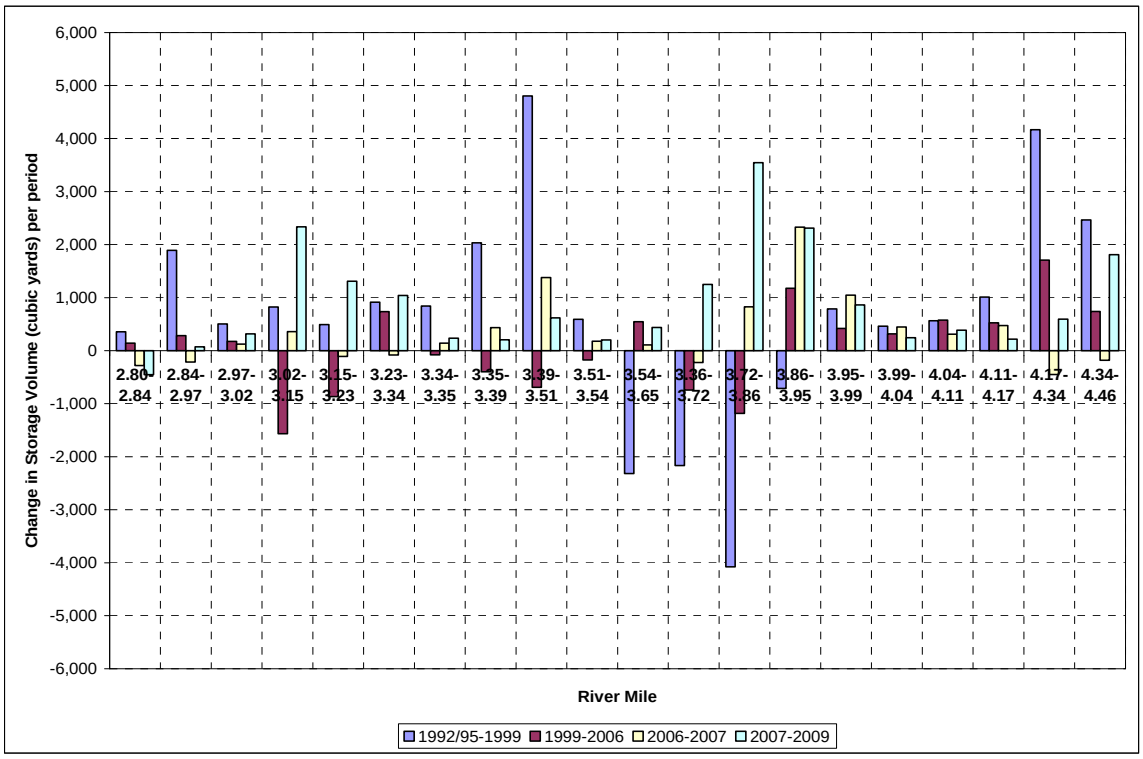


**Figure 5-15: South Fork Snoqualmie River change in sediment storage volume from cross section to cross section, by individual study period**

Both Figures 5-15 and 5-16 suggest the following temporal trends in this study reach: moderate to high changes in sediment levels during 1992/95-1999, negligible changes in 1999-2006, and moderate to high changes during 2006-2007 and 2007-2009.

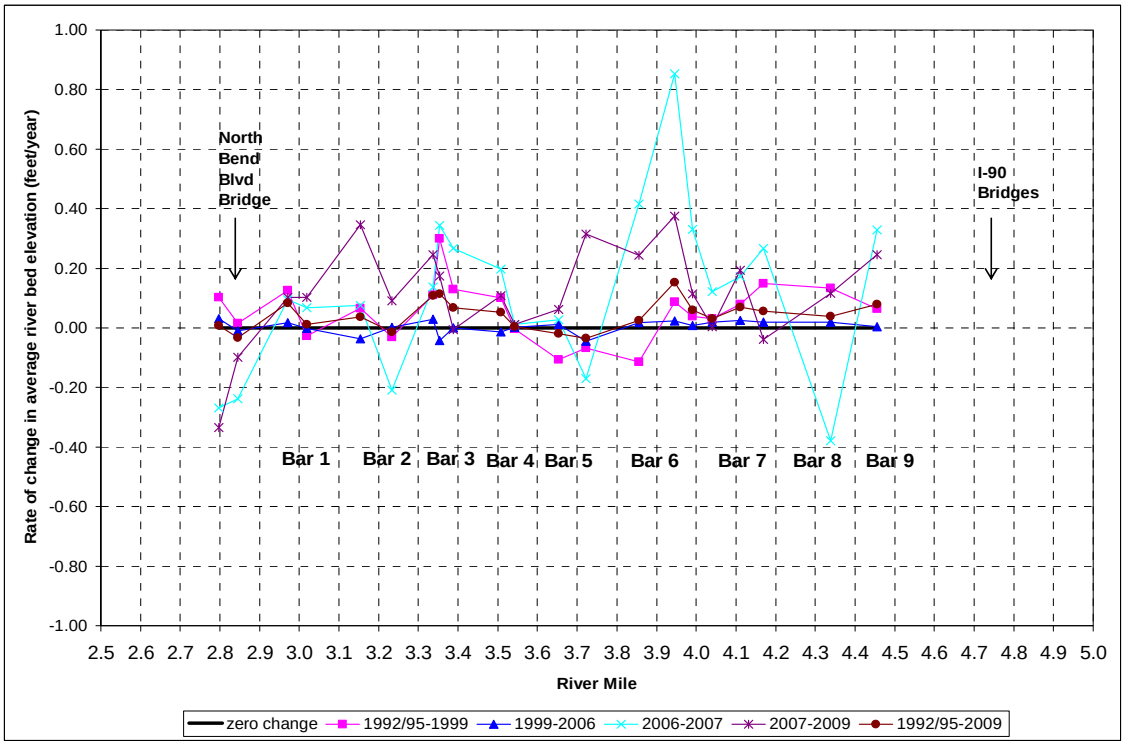


**Figure 5-16: South Fork Snoqualmie River rate of change of average riverbed elevation at each cross section**

An average annual reachwide rate of change in bed elevation was calculated as the mean of the vertical change in sediment levels at all 21 cross sections in this study. The reachwide average annual rate values in Table 5-6 are averages of the 21 points plotted for each year in Figure 5-16. Although this single, reachwide value greatly simplifies the actual spatial variability of deposition, this calculation allows comparison of reachwide conditions from period to period. The South Fork Snoqualmie River average changes in bed elevation have varied dramatically through the individual time periods in this study (Table 5-6), from as little as essentially zero feet per year in 1999 to 2006 to a tenth of a foot per year in the two time intervals since 2006.

**Table 5-6: South Fork Snoqualmie River, reachwide average rates of change in riverbed elevations**

| Period | Reachwide average rate of change in bed elevation (ft/yr) | Elevation change after 10 years (feet) | Time to deposit one foot (years) |
|---|---|---|---|
| 1992/95 to 1999 | 0.06 | 0.6 | 17 |
| 1999 to 2006 | 0.006 | 0.06 | 170 |
| 2006 to 2007 | 0.1 | 1.0 | 10 |
| 2007 to 2009 | 0.1 | 1.0 | 10 |
| Full study period 1992/95 to 2009 | 0.04 | 0.4 | 25 |

For comparison to another local river, the average annual rate of change in riverbed elevation calculated for the 1.7 mile leveed reach of the lower Tolt River from 1994 to 2000 was 0.7 foot per decade (Parametrix 2001).

Most of the other factors that affect deposition rates in this reach have been relatively constant throughout the study period (e.g., channel gradient, channel width, sediment supply in excess of transport capacity [Section 5.3.1], confinement by the levees and North Bend Blvd Bridge); therefore the primary factor affecting the variability of reach-scale deposition among the different individual periods is the flows that occurred in each period.

#### 5.3.3.7 Effect of flow on sediment movement

Initiation of motion:

Boundary shear stress is the erosive pressure that flowing water exerts on the sediment of the riverbed. The HEC-RAS hydraulic computer model calculates a channel-averaged boundary shear stress at each cross section (which does not account for variations within that cross section) as the product of water depth, water slope, and the unit weight of water. Critical shear stress is the threshold boundary shear stress at which movement of sediment is initiated. The critical shear stress calculation uses representative sediment particle sizes to characterize the channel in question, so the calculated threshold of motion applies to those particle size(s); smaller particles may be mobilized at lesser flows.

Critical shear was calculated through the study reach using the Andrews equation (1983) plus substrate data from previous studies of the South Fork Snoqualmie River (Booth et al. 1991; Shannon & Wilson 1993). Although the channel-averaged boundary shear is calculated by HEC-RAS at each cross section, there were only three critical shear values calculated for this study reach because the substrate data necessary for critical shear calculation were available only specific to the three subreaches identified by Shannon & Wilson (1993). With critical shear calculated at 1.0 lbs/sqft in the downstream subreach (RM 2.85 to RM 3.23), 0.72 lbs/sqft in the middle subreach (RM 3.23 to RM 4.17), and 1.22 lbs/sqft in the upstream subreach (RM 4.17 to RM 4.46), initiation of motion is indicated to occur at many cross sections during a flow of about 7400 cfs (a 5-year flood). Flood flows of 8,000 to 9,000 cfs (about a 7-year to 10-year flood) and greater would have the coarse sediment mobilized as bedload at most cross sections throughout the study reach.

Bedload transport modeling:

Various empirically derived bedload transport equations calculate the bedload transport capacity of a gravel-bedded river channel, some of which have been applied to the South Fork Snoqualmie River. Booth et al. (1991) created one bedload transport model based on the Bagnold equation (1980) for the South Fork Snoqualmie River and the mainstem Snoqualmie. That model included one river reach (Reach 23) that is very similar in length and location to the present study reach. The model calculates these average annual amounts per average year (also in Table 5-5): an influx of coarse sediment into this reach of 6,100 metric tons (4,400 cubic yards), a transport capacity through and amount exiting this reach of 3,300 metric tons (2,300 cubic yards), and deposition within the reach of 2,800 metric tons (2,000 cubic yards).

Shannon & Wilson (1993) also created a bedload transport model based on the Bagnold equation (1980) that calculates bedload transport capacity for what is essentially this same South Fork Snoqualmie River study reach, using the three subreaches identified earlier. A long-term average deposition rate was calculated as approximately 700 cubic yards to 3,200 cubic yards per average year (in their subreaches 1 and 2, which run from RM 2.84 to RM 4.17). Deposition during a single large flood event (November 1990, approximately a 20-year flood) was calculated as 1,140 cubic yards (Shannon & Wilson 1993). The influence of flow discharge on sediment movement and deposition can be seen in these calculated values, where deposition during a single large flood falls within the range of deposition volumes for an average year.

Existing sediment deposition data and recent flood events:

A comparison of reach-scale volumes of deposition (Table 5-4) to the South Fork Snoqualmie River flow record (Figure 5-3) during the four individual study intervals in this study makes use of real data regarding the relation between flow and sediment movement in this reach. Reachwide sediment deposition averaged 2,900 cubic yards/year from1992/95 to 1999, a period that included the November 1995 (10,000 cfs) and February 1996 (10,300 cfs) floods (both close to a 20-year event). Other than those flows, the peak annual flow did not exceed 7,400 cfs (5-year flood) in that period. There was minimal reachwide sediment deposition from 1999 to 2006, a period in which the two largest floods were in the 8,000 cfs range (7-year flood). There was a moderately large volume of reachwide deposition from 2006 to 2007, a period during which the 13,600 cfs (65-year) flood of record occurred. There was a large volume deposited reachwide during 2007-2009 when two flows occurred in about the 10,000 cfs to 11,600 cfs range (November 2008, January 2009).

The information available from different sources and methods suggests the following relation between flow discharge and sediment movement and deposition. When flows remain below a threshold of approximately 7,400 cfs (5-year flood), negligible movement and deposition can be expected. Flows in the range of 11,000 cfs (about a 20-year flood) likely will result in measureable reachwide coarse sediment movement and deposition, deposition that may be on the order of the estimated average annual deposition rate. Much larger flows or a combination of two or more moderate flows likely will result in much larger reachwide volumes of sediment movement and deposition.

In addition to peak flow magnitude, the duration of flow above these thresholds of motion can be equally important because of the significant sediment transport that occurs at moderate to higher flows. For example, the November 2006 flood of record (13,600 cfs) equaled or exceeded 12,000 cfs for eight hours, whereas both the November 2008 and January 2009 flows did not reach or exceed that flow level. However, the November 2008 and January 2009 floods (with peak discharges of 9,900 cfs and 11,600 cfs) had a combined duration of 23 more hours of flow in the range of 7,000 to 12,000 cfs than did the November 2006 flood event. The reachwide deposition volume during the 2007-2009 period is almost triple that of the volume of the 2006-2007 period. A more specific relation between flow and deposition could be established based on a sediment sampling regimen or a higher resolution sediment transport model than those in previous studies, but reasonable management decisions can be made without such additional efforts**.**

## 5.4 Hydraulic modeling of existing conditions

The existing hydraulic computer model prepared for the South Fork Snoqualmie River Flood Insurance Study (FEMA 2005) is used here to characterize the effect of channel changes on flood water surface elevations. The same surveyed cross sections that were used to monitor changes in sediment levels are used in this section to hydraulically model water surfaces in 1992/95, 1999, 2006, 2007 and 2009 and describe changes in modeled water surface elevations for the periods bracketed by each year (i.e., 1992/95 to 1999, 1999 to 2006, 2006 to 2007, 2007 to 2009, and in summation, 1992/95 to 2009).

Based on the hydraulic modeling results presented here, plus historical occurrences of overbank flows, there are two parts of the overall study area within which there appear to have generally distinct flooding characteristics: a downstream part from North Bend Blvd (Bendigo) Bridge to upstream of gravel bar 4 (RM 2.85 to about RM 3.54), and an upstream part from gravel bar 5 through gravel bar 9 (RM 3.65 to RM 4.46). See Figure 5-4 for river miles and gravel bar numbers. These two parts of the study area are referred to throughout this report. The set of analyzed flows includes the 9,000 cfs (10-year), November 1990 at 10,900 cfs (approx 20-year), 11,700 cfs (30-year), 13,000 cfs (50-year) and the 15,000 cfs (100-year) floods.

Modeled water surface elevations reported herein that are at a higher elevation than the top of bank will be less accurate than water surface elevations that are entirely contained below the top of bank, due to the “Raised Levee” feature used in this hydraulic model (see Section 3.3). Also, the changes in water surface elevations listed in the following tables were calculated by subtracting the water surface elevation in the earlier year from that in the later year. For example, the change in water surface elevation going from 436.5 feet in 2007 to 436.7 feet in 2009 would be 0.2 feet (not -0.2 feet).

Figures that plot HEC-RAS results in this report include the following abbreviations and symbols. “Right Levee” or “Left Levee” refer to the Raised Levee elevation on either bank. In cross section view, the Raised Levee feature appears as a vertical red line extending upward from both the left and right bank levee tops. “ROB and LOB” stand for Right Overbank and Left Overbank, which is the top of the levee prism surface on either bank. The scenario “ExtgCondRL” stands for existing conditions, Raised Levee. “Ground” refers to the riverbed elevation; WS or WSEL refers to the computed Water Surface Elevation.

### 5.4.1 Comparison of hydraulic modeling results for 1992/95 and 1999 channel conditions

Figure 5-17 compares water surface elevations in profile view through the study reach for the 1992/95 and 1999 conditions at a discharge of 13,000 cfs (50-year flood). Figure 5-18 compares water surface elevations in profile view through the study reach for the 1992/95 and 1999 conditions at a discharge of 11,700 cfs (30-year flood). The changes in water surface elevations for the range of analyzed flows going from 1992/95 to 1999 channel conditions are summarized in Table 5-7.

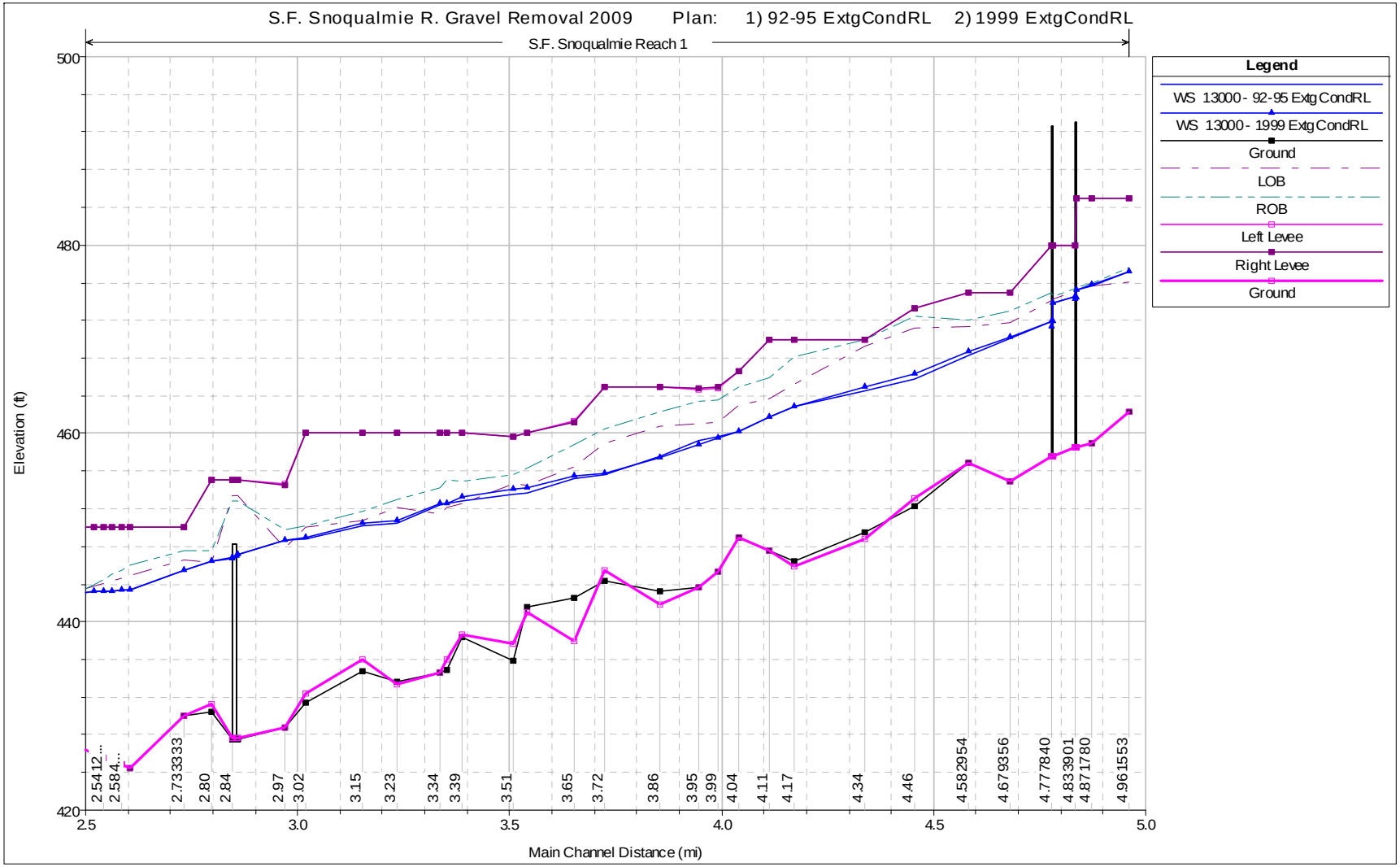


**Figure 5-17: South Fork Snoqualmie River 1992/95 and 1999 channel conditions, profile view of water surface elevations for a discharge of 13,000 cfs (50-year)**

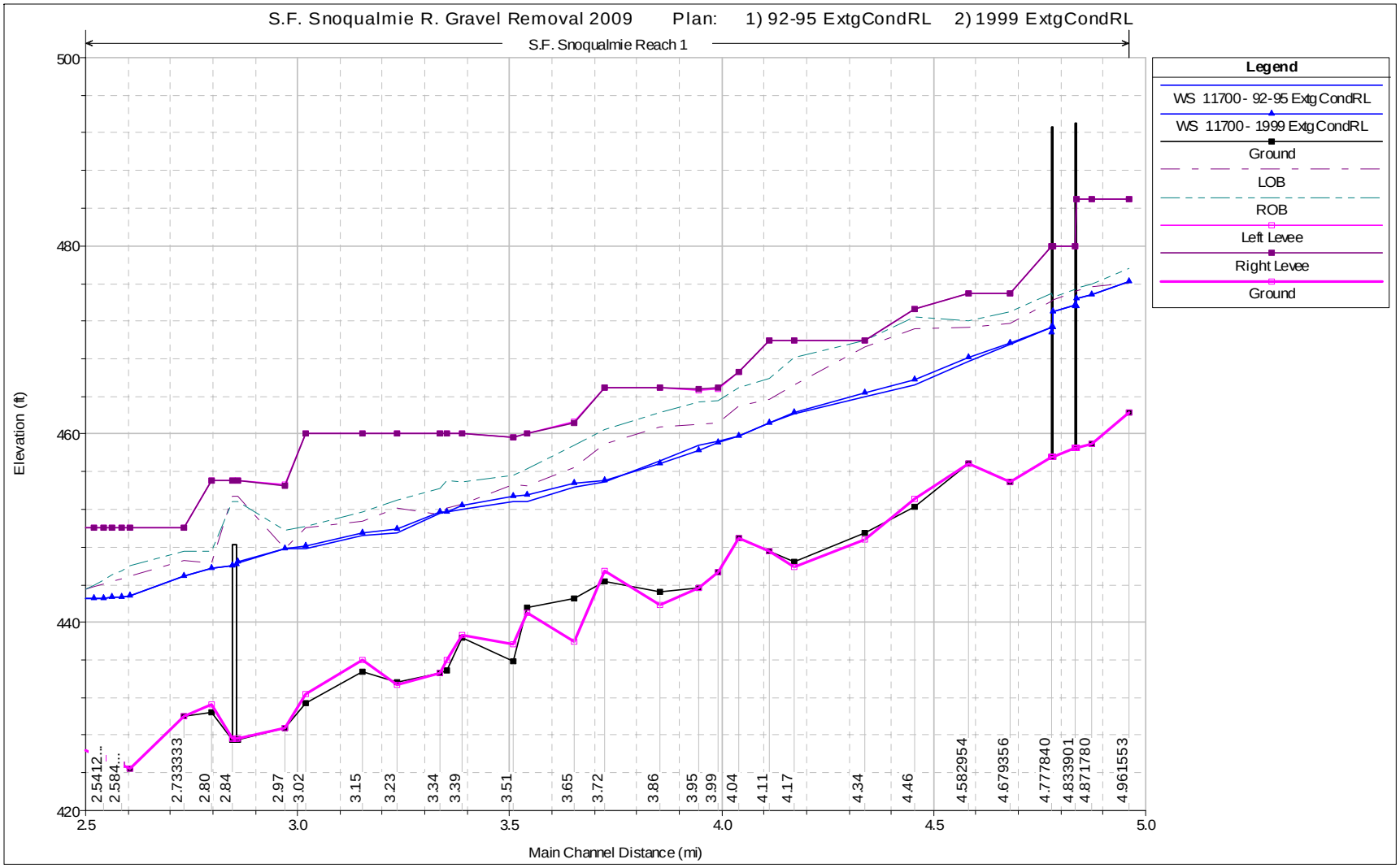


**Figure 5-18: South Fork Snoqualmie River 1992/95 and 1999 channel conditions, profile view of water surface elevations for a discharge of 11,700 cfs (30-year)**

**Table 5-7: Change in water surface elevations (feet) in the South Fork Snoqualmie River from 1992/95 channel conditions to 1999 channel conditions**

| River Station | 9,000 cfs: 10-year Flow (feet) | 10,900 cfs: Nov 1990 Flow (feet) | 11,700 cfs: 30-year Flow (feet) | 13,000 cfs: 50-year Flow (feet) | 15,000 cfs: 100-year Flow (feet) |
|---|---|---|---|---|---|
| | Upstream end of study reach | | | | |
| 4.46 | 0.6 | 0.6 | 0.6 | 0.5 | 0.5 |
| 4.34 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 |
| 4.17 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 |
| 4.11 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| 4.04 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.99 | -0.2 | -0.2 | -0.2 | -0.2 | -0.1 |
| 3.95 | -0.5 | -0.4 | -0.4 | -0.4 | -0.3 |
| 3.86 | -0.5 | -0.4 | -0.3 | -0.2 | -0.1 |
| 3.72 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 |
| 3.65 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| | Approx split between upper and lower parts of study reach | | | | |
| 3.54 | 0.7 | 0.7 | 0.7 | 0.6 | 0.5 |
| 3.51 | 0.7 | 0.6 | 0.6 | 0.5 | 0.4 |
| 3.39 | 0.5 | 0.4 | 0.4 | 0.3 | 0.3 |
| 3.35 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 |
| 3.34 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| 3.23 | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 |
| 3.15 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| 3.02 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| 2.97 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 |
| 2.85 | North Bend Blvd Bridge<br>Downstream end of study reach | | | | |
| **FULL STUDY REACH** | | | | | |
| Maximum | 0.7 | 0.7 | 0.7 | 0.6 | 0.5 |
| Minimum | -0.5 | -0.4 | -0.4 | -0.4 | -0.3 |
| Mean | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| Median | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| Std Dev | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 |
| **UPSTREAM PART OF STUDY REACH** | | | | | |
| Maximum | 0.6 | 0.6 | 0.6 | 0.5 | 0.5 |
| Minimum | -0.5 | -0.4 | -0.4 | -0.4 | -0.3 |
| Mean | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Median | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Std Dev | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 |
| **DOWNSTREAM PART OF STUDY REACH** | | | | | |
| Maximum | 0.7 | 0.7 | 0.7 | 0.6 | 0.5 |
| Minimum | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| Mean | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 |
| Median | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| Std Dev | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |

As shown in Table 5-7 for the upstream part of the study reach (RM 3.65 to RM 4.46), changes in water surface elevations ranged from a minimum of -0.5 feet to a maximum of 0.6 feet, with mean and median changes of 0.1 feet for the analyzed flows. In the downstream part of the study

reach (RM 2.85 to RM 3.54), changes in water surface elevations ranged from a minimum of 0.0 feet to a maximum of 0.7 feet, with mean and median changes ranging from 0.1 feet to 0.3 feet for the analyzed flows. All changes in water surface elevations for all analyzed flows in the downstream part of the study area were increases during this period.

### 5.4.2 Comparison of hydraulic modeling results for 1999 and 2006 channel conditions

Figure 5-19 compares water surface elevations in profile view through the study reach for the 1999 and 2006 conditions at a discharge of 13,000 cfs (50-year flood). Figure 5-20 compares water surface elevations in profile view through the study reach for the 1999 and 2006 conditions at a discharge of 11,700 cfs (30-year). The changes in water surface elevations for the range of analyzed flows going from 1999 to 2006 channel conditions are summarized in Table 5-8.

As shown in Table 5-8 for the upstream part of the study reach, changes in water surface elevations ranged from -0.2 feet to 0.3 feet, with mean and median changes of 0.1 to 0.2 feet over the range of analyzed flows. In the downstream part of the study reach, changes ranged from a minimum of -0.2 feet to a maximum of 0.1 feet, with a mean and median changes ranging from of -0.1 feet to 0.0 feet for the analyzed flows in this period. There were no increases in the downstream part of the study area greater than 0.1 feet for this period. Most of the changes in this downstream area were negative or zero and can be considered to be negligible for this period.

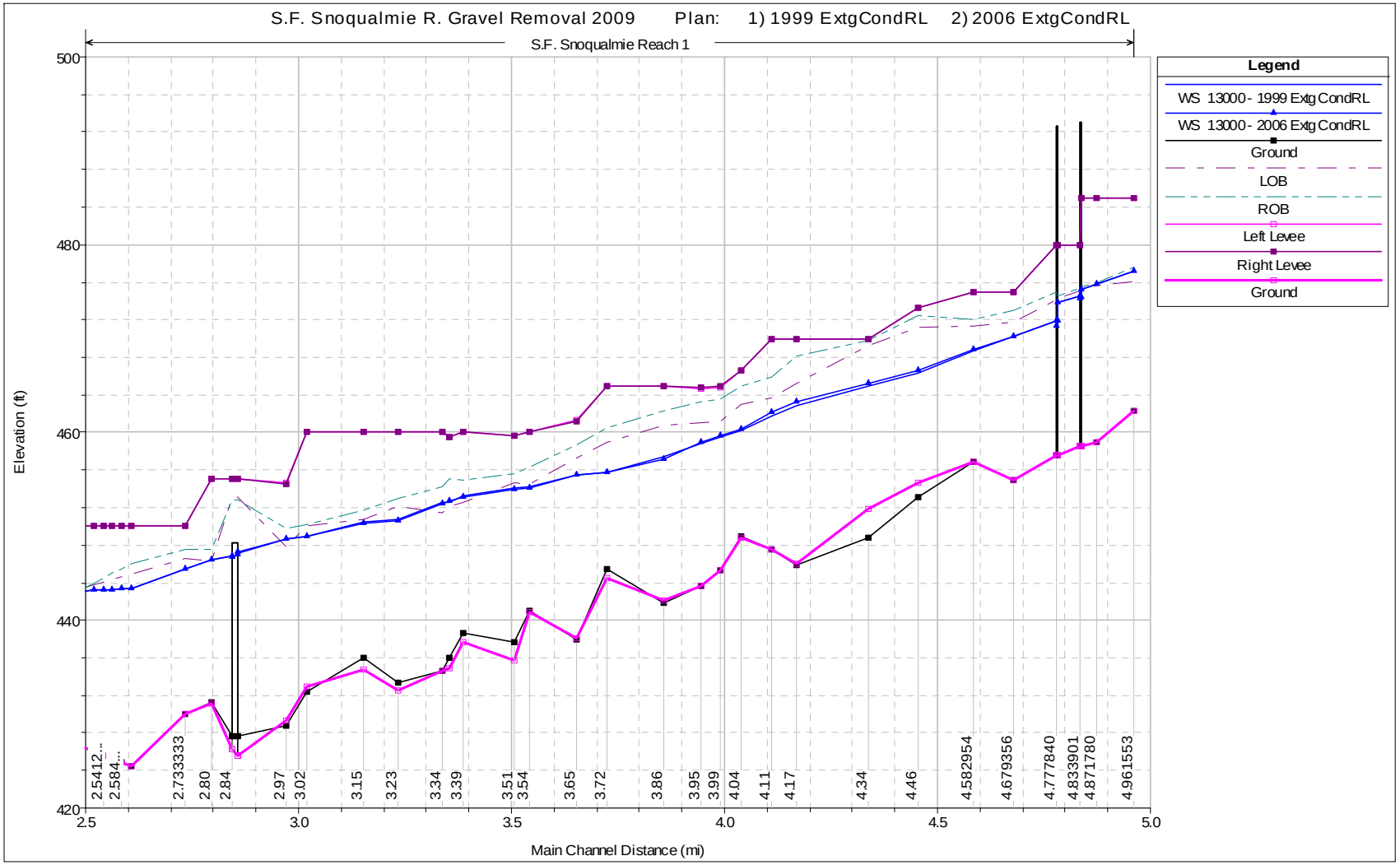


**Figure 5-19: South Fork Snoqualmie River 1999 and 2006 channel conditions, profile view of water surface elevations for a discharge of 13,000 cfs (50-year)**

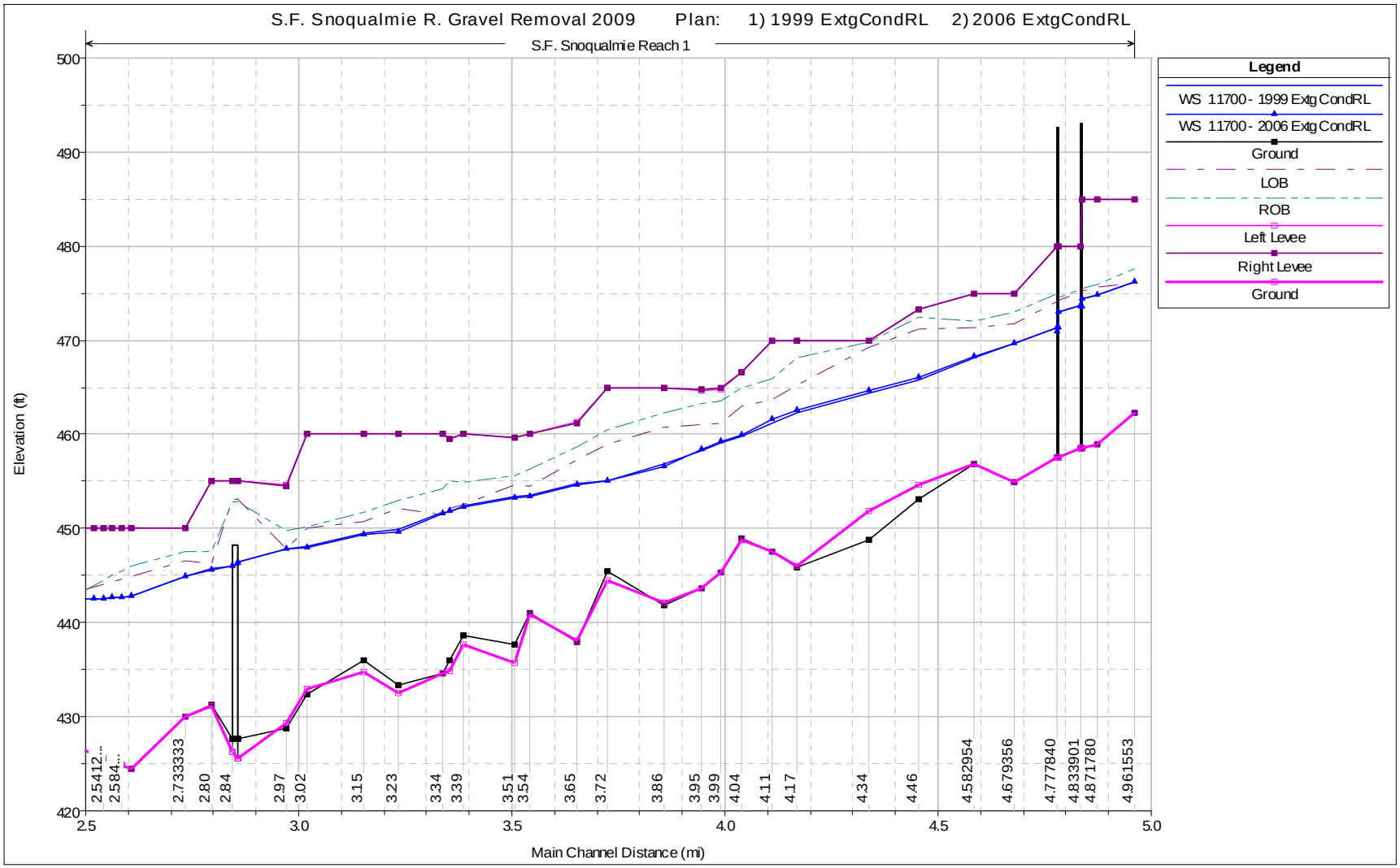


**Figure 5-20: South Fork Snoqualmie River 1999 and 2006 channel conditions, profile view of water surface elevations for a discharge of 11,700 cfs (30-year)**

**Table 5-8: Change in water surface elevations (feet) in the South Fork Snoqualmie River from 1999 to 2006 channel conditions**

| River Mile | 9,000 cfs 10-year Flow (feet) | 10,900 cfs Nov 1990 Flow (feet) | 11,700 cfs 30-year Flow (feet) | 13,000 cfs 50-year Flow (feet) | 15,000 cfs 100-year flow (feet) |
|---|---|---|---|---|---|
| | Upstream end of study reach | | | | |
| 4.46 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| 4.34 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| 4.17 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| 4.11 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| 4.04 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 |
| 3.99 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 3.95 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 |
| 3.86 | -0.2 | -0.2 | -0.2 | -0.2 | -0.2 |
| 3.72 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.65 | -0.1 | 0.0 | -0.1 | -0.1 | -0.1 |
| | Approx split between upper and lower parts of study reach | | | | |
| 3.54 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 |
| 3.51 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 |
| 3.39 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 |
| 3.35 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 |
| 3.34 | 0.0 | 0.0 | -0.1 | -0.1 | -0.1 |
| 3.23 | -0.2 | -0.2 | -0.2 | -0.2 | -0.2 |
| 3.15 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 |
| 3.02 | 0.0 | 0.0 | 0.0 | 0.0 | -0.2 |
| 2.97 | -0.1 | -0.1 | -0.1 | -0.1 | -0.2 |
| 2.85 | North Bend Blvd Bridge Downstream end | | | | |
| **FULL STUDY REACH** | | | | | |
| Maximum | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Minimum | -0.2 | -0.2 | -0.2 | -0.2 | -0.2 |
| Mean | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Median | 0.0 | 0.0 | 0.0 | 0.0 | -0.1 |
| Std Dev | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **UPSTREAM PART OF STUDY REACH** | | | | | |
| Maximum | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Minimum | -0.2 | -0.2 | -0.2 | -0.2 | -0.2 |
| Mean | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Median | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| Std Dev | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **DOWNSTREAM PART OF STUDY REACH** | | | | | |
| Maximum | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 |
| Minimum | -0.2 | -0.2 | -0.2 | -0.2 | -0.2 |
| Mean | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 |
| Median | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 |
| Std Dev | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

### 5.4.3 Comparison of hydraulic modeling results for 2006 and 2007 channel conditions

Figure 5-21 compares water surface elevations in profile view through the study reach for the 2006 and 2007 conditions at a discharge of 13,000 cfs (50-year flood). Figure 5-22 compares water surface elevations in profile view through the study reach for the 2006 and 2007 conditions at a discharge of 11,700 cfs (30-year). The changes in water surface elevations for the range of analyzed flows going from 2006 to 2007 channel conditions are summarized in Table 5-9.

Changes in water surface elevations in the upstream part of the study reach for this period ranged from a minimum of -0.1 feet to a maximum of 0.6 feet, with mean and median changes of 0.2 feet (Table 5-9). The locations of largest changes for the analyzed flows consistently occurred along RM 3.95 to RM 4.04, which is at and just upstream of gravel bar 6.

Changes in the downstream part of the study reach ranged from a minimum of -0.1 feet to a maximum of 0.2 feet, with a mean and median change of 0.0 feet for this period (Table 5-9). Most of the changes in the downstream area for this period were zero. The predominance of zero or negative changes in water surface elevations listed for the downstream part of Table 5-9 suggests that deposition brought by the November 2006 flood event (Table 5-4) resulted in no increase in flood hazard from 2006 to 2007 conditions in the downstream part of this study reach.

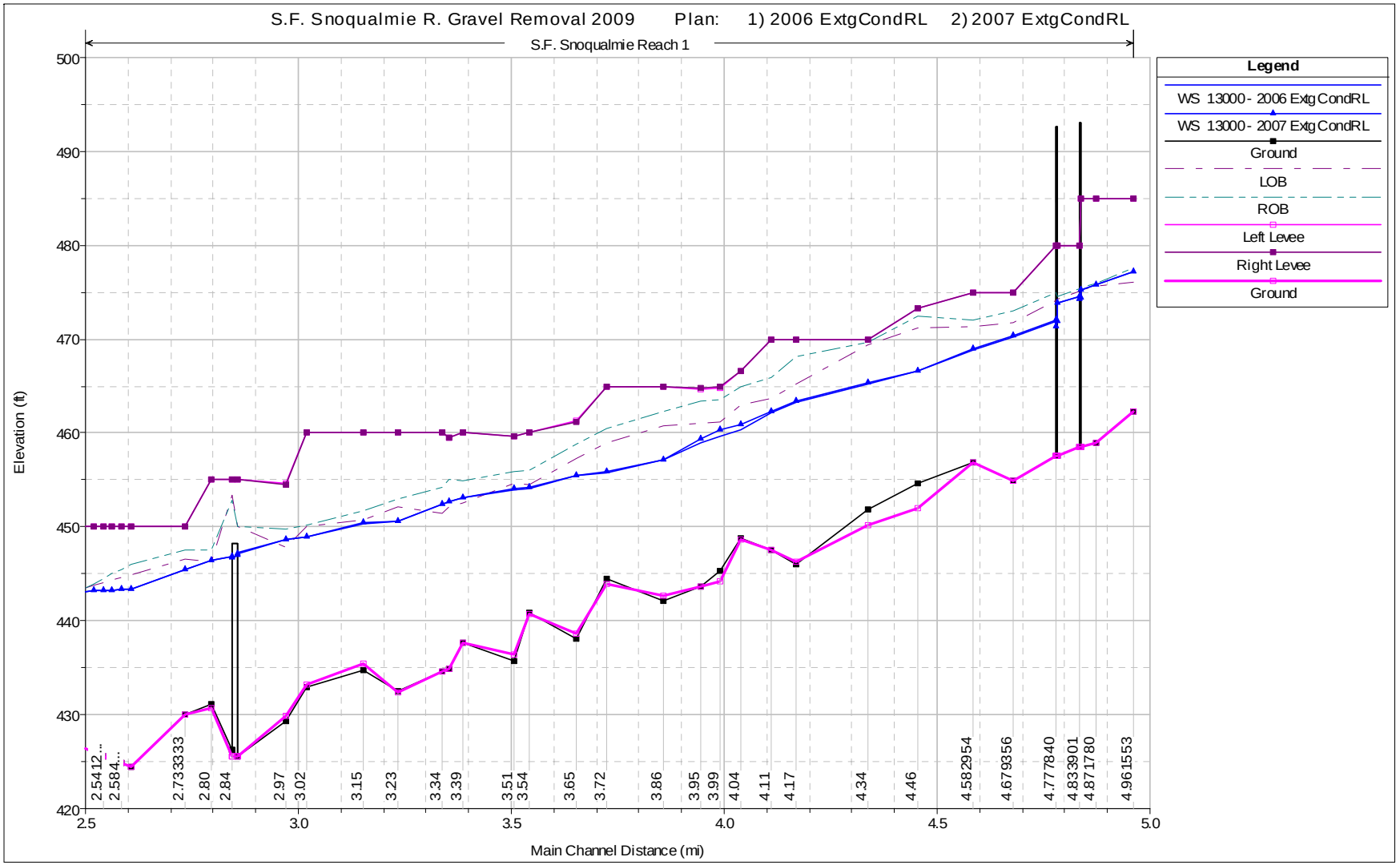


**Figure 5-21: South Fork Snoqualmie River 2006 and 2007 channel conditions, profile view of water surface elevations for a discharge of 13,000 cfs (50-year)**

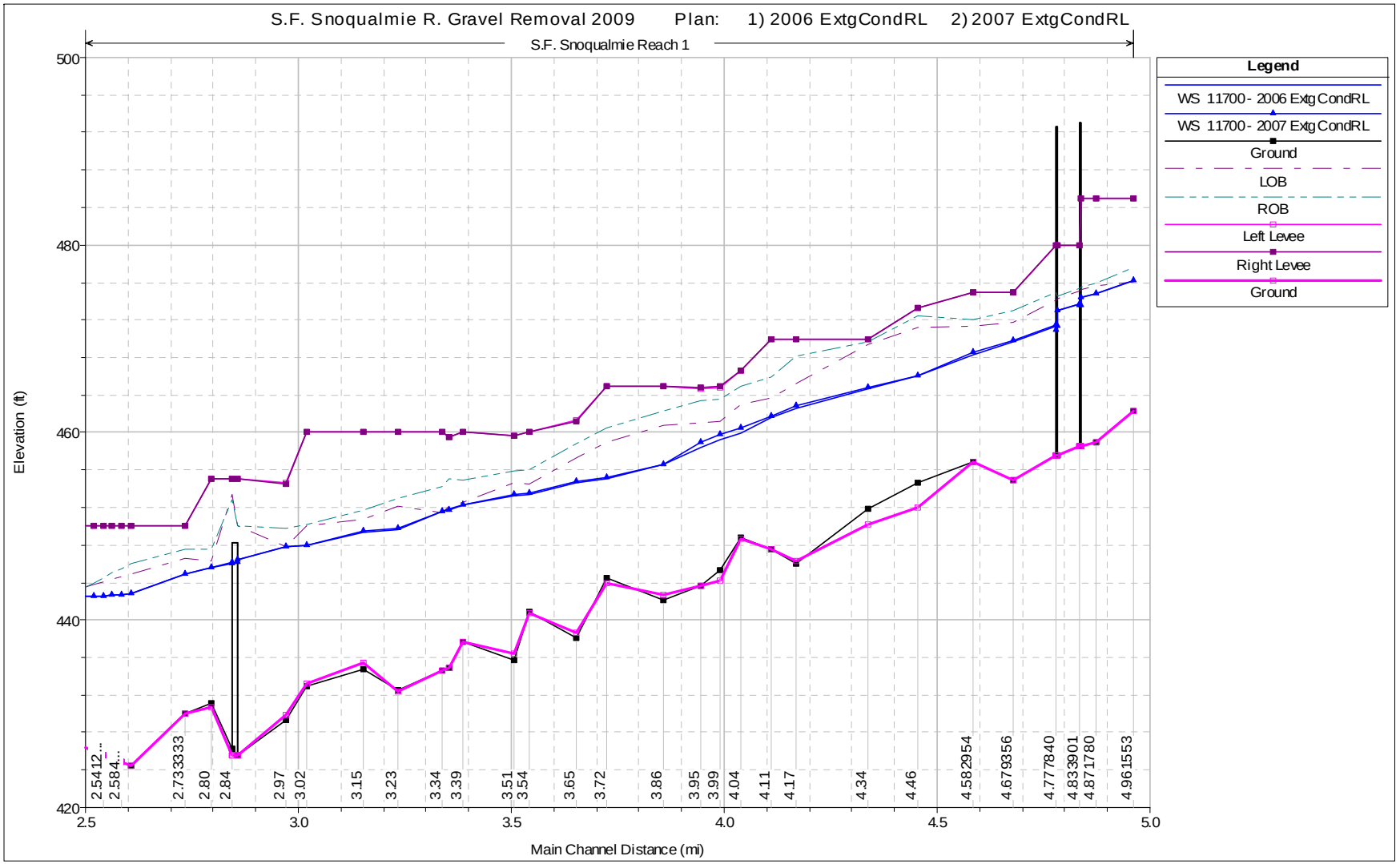


**Figure 5-22: South Fork Snoqualmie River 2006 and 2007 channel conditions, profile view of water surface elevations for a discharge of 11,700 cfs (30-year)**

**Table 5-9: Change in water surface elevations (feet) in the South Fork Snoqualmie River from 2006 to 2007 channel conditions**

| River Mile | 9,000 cfs 10-year Flow (feet) | 10,900 cfs Nov 1990 Flow (feet) | 11,700 cfs 30-year Flow (feet) | 13,000 cfs 50-year Flow (feet) | 15,000 cfs 100-year Flow (feet) |
|---|---|---|---|---|---|
| | Upstream end of study reach | | | | |
| 4.46 | -0.1 | -0.1 | -0.1 | -0.1 | 0.0 |
| 4.34 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| 4.17 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| 4.11 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| 4.04 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 3.99 | 0.6 | 0.6 | 0.6 | 0.6 | 0.5 |
| 3.95 | 0.5 | 0.5 | 0.4 | 0.4 | 0.3 |
| 3.86 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.72 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| 3.65 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | Approx split between upper and lower parts of study reach | | | | |
| 3.54 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| 3.51 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 |
| 3.39 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.35 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.34 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.23 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| 3.15 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.02 | 0.0 | -0.1 | 0.0 | -0.1 | 0.0 |
| 2.97 | 0.0 | -0.1 | 0.0 | -0.1 | 0.0 |
| 2.85 | N Bend Blvd Bridge | | | | |
| | Downstream end of study reach | | | | |
| **FULL STUDY REACH** | | | | | |
| Maximum | 0.6 | 0.6 | 0.6 | 0.6 | 0.5 |
| Minimum | -0.1 | -0.1 | -0.1 | -0.1 | 0.0 |
| Mean | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Median | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 |
| Std Dev | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **UPSTREAM PART OF STUDY REACH** | | | | | |
| Maximum | 0.6 | 0.6 | 0.6 | 0.6 | 0.5 |
| Minimum | -0.1 | -0.1 | -0.1 | -0.1 | 0.0 |
| Mean | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Median | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| Std Dev | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **DOWNSTREAM PART OF STUDY REACH** | | | | | |
| Maximum | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| Minimum | -0.1 | -0.1 | -0.1 | -0.1 | 0.0 |
| Mean | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Median | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Std Dev | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 |

### 5.4.4 Comparison of hydraulic modeling results for 2007 and 2009 channel conditions

Figure 5-23 and Figure 5-24 compare water surface elevations in profile view through the study reach for 2007 and 2009 conditions at a discharge of 13,000 cfs (50-year) and 11,700 cfs (30-year), respectively. The changes in water surface elevations for the range of analyzed flows going from 2006 to 2007 channel conditions are summarized in Table 5-10.

In the upstream part of the study reach, changes in water surface elevations ranged from a minimum of 0.1 feet to a maximum of 0.6 feet in this period, with mean and median values of 0.3 to 0.4 feet for the analyzed flows (Table 5-10). The largest increases in modeled water surfaces occur at RM 3.95 and RM 4.04, along gravel bar 6.

In the downstream part of the study reach, changes in water surface elevation ranged from a minimum of -0.1 feet to a maximum of 0.3 feet, with mean and median changes of 0.1 feet to 0.2 feet for the analyzed flows (Table 5-10). Water surface increases of 0.2 feet occurred consistently throughout the downstream part of the study reach, upstream of backwater effects, and at all analyzed flows.

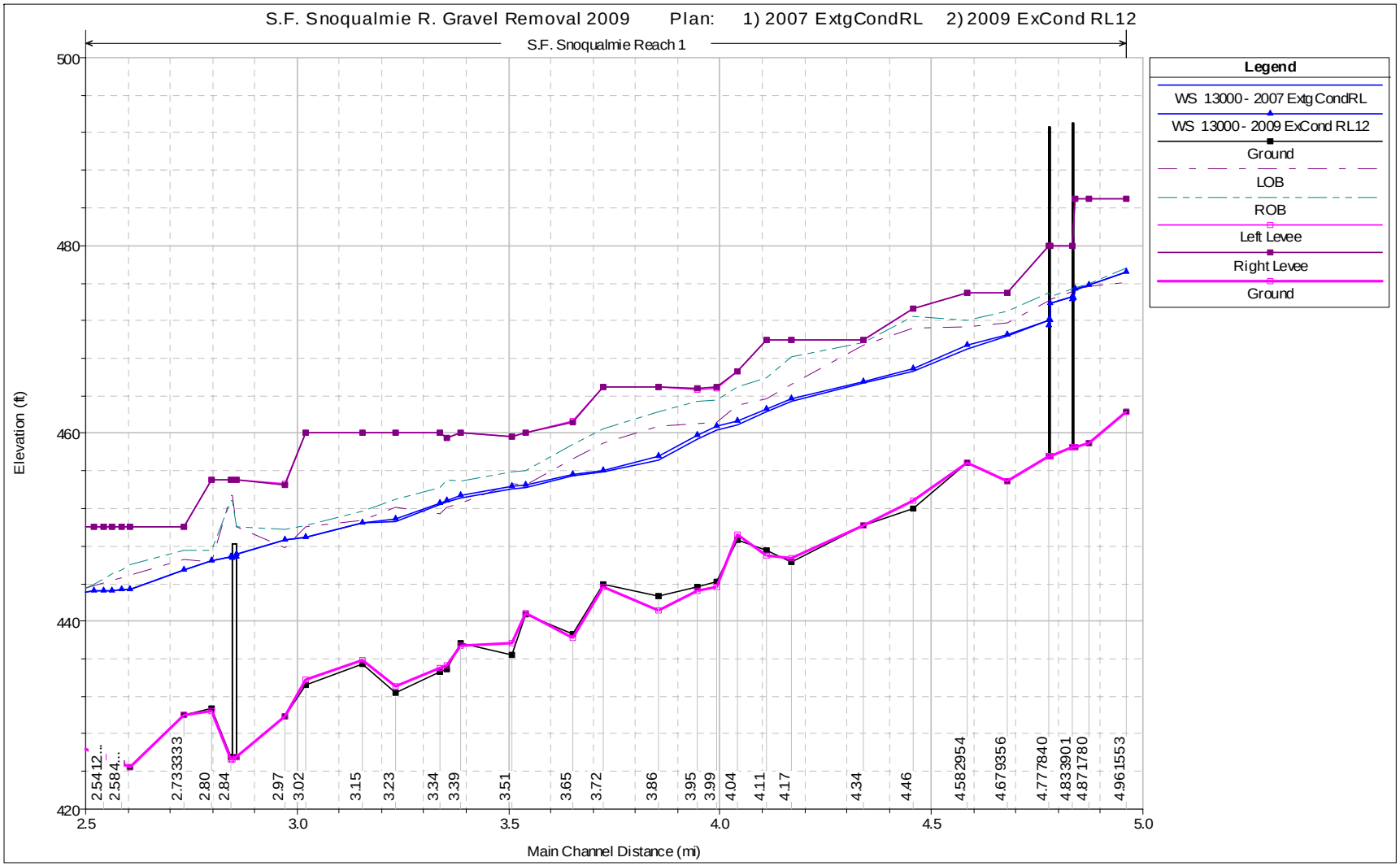


**Figure 5-23: South Fork Snoqualmie River 2007 and 2009 channel conditions, profile view of water surface elevations for a discharge of 13,000 cfs (50-year)**

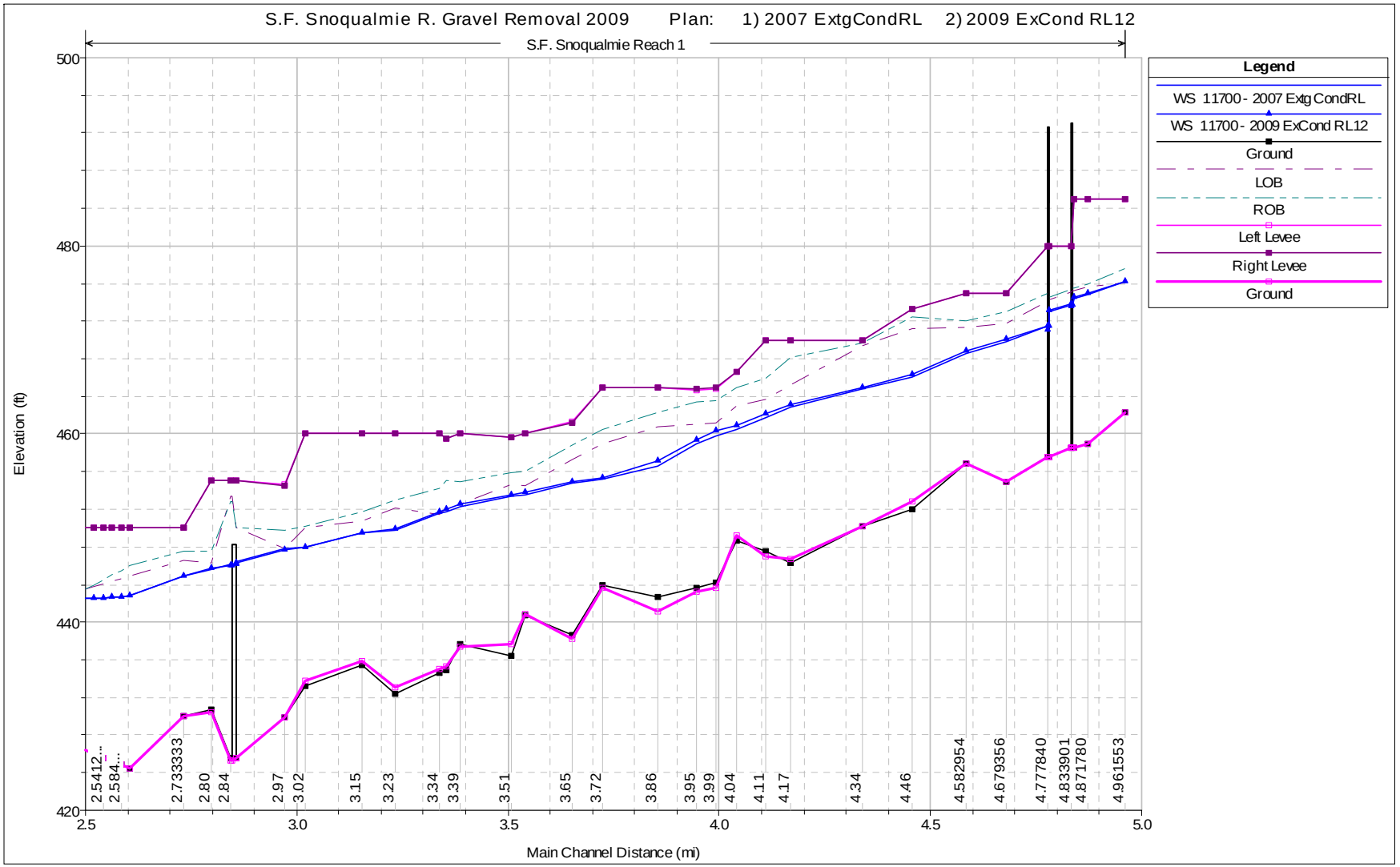


**Figure 5-24: South Fork Snoqualmie River 2007 and 2009 channel conditions, profile view of water surface elevations for a discharge of 11,700 cfs (30-year)**

**Table 5-10: Change in water surface elevations (feet) in the South Fork Snoqualmie River from 2007 to 2009 channel conditions**

| River Mile | 9,000 cfs 10-year flow (feet) | 10,900 cfs Nov 1990 Flow (feet) | 11,700 cfs 30-year Flow (feet) | 13,000 cfs 50-year Flow (feet) | 15,000 cfs 100-year Flow (feet) |
|---|---|---|---|---|---|
| | Upstream end of study reach | | | | |
| 4.46 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| 4.34 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 4.17 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 |
| 4.11 | 0.4 | 0.3 | 0.4 | 0.4 | 0.4 |
| 4.04 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 3.99 | 0.5 | 0.6 | 0.6 | 0.5 | 0.5 |
| 3.95 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 3.86 | 0.5 | 0.5 | 0.4 | 0.4 | 0.3 |
| 3.72 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| 3.65 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | Approx split between upper and lower parts of study reach | | | | |
| 3.54 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 3.51 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 3.39 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 |
| 3.35 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 3.34 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| 3.23 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| 3.15 | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 |
| 3.02 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2.97 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2.85 | North Bend Blvd Bridge | | | | |
| | Downstream end of study reach | | | | |
| **FULL STUDY REACH** | | | | | |
| Maximum | 0.5 | 0.6 | 0.6 | 0.5 | 0.5 |
| Minimum | -0.1 | -0.1 | -0.1 | -0.1 | 0.0 |
| Mean | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Median | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Std Dev | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **UPSTREAM PART OF STUDY REACH** | | | | | |
| Maximum | 0.5 | 0.6 | 0.6 | 0.5 | 0.5 |
| Minimum | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Mean | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 |
| Median | 0.3 | 0.3 | 0.4 | 0.4 | 0.3 |
| Std Dev | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 |
| **DOWNSTREAM PART OF STUDY REACH** | | | | | |
| Maximum | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 |
| Minimum | -0.1 | -0.1 | -0.1 | -0.1 | 0.0 |
| Mean | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Median | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| Std Dev | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

### 5.4.5 Comparison of hydraulic modeling results for 1992/95 and 2009 channel conditions

Figure 5-25 and Figure 5-26 compare water surface elevations in profile view through the study reach for 1992/95 and 2009 conditions at a discharge of 13,000 cfs (50-year flood) and 11,700 cfs (30-year), respectively. Table 5-11 compares the computed water surface elevations for the range of analyzed flows for 1992/95 and 2009 channel conditions.

For the full study period of 1992/95 to 2009, there was an increase in water surface elevation at almost all cross sections through the range of analyzed flows. In the upstream part of the study reach, water surface elevation changes for the analyzed flows ranged from a minimum of -0.1 feet to a maximum of 1.2 feet (at RM 3.99 and RM 4.04), with mean and median changes of 0.7 feet to 1.0 feet (Table 5-11). Most modeled water surface increases in this upper part of the study area exceeded a half foot for this period; many increases equaled or exceeded one foot. In the downstream part of the study reach, increases in modeled water surface elevations ranged from -0.1 feet to 1.0 feet, with mean and median changes of 0.2 feet to 0.4 feet (Table 5-11). Most of the changes in this lower area are increases, most of which are less than a half foot.

Figures 5-27, 5-28, and 5-29 compare water surface elevations in cross section view with 1992/95 and 2009 channel conditions for the flows of 11,700 cfs (30-year), 13,000 cfs (50-year), and 15,000 cfs (100-year flood). These three cross section views depict the channel at gravel bar 3, which is directly across from the left bank location of past overtopping flows along Berry Estates. Figure 5-27, at RM 3.39, shows increases in water surface elevation of up to 0.6 feet from 1992/95 to 2007 channel conditions. Figure 5-28, at RM 3.35, shows increases in water surface elevation of up to 0.4 feet from 1992/95 to 2009 channel conditions. Figure 5-29, at RM 3.34, shows increases in water surface elevation of up to 0.3 feet from 1992/95 to 2009 channel conditions. The consistent increases in modeled water surface elevations across the full range of analyzed flows along RM 3.34 to RM 3.39 going from 1992/95 to 2009 conditions (Table 5-11) are important findings because the magnitude of these increases approach or exceed inherent modeling uncertainties of plus or minus one-half foot (Section 3.3) and these water surface increases occur adjacent to the location where past overtopping floods have caused flood damage.

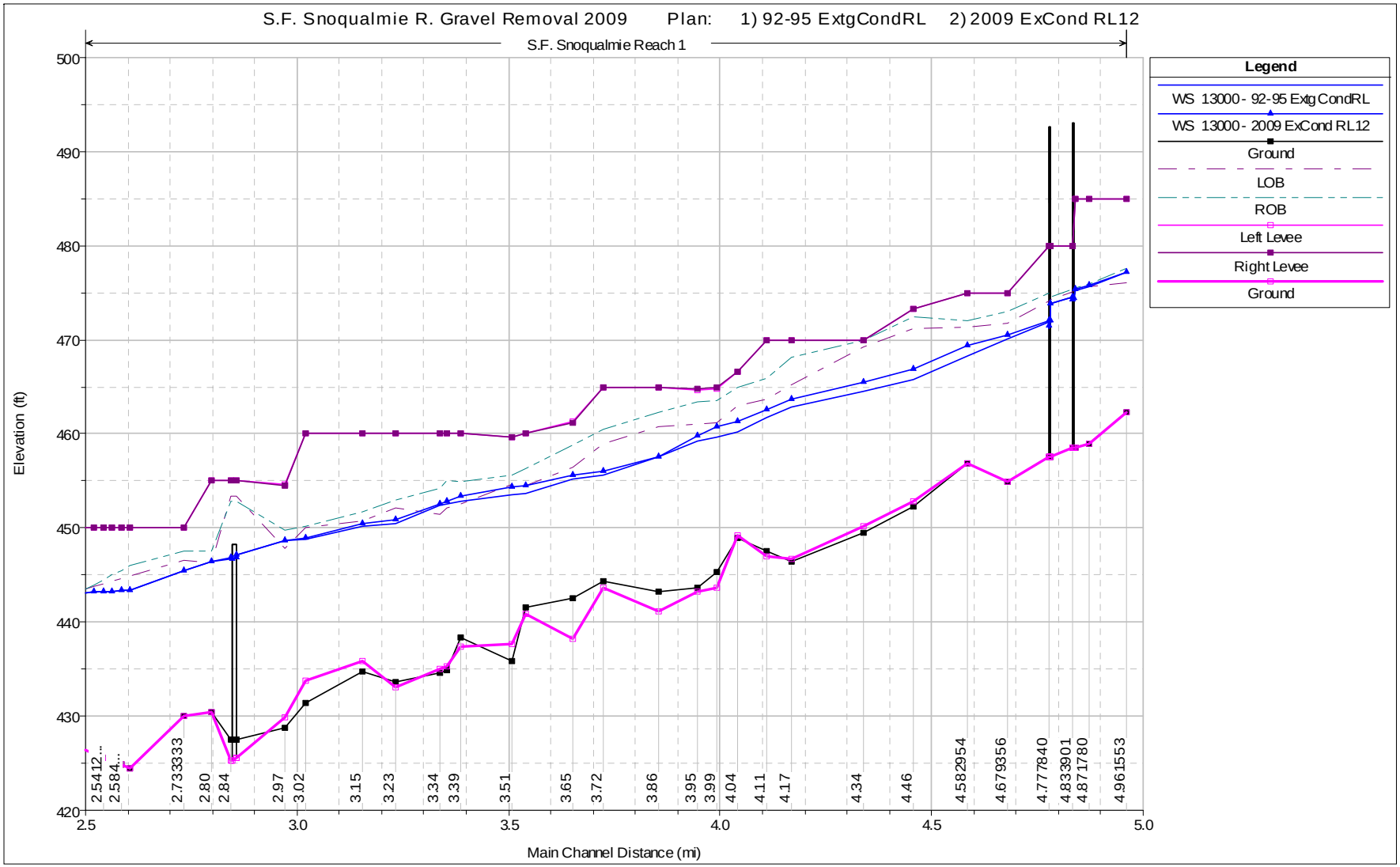


**Figure 5-25: South Fork Snoqualmie River 1992/95 and 2009 channel conditions, profile view of water surface elevations for a discharge of 13,000 cfs (50-year)**

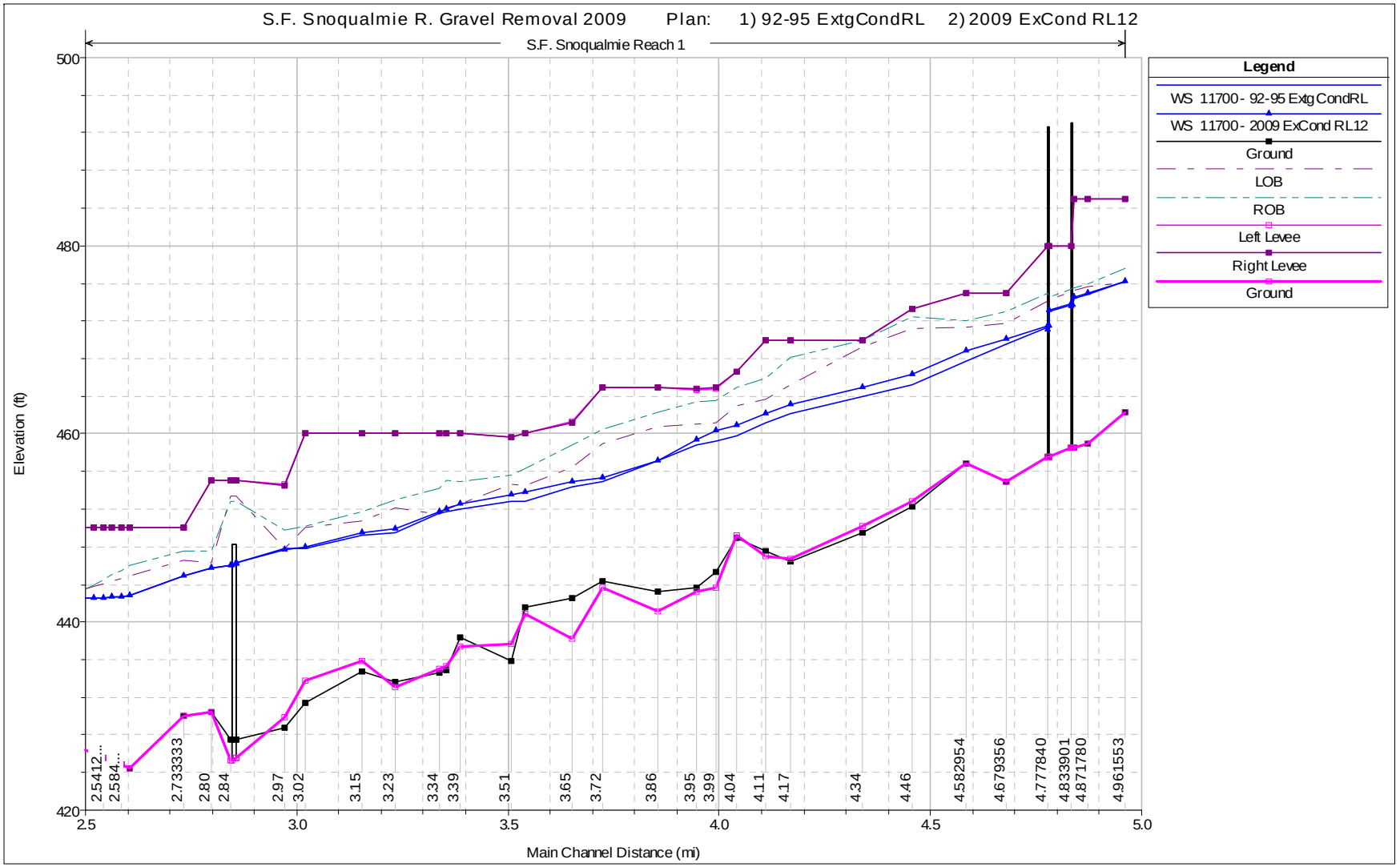


**Figure 5-26: South Fork Snoqualmie River 1992/95 and 2009 channel conditions, profile view of water surface elevations for a discharge of 11,700 cfs (30-year)**

**Table 5-11: Changes in water surface elevations (feet) in the South Fork Snoqualmie River from 1992/95 channel conditions to 2009 channel conditions**

| River Mile | 9,000 cfs 10-year Flow (feet) | 10,900 cfs Nov 1990 Flow (feet) | 11,700 cfs 30-year Flow (feet) | 13,000 cfs 50-year Flow (feet) | 15,000 cfs 100-year Flow (feet) |
|---|---|---|---|---|---|
| | Upstream end of study reach | | | | |
| 4.46 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 4.34 | 1.1 | 1.1 | 1.0 | 1.0 | 1.0 |
| 4.17 | 1.0 | 1.0 | 0.9 | 0.9 | 0.9 |
| 4.11 | 1.0 | 0.9 | 0.9 | 0.9 | 0.9 |
| 4.04 | 1.2 | 1.2 | 1.2 | 1.2 | 1.1 |
| 3.99 | 1.2 | 1.2 | 1.2 | 1.1 | 1.1 |
| 3.95 | 0.8 | 0.7 | 0.7 | 0.6 | 0.5 |
| 3.86 | -0.1 | -0.1 | -0.1 | 0.0 | 0.0 |
| 3.72 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 |
| 3.65 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 |
| | Approx split between upper and lower parts of study reach | | | | |
| 3.54 | 1.0 | 0.9 | 0.9 | 0.8 | 0.6 |
| 3.51 | 0.9 | 0.8 | 0.8 | 0.7 | 0.5 |
| 3.39 | 0.6 | 0.6 | 0.5 | 0.5 | 0.4 |
| 3.35 | 0.4 | 0.3 | 0.3 | 0.3 | 0.2 |
| 3.34 | 0.3 | 0.3 | 0.3 | 0.2 | 0.1 |
| 3.23 | 0.4 | 0.4 | 0.4 | 0.4 | 0.3 |
| 3.15 | 0.3 | 0.2 | 0.2 | 0.2 | 0.1 |
| 3.02 | 0.2 | 0.1 | 0.1 | 0.1 | 0.0 |
| 2.97 | 0.0 | 0.0 | 0.0 | -0.1 | -0.1 |
| 2.85 | North Bend Blvd Bridge Downstream end | | | | |
| **FULL STUDY REACH** | | | | | |
| Maximum | 1.2 | 1.2 | 1.2 | 1.2 | 1.1 |
| Minimum | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 |
| Mean | 0.6 | 0.6 | 0.6 | 0.5 | 0.5 |
| Median | 0.6 | 0.5 | 0.5 | 0.5 | 0.4 |
| Std Dev | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| **UPSTREAM PART OF STUDY REACH** | | | | | |
| Maximum | 1.2 | 1.2 | 1.2 | 1.2 | 1.1 |
| Minimum | -0.1 | -0.1 | -0.1 | 0.0 | 0.0 |
| Mean | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 |
| Median | 1.0 | 0.9 | 0.9 | 0.9 | 0.9 |
| Std Dev | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| **DOWNSTREAM PART OF STUDY REACH** | | | | | |
| Maximum | 1.0 | 0.9 | 0.9 | 0.8 | 0.6 |
| Minimum | 0.0 | 0.0 | 0.0 | -0.1 | -0.1 |
| Mean | 0.4 | 0.4 | 0.3 | 0.3 | 0.2 |
| Median | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 |
| Std Dev | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |

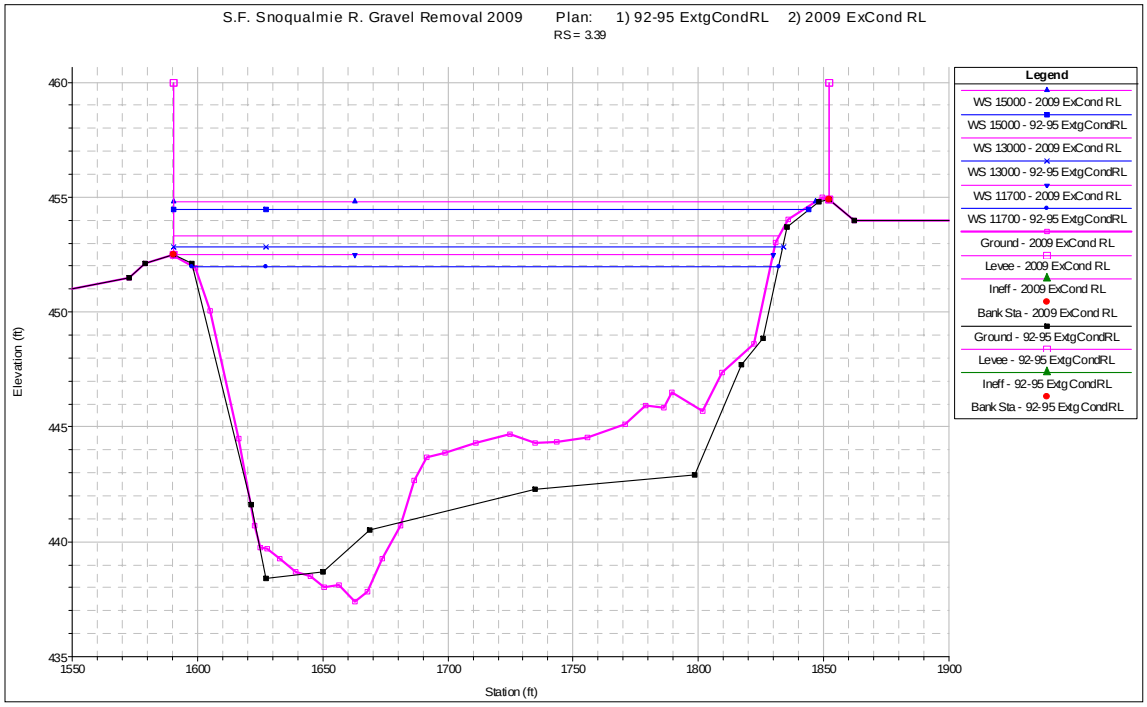


**Figure 5-27: South Fork Snoqualmie River 1992/95 and 2009 channel conditions, cross section view of water surface elevations at RM 3.39 at discharges of 11,700 cfs (30-year), 13,000 cfs (50-year) and 15,000 cfs (100-year)**

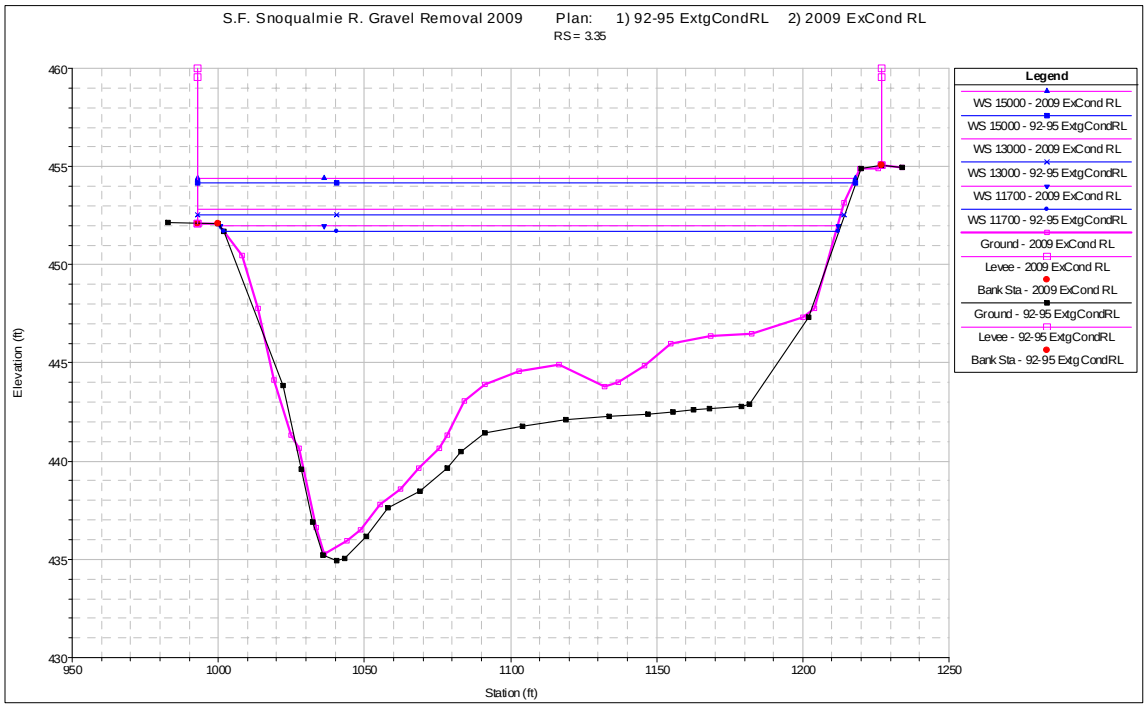


**Figure 5-28: South Fork Snoqualmie River 1992/95 and 2009 channel conditions, cross section view of water surface elevations at RM 3.35 at discharges of 11,700 cfs (30-year), 13,000 cfs (50-year) and 15,000 cfs (100-year). The 1992/95 topography is estimated.**

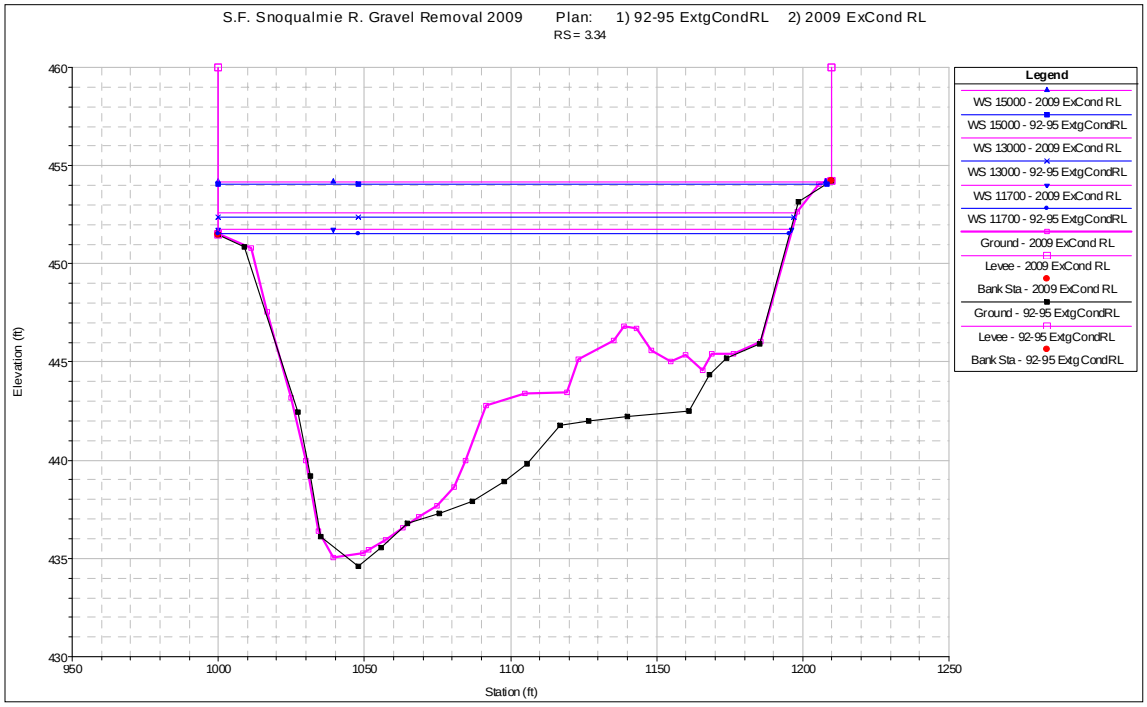


**Figure 5-29: South Fork Snoqualmie River 1992/95 and 2009 channel conditions, cross section view of water surface elevations at RM 3.34 at discharges 11,700 cfs (30-year), 13,000 cfs (50-year) and 15,000 cfs (100-year). The 1992/95 topography is estimated.**

Figure 5-30 compares water surface elevations for 1992/95 and 2009 channel conditions for analyzed flows in cross section view at RM 2.97, which is adjacent to Shamrock Park. Figure 5-30 shows no (zero to -0.1 foot) increase in water surface elevations at any given flow through the 1992/95 to 2009 full study period. Such negligible changes in water surface elevations over 17 years, even with sediment deposition evident at this location, are consistent with backwater conditions. The changes in water surface elevations depicted in Figures 5-27 through 5-30 are reported numerically in Table 5-11.

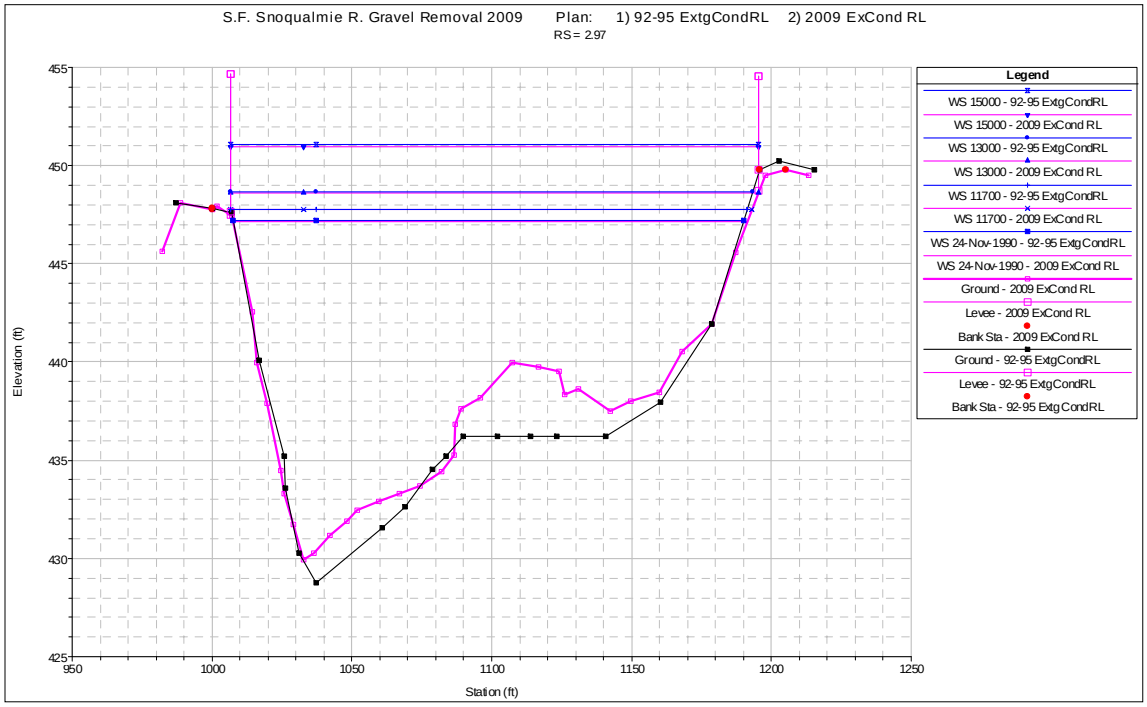


**Figure 5-30: South Fork Snoqualmie River 1992/95 and 2009 channel conditions, cross section view of water surface elevations at RM 2.97 at discharges of 10,900 cfs (November 1990), 11,700 cfs (30-year), 13,000 cfs (50-year) and 15,000 cfs (100-year). The 1992/95 topography is estimated.**

### 5.4.6 Channel conveyance capacity

The existing conditions channel conveyance capacity at every cross section in the study reach is identified in this subsection. Channel conveyance capacity is defined as the discharge at which the modeled water surface elevation is just contained by the top of the riverbank or levee. In the case where the left bank and right bank (viewed looking downstream) are at different elevations, the lower elevation is used to identify the channel conveyance capacity because that is the elevation at which overbank flow would occur first at that location.

On the South Fork Snoqualmie River, the top of bank elevation along the right bank is greater than the left bank at every cross section in this study reach. The right bank top elevation generally is about one to two feet higher than the left bank at most cross sections in the downstream part of the study reach (except at RM 3.02, as described in the last paragraph of this subsection). The right bank top elevation generally is about two to three feet higher than the left bank in the upstream part of the study reach.

Because the right bank is at a higher elevation than the left bank throughout this reach, the channel conveyance capacity reported here is equal to the maximum flow contained by the left bank at every cross section throughout this reach.

A channel conveyance capacity that meets the flood reduction objective of containing 13,000 cfs plus one foot of freeboard is not equivalent to any one discharge throughout this study reach

because specific hydraulics will determine how much flow discharge would occur in one foot of freeboard at each location. However, the existing conditions hydraulic model indicates that 13,000 cfs plus one foot of freeboard is roughly equivalent to a channel conveyance capacity of 13,500 to 14,000 cfs throughout this study reach.

Table 5-12 lists and Figure 5-31 plots the channel conveyance capacity at each cross section along the left bank for existing conditions in 1992/95, 1999, 2006, 2007 and 2009. The maximum discharge modeled was 19,700 cfs (the 500-year flood); the few locations that had greater channel conveyance capacities are indicated as >19,700 cfs in Table 5-12 and plotted as 19,700 cfs in Figure 5-31. In general, there is greater channel conveyance capacity in the upstream part of the study reach (e.g., from RM 3.65 to 4.46) than in the downstream part, and as stated above, greater channel conveyance capacity along the right bank than the left bank.

In the upstream part of the reach, there is channel conveyance capacity of 15,000 cfs (100-year flood) at all cross sections in existing conditions during 1992/95, 1999, 2006, 2007 and 2009 channel conditions except at RM 3.99 in 2009. Furthermore, 19,700 cfs and greater would be contained by both banks in all years at RM 4.34 and RM 4.46 and at RM 3.86 and RM 4.40 in most years. Decreases in channel conveyance capacity have been relatively minor at most of the cross sections in the upstream part of the study reach from 1992/95 through 2009. Channel conveyance capacity at RM 3.99 remained above 17,000 cfs through 2006, but has decreased steadily since then to 14,200 cfs in 2009. Channel conveyance capacity at all cross sections in this upstream area exceeds the flood reduction objective for all years except RM 3.99 in 2009 (shown in Table 6-3). Any decreased channel conveyance capacity in this upstream area would manifest physically as decreased freeboard above the flood reduction objective (except at RM 3.99).

In the downstream part of the study reach (RM 2.85 to RM 3.54), there are no places that have had a channel conveyance capacity of 15,000 cfs (100-year flood) at any time from 1992/95 to 2009. There are three locations where the flood hazard reduction objective is met in 2009, at RMs 3.02, 3.23, and 3.51, which have a channel conveyance capacity of 14,000 cfs or greater. There is a channel conveyance capacity of 13,000 cfs (50-year flood) and greater in the 2009 existing conditions at all cross section locations except at RM 3.34 to RM 3.39 (adjacent to Berry Estates) and RM 2.97 (adjacent to Shamrock Park).

The modeled channel conveyance capacity decreased by 400 cfs from 1992/95 to 2009 existing conditions at both RM 3.34 and RM 3.35. The modeled channel conveyance capacity decreased by 800 cfs (from 12,500 to 11,700 cfs) from the 1992/95 to 2009 existing conditions at RM 3.39. The modeled channel conveyance at RM 2.97 through these five years of existing channel conditions remained essentially the same, fluctuating between 11,800 cfs and 12,000 cfs. All changes in channel conveyance capacity are based on values in Table 5-12 and Figure 5-31.

**Table 5-12: Channel conveyance capacity under existing conditions on the South Fork Snoqualmie River in 1992/95, 1999, 2006, 2007 and 2009**

| River Mile | **1992/95 Channel Conditions:** Channel Conveyance Capacity (cfs) | **1999 Channel Conditions:** Channel Conveyance Capacity (cfs) | **2006 Channel Conditions:** Channel Conveyance Capacity (cfs) | **2007 Channel Conditions:** Channel Conveyance Capacity (cfs) | **2009 Channel Conditions:** Channel Conveyance Capacity (cfs) |
|---|---|---|---|---|---|
| | Upstream end of study reach | | | | |
| 4.46 | >19,700 | >19,700 | >19,700 | >19,700 | > 19700 |
| 4.34 | >19,700 | >19,700 | >19,700 | >19,700 | > 19700 |
| 4.17 | 18,800 | 18,500 | 17,800 | 17,500 | 16,600 |
| 4.11 | 18,000 | 17,900 | 17,100 | 16,700 | 15,700 |
| 4.04 | >19,700 | >19,700 | >19,700 | 19,300 | 18,000 |
| 3.99 | 17,400 | 17,700 | 17,400 | 15,900 | 14,200 |
| 3.95 | 18,300 | 18,900 | 18,900 | 18,300 | 17,100 |
| 3.86 | >19,700 | >19,700 | > 19,700 | 19,400 | > 19700 |
| 3.72 | 19,400 | 19,000 | 19,000 | 17,200 | 18,700 |
| 3.65 | 16,800 | 16,100 | 16,200 | 16,100 | 15,800 |
| | Approximate split between upper and lower parts of study area | | | | |
| 3.54 | 14,000 | 13,400 | 13,600 | 13,400 | 13,100 |
| 3.51 | 14,300 | 13,900 | 13,900 | 13,700 | 14,000 |
| 3.39 | 12,500 | 11,900 | 12,100 | 12,000 | 11,700 |
| 3.35 | 12,300 | 12,200 | 12,100 | 12,200 | 11,900 |
| 3.34 | 11,700 | 11,400 | 11,500 | 11,500 | 11,300 |
| 3.23 | 14,700 | 14,500 | 14,700 | 14,600 | 14,500 |
| 3.15 | 13,500 | 13,300 | 13,400 | 13,300 | 13,300 |
| 3.02 | 14,000 | 14,000 | 13,900 | 14,000 | 14,300 |
| 2.97 | 12,000 | 11,800 | 11,900 | 12,000 | 12,000 |
| 2.85 | North Bend Blvd Bridge | | | | |
| | Downstream end of study reach | | | | |

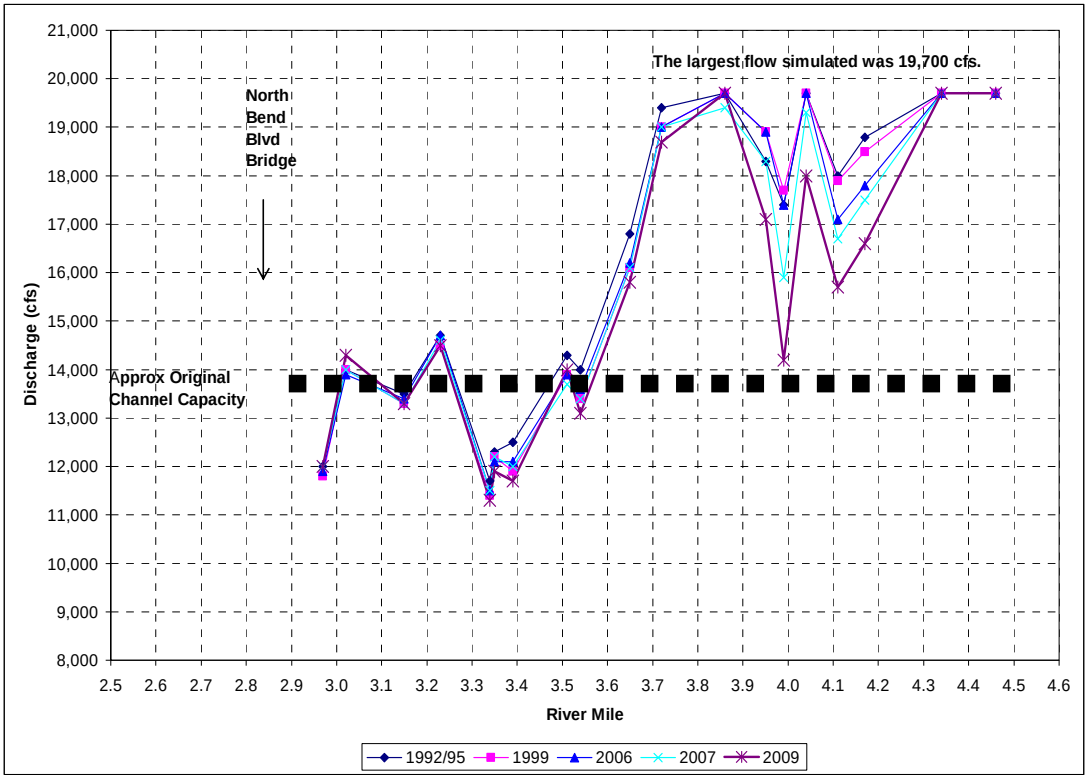


**Figure 5-31: Channel conveyance capacity for 1992/95, 1999, 2006, 2007 and 2009 existing conditions on the South Fork Snoqualmie River**

In both upstream and downstream areas, there generally was not much change in the channel conveyance capacity for the years 1992/95 through 2006. Most of the changes in channel conveyance capacity occurred from 2006 to 2009.

The January 2009 flood of 11,600 cfs overtopped the left bank near RM 3.34 to RM 3.39, but no other parts of the study reach, generally corroborating the HEC-RAS hydraulic modeling results for channel conveyance capacity in this study reach.

Though the channel conveyance capacity of the right bank is not presented here explicitly, hydraulic modeling indicates that the right bank meets or exceeds the stated flood reduction objective throughout the entire study reach for all modeled years including 2009. The channel conveyance capacity, or maximum flow contained, along the right bank can be identified using the Raised Levee condition in the HEC-RAS model, which artificially contains overbank flow along both banks. Any such maximum flow contained by the right bank is a hypothetical value, because the lower elevation left bank actually would overtop first. The one exception is at RM 3.02, where backwater conditions exist, the right bank is only about 0.4 feet higher than the left, and the November 2006 discharge of 13,600 cfs overtopped both the left bank and the right bank. This November 2006 overtopping of the right bank at about RM 3.02 should be noted as a real-world check on the hydraulic model, which suggests a lack of containment of 13,000 cfs plus one foot of freeboard at that right bank location.

### 5.4.7 Comparison of changes in average riverbed elevations and changes in average water surface elevations

Reach-scale and subreach-scale changes in average riverbed elevations and changes in average water surface elevations during a 13,000 cfs (50-year) flood are plotted by individual and full study periods in Figure 5-32 (A and B). The values plotted for riverbed elevation changes (Figure 5-32A) were derived from sediment volume tables in Appendix A. The values plotted for changes in water surface elevations during a 13,000 cfs discharge (Figure 5-32B) are extracted from Tables 5-6 through 5-10 (bottom boxes, mean values). There appears to be a consistent similarity in the magnitude and direction of changes in sediment levels and changes in water surface elevations at both the reach scale and the subreach scale. Though not shown here, the same similarities occur with a 11,700 cfs (30-year) flood.

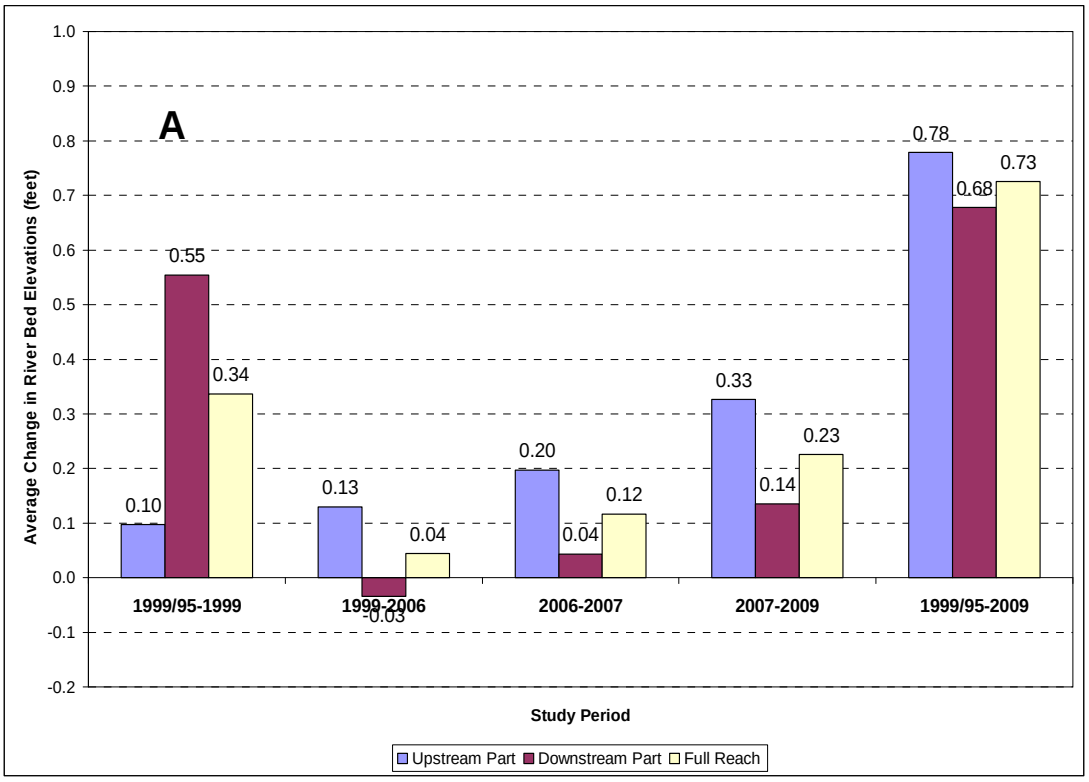


**Figure 5-32A: Changes at the subreach scale and reach scale in average riverbed elevations, by study period**

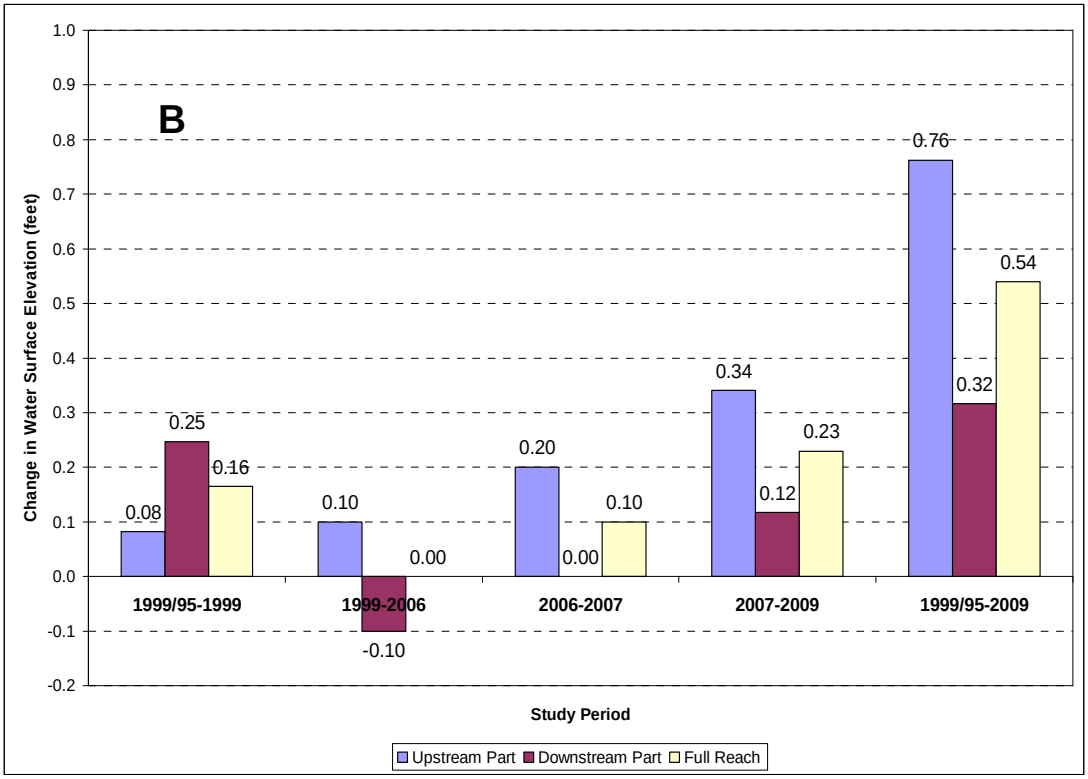


**Figure 5-32B: Changes at the subreach scale and reach scale in water surface elevations during a 13,000 cfs (50-year) flood, by study period**

More spatial detail is provided in Figure 5-33, where vertical changes in riverbed elevations and water surface elevations are compared at each cross section from 1992/95 to 2009 conditions. The shape and relative magnitude of plots suggest that there are different processes and responses occurring in the different parts of this study reach, but also that there are some similarities between the plots of average riverbed and water surface elevations. For example, from RM 2.85 to RM 3.02, there were minimal changes in water surface elevations even where there were moderate increases in riverbed elevations (e.g., at RM 2.97). This apparent insensitivity of water level changes to sediment level changes would be consistent with backwater conditions upstream of the North Bend Boulevard (Bendigo) Bridge.

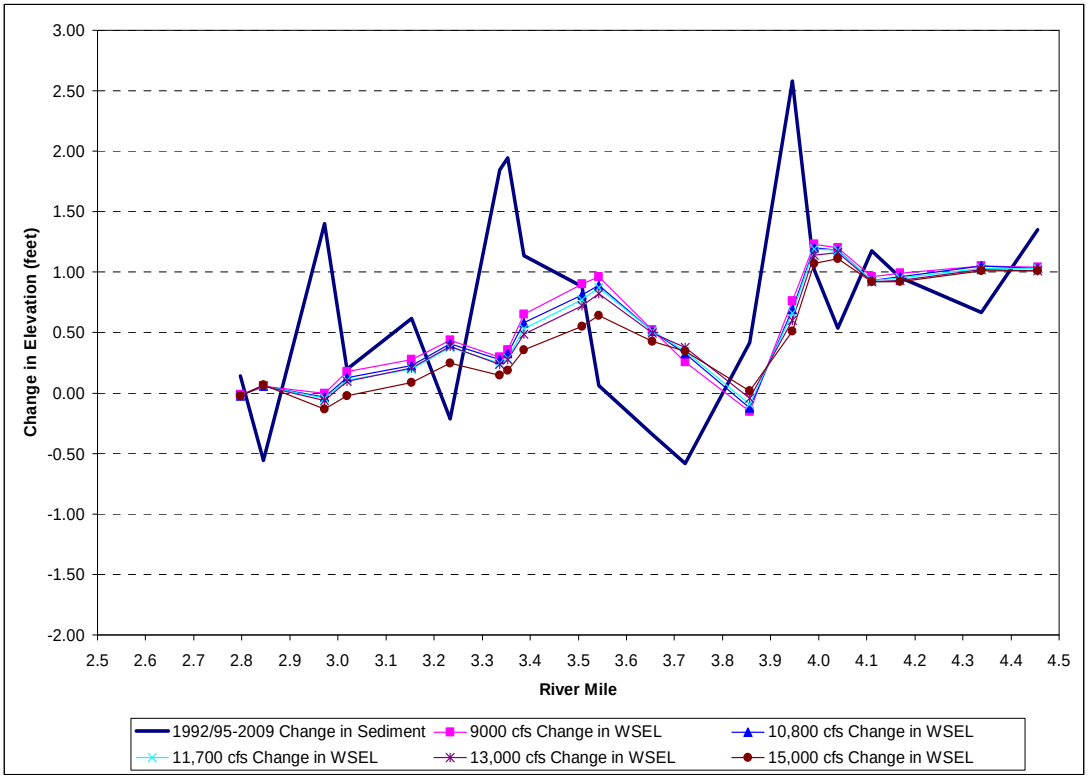


**Figure 5-33: Change in average riverbed elevations and water surface elevations at each cross section comparing 1992/95 to 2009 channel conditions on the South Fork Snoqualmie River**

From RM 3.23 to the upstream end of this reach, the plots of changes in water surface elevations have a generally similar shape and directional trend as the plot of changes in riverbed elevations, but the plots of water surface elevation changes are offset from the plot of riverbed changes in the upstream direction by about 0.2 to 0.25 river miles. It is consistent with hydraulic principles that water surface responses to channel changes would manifest in the upstream direction in this flow regime. The general similarity of the shape and trends in the plots in Figure 5-33 suggests that both depositional and erosional channel changes (upstream of backwater conditions) consistently were reflected in water surface elevation changes, though offset a certain distance upstream.

### 5.4.8 Discussion of flooding under existing conditions and changes since the beginning of the study time period

This subsection briefly recaps changes in computed water surface elevations through the time periods of 1992/95 to 1999, 1999 to 2006, 2006 to 2007, 2007 to 2009 and 1992-95 to 2009, for the upstream and downstream parts of the study reach. The downstream part of the study reach is taken as RM 2.85 to RM 3.54 and the upstream part is taken as RM 3.65 to RM 4.46. Findings from this study would be considered notable and of concern if there were clearly identified increases in water surface elevations under existing conditions through the study period that can be attributed to sediment accumulation, where the increased water surface elevations result in increased flooding, and where the increased flooding causes damage to structures or threatens public safety.

The most clearly identified increases in water surface elevations for all of the analyzed flows occurred in the upstream part of the study reach during the 1992/95 to 2009 full study period, particularly in the vicinity of RM 3.95 to RM 4.46. The upstream part of the study reach had increases in water surface elevations up to 1.2 feet during the full study period, with most increases exceeding a half foot through the range of analyzed flows. However, these increases in water surface elevations did not increase the occurrence or extent of flooding nor increase flood damages or the threat to public safety. Continued channel conveyance capacity by the existing levees of not just 13,000 cfs plus one foot of freeboard but also containment of 15,000 cfs (100-year flood) and greater along both banks and at almost every cross section in this upstream area through the full study period of 1992/95 to 2009 demonstrates a considerable level of flood protection for this upstream area. The notable exception is that channel conveyance capacity has decreased from 17,400 cfs to 14,200 cfs in the last three years along the left bank at RM 3.99. Channel conveyance capacity in the upstream part of the study reach continues to meet or exceed the original design capacity at all locations except at RM 3.99.

In the downstream part of the study reach, changes in water surface elevations over the full study period present a less clear picture. Changes in water surface elevations in this area during individual periods include: minor to moderate increases in water surface elevations during the 1992/95 to 1999 period, negligible to negative changes from 1999 to 2006, negligible to minor increases from 2006 to 2007, and minor increases from 2007 to 2009. A minor increase might be considered less than one-half foot; a moderate increase might be one-half foot to a foot. The changes in each of these individual time periods combine to make minor to moderate cumulative water surface elevation increases from 1992/95 to 2009. Specific elevation changes are listed in Tables 5-7 through 5-11. Overall, there does not appear to be a consistent trend in water surface elevation changes throughout the downstream part of the study reach through the full 1992/95 to 2009 study period. However, the localized increases in water surface elevations of about one-half foot (Table 5-11) along RM 3.34 to RM 3.39 from 1992/95 to 2009 conditions, much of which occurred in the 2007 to 2009 period, are important findings in this downstream area because these increases are adjacent to locations of previous overtopping and damaging flood flows. It should be noted that the short-term increases in both sediment deposition and resulting water surfaces are closely related to the magnitude and duration of river flows during those time intervals. Thus, the large changes in recent years appear to be a result of the record and high flows that occurred in November 2006, November 2008 and January 2009.

As described in Section 3, agreement between a calibrated hydraulic model and observed flood levels to within plus or minus one-half foot is assumed to be adequate accuracy for a flood study (FEMA 1992). This inherent modeling uncertainty of plus or minus one-half foot provides context for the results of this analysis, where changes in water surface elevations in the upstream part of the study reach from 1992/95 to 2009 conditions (up to 1.2 feet increase) clearly exceeded inherent modeling uncertainty and changes in water surface elevations in the downstream part of the study reach (up to 0.6 feet increase) approached or exceeded inherent modeling uncertainty.

The channel conveyance capacity in the downstream part of the study reach decreased by 800 cfs (from 12,500 cfs to 11,700 cfs) from 1992/95 to 2009 at RM 3.39. The channel conveyance capacity decreased by 400 cfs during the same period at both RM 3.34 and RM 3.35. The channel conveyance capacity at RM 2.97 stayed essentially unchanged at 11,800 cfs to 12,000 cfs through the full study period. All of these conveyance capacities are less than the flood reduction objective of containing 13,000 cfs plus one foot of freeboard.

Changes in modeled water surface elevations at RM 2.97 and RM 3.02 were negligible through the full study period and full range of analyzed flows (Table 5-11), even as sedimentation occurred in the same locations (e.g., Figure 5-30), which is consistent with backwater conditions due to North Bend Blvd Bridge. However, changes in the existing conditions modeled water surface elevations throughout the study period in the area of RM 3.15 to RM 3.23 (Table 5-11) suggest that noticeable backwater conditions may not extend far upstream of RM 3.02. This would be a lesser extent of backwater influence than described by Kato and Warren, Inc (2000), who assert that backwater during a 13,000 cfs flood and larger would propagate upstream to RM 3.23. The difference in extent of modeled backwater influence between the two studies, especially at 13,000 cfs, may be due to the use of different hydraulic equations at the North Bend Blvd Bridge (see explanation in Section 3.3). In any case, backwater conditions dominate the downstream end of this study reach, at least within about 1,000 feet of North Bend Blvd Bridge, and remain a major factor to consider in characterizing and attempting to reduce existing flood hazards.

For the full study reach and its upstream and downstream parts, the trends in water surface elevation changes generally track the trends in sediment levels, with some exceptions. A large portion of the overall sediment deposition during the full study period occurred in the 1992/95 to 1999 period, a period immediately after gravel removal operations. While those excavations would have increased channel capacity, they also created conditions such as locally wider channels and locally decreased channel gradient that the literature (Section 2) indicates can favor sediment deposition. This same period also saw a large portion of the overall increases in water surface elevations. From 1999 to 2006, it is consistent that the negligible changes in sediment levels had corresponding negligible increases or even decreases in water surfaces. These negligible sediment changes corresponded to a time period with relatively small annual peak flows. The moderately large amount of deposition throughout the reach brought in by the November 2006 flood resulted in negligible to minor increases in water surface elevations comparing 2006 to 2007 conditions throughout the study reach except at RM 3.95 to RM 4.04 (gravel bar 6), where there were moderate increased water surface elevations in this period. From 2007 to 2009, the minor to moderate increases in water surface elevations were evident after a large amount of deposition occurred reachwide. A minor change in water surface

elevation might be considered less than one-half foot; a moderate change might be considered one-half foot to a foot.

The only differences between the hydraulic models for the 1992/95, 1999, 2006, 2007 and 2009 conditions are in the channel geometry, and those channel changes are due to changes in sediment levels. Because all other hydraulic modeling variables were held unchanged in this study, any increases in computed water surface elevations throughout the study reach from 1992/95 to 2009 are attributed to sediment deposition. Given this result, further consideration of sediment management actions may be warranted and gravel removal is one such sediment management action (King County 2006). Analyses that evaluate the flood hazard reduction effectiveness and likely effects of gravel removal are presented in subsequent sections of this report.

## 5.5 Fishes of the South Fork Snoqualmie River and their habitats

### 5.5.1 Fishes of the South Fork Snoqualmie River

Salmonids:

Because Snoqualmie Falls lies on the Snoqualmie River mainstem downstream of the three forks of the upper river, no anadromous salmonids are present in the South Fork Snoqualmie River. Nevertheless, four species of salmonid, two native and two introduced, can be found throughout the South Fork Snoqualmie River. Coastal cutthroat trout (*Oncorhynchus clarki clarki*) are native to the South Fork Snoqualmie River and can be found throughout the river, from the headwaters at Source Lake to Snoqualmie Falls. In the channelized reaches and along I-90, the specimens tend to be small due to the lack of extensive pool habitat. A related sub-species, westslope cutthroat trout (*Oncorhynchus clarki lewisi*), is found in the upstream, colder reaches of the river, generally above 2,500 feet elevation and its range probably does not extend downstream past Twin Falls (Overman 2008). A second native species, mountain whitefish (*Prosopium williamsoni*), is found in low numbers from Twin Falls downstream to Snoqualmie Falls. The two introduced salmonid species are rainbow trout (*Oncorhynchus mykiss*) and Brook trout (*Salvelinus fontinalis*). Despite having appropriate habitat conditions for bull trout (*Salvelinus malma*), none of this species have been found upstream of Snoqualmie Falls (see the discussion below).

The salmonid species that occupy the South Fork Snoqualmie River exhibit some shared life history traits but have some distinct attributes that separate species and sub-species as well. Coastal cutthroat and westslope cutthroat share three life history forms: an adfluvial form where the individuals spawn in streams and move to lakes to feed; a fluvial form where the individuals spawn and rear in streams and move to large rivers as adults; and the resident form where the individuals remain is small streams throughout their lives. While not much is known with certainty about the various life history forms of cutthroat in the South Fork Snoqualmie River, it is likely that the coastal form exhibits both the fluvial and resident life history, while westslope cutthroat are likely to be dominated by the adfluvial and resident forms, given their access to

alpine lakes and the small size of their home streams. Nevertheless, some fluvial forms probably occur in the mainstem river above Twin Falls.

Spawn timing for each of these species is critical to evaluating the effects of gravel removal on the populations. In general, salmonids are either autumn spawners or spring spawners. The several species present in the South Fork Snoqualmie River show that variation clearly. Coastal cutthroat trout generally spawn in smaller, headwater streams where flow does not exceed about 5 cfs and tend to select patches of small gravel (up to 2 inches) in water depths from 0.5 to 1.5 feet and velocities between 6 and 15 inches per second. Spawning in the South Fork Snoqualmie River cutthroat generally is assumed to occur between March and late July when the fish are about four years old. A 2006 survey in the lower South Fork Snoqualmie River, below the study reach, found cutthroat redds and eggs in early March (personal communication, N.C. Overman, 2009). Given the water temperature during this time of the year, this may be an indication of the earliest spawning activity in the system and the timing would hold for the project reach as well. Cutthroat living higher in the system would be expected to spawn toward the end of the assumed window, probably in July as streams warm after spring snowmelt.

Rainbow trout (*Oncorhynchus mykiss*), though native to the west, are probably not native to the South Fork Snoqualmie River. Most native populations occur in coastal streams and rivers downstream of impassable barriers such as Snoqualmie Falls. The species has been planted throughout the upper Snoqualmie River system and can be found in all three forks of the river. In the South Fork Snoqualmie River, rainbows are distributed all the way to the headwaters at Source Lake near Snoqualmie Pass. In recent years, rainbow-cutthroat hybrids have been reported from all three forks of the Snoqualmie. Rainbow trout share a late winter to spring spawning timing with cutthroat in the South Fork Snoqualmie River. Beginning in late February or early March in the lower river, when the fish are three years old, spawning may continue through June in the upper reaches accessible to rainbow.

Although consistent data are quite poor, both cutthroat and rainbow trout have been observed spawning in the study reach, particularly on the tail-outs of the few pools that occur in this reach. Casual observation has also revealed both cutthroat adults and juveniles in the larger pools. However, since the information about spawning and rearing distribution through the project reach is relatively poor, further observations would be necessary to estimate the full extent of salmonid use here. Mountain whitefish also spawn in the fall as temperatures decline, generally from September to December depending on elevation. The fish stage in deep pools until the eggs are ripe, then move to riffles to construct nests and deposit eggs. The species becomes sexually mature at about age 4, similar to other salmonids in the South Fork Snoqualmie River.

The second non-native is Brook trout (*Salvelinus fontinalis*), really a char, and was planted throughout Pacific Northwest streams in the late 19$^{th}$ and early 20$^{th}$ century to improve what was thought to be a “poor” fishery in many streams. This char is generally confined to the colder portions of the rivers in which it is found. Eastern brook trout spawn in the fall, at age 2-3, beginning in August and continuing through December as water temperatures are dropping. The fish prefer cool, clear, headwater streams fed by springs and are most likely to be found far upstream from the project area.

In these cooler, higher elevation streams, the various salmonid species are not nearly so prolific as their downstream counterparts. South Fork Snoqualmie River cutthroat, for example, may carry less than 250 eggs at the time of spawning whereas lower river females may carry as many as 2,500. Egg production tends to be related to size and the cold, somewhat infertile, waters of the South Fork Snoqualmie River do not allow for high growth rates or great size at maturity. Some of the females are repeat spawners, however, although the percentage varies between 0.7 percent and 24 percent, and some may spawn in alternate years. In contrast, whitefish may contain between 2,900 and 7,000 eggs for a fish about one foot long.

In 1999, the Puget Sound populations of bull trout (*Salvelinus malma*), were listed as "threatened" by the USFWS. This species prefers cold, clear water for rearing and spawning and, according to the USFWS, *may* occur in the upper reaches of the forks of the Snoqualmie, including the South Fork Snoqualmie River. Occasional anglers have reported "Dollies" (Dolly Varden is a close relative of bull trout) above Snoqualmie Falls and, in 2000, a catch of a Dolly Varden was reported by an angler fishing the South Fork Snoqualmie River near the Washington State Fire Academy at about river mile 14. In response to the listing, King County, together with U.S. Forest Service, and the University of Washington conducted electrofishing and snorkel surveys for bull trout in the three forks of the Snoqualmie in the fall of 2000. Despite extensive surveys, neither bull trout nor Dolly Varden was detected. Although lack of detection does not mean that the species are absent from the South Fork Snoqualmie River, it does suggest that, if they are present, their density is quite low.

Other, non-salmonid fishes of the South Fork Snoqualmie River:

Largescale sucker (*Catostomus macrocheilus*), shorthead sculpin (*Cottus confusus*), and mottled sculpin (*Cottus bairdi*) are present in the South Fork Snoqualmie River (WDFW 2008); torrent sculpin (*Cottus rhotheus*) and Paiute sculpin (*Cottus beldingii*) were collected in the South Fork Snoqualmie River some 80 years ago (Smithsonian Museum Collections, 1929) but their status today is unknown. Three-spined stickleback (*Gasterosteus aculeatus*), longnose dace (*Rhinicthys cartaractae*), and the redside shiner (*Richardsonius balteatus*) are also likely to be found in the South Fork Snoqualmie River. None of these species are considered sensitive in the meaning of the ESA nor are they listed by Washington State as Species of Concern.

### 5.5.2 Habitat characteristics of the South Fork Snoqualmie River and the study reach

The South Fork Snoqualmie River rises in Source Lake, above Snoqualmie Pass, and flows some 31 river miles to its confluence with the mainstem Snoqualmie about two miles north of North Bend. The upper six to seven miles of the river is steep, with numerous falls, cascades, and rapids occasionally separated by short pool-riffle sections. The bottom and banks are bedrock, boulder and rubble, with rare gravel patches.

In the next 12 miles, to the confluence with Change Creek at about RM 12.9, the gradient eases and the river valley broadens and narrows intermittently. Channel splits are few and a good pool-riffle balance exists throughout. The bed is mostly large cobble and gravel with few boulders, and the banks are earth cuts, bedrock and gently sloping gravel-cobble beaches. The

riparian zone is densely forested with conifer and deciduous trees, and woody debris—mostly in large jams—is abundant. Considerable logging has taken place in the local watershed on the slopes above this segment of the South Fork and the channel exhibits splits and braids where large sediment flows have entered the river from upslope. This segment of the river is sediment-rich and gravel bars are large and extensive.

Below Change Creek, the river once again enters a narrow canyon. There are numerous cascades and drops, and two large falls; the largest is Twin Falls at RM 11 where a hydroelectric project is in place near Twin Falls State Park. Below Twin Falls, the river gradient decreases and remains moderate to the confluence with the mainstem Snoqualmie. Pools and riffles alternate with a few split channel areas until the City of North Bend. As the river approaches North Bend at about RM 6.0, natural banks and contours give way to artificial contouring and bank protection (riprap) that is continuous through the city until approximately RM 1.8. This segment contains the study reach (RM 2.85 to RM 4.46) for the gravel removal analysis and the description of this segment of the river is taken from reconnaissance-level field work carried out in the summer of 2008. From the lower end of the study reach downstream, bank protection continues for another 0.9 miles then gives way to natural banks through Three Forks Natural Area. In the Three Forks reach, the river is free to meander across its floodplain, creating a broad active channel. Within the channel, a balanced pool-riffle character occurs and habitat diversity is comparatively high. Large woody debris, while not abundant, is common and well-distributed, anchoring many pool features and side channels.

Habitat of the study reach

When contrasted with the unconfined reaches of the South Fork Snoqualmie River, the quality and diversity of stream and riparian habitats within the study reach tends to be quite low. Few significant pools occur, except at sharp outbends; channel splits and bar-based channels are quite rare, and riparian vegetation is patchy, consisting of young stands of deciduous species—mainly alder, willow, and cottonwood—occupying gravel bars within the channel prism. At the uppermost subreach in the study reach (gravel bars 9 and 8; approximately RM 4.46 to RM 4.17), the in-stream habitats are riffle-run combinations, essentially fast-moving, shallow water areas with very little variation in depth from bank to bank. No pools of any note occur here and only one or two areas of still or backwater alcoves are found along the bar edges. At this writing, vegetation on the uppermost channel bar (gravel bar 9; coverage 30 percent) is dominated by shrubs and small (< 5 feet tall) trees with noticeable patches of the invasive plant Japanese knotweed (*Polygonum cuspidatum*). The lowermost gravel bar in the subreach (gravel bar 8; coverage 50 percent) is somewhat more vegetated, with significant tree cover composed mostly of 20 to 30 foot cottonwood and alder. Pieces and accumulations of large wood —logs, stumps, and rootwads—are rare in this uppermost subreach and throughout the study reach in general, but the occasional small log and debris pile can be found rafted up on the gravel bars.

In the middle part of this study reach, from RM 4.11 to about RM 3.3 (gravel bars 7, 6, 5, 4, and 3), the channel is once again dominated by riffle-run habitat units. This is somewhat surprising given that the channel contains a long meander (from about RM 3.8 to RM 4.0 along gravel bar 6) where deep pools along the outside edge would be expected. Instead, a narrow chute of fast water occurs along the rocked toe of the channel bank. Overall, there is little depth variation from inside to outside bend here, and shallow water edges dominate the river along the bars.

Gravel bar 6 has a long back-bar channel with several scour pools, some with standing water during field reconnaissance in summer 2008, but no fish were observed in them. Further down in this subreach at gravel bar 5 (RM 3.65), there are multiple back-bar channels. The gravel bar 5 and 6 back-bar channels are the only variations in habitats off the main channel in the entire study reach. The two largest bar channels originate at the upstream end of gravel bar 5 where the channel is flowing west. The bar channels cross the large meander at RM 3.65 to exit to the river at the gravel bar 5 apex. During field reconnaissance, several small salmonids—probably cutthroat trout—were observed in the largest of these bar channels. Beaver cutting were obvious in the willow stands surrounding the multiple channels along gravel bar 5. A shallow backwater area occurs along the back side of gravel bar 4 at its downstream end and there is evidence of moving water through the area when flows rise sufficiently.

Vegetation conditions vary greatly from bar to bar in this subreach and tend to be dominated by shrubs and young, small trees—a legacy of the last gravel removal work done in the early 1990s. Willow, cottonwood and alder dominate the shrub and tree layer but most are less than 20 feet in height. Gravel bar 4 is entirely vegetated (100 percent), and tree-dominated, mainly by alder and cottonwood, with an understory of small willow. Gravel bar 3 is less than 20 percent vegetated—mostly bare gravel—with shrubs and a few large trees about mid-bar. Gravel bar 5 is almost completely vegetated (> 90 percent) with willow and alder, while gravel bar 6 has the largest trees (some greater than 30 feet tall) but only 10 percent total cover. Gravel bar 7 has about 30 percent vegetative cover, mostly shrubs and small trees. Three invasive species are common throughout the full study reach: knotweed, butterfly bush (*Buddleja davidii*) and tansy ragwort (*Seneceo jacobaea*).

Woody debris pieces are few and scattered in this subreach. Three logs about 15 feet long reside on gravel bar 7, five pieces on the downstream end of gravel bar 6, and gravel bar 5 has several large pieces rafted into a jam between and aligned with the bar channels described above. About four large trunks—24 inches in diameter by 30 feet in length—form the nucleus of the jam and several smaller pieces are wedged within the main jam. Gravel bar 4 has several pieces but they are relatively small and are not well-anchored in the gravel.

The lowermost subreach in the study reach comprises gravel bars 2 and 1 from RM 3.3 downstream to the end of the study area at RM 2.85. Once again, riffle-run habitats dominate the river but a single pool at the outside bend at RM 3.23 is long and deep, extending almost the total length of the left bank gravel bar 2. Gravel bar habitats are dominated by shallow, sloping edges, especially in the downstream portions of the bars (where lower velocities allow finer gravel to settle at shallow angles) except at gravel bar 1 where the gravel face is rather steep to the channel bed. Gravel bar 2 is entirely vegetated (100 percent) with shrubs and trees—some very large cottonwoods occur along the back edge of the bar and others overhang the channel edge. Gravel bar 1 is entirely vegetated but mostly with grasses and shrubs. Some small trees—mostly willow—occur on the downstream end of the bar where the shallow edge habitat is found. Vegetation on the upstream 75 percent of the gravel bar has been systematically cut in front of a series of condominiums that face the river. One value of this maintenance may be the control of a large infestation of knotweed that occupies the gravel bar. Knotweed and Scot's broom (*Cytisus scoparius*) are common invasives on all bars in this downstream subreach. Large wood is rare but one or two pieces are present on all bars.

### 5.5.3 Conclusions regarding salmonid habitat

The habitats through the study reach tend to be simple and lack variation in depth and structure, most likely a legacy of the historic channelization of the river, the occasional and recent removal of gravel, and, quite possibly, the greater loads of gravel being transported down the river in recent times (USFS 1995). In the main channel, fast-moving water dominates in the form of riffles and runs with only rare pools and very few still-water areas of any size and these are associated with the downstream end of the gravel bars, in the lee of the flow. In fact, run habitats make up some 70 percent of the habitat units surveyed during the summer of 2008. Still-water features, including backwaters, alcoves, the back-bar channels of gravel bars 5 and 6, and other slackwater habitats account for less than 10 percent; the main channel riffles and the single long pool at gravel bar 2 account for the remaining 20 percent.

Young, small trees and shrubs dominate the vegetation on all gravel bars where they occur, a legacy of past gravel management, although large areas of some gravel bars are devoid of vegetation (average gravel bar coverage is about 60 percent). Three invasive species are common throughout the study reach: knotweed, butterfly bush, and Scot's broom. Large wood in the form of logs and stumps are rare and few of the pieces are in contact with the flow at the river level observed during this survey. Only the pieces on gravel bar 5 seem to be in a position to form and influence habitat structure. The gravel bar 5 large wood may be responsible for the formation of the cross-bar channel features found on this bar. In total, the survey of the entire study reach in 2008 found only 23 pieces that qualify as large woody debris (10 feet long and 6 inches in diameter). High flow events since the field reconnaissance in summer 2008 (including November 2008 and January 2009) may have added or removed pieces from the study reach. Any proposal to remove gravel from the study reach should include a current survey of habitat types, riparian vegetation, and woody debris.

## 5.6 Conclusions regarding existing conditions

The following is a summary of conclusions or main findings from this section of the report on existing conditions. The conclusions are listed in the same general order as the topics in this section—sediment, hydraulics and flooding, and salmonid habitat. There is no priority of conclusions intended in the order this list.

1. The study reach is located in an area of decreasing channel gradient, constrained laterally by levees and confined at the downstream end by a bridge that causes backwater conditions, all of which are conditions that can favor sediment deposition. Based on upstream conditions, it is assumed that coarse sediment will continue to be delivered to this study reach at its current rates, which appear to exceed historical rates, for decades to come.

2. The estimated average annual sediment deposition rate from 1992/95 to 2009 and over the full study reach is 2,700 cubic yards/ year, with much variability among the individual study intervals. This calculated average deposition rate is within the range of sediment deposition estimated in previous studies of this same study reach, and consistent with deposition observed on similar rivers in the region.

3. Spatial patterns of sediment deposition are evident within the study reach, where deposition consistently occurred in some areas, erosion occurred in other areas, and some areas exhibited negligible change. These patterns remained consistent through much of the full study period.

4. The amount of deposition during any of the four individual study periods (1992/95-1999, 1999-2006, 2006-2007, and 2007-2009) appears to have been influenced primarily by both the magnitude and duration of the flood flows that occurred during that period and possibly by how recently prior gravel removal occurred.

5. The original design capacity of the channel, which is estimated at 13,000 cfs plus one foot of freeboard, is contained by the existing conditions along both banks everywhere in the upstream part of the study reach (RM 3.64 to RM 4.46) except the left bank at RM 3.99. Existing conditions along the right bank also continues to meet or exceed the original channel design capacity in the downstream part of the study reach (RM 2.85 to RM 3.54) except near North Bend Blvd (Bendigo) Bridge. The left bank along most of the downstream part of the study reach does not presently contain 13,000 cfs plus one foot of freeboard.

6. Hydraulic modeling results of this study indicate that backwater conditions due to the North Bend Blvd (Bendigo) Bridge clearly exist upstream to about RM 3.02. Kato and Warren, Inc (2000) state that the North Bend Blvd Bridge would not have freeboard for the present-day 50-year (13,000 cfs) and greater floods, and that the associated backwater conditions would propagate upriver to about RM 3.23. These backwater conditions overwhelm any effects of gravel deposition on water surface elevations in this downstream portion of the study reach.

7. Changes in modeled water surface elevations varied for the four individual study periods and in the upstream and downstream parts of the study reach. A minor increase might be considered less than one-half foot and a moderate increase might be considered between one-half foot and one foot. In the downstream part of the study reach (RM 2.85 to RM 3.54), there were minor to moderate increases from 1992/95 to 1999, negligible increases or decreases from 1999 to 2006, negligible to minor increases from 2006 to 2007 (which included the November 2006 flood of record) and minor increases from 2007 to 2009. In these same individual study periods, there were minor to moderate increases in water surface elevations in the upstream part of the study area (RM 3.65 to RM 4.46) in each of the individual study periods. Inherent modeling uncertainty is assumed to be about plus or minus one-half foot (Section 3.3).

8. Through the full study period (1992/95 to 2009), modeled water surface elevations have increased at almost every cross section in the study reach at each of the analyzed flows. These increases are clearest in the upstream part of the study reach (RM 3.65 to RM 4.46), where there was a mean increase of about 0.8 feet in the analyzed flows through the full study period (Table 5-11). In the downstream part of the study reach (RM 2.85 to RM 3.54), there was a mean increase in the water surface elevations of about 0.3 feet seen in the analyzed flows through the full study period (Table 5-11).

9. More recently, the 2007 to 2009 period saw increases in water surface elevations of about 0.2 feet along RM 3.34 to RM 3.39 (adjacent to Berry Estates). While these are minor increases, they occurred over a relatively short time interval, were consistent across the range of analyzed flows at the three cross sections (Table 5-10), and occurred adjacent to the location of previous overtopping and damaging flood flows. Along gravel bar 6 (RM 3.95 to RM 4.04), there have been marked increases in water surface elevations from 2006 through 2009, with a cumulative total increase in water surface elevations across the analyzed flows of about one foot in those three years (Tables 5-9 and 5-10). These recent increases in water surface elevations at these two locations are important findings of this study.

10. The trends in increases (and decreases) in water surface elevation changes appear to generally correspond to the trends of changes in sediment deposition (and erosion) on the reach scale and the subreach scale during individual study periods and through the full study period. The timing of greatest sediment deposition appears to be closely correlated to the occurrence of flood flows of high magnitude or long duration above a threshold of coarse sediment movement, or both.

11. Because the only differences between the hydraulic models for the 1992/95, 1999, 2006, 2007 and 2009 existing conditions are in the channel geometry, and those changes in channel geometry are due to changes in sediment levels, increases in water surface elevations throughout the study reach from 1992/95 to 2009 are attributed to sediment deposition.

12. The changes in sediment levels and resulting modeled water surface elevations indicate that further consideration of a sediment management action (King County 2006) for this study reach is warranted. Gravel removal is one such sediment management action. Analyses that evaluate the flood hazard reduction effectiveness and likely effects of gravel removal are presented in subsequent sections of this report.

13. No anadromous salmonids inhabit the South Fork Snoqualmie River, which is upstream of Snoqualmie Falls. This reach of the South Fork Snoqualmie River supports the two native salmonid species, the western cutthroat trout and the mountain whitefish, and two non-native salmonid species, the rainbow trout and Brook trout. Bull trout, which are listed as "threatened" under the ESA, have not been detected in this part of the South Fork Snoqualmie River.

14. The habitats through the study reach tend to be simple and lack variation in depth and structure. In the main channel, fast-moving water dominates in the form of riffles and runs with only rare pools and very few still-water areas of any size. The reconnaissance-level field observations of summer 2008 noted that run habitats make up some 70 percent of the habitat units; still-water features, including backwaters, alcoves, the back-bar channels of gravel bars 5 and 6, and other slackwater habitats account for less than 10 percent; the main channel riffles and the single long pool near RM 3.23 account for the remaining 20 percent.

# 6. Hydraulic modeling of gravel removal

## 6.1 South Fork Snoqualmie River gravel removal scenarios analyzed by modeling

The gravel removal scenarios on the South Fork Snoqualmie River study reach analyzed by hydraulic computer modeling in this study are the gravel bar Scalp Scenario 1, Scalp Scenario 2 and Scalp Scenario 3. These scenarios are described generally in Section 4. The specific application of these scenarios to this study reach is described and the modeling results are presented in this section. The existing condition against which the gravel removal scenarios are compared is the 2009 channel condition. A summary of the modifications to cross sections in the hydraulic model that represent each gravel removal scenario is presented in Table 6-1.

A low flow analysis determined that the mean seven-day low flow averaged over a 20-year period is 104 cfs at the South Fork Snoqualmie River at North Bend USGS gage 12144000. This low flow discharge was used in the hydraulic model to determine the low flow elevation at each cross section, which was used to configure the bar scalping scenarios.

All of the hydraulic modeling completed to evaluate the effect of gravel removal scenarios on flood levels was done using the “Raised Levee” condition in the HEC-RAS model (described in Section 3.3). Hence, all elevations of modeled water surfaces for flows that occur above the top of the river bank are overstated to some degree (i.e., water surface elevations computed with Raised Levees likely are slightly greater than those that would occur during actual overbank flow).

Experience from past observed flood events plus hydraulic modeling results indicate that the lower and upper parts of this study reach have distinct flooding characteristics, as described in Section 5. The downstream part of the study reach refers to RM 2.85 to RM 3.54 and the upstream part of the study reach refers to RM 3.65 to RM 4.46.

Bar Scalp Scenario 1:

Gravel removal is simulated under Scalp Scenario 1 at seven of the 21 cross sections in this reach (RM 2.97, 3.34, 3.35, 3.51, 3.95, 4.04, and 4.11) and would affect gravel bars 1, 3, 4, 6, and 7 (Figure 6-1). The volume of gravel that would be removed in this scenario is about 22,000 cubic yards.

Bar Scalp Scenario 2:

Gravel removal is simulated under Scalp Scenario 2 at 15 of the 21 cross sections in this reach (RM 2.97, 3.02, 3.23, 3.34, 3.35, 3.39, 3.51, 3.65, 3.95, 3.99, 4.04, 4.11, 4.17, 4.34 and 4.46) and would affect gravel bars 1, 2, 3, 4, 5, 6, 7, 8, and 9 (Figure 6-2). The volume of gravel that would be removed in this scenario is about 51,000 cubic yards.

**Table 6-1: South Fork Snoqualmie River cross sections modified for gravel removal scenarios**

| Cross Section (River Mile) | Gravel Bar Number (note A) | Scalp Scenario 1 (note B) | Scalp Scenario 2 (note C) | Scalp Scenario 3 (note D) |
|---|---|---|---|---|
| Upstream | | | | |
| 4.46 | Bar 9 | | X | |
| 4.34 | Bar 8 | | X | |
| 4.17 | Bar 7 | | X | |
| 4.11 | Bar 7 | X | X | |
| 4.04 | Bar 6 to 7 | X | X | |
| 3.99 | Bar 6 | | X | |
| 3.95 | Bar 6 | X | X | |
| 3.86 | Bar 6 | | | |
| 3.72 | Bar 5 to 6 | | | |
| 3.65 | Bar 5 | | X | |
| 3.54 | Bar 4 | | | |
| 3.51 | Bar 4 | X | X | X |
| 3.39 | Bar 3 | | X | X |
| 3.35 | Bar 3 | X | X | X |
| 3.34 | Bar 3 | X | X | X |
| 3.23 | Bar 2 | | X | X |
| 3.15 | Bar 2 | | | |
| 3.02 | Bar 1 | | X | X |
| 2.97 | Bar 1 | X | X | X |
| Downstream | | | | |

**Table 6-1 Notes:**
**"X"** means that the 2009 existing conditions cross section was modified to simulate bar scalping for this gravel removal scenario. A blank cell means the cross section was not modified.
A: Gravel bars are numbered sequentially going upstream from North Bend Blvd Bridge per Shannon & Wilson (1993).
B: Scalp Scenario 1 would excavate to within 2 feet vertical of the low flow water elevation, with no scalping at the upstream third of the gravel bar or where woody vegetation exists. The finished scalp surface of the bar would slope at 2 percent up and away from the channel.
C: Scalp Scenario 2 would excavate to within 1 foot vertical of the low flow water elevation. It also would excavate areas regardless of the presence of woody vegetation and the upstream third of the gravel bar. The finished scalp surface of the bar would slope at 2 percent up and away from the channel.
D: Scalp Scenario 3 is identical to Scalp Scenario 2 in the downstream part of the study reach; no excavation would occur upstream of RM 3.51.

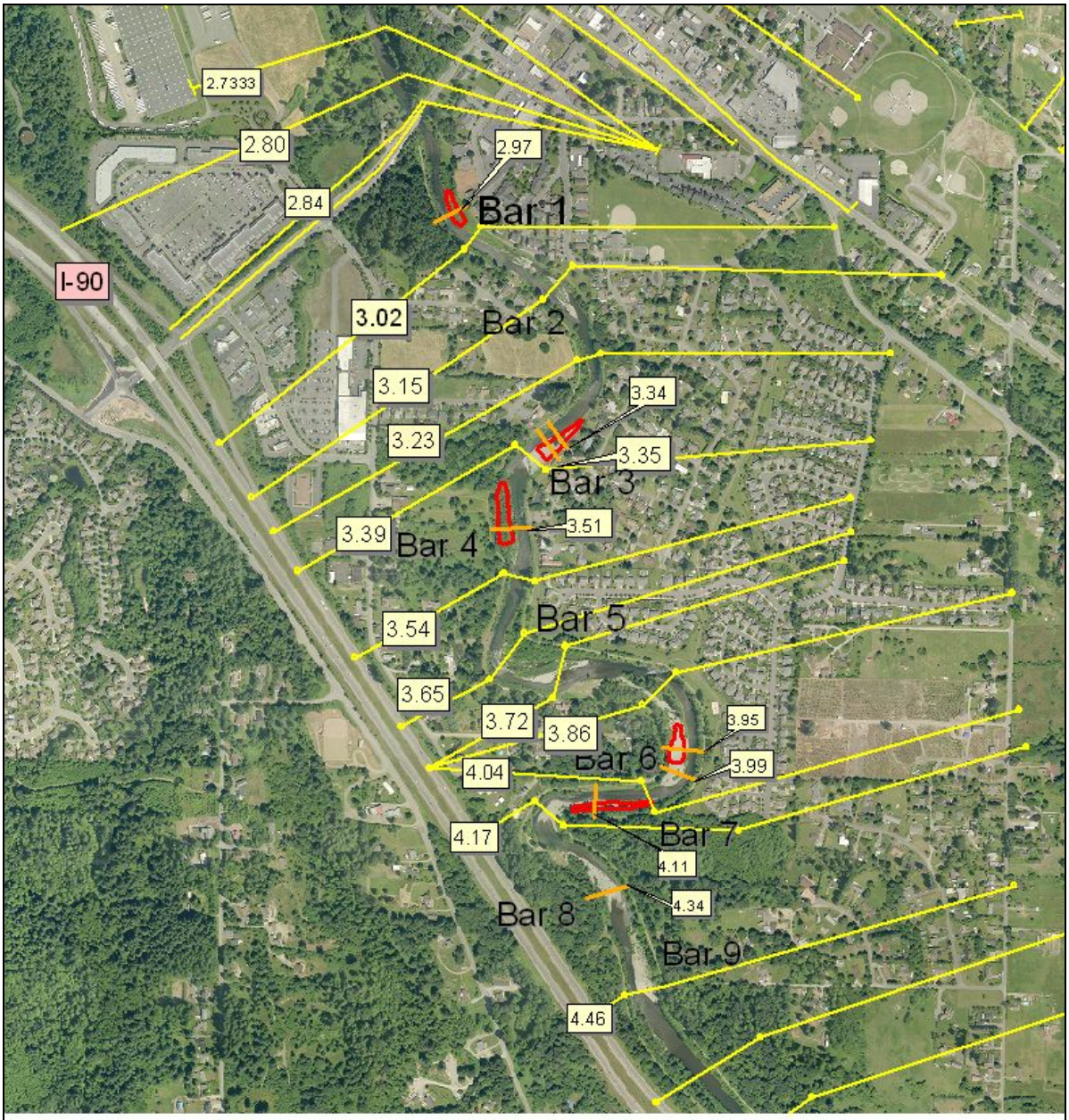


**Figure 6-1:**
**South Fork Snoqualmie River**
**Schematic of Bar Scalping Scenario 1**
**Yellow = Flood Study (FEMA 2005) cross sections**
**Orange = Additional surveyed cross sections**
**Red = Bar Scalping simulated in this scenario**

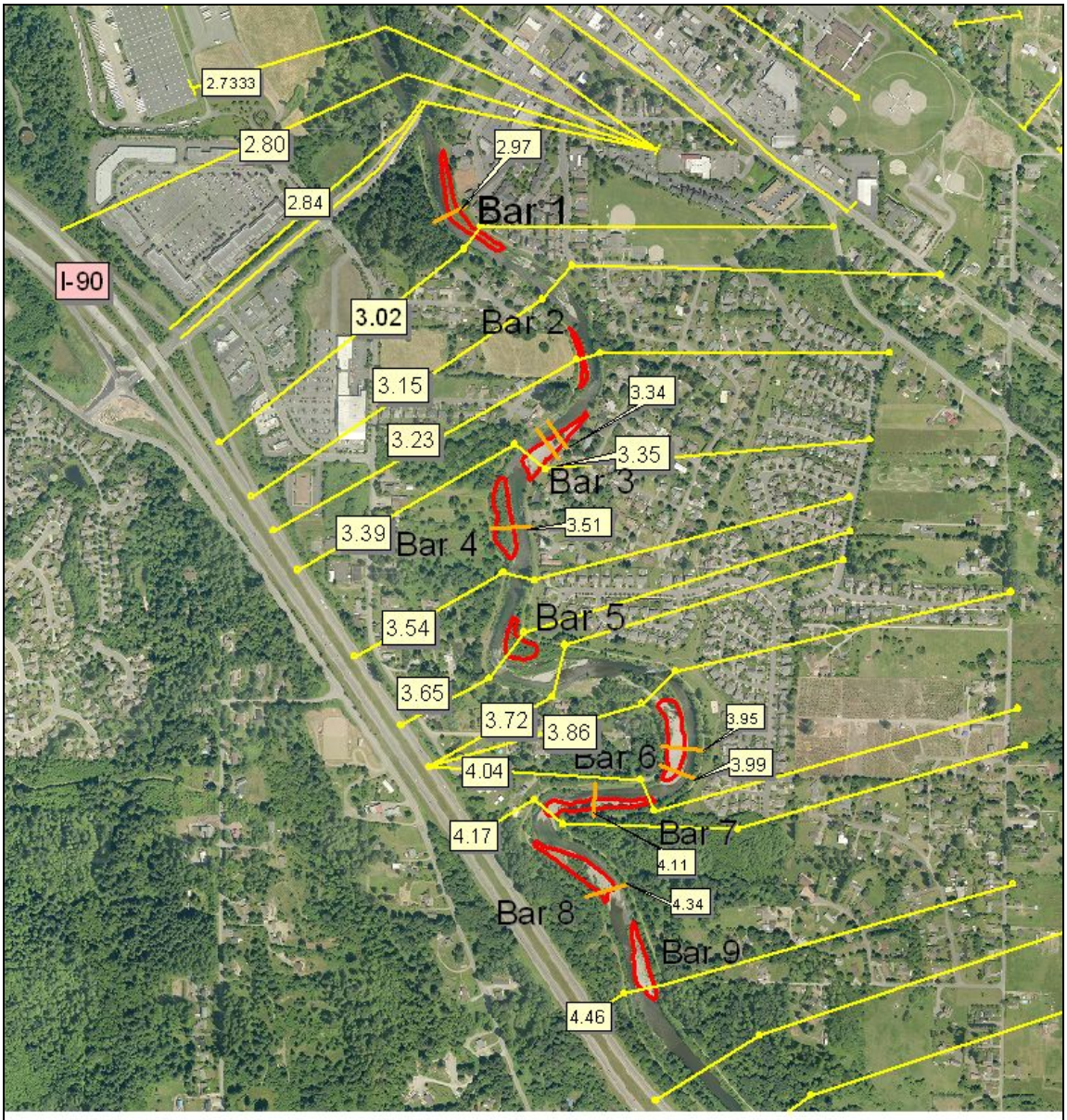


**Figure 6-2:**
**South Fork Snoqualmie River**
**Schematic of Bar Scalping Scenario 2**
**Yellow = Flood Study (FEMA 2005) cross sections**
**Orange = Additional surveyed cross sections**
**Red = Bar Scalping simulated in this scenario**

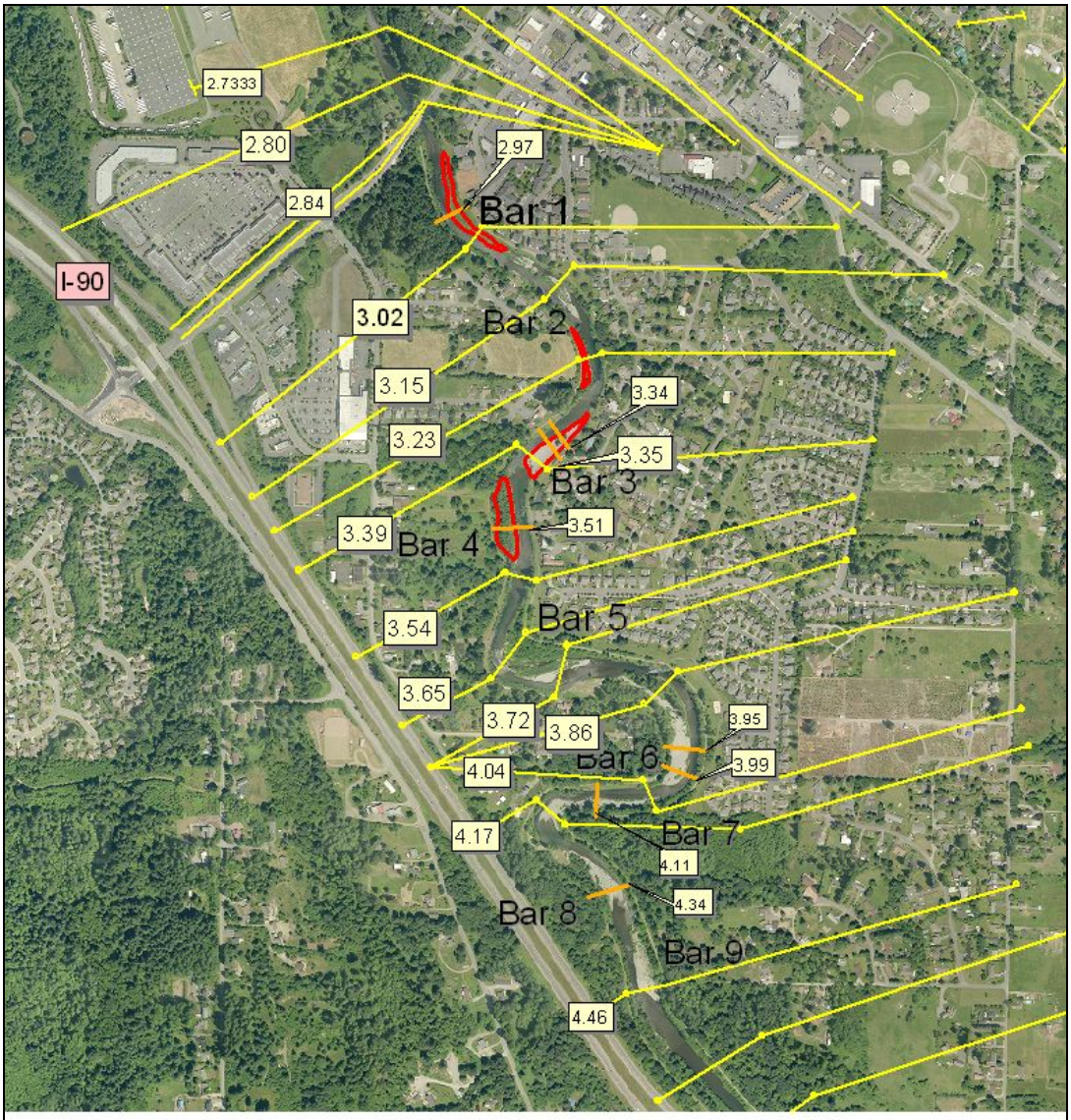


**Figure 6-3:**
**South Fork Snoqualmie River**
**Schematic of Bar Scalping Scenario 3**
**Yellow = Flood Study (FEMA 2005) cross sections**
**Orange = Additional surveyed cross sections**
**Red = Bar Scalping simulated in this scenario**

Bar Scalp Scenario 3:

Scalp Scenario 3 simulates gravel removal focused in the area where hydraulic modeling and past observed flooding indicates that overtopping is most likely to occur, along the left bank from near the North Bend Blvd Bridge upstream to gravel bar 4 (RM 2.97 to about RM 3.4). Gravel removal is simulated under Scalp Scenario 3 at seven of the 21 cross sections in this reach (RM 2.97, 3.02, 3.23, 3.34, 3.35, 3.39, 3.51) and would affect gravel bars 1, 2, 3, and 4 (Figure 6-3). Scalp Scenario 3 would be similar to the bar scalping gravel removal that was done in 1991. The volume of gravel that would be removed in this scenario is about 24,000 cubic yards.

## 6.2 Effect of gravel removal on water surface elevations

### 6.2.1 Channel conveyance capacity if gravel removal were implemented

Using the same methods as in Section 5 (existing conditions), the channel conveyance capacity at every cross section in the study reach is identified in this subsection for conditions with the gravel removal scenarios implemented. Because the right bank is at a higher elevation than the left bank at every cross section in the study reach, the maximum flow contained by the left bank is used to identify the channel conveyance capacity at every cross section.

Table 6-2 lists the channel conveyance capacity at each cross section for 2009 existing conditions and the three bar scalping gravel removal scenarios. Figure 6-4 plots the same information. In general, the gravel removal scenarios would result in larger increases in channel conveyance capacity in the upstream part of this reach than the downstream part of the study reach. There would be minimal changes in capacity at the downstream end of the study reach within backwater conditions near North Bend Blvd (Bendigo) Bridge.

**Table 6-2: Channel conveyance capacity of the South Fork Snoqualmie River with 2009 existing conditions and three gravel bar scalp scenarios implemented**

| River Mile | **2009 Existing Conditions** Channel Conveyance Capacity (cfs) | **Scalp Scenario 1** Channel Conveyance Capacity (cfs) | **Scalp Scenario 2** Channel Conveyance Capacity (cfs) | **Scalp Scenario 3** Channel Conveyance Capacity (cfs) | |
|---|---|---|---|---|---|
| | Upstream end of study reach | | | | |
| 4.46 | > 19,700 | >19,700 | >19,700 | >19,700 | |
| 4.34 | > 19,700 | >19,700 | >19,700 | >19,700 | |
| 4.17 | 16,600 | 17,700 | 18,700 | 16,600 | |
| 4.11 | 15,700 | 16,800 | 18,300 | 15,700 | |
| 4.04 | 18,000 | >19,700 | >19,700 | 18,400 | |
| 3.99 | 14,200 | 18,300 | 17,800 | 14,300 | |
| 3.95 | 17,100 | 18,000 | 18,200 | 17,300 | |
| 3.86 | > 19700 | >19,700 | >19,700 | >19,700 | |
| 3.72 | 18,700 | 19,200 | >19,700 | 19,610 | |
| 3.65 | 15,800 | 16,500 | 17,000 | 17,000 | |
| | Approx split between upper and lower parts of study reach | | | | |
| 3.54 | 13,100 | 14,100 | 14,600 | 14,600 | A |
| 3.51 | 14,000 | 14,500 | 15,000 | 15,000 | A |
| 3.39 | 11,700 | 12,500 | 12,800 | 12,800 | A |
| 3.35 | 11,900 | 12,200 | 12,600 | 12,600 | A |
| 3.34 | 11,300 | 11,600 | 12,000 | 12,000 | A |
| 3.23 | 14,500 | 14,600 | 14,700 | 14,700 | A |
| 3.15 | 13,300 | 13,500 | 13,700 | 13,700 | A |
| 3.02 | 14,300 | 14,400 | 14,400 | 14,400 | A |
| 2.97 | 12,200 | 12,300 | 12,300 | 12,300 | A |
| 2.85 | North Bend Blvd Bridge<br>Downstream end of study reach | | | | |

Note:
A: Results for Scalp Scenarios 2 and 3 are identical in the downstream part of the study reach because the two scenarios are configured identically there.

In the upstream part of the study reach (RM 3.65 to RM 4.46), the channel conveyance capacity under 2009 existing conditions equals or exceeds 15,000 cfs (100-year flood) at every cross section except at RM 3.99. The configuration and extent of gravel removal varies between Scalp Scenarios 1 and 2, as would their effect on channel conveyance capacity. However, gravel removal by both Scalp Scenarios 1 and 2 would result in increased channel conveyance capacity that would be greatest at RM 3.99 to RM 4.04, which is at or just upstream of the excavation that would occur on the relatively large gravel bar 6. Scalp Scenario 1 would increase channel conveyance capacity by as much as 1,700 cfs (or more), from 18,000 to at least 19,700 cfs, at RM 4.04. Scalp Scenario 2 would increase channel conveyance capacity by as much as 3,600 cfs, from 14,200 to 17,800 cfs, at RM 3.99. Because Scalp Scenario 3 does not include any

gravel removal upstream of RM 3.51, the effect of this scenario on channel conveyance capacity in this upstream area would be at a maximum at RM 3.65 and diminish to no effect at RM 4.11 and upstream. The 2009 existing conditions channel conveyance capacity is well above the flood reduction objective at all locations in the upstream area except the left bank at RM 3.99. Any increases in channel capacity due to gravel removal everywhere but at RM 3.99 would manifest as increased freeboard above that objective in this upstream area. Scalp Scenario 1 and 2 would reestablish the flood hazard reduction objective channel conveyance capacity at RM 3.99; Scalp Scenario 3 would not.

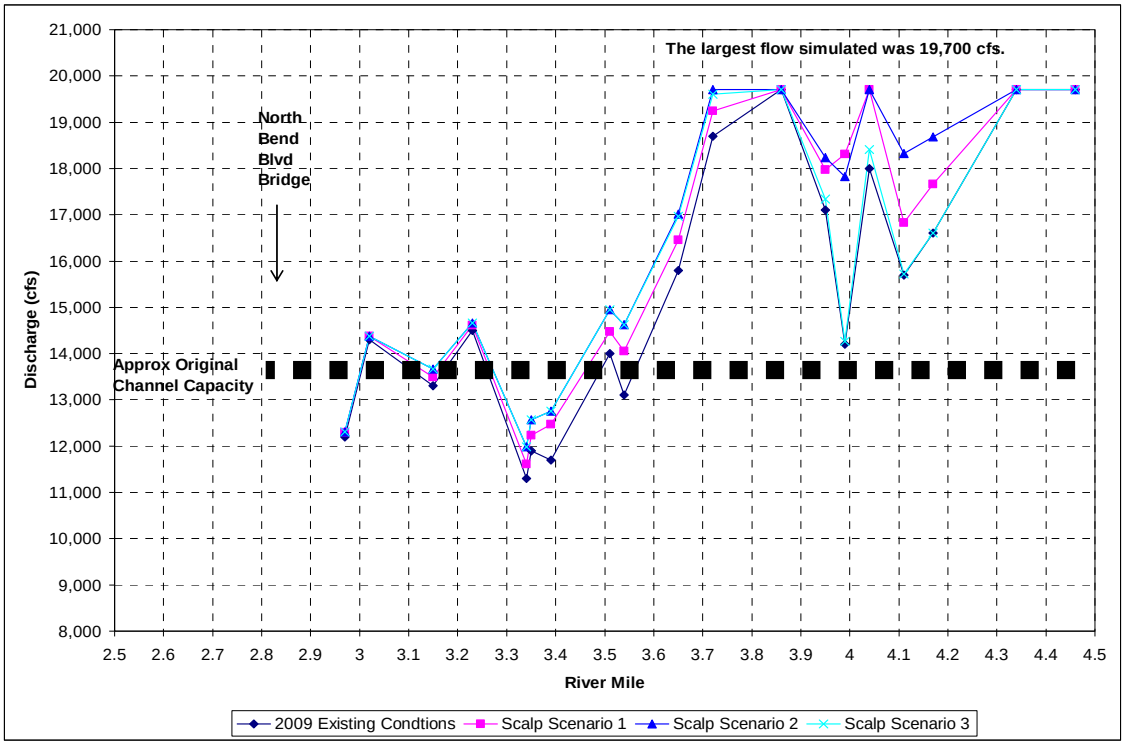


**Figure 6-4: Channel conveyance capacity along the South Fork Snoqualmie River under 2009 existing conditions and Scalp Scenarios 1, 2 and 3**

In the downstream part of the study reach (RM 2.85 to RM 3.54), there is an existing channel conveyance capacity of 13,000 cfs (50-year flood) and greater for 2009 existing conditions at all cross section locations except at RM 3.34 to RM 3.39 (adjacent to Berry Estates) and RM 2.97 (adjacent to Shamrock Park). Gravel removal generally would result in a minor to moderate increased channel conveyance capacity in this downstream area, e.g., increases by a few hundred cfs to as much as 1,500 cfs. It also would result in containment of 14,000 cfs at RM 3.54, which does not occur under existing conditions.

Relative to 2009 existing conditions, Scalp Scenario 1 would increase the channel conveyance capacity by 300 cfs at RM 3.34 and RM 3.35 and by 800 cfs (from 11,700 to 12,500 cfs) at RM 3.39. Relative to 2009 existing conditions, Scalp Scenarios 2 and 3 each would increase the channel conveyance capacity by 700 cfs at RM 3.34 and RM 3.35 and by 1,100 cfs (from 11,700 to 12,800 cfs) at RM 3.39. At RM 2.97, there would be negligible changes in channel

conveyance capacity comparing any of the three of the bar scalp scenarios to existing conditions. All increased channel conveyance capacities reported here are based on the values listed in Table 6-2 and plotted in Figure 6-4.

The following subsections describe the effect of the gravel removal scenarios on specific discharges throughout the study reach.

### 6.2.2 Effect of gravel removal scenarios on a discharge of 13,000 cfs (50-year flood)

Modeled water surface elevations for the 13,000 cfs discharge for existing 2009 conditions and the three gravel bar scalping scenarios are shown in profile view through the study reach in Figure 6-5. Table 6-3 lists freeboard along both river banks for a modeled 13,000 cfs flood. The shaded cells in Table 6-3 indicate that most of downstream part of the reach along the left bank would not contain a discharge of 13,000 cfs plus one foot of freeboard under 2009 existing conditions, nor if gravel removal were to be implemented. The fact that an observed flow of 13,600 cfs overtopped the right bank at RM 2.97 to about RM 3.02 in November 2006 indicates that the 1.2 to 1.3 feet of freeboard shown in Table 6-3 under existing conditions may not actually exist during a discharge of 13,000 cfs.

The changes in the 13,000 cfs water surface elevations that would occur relative to the 2009 existing conditions for the gravel removal scenarios are shown in Table 6-4 and Figure 6-6.

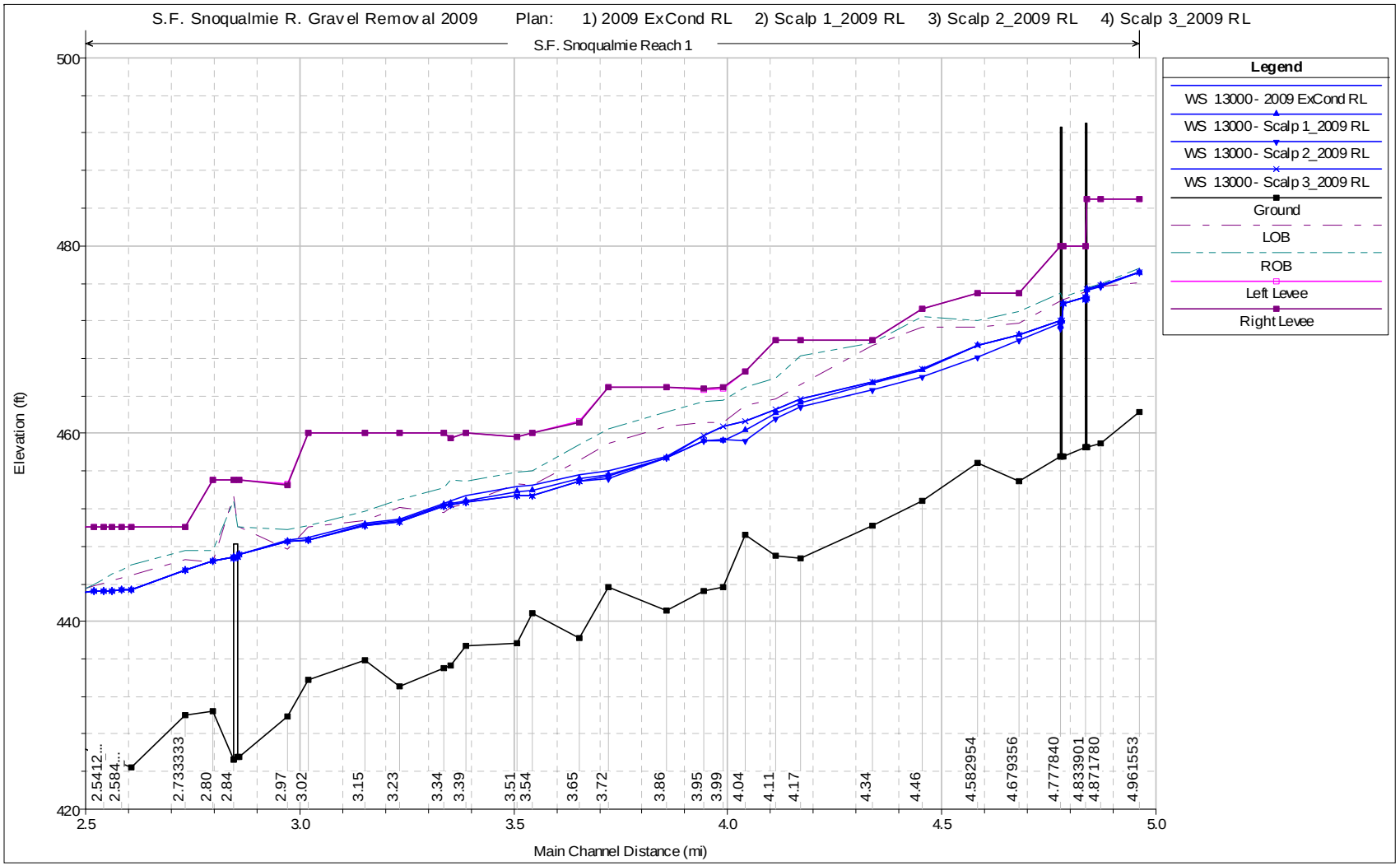


**Figure 6-5: South Fork Snoqualmie River profile view of the 13,000 cfs (50-year flood) water surface elevations for 2009 existing conditions and Scalp Scenarios 1, 2 and 3**

**Table 6-3: Freeboard along both river banks of the South Fork Snoqualmie River during a 13,000 cfs (50-year) flood with 2009 existing conditions and three bar scalping gravel removal scenarios**

| River Mile | 2009 Existing Conditions Left Bank Freeboard at 13,000 cfs (ft) | 2009 Existing Conditions Right Bank Freeboard at 13,000 cfs (ft) | Scalp Scenario 1 Left Bank Freeboard at 13,000 cfs (ft) | Scalp Scenario 2 Left Bank Freeboard at 13,000 cfs (ft) | Scalp Scenario3 Left Bank Freeboard at 13,000 cfs (ft) | Scalp Scenario 1 Right Bank Freeboard at 13,000 cfs (ft) | Scalp Scenario 2 Right Bank Freeboard at 13,000 cfs (ft) | Scalp Scenario3 Right Bank Freeboard at 13,000 cfs (ft) |
|---|---|---|---|---|---|---|---|---|
| | Upstream end | | | | | | | |
| 4.46 | 4.5 | 5.7 | 4.6 | **5.3** | 4.5 | 5.8 | **6.5** | 5.7 |
| 4.34 | 3.8 | 4.1 | 4.0 | **4.8** | 3.8 | 4.3 | **5.1** | 4.1 |
| 4.17 | 1.5 | 4.5 | 1.9 | **2.3** | 1.5 | 5.0 | **5.4** | 4.5 |
| 4.11 | 1.0 | 3.3 | **1.5** | **2.0** | 1.0 | **3.8** | **4.3** | 3.3 |
| 4.04 | 1.6 | 3.5 | **2.6** | **3.7** | 1.6 | **4.5** | **5.6** | 3.5 |
| 3.99 | 0.4 | 2.8 | 2.0 | **1.8** | 0.4 | 4.4 | **4.2** | 2.8 |
| 3.95 | 1.3 | 3.5 | **1.9** | **1.9** | 1.3 | **4.1** | **4.2** | 3.5 |
| 3.86 | 3.1 | 4.7 | 3.2 | 3.3 | 3.3 | 4.8 | 4.9 | 4.9 |
| 3.72 | 3.0 | 4.5 | 3.3 | 3.8 | 3.6 | 4.8 | 5.3 | 5.1 |
| 3.65 | 1.6 | 3.2 | 2.0 | **2.3** | 2.3 | 3.6 | 4.0 | 3.9 |
| 3.54 | 0.1 | 1.5 | 0.7 | 1.2 | 1.2 | 2.1 | 2.6 | 2.6 |
| 3.51 | 0.3 | 1.6 | **0.7** | **1.2** | **1.2** | **2.0** | **2.5** | **2.5** |
| 3.39 | -0.8 | 1.6 | -0.3 | **-0.2** | **-0.2** | 2.1 | **2.2** | **2.2** |
| 3.35 | -0.7 | 2.3 | **-0.5** | **-0.3** | **-0.3** | **2.5** | **2.7** | **2.7** |
| 3.34 | -1.1 | 1.6 | **-0.9** | **-0.7** | **-0.7** | **1.8** | **2.0** | **2.0** |
| 3.23 | 1.2 | 2.1 | 1.4 | **1.5** | **1.5** | 2.3 | **2.4** | **2.4** |
| 3.15 | 0.2 | 1.2 | 0.4 | 0.5 | 0.5 | 1.4 | 1.5 | 1.5 |
| 3.02 | 1.1 | 1.3 | 1.3 | **1.4** | **1.4** | 1.5 | **1.6** | **1.6** |
| 2.97 | -0.8 | 1.2 | **-0.8** | **-0.8** | **-0.8** | **1.3** | **1.3** | **1.3** |
| 2.85 | North Bend Blvd (Bendigo) Bridge | | | | | | | |

**Bold** indicates a cross section at which gravel removal by bar scalping was simulated in the hydraulic model.
Negative Freeboard indicates overtopping.
Shading Indicates less than one foot of freeboard WSEL: Water Surface Elevation

**Table 6-4: Change in Water Surface Elevations (WSELs) along the South Fork Snoqualmie River during a flood of 13,000 cfs (50-year) from 1992/95 to 2009 in existing conditions and from 2009 existing conditions to the three bar scalping scenarios**

| River Mile | Change in WSEL at 13,000 cfs from 1992/95 to 2009 Existing Conditions (ft) | Change in WSEL at 13,000 cfs from 2009 Existing Conditions to Scalp Scenario 1 (ft) | Change in WSEL at 13,000 cfs from 2009 Existing Conditions to Scalp Scenario 2 (ft) | Change in WSEL at 13,000 cfs from 2009 Existing Conditions to Scalp Scenario 3 (ft) |
|---|---|---|---|---|
| 4.7797 | | I-90 Bridge | | |
| 4.7778 | | 0.0 | -0.3 | 0.0 |
| 4.6794 | | 0.0 | -0.6 | 0.0 |
| 4.5830 | | 0.0 | -1.2 | 0.0 |
| | | Upstream end of study reach | | |
| 4.46 | 1.0 | -0.1 | **-0.9** | 0.0 |
| 4.34 | 1.0 | -0.2 | **-0.9** | 0.0 |
| 4.17 | 0.9 | -0.5 | **-0.9** | 0.0 |
| 4.11 | 0.9 | **-0.5** | **-1.0** | 0.0 |
| 4.04 | 1.2 | **-1.0** | **-2.1** | 0.0 |
| 3.99 | 1.1 | -1.6 | **-1.4** | 0.0 |
| 3.95 | 0.6 | **-0.6** | **-0.6** | 0.0 |
| 3.86 | 0.0 | -0.1 | -0.2 | -0.1 |
| 3.72 | 0.4 | -0.3 | -0.8 | -0.6 |
| 3.65 | 0.5 | -0.4 | **-0.8** | -0.7 |
| | | Approx split between upper and lower parts of study reach | | |
| 3.54 | 0.8 | -0.6 | -1.1 | -1.1 |
| 3.51 | 0.7 | **-0.4** | **-0.9** | **-0.9** |
| 3.39 | 0.5 | -0.5 | **-0.7** | **-0.7** |
| 3.35 | 0.3 | **-0.2** | **-0.4** | **-0.4** |
| 3.34 | 0.2 | **-0.2** | **-0.4** | **-0.4** |
| 3.23 | 0.4 | -0.1 | **-0.2** | **-0.2** |
| 3.15 | 0.2 | -0.1 | -0.3 | -0.3 |
| 3.02 | 0.1 | -0.2 | **-0.2** | **-0.2** |
| 2.97 | -0.1 | **0.0** | **-0.1** | **-0.1** |
| 2.85 | | North Bend Blvd (Bendigo) Bridge<br>Downstream end of study reach | | |

**Bold** indicates a cross section at which bar scalping gravel removal was simulated in the hydraulic model.
WSEL: Water Surface Elevation

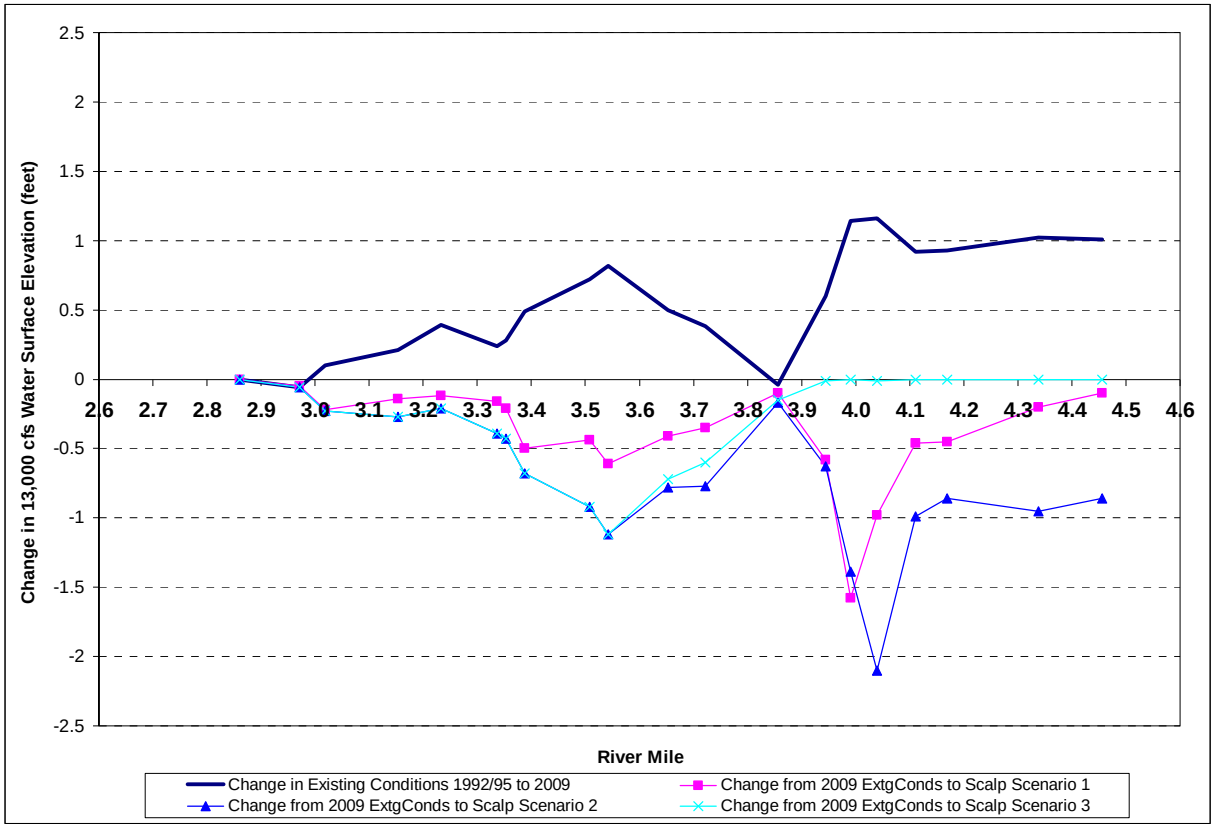


**Figure 6-6: Changes in the 13,000 cfs (50-year) water surface elevations along the South Fork Snoqualmie River from 1992/95 to 2009 existing conditions and from 2009 existing conditions to Scalp Scenario 1, 2 and 3**

Scalp Scenario 1:

In the downstream part of the study reach, modeled water surface elevations (Table 6-3) indicate that 13,000 cfs would overtop the left bank adjacent to Berry Estates (RM 3.34 to RM 3.39) and adjacent to Shamrock Park (RM 2.97) with Scalp Scenario 1 implemented. In the upstream part of the study reach, where there is containment of 13,000 cfs plus one foot of freeboard under existing conditions at most locations, decreases in water surface elevations due to gravel removal would increase existing freeboard.

Scalp Scenario 1 would result in a maximum decrease in the 13,000 cfs water surface elevations of 0.6 feet in the downstream part of the study reach, at RM 3.54 (Table 6-4). The 13,000 cfs water surface elevation would decrease by 0.2 feet at RM 3.35 (Table 6-4 and Figure 6-7). There would be no change in the 13,000 cfs water surface elevation at RM 2.97 (Table 6-4 and Figure 6-8).

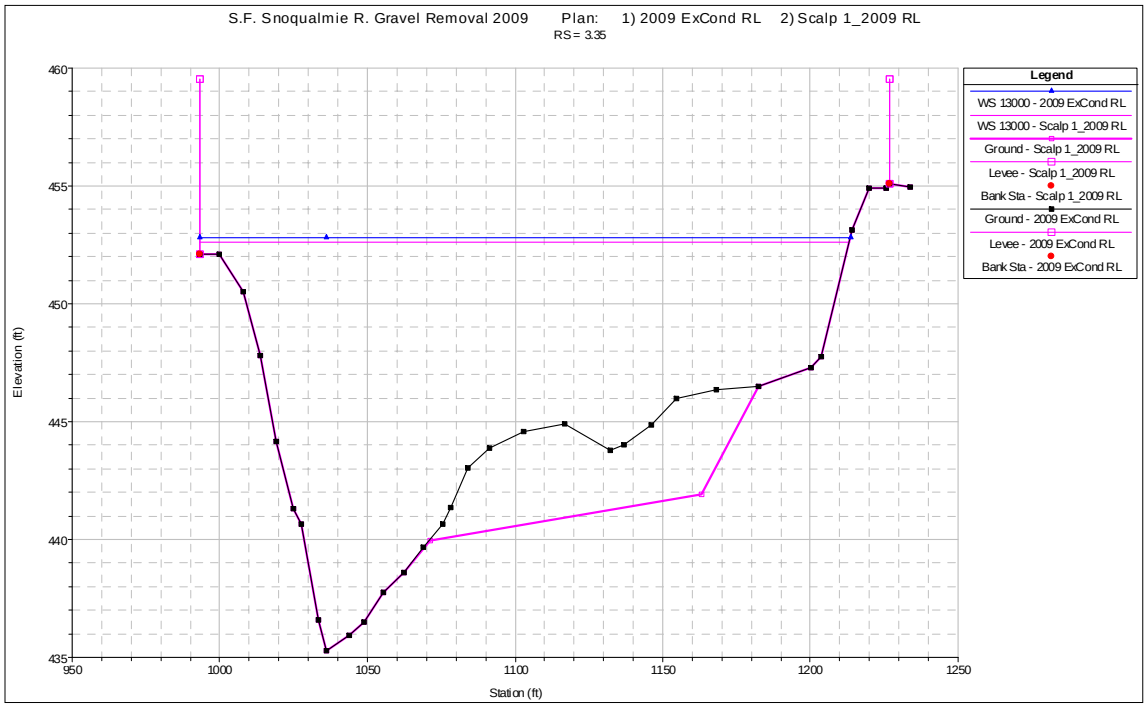


**Figure 6-7: South Fork Snoqualmie River, cross section view of 13,000 cfs (50-year) water surface elevations at RM 3.35 with 2009 existing conditions and Scalp Scenario 1**

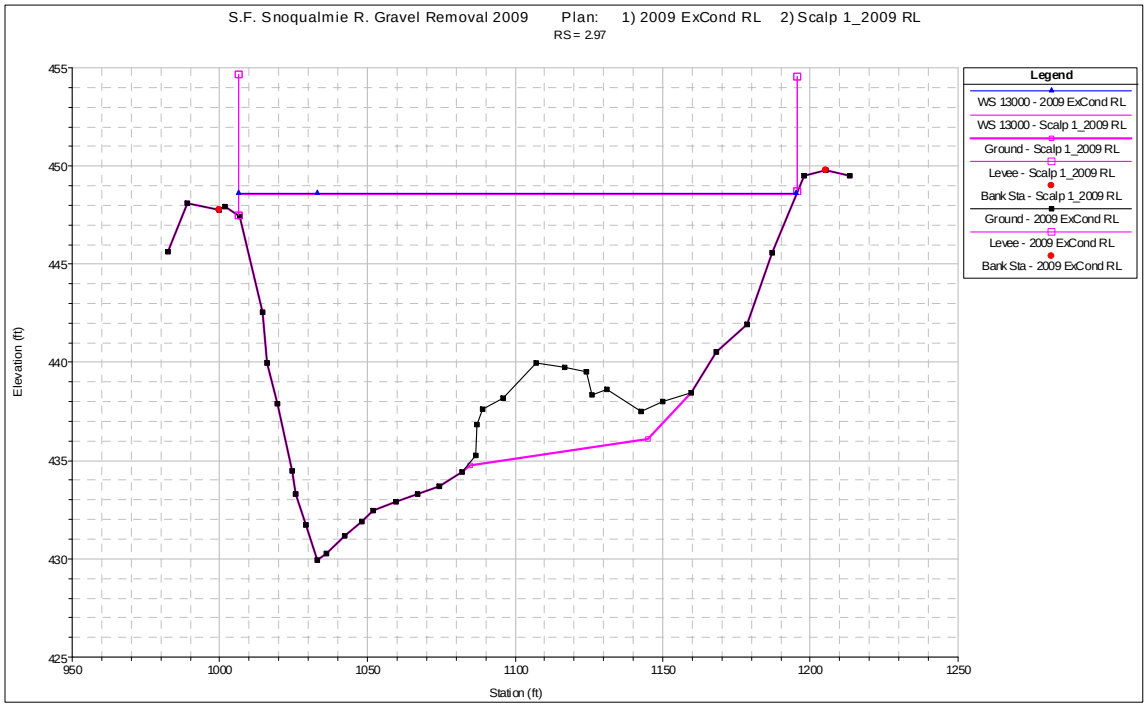


**Figure 6-8: South Fork Snoqualmie River, cross section view of 13,000 cfs (50-year) water surface elevations at RM 2.97 with 2009 existing conditions and Scalp Scenario 1**

Scalp Scenario 1 would not result in full containment of 13,000 cfs plus one foot of freeboard throughout the study reach.

Decreases in the 13,000 cfs water surface elevations due to Scalp Scenario 1 would approximately counteract the increases in the 13,000 cfs water surface elevations along RM 3.34 to RM 3.39 (along Berry Estates) and RM 3.95 to RM 4.04 (gravel bar 6) that have occurred from 1992/95 to 2009 under existing conditions, though that is not true throughout the study reach (Table 6-4 and Figure 6-6).

Scalp Scenario 2:

In the downstream part of the study reach, modeled water surface elevations (Table 6-3) indicate that 13,000 cfs would overtop the left bank adjacent to Berry Estates (at RM 3.34 to RM 3.39) and adjacent to Shamrock Park (RM 2.97) with Scalp Scenario 2 implemented. In the upstream part of the study reach, where there is containment of 13,000 cfs plus one foot of freeboard under existing conditions at most locations, decreases in water levels due to gravel removal would increase existing freeboard.

Scalp Scenario 2 would result in a maximum decrease in the 13,000 cfs water surface elevations of 1.1 feet in the downstream part of the study reach, at RM 3.54 (Table 6-4). The 13,000 cfs water surface elevation would decrease by 0.1 foot at RM 2.97 (Table 6-4 and Figure 6-9) and it would decrease by 0.4 feet at RM 3.35 (Table 6-4 and Figure 6-10).

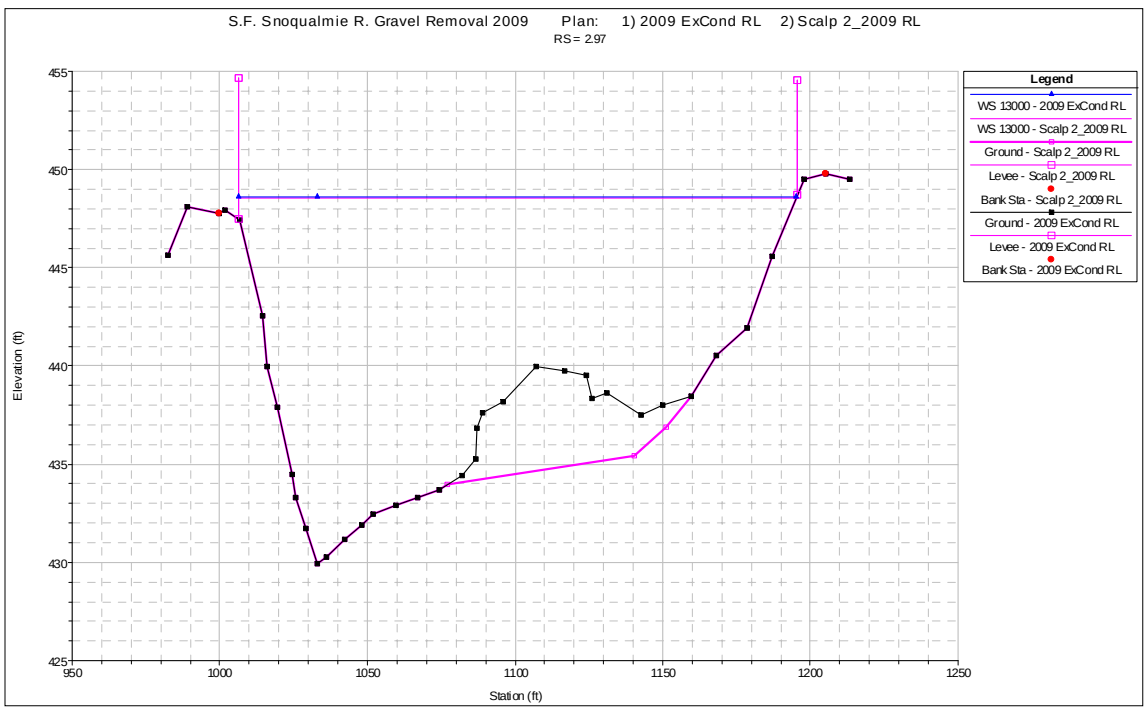


**Figure 6-9: South Fork Snoqualmie River, cross section view of 13,000 cfs (50-year) water surface elevations at RM 2.97 with 2009 existing conditions and Scalp Scenario 2 (and Scalp Scenario 3)**

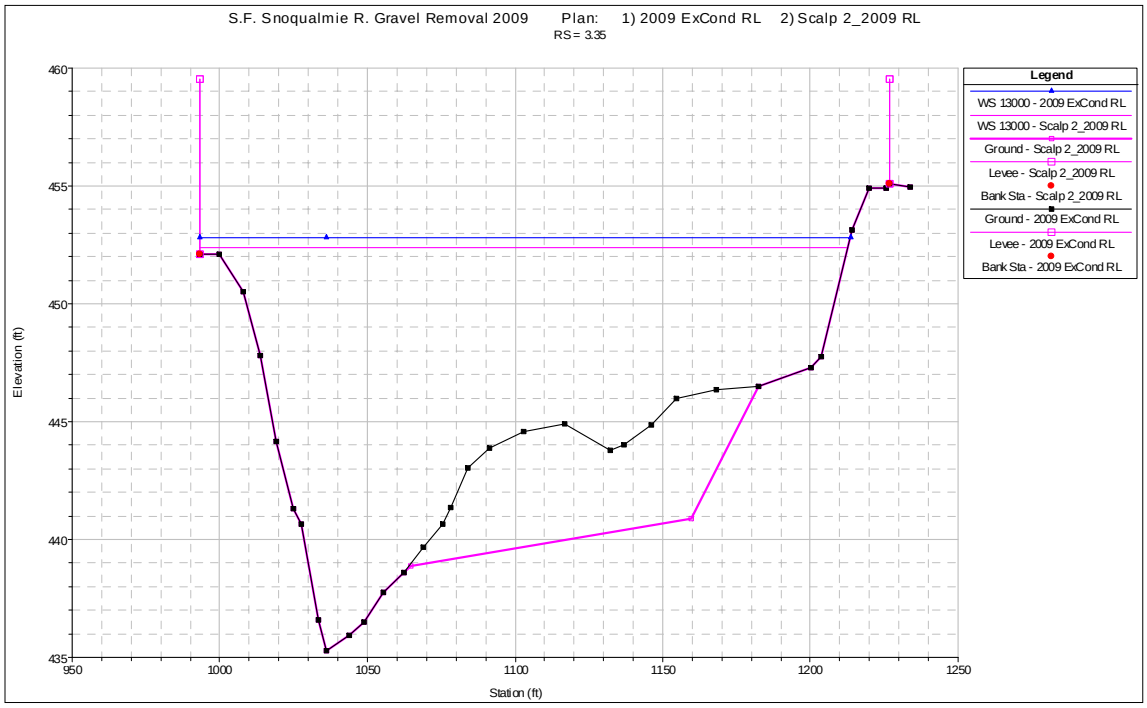


**Figure 6-10: South Fork Snoqualmie River, cross section view of 13,000 cfs (50-year) water surface elevations at RM 3.35 with 2009 existing conditions and Scalp Scenario 2 (and Scalp Scenario 3)**

Scalp Scenario 2 would not result in full containment of 13,000 cfs plus one foot of freeboard throughout this study reach.

Decreases in the 13,000 cfs water surface elevations due to Scalp Scenario 2 would approximately counteract or more than counteract the increases in the 13,000 cfs water surface elevations that have occurred from 1992/95 to 2009 under existing conditions at RM 3.35 to RM 3.39 along Berry Estates and at RM 3.99 to RM 4.04 along gravel bar 6 (Table 6-4 and Figure 6-6). The relation between decreases in water surfaces resulting from gravel removal and increases in existing conditions water surfaces since 1992/95 varies throughout the rest of the study reach.

Scalp Scenario 3:

In the downstream part of the study reach, modeled water surface elevations indicate that the 13,000 cfs discharge would overtop the left bank adjacent to Berry Estates (RM 3.34 and to RM 3.39) and adjacent to Shamrock Park (RM 2.97) with Scalp Scenario 3 implemented (Table 6-3). In the upstream part of this study reach, where there is containment of 13,000 cfs plus one foot of freeboard under existing conditions at most locations, decreases in water levels due to gravel removal would increase existing freeboard.

Scalp Scenario 3 is identical to Scalp Scenario 2 from RM 2.97 to RM 3.51. As with Scalp Scenario 2, Scalp Scenario 3 would result in a maximum decrease in the 13,000 cfs water surface elevations of 1.1 feet in the downstream part of the study reach, at RM 3.54 (Table 6-4). The

water surface elevation would decrease by 0.1 foot at RM 2.97 (Figure 6-9) and it would decrease by 0.4 feet at RM 3.35 (Table 6-4 and Figure 6-10). With no gravel removal simulated upstream of RM 3.51, the effect of Scalp Scenario 3 on water surfaces diminishes in the upstream direction to zero at RM 3.95 (Table 6-4 and Figure 6-6).

Scalp Scenario 3 would not result in full containment of 13,000 cfs plus one foot of freeboard throughout this study reach.

Decreases in the 13,000 cfs water surface elevations due to Scalp Scenario 3 would approximately counteract or more than counteract the increases in the 13,000 cfs water surface elevations that have occurred from 1992/95 to 2009 under existing conditions along Berry Estates at RM 3.35 to RM 3.39, as well as most locations from RM 2.97 to about RM 3.86 (Table 6-4 and Figure 6-6). Scalp Scenario 3 would not include any excavation upstream of RM 3.51, so it would have no effect in the area around RM 3.99 to RM 4.04.

### 6.2.3 Effect of gravel removal scenarios on a discharge of 11,700 cfs (30-year flood):

Modeled water surface elevations for a discharge of 11,700 cfs in existing conditions and all bar scalping scenarios are shown in profile view through the study reach in Figure 6-11. As indicated in Table 6-5, a flow of 11,700 cfs is contained under existing conditions along the entire right bank at all locations and along the left bank everywhere but at RM 3.34. Changes in the water surface elevations that would occur relative to the 2009 existing conditions with the gravel removal scenarios implemented are shown in Table 6-6 and Figure 6-12.

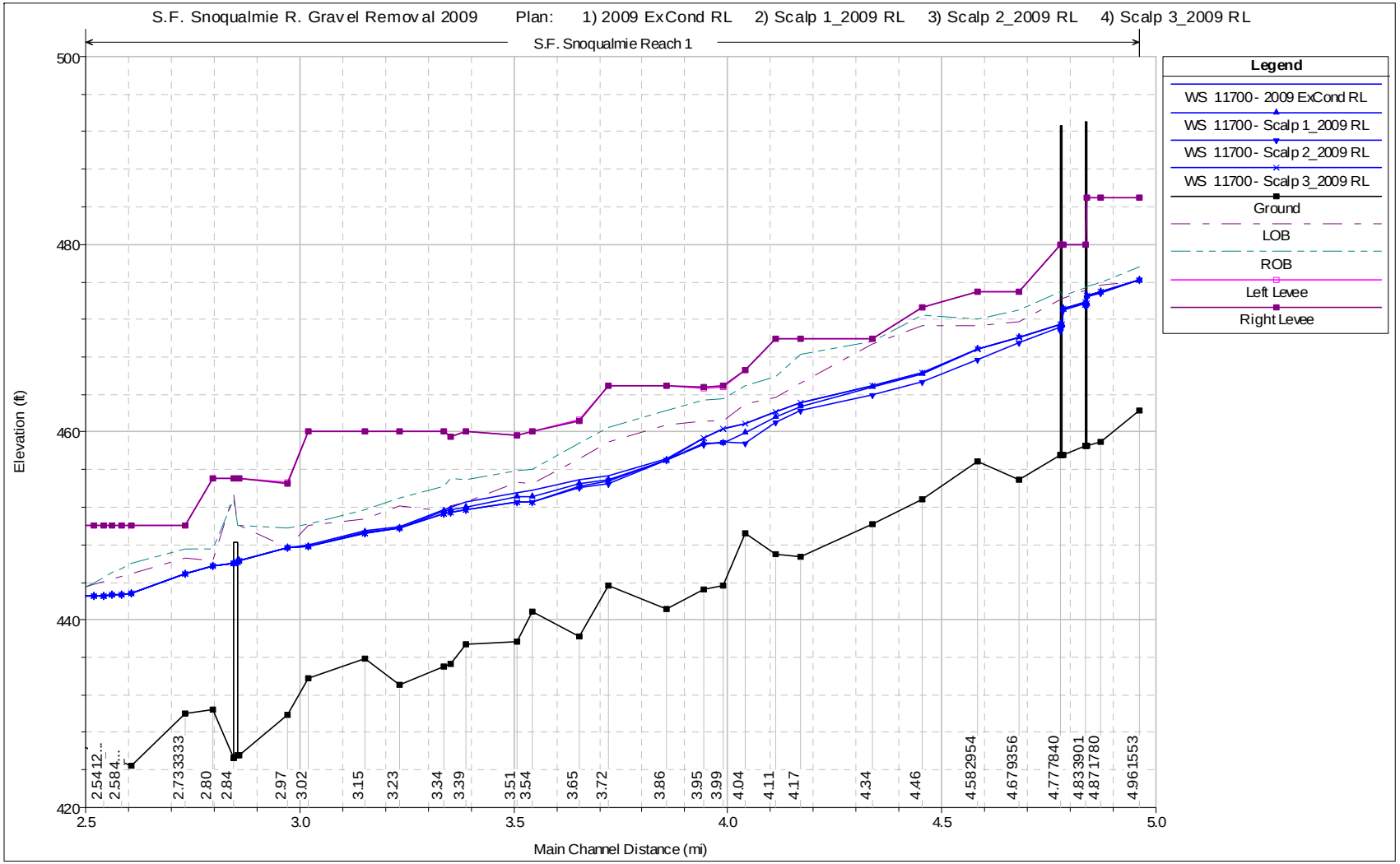


**Figure 6-11: South Fork Snoqualmie River profile view of 11,700 cfs (30-year) water surface elevations with 2009 existing conditions and Scalp Scenarios 1, 2, and 3**

**Table 6-5: Freeboard along both river banks of the South Fork Snoqualmie River during an 11,700 cfs (30-year) flood with 2009 existing conditions and with three bar scalping gravel removal scenarios**

| River Mile | 2009 Existing Conditions Left Bank Freeboard at 11,700 cfs (ft) | 2009 Existing Conditions Right Bank Freeboard at 11,700 cfs (ft) | Scalp Scenario 1 Left Bank Freeboard 11,700 cfs (ft) | Scalp Scenario 2 Left Bank Freeboard 11,700 cfs (ft) | Scalp Scenario 3 Left Bank Freeboard 11,700 cfs (ft) | Scalp Scenario 1 Right Bank Freeboard 11,700 cfs (ft) | Scalp Scenario 2 Right Bank Freeboard 11,700 cfs (ft) | Scalp Scenario 3 Right Bank Freeboard 11,700 cfs (ft) |
|---|---|---|---|---|---|---|---|---|
| | Upstream end | | | | | | | |
| 4.46 | 5.1 | 6.2 | 5.2 | **5.9** | 5.1 | 6.3 | **7.1** | 6.2 |
| 4.34 | 4.4 | 4.7 | 4.6 | **5.4** | 4.4 | 4.9 | **5.7** | 4.7 |
| 4.17 | 2.1 | 5.1 | 2.5 | **2.9** | 2.1 | 5.5 | **6.0** | 5.1 |
| 4.11 | 1.6 | 3.8 | **2.0** | **2.6** | 1.6 | **4.3** | **4.8** | 3.8 |
| 4.04 | 2.1 | 4.0 | **3.1** | **4.2** | 2.1 | **5.0** | **6.1** | 4.0 |
| 3.99 | 0.8 | 3.2 | 2.5 | **2.3** | 0.8 | 4.8 | **4.6** | 3.2 |
| 3.95 | 1.7 | 3.9 | **2.4** | **2.4** | 1.7 | **4.6** | **4.6** | 3.9 |
| 3.86 | 3.6 | 5.2 | 3.7 | 3.7 | 3.7 | 5.3 | 5.3 | 5.3 |
| 3.72 | 3.7 | 5.2 | 4.0 | 4.5 | 4.3 | 5.5 | 6.0 | 5.8 |
| 3.65 | 2.3 | 3.9 | 2.7 | 3.1 | 3.0 | 4.3 | 4.7 | 4.7 |
| 3.54 | 0.8 | 2.2 | 1.4 | 2.0 | 2.0 | 2.9 | 3.5 | 3.5 |
| 3.51 | 1.1 | 2.3 | **1.5** | **2.1** | **2.1** | **2.8** | **3.3** | **3.3** |
| 3.39 | 0.0 | 2.4 | 0.5 | **0.7** | **0.7** | 2.9 | **3.1** | **3.1** |
| 3.35 | 0.1 | 3.1 | **0.4** | **0.6** | **0.6** | **3.3** | **3.6** | **3.6** |
| 3.34 | -0.2 | 2.5 | **-0.1** | **0.2** | **0.2** | **2.6** | **2.9** | **2.9** |
| 3.23 | 2.2 | 3.1 | 2.3 | **2.4** | **2.4** | 3.2 | **3.3** | **3.3** |
| 3.15 | 1.2 | 2.2 | 1.4 | 1.5 | 1.5 | 2.4 | 2.5 | 2.5 |
| 3.02 | 2.0 | 2.2 | 2.2 | **2.2** | **2.2** | 2.4 | **2.4** | **2.4** |
| 2.97 | 0.0 | 2.1 | **0.1** | **0.1** | **0.1** | **2.1** | **2.1** | **2.1** |
| 2.86 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 |
| 2.85 | North Bend Blvd (Bendigo) Bridge | | | | | | | |

**Bold** indicates a cross section at which gravel removal by bar scalping was simulated in the hydraulic computer model.
Negative Freeboard indicates overtopping. WSEL: Water Surface Elevation

**Table 6-6: Change in Water Surface Elevations (WSELs) along the South Fork Snoqualmie River during a flood of 11,700 cfs (30-year) from 1992/95 to 2009 in existing conditions and from 2009 existing conditions to the three bar scalping scenarios**

| River Mile | Change in WSEL at 11,700 cfs from 1992/95 to 2009 Existing Conditions (ft) | Change in WSEL at 11,700 cfs from 2009 Existing Conditions to Scalp Scenario 1 (ft) | Change in WSEL at 11,700 cfs from 2009 Existing Conditions to Scalp Scenario 2 (ft) | Change in WSEL at 11,700 cfs from 2009 Existing Conditions to Scalp Scenario 3 (ft) |
|---|---|---|---|---|
| 4.7797 | | I-90 Bridge | | |
| 4.7778 | | 0.0 | -0.2 | 0.0 |
| 4.6794 | | 0.0 | -0.5 | 0.0 |
| 4.5830 | | 0.0 | -1.2 | 0.0 |
| | | Upstream end of study reach | | |
| 4.46 | 1.0 | -0.1 | **-0.9** | 0.0 |
| 4.34 | 1.0 | -0.2 | **-1.0** | 0.0 |
| 4.17 | 0.9 | -0.5 | **-0.9** | 0.0 |
| 4.11 | 0.9 | **-0.5** | **-1.0** | 0.0 |
| 4.04 | 1.2 | **-1.0** | **-2.1** | 0.0 |
| 3.99 | 1.2 | -1.6 | **-1.4** | 0.0 |
| 3.95 | 0.7 | **-0.7** | **-0.7** | 0.0 |
| 3.86 | -0.1 | -0.1 | -0.1 | -0.1 |
| 3.72 | 0.4 | -0.3 | -0.8 | -0.6 |
| 3.65 | 0.5 | -0.4 | **-0.8** | -0.8 |
| | | Approx split between upper and lower parts of study reach | | |
| 3.54 | 0.9 | -0.6 | -1.2 | -1.2 |
| 3.51 | 0.8 | **-0.5** | **-1.0** | **-1.0** |
| 3.39 | 0.5 | -0.5 | **-0.8** | **-0.8** |
| 3.35 | 0.3 | **-0.2** | **-0.5** | **-0.5** |
| 3.34 | 0.3 | **-0.2** | **-0.4** | **-0.4** |
| 3.23 | 0.4 | -0.1 | **-0.2** | **-0.2** |
| 3.15 | 0.2 | -0.1 | -0.3 | -0.3 |
| 3.02 | 0.1 | -0.2 | **-0.2** | **-0.2** |
| 2.97 | 0.0 | **-0.1** | **-0.1** | **-0.1** |
| 2.85 | | North Bend Blvd (Bendigo) Bridge<br>Downstream end of study reach | | |

**Bold** indicates a cross section at which bar scalping gravel removal was simulated in the hydraulic model.
WSEL = Water Surface Elevation

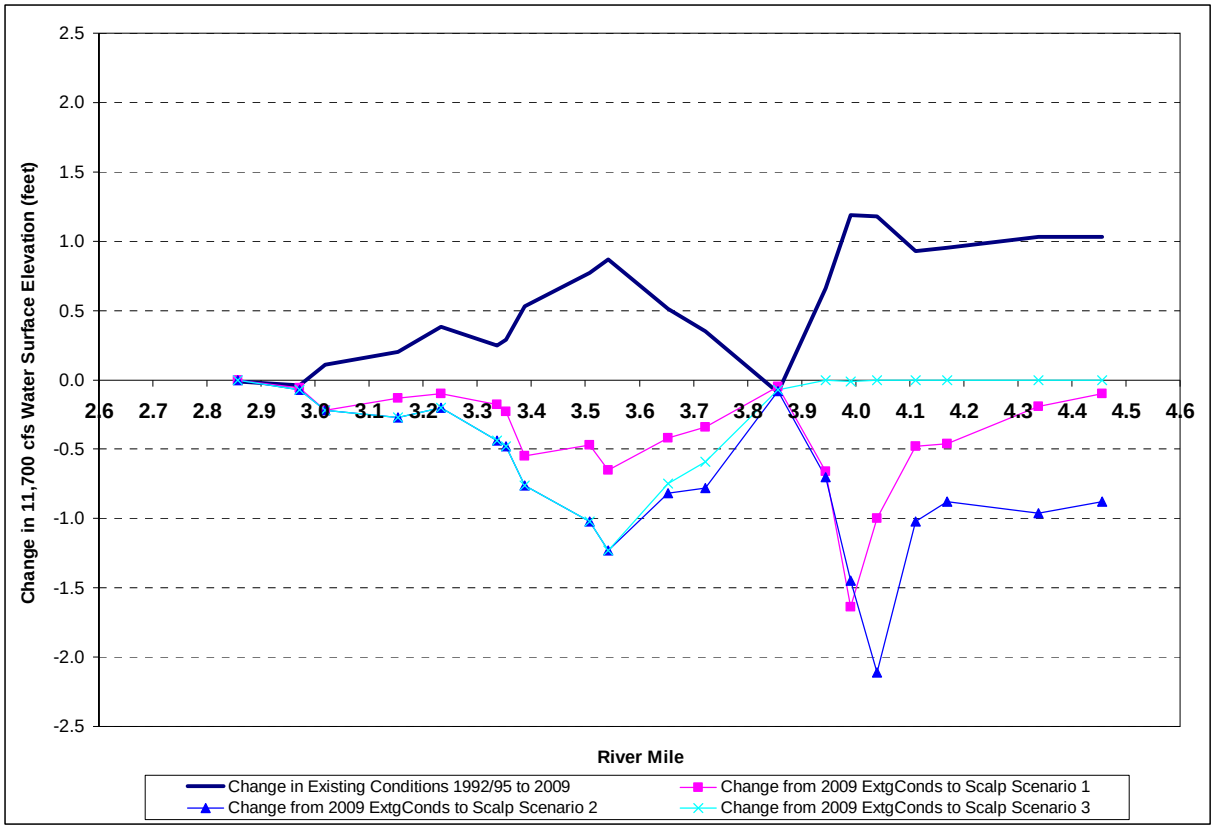


**Figure 6-12 Changes in 11,700 cfs (30-year) water surface elevations along the South Fork Snoqualmie River from 1992/95 to 2009 existing conditions and from 2009 existing conditions to Scalp Scenarios 1, 2 and 3**

Scalp Scenario 1:

Modeled water surface elevations (Table 6-5) indicate that the 11,700 cfs discharge would be contained throughout the downstream part of the study reach except at RM 3.34 with Scalp Scenario 1 implemented. There is containment of 11,700 cfs in the upstream part of this study reach under existing conditions, so any decrease in water levels would increase existing freeboard (Table 6-5).

The 11,700 cfs water surface elevations would decrease by as much as 0.6 feet at RM 3.54, and 0.5 feet at RM 3.39 (Table 6-6) in the downstream part of the study reach under Scalp Scenario 1. The 11,700 cfs water surface elevation would decrease by 0.1 foot at RM 2.97 (Table 6-6 and Figure 6-13). There would be a decrease of 0.2 feet at RM 3.35 (Table 6-6 and Figure 6-14). In the upstream part of the study reach, the maximum decrease in water surface elevations would be 1.6 feet at RM 3.99 (Table 6-6).

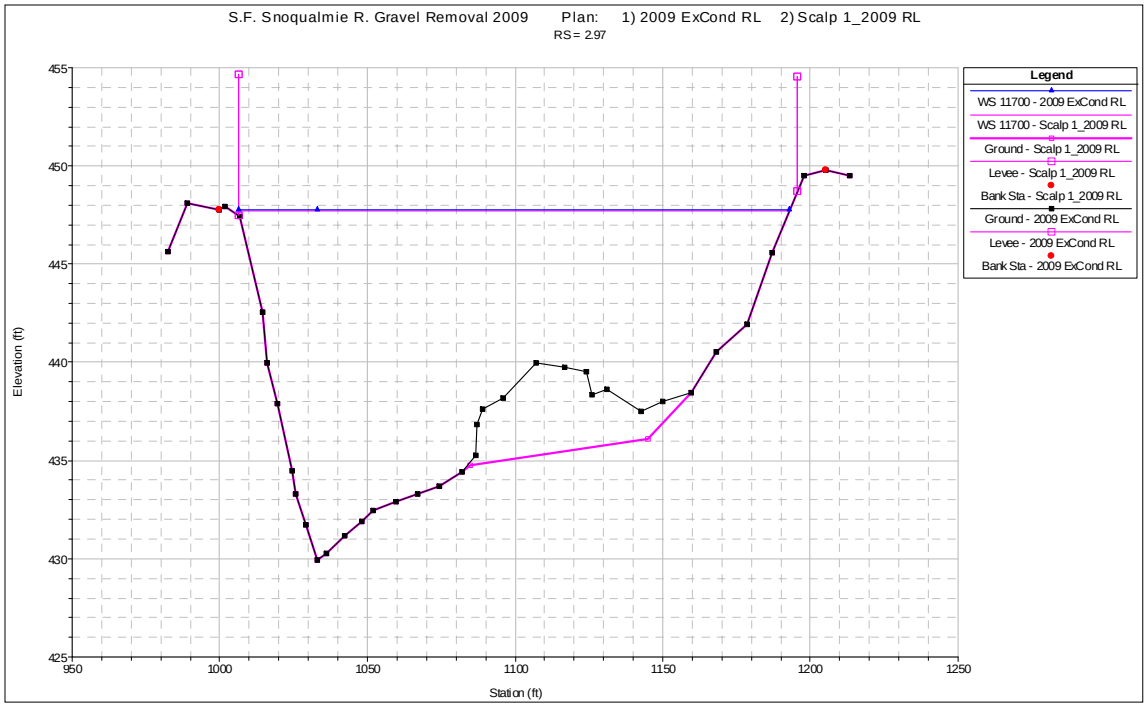


**Figure 6-13: South Fork Snoqualmie River, cross section view of 11,700 cfs (30-year) water surface elevations at RM 2.97 with 2009 existing conditions and Scalp Scenario 1**

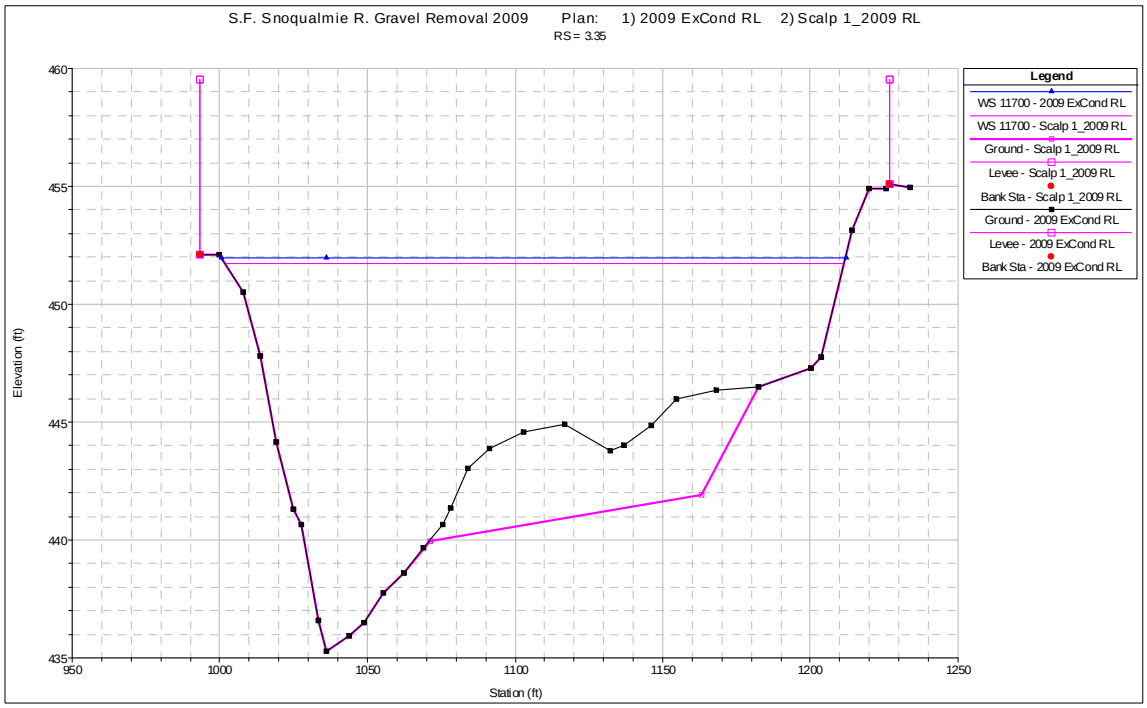


**Figure 6-14: South Fork Snoqualmie River, cross section view of 11,700 cfs (30-year) water surface elevations at RM 3.35 with 2009 existing conditions and Scalp Scenario 1**

Scalp Scenario 1 would not result in full containment of 11,700 cfs (30-year flood) throughout this study reach (although overtopping would occur only at one location by 0.1 foot).

Decreases in the 11,700 cfs water surface elevations due to Scalp Scenario 1 would approximately counteract the increases in the 11,700 cfs water surface elevations along Berry Estates at RM 3.34 to RM 3.39 and along gravel bar 6 at RM 3.95 to RM 4.04 that have occurred from 1992/95 to 2009 under existing conditions, though that is not true throughout the study reach (Table 6-6 and Figure 6-12).

Scalp Scenario 2:

Modeled water surface elevations indicate that the 11,700 cfs flood would be contained along the left bank adjacent to Berry Estates (RM 3.34 to RM 3.39) and adjacent to Shamrock Park (RM 2.97) with Scalp Scenario 2 implemented (Table 6-5). There is containment of 11,700 cfs in the upstream part of this study reach under existing conditions, so any decrease in water levels due to gravel removal would increase existing freeboard (Table 6-5).

In the downstream part of the study reach, the 11,700 cfs water surface elevations would decrease by as much as 1.2 feet, at RM 3.54 (Table 6-6 and Figure 6-12). The 11,700 cfs water surface elevation would decrease by 0.1 foot at RM 2.97 (Table 6-6 and Figure 6-15) and decrease by 0.5 feet at RM 3.35 (Table 6-6 and Figure 6-16) with Scalp Scenario 2 implemented. In the upstream part of the study reach, the maximum decrease in water surface elevations would be 2.1 feet at RM 4.04 (Table 6-6).

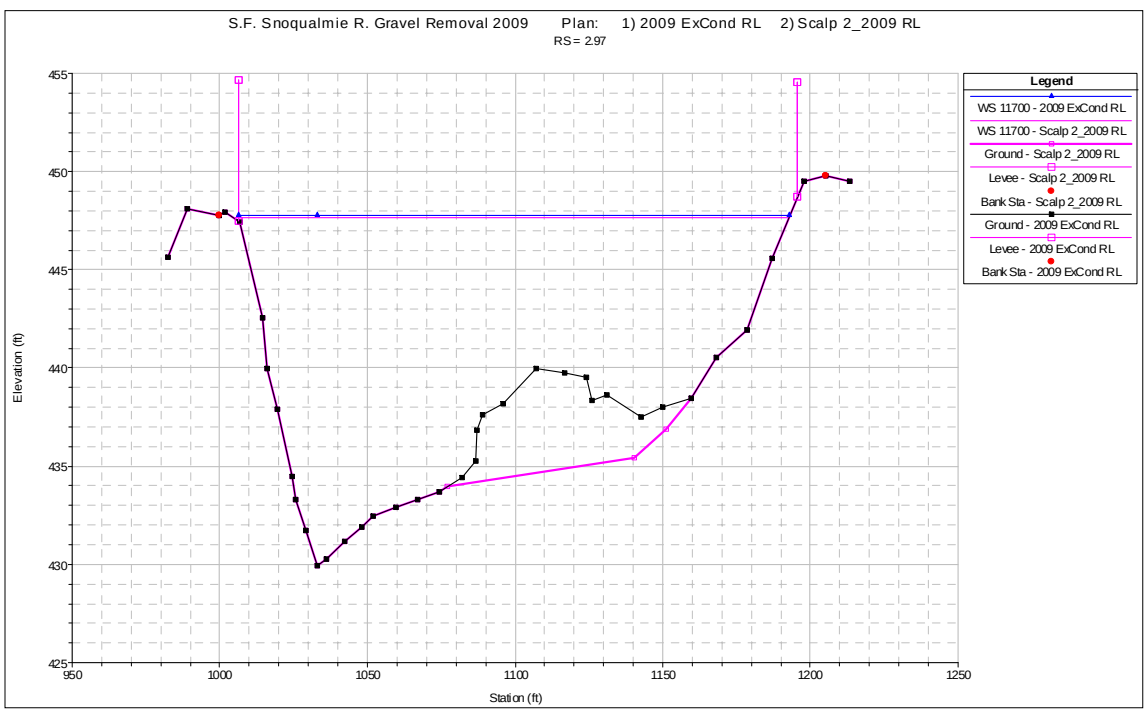


**Figure 6-15: South Fork Snoqualmie River, cross section view of 11,700 cfs (30-year) water surface elevations at RM 2.97 with 2009 existing conditions and Scalp Scenario 2 (and Scalp Scenario 3)**

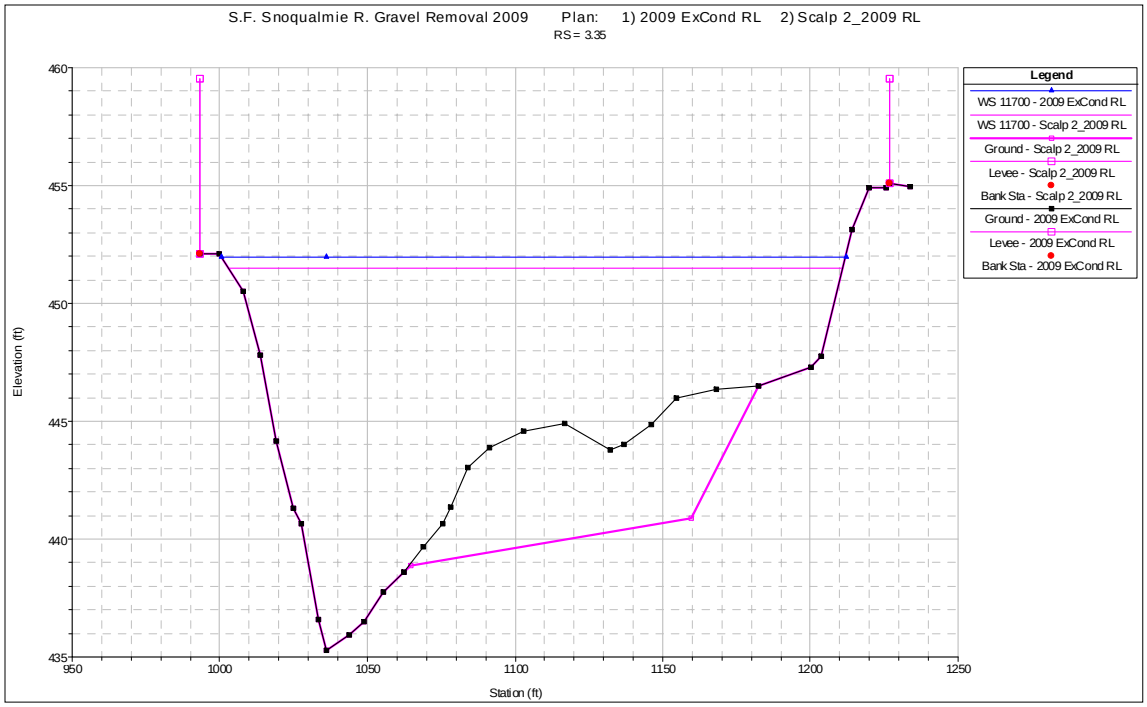


**Figure 6-16: South Fork Snoqualmie River, cross section view of 11,700 cfs (30-year) water surface elevations at RM 3.35 with 2009 existing conditions and Scalp Scenario 2 (and Scalp Scenario 3)**

Scalp Scenario 2 would result in containment of 11,700 cfs (30-year flood) throughout this study reach.

Decreases in the 11,700 cfs water surface elevations due to Scalp Scenario 2 would approximately counteract or more than counteract the increases in the 11,700 cfs water surface elevations along Berry Estates at RM 3.34 to RM 3.39 and along gravel bar 6 at RM 3.99 to RM 4.04 that have occurred from 1992/95 to 2009 under existing conditions (Table 6-6 and Figure 6-12). The relation between decreases in water surfaces due to Scalp Scenario 2 and increases in existing conditions water surfaces since 1992/95 varies throughout the rest of the study reach.

Scalp Scenario 3:

Modeled water surface elevations indicate that the 11,700 cfs flood flows would be contained by the left bank adjacent to Berry Estates (RM 3.34 to RM 3.39) and adjacent to Shamrock Park (RM 2.97) with Scalp Scenario 3 implemented (Table 6-5). There is containment of 11,700 cfs in the upstream part of this study reach under existing conditions, so any decrease in water levels due to gravel removal would increase existing freeboard (Table 6-5).

As with Scalp Scenario 2, Scalp Scenario 3 would result in a maximum decrease of the 11,700 cfs water surface elevations of 1.2 feet in the downstream part of the study reach, at RM 3.54 (Table 6-6 and Figure 6-12). The water surface elevation would decrease by 0.1 feet at RM 2.97 (Figure 6-15) and by 0.5 feet at RM 3.35 (Figure 6-16) with Scalp Scenario 3 implemented.

With no gravel removal simulated upstream of RM 3.51, the effect of Scalp Scenario 3 on the 11,700 cfs water surface diminishes to zero in the upstream direction at RM 3.95.

Scalp Scenario 3 would result in containment of 11,700 cfs (30-year flood) throughout this study reach.

Decreases in the 11,700 cfs water surface elevations due to Scalp Scenario 3 would approximately counteract or more than counteract the increases in the 11,700 cfs water surface elevations that have occurred from 1992/95 to 2009 under existing conditions along Berry Estates at RM 3.34 to RM 3.39, as well as most locations from RM 2.97 to about RM 3.86 (Table 6-6 and Figure 6-12). Scalp Scenario 3 would not include excavation upstream of RM 3.51, so it would have no effect in the area of RM 3.99 to RM 4.04.

### 6.2.4 Channel conveyance capacity and associated probabilities

Each channel conveyance capacity has a recurrence interval and an associated percent chance of exceedance at any given location in any given year. A discharge of 13,000 cfs at the USGS gage in North Bend has a 2 percent chance of exceedance in any given year and a discharge of 11,700 cfs at the USGS gage in North Bend has a 3.3 percent chance of exceedance in any given year (Table 5-1). Percent chance of exceedance can be taken as being equivalent to the probability of overtopping; as such, the difference in probability of overtopping between a discharge of 13,000 cfs and a discharge of 11,700 cfs is 1.33 percent in any given year.

A similar comparison can be made at any given location where a channel conveyance capacity flow has been determined. For example, the channel conveyance capacity at RM 3.39 is 11,700 cfs under 2009 existing conditions and 12,800 cfs with Scalp Scenario 2 implemented (Table 6-2). It can be inferred that the difference in the percent chance of exceedance between 2009 existing conditions and Scalp Scenario 2 would be on the order of about 1 percent in any given year (e.g., by comparing to probabilities calculated in Table 5-1). Stated differently, gravel removal by Scalp Scenario 2 would decrease the probability of overtopping at RM 3.39 by about 1 percent in any given year, for the duration of time through which the gravel removal remains effective (see Section 6.3 on longevity).

Table 6-2 lists negligible changes in the channel conveyance capacity at RM 2.97 under 2009 existing conditions (12,200 cfs) and with Scalp Scenario 2 in place (12,300 cfs). It can be inferred that the difference in probability of overtopping between existing conditions and a bar scalp scenario at this location would be a correspondingly negligible amount, e.g., a number approaching zero percent in any given year. This lack of response in modeled water surface elevations to gravel removal scenarios at RM 2.97 is interpreted to result from backwater conditions due to the North Bend Blvd (Bendigo) Bridge.

For a longer-term perspective, there is a 40 percent chance that a flood of 11,700 cfs will occur in the next 15 years, based on a simple statistical calculation of the probability of flood events occurring within a specific future time period (Linsley et al. 1982; p. 368). If gravel removal is not conducted (or some other flood reduction measure is not implemented), then there would be a 40 percent chance that flow would overtop along the left bank from RM 3.34 to RM 3.39 at

some point in the next 15 years, as did the January 2009 flood of 11,600 cfs. If rates of aggradation at this location continue at rates observed over the last 15 years, it is likely that the overtopping depth of 11,700 cfs flood some 10 to 15 years hence would be a little deeper than the same flood under 2009 existing conditions. If gravel removal were implemented first, then that 11,700 cfs discharge probably would be contained at the same left bank location (Table 6-2), depending on its timing within the next 15 years. But the same 11,700 cfs flow probably would not be contained 15 or more years after gravel removal, as ongoing sedimentation would negate the temporary flood hazard reduction benefits of gravel removal. These longer-term probabilities refer only to South Fork Snoqualmie River in-channel flows as a source of flooding, and potential temporary flood hazard reduction from in-channel gravel removal, and do not account for the probability of flooding from other sources (e.g., stormwater, tributaries, or groundwater) nor potential reduction from flooding by means other than gravel removal (e.g., property acquisitions, home elevations, stormwater improvements, etc.).

## 6.3 Longevity of flood hazard reduction benefits

The period of time that flood reduction benefits would persist, or its longevity, differs for each gravel removal scenario. The longevity of flood reduction benefits (in years) is estimated in this study as a simple calculation of the volume that would be extracted (cubic yards) divided by the reachwide average annual deposition rate (cubic yards/year). The best estimate of a reachwide average annual deposition rate is 2,700 cubic yards/year (Section 5.3). The longevity of flood reduction benefits of the bar scalping scenarios thus calculated would range from eight to 19 years (Table 6-7). It is important to recall that the calculated reachwide rates of deposition can vary by an order of magnitude between different time intervals (Table 5-4), so the actual period of longevity after gravel removal may vary considerably from the values calculated in Table 6-7.

**Table 6-7: Estimated longevity of gravel removal scenarios**

| Gravel removal Scenario | Estimated extraction volume (cubic yards) | Estimated longevity (average years) based on deposition rates | Estimated longevity (average years) based on influx rates |
|---|---|---|---|
| Scalp Scenario 1 | 22,000 | 8 | 5 |
| Scalp Scenario 2 | 51,000 | 19 | 12 |
| Scalp Scenario 3 | 24,000 | 9 | 6 |

These estimates of longevity by this calculation greatly simplify the actual periods of the longevity of flood reduction benefits for a few reasons. The full flood capacity resulting from a gravel removal scenario truly will persist only until there is a flow that moves and deposits sediment, which was estimated at about 7,400 cfs (approx. a 5-year flood) in Section 5. After gravel removal is completed, its flood reduction benefits will decrease as sediment moves into and deposits in the area of gravel removal. Because of the natural deviation of sediment transport and deposition from the “average annual” rate of deposition (Table 5-4), the loss of flood reduction benefit will not proceed at a regular or linear rate. Furthermore, an individual flood or a winter of high flows with high rates of sediment transport and deposition could decrease the overall longevity of the bar scalping scenarios listed in Table 6-7, possibly

significantly. For example, deposition of almost 18,000 cubic yards during the 2007-2009 period would almost match the total excavation volume of either Scalp Scenario 1 or 3 and thereby effectively eliminate most of their flood reduction benefits in a short period of time.

In addition, because deposition may be enhanced after bar scalping due to changes in local channel slope and depth of flow (Section 2.3.1), the calculated periods of longevity in Table 6-7 may overestimate the actual time through which flood hazard reduction benefits would persist. If gravel removal results in a partial or complete interruption of gravel flux through the study reach, as referenced in Section 2, then some or all of the bedload influx to the study reach may deposit within the study reach. The estimated average annual bedload influx of 4,400 cubic yards/year (Booth et al. 1991) was used as a representative value by which to divide the extraction volume in order to derive the longevity estimates that range from five to 12 years in the right hand column of Table 6-7.

## 6.4 Discussion

Flood characteristics under existing conditions inform the discussion of where gravel removal for flood reduction purposes would best be considered, if it is to occur. For 2009 existing conditions, modeling indicates that a flow of 13,000 cfs plus one foot of freeboard is contained along the left bank in the upstream part of the study reach except at RM 3.99 and along the right bank through the entire reach except near North Bend Blvd Bridge. Any discussion of gravel removal for flood reduction purposes would do well to focus on the left bank from RM 3.34 to RM 3.39 in this study reach because that area is upstream of backwater effects of North Bend Blvd (Bendigo) Bridge and it is the location of past overtopping and damaging flood flows.

The three bar scalping scenarios would increase channel conveyance capacity but would not contain 13,000 cfs plus one foot of freeboard along the left bank at RM 3.34 to RM 3.39. A flow of about 12,000 cfs would be contained at the same left bank location if any one of the gravel removal scenarios were to be implemented. Gravel removal would decrease the water surface elevations at this RM 3.34 to RM 3.39 location during a 13,000 cfs discharge (50-year flood) by as little as 0.2 feet and as much as 0.7 feet and during a 11,700 cfs discharge (30-year flood) by as little as 0.2 feet and as much as 0.8 feet (Table 6-4 and 6-6). There would be little to no change in water surface elevations due to gravel removal by any of the three scenarios along RM 2.97 to RM 3.02, which is consistent with the presence of backwater conditions.

Although full containment of 13,000 cfs plus one foot is not attained throughout, gravel removal by any of the three scalp scenarios would result in vertical decreases in water surface elevations that would, to a lesser or greater extent, counteract some or all of the vertical increases in water surface elevations that have occurred under existing conditions since 1992/95 at RM 3.34 to RM 3.39 (along Berry Estates). Implementation of either Scalp Scenario 1 or 2 would have the same result at RM 3.95 to RM 4.04 (gravel bar 6). The extent to which the gravel removal scenarios would counteract the increases in water surface elevations that have occurred since 1992/95 varies elsewhere throughout the study reach.

The longevity of flood reduction benefits would be about eight to19 years for the three different scenarios when longevity is calculated based on an average annual deposition rate and about five to 12 years when longevity is calculated based on an average annual coarse sediment influx rate (which would be applicable if gravel removal induces full interruption of gravel flux through the reach). These timeframes also are consistent with the apparent longevity of flood reduction benefits resulting from the 1991 and 1994 gravel removal operations in this study reach. Hence, a generalized estimate of the longevity of flood reduction benefits of the gravel removal scenarios in this study would be about a decade or so, depending on the gravel removal scenario implemented and the magnitudes and durations of the floods that occur soon thereafter. In any case, the full flood hazard reduction benefit of gravel removal would not last the full period of calculated longevity, because sediment will begin to fill in the locations where gravel bars were scalped as soon as there is a flood that moves and deposits sediment.

The fact that none of the three bar scalping scenarios in this study would contain 13,000 cfs plus one foot of freeboard throughout the study reach, although the 1964 As-Built levees presumably did, can be explained by several reasons. The 1964 As-Built excavations probably went deeper and wider at each gravel bar than could be implemented today under existing regulatory requirements. Specifically, the 1964 bar scalping probably left the gravel bar tops flat and excavated all the way down to the low flow water elevation, whereas today a 2 percent sloping gravel bar top is required of any bar scalp and these scalp scenarios begin at least one foot above the low flow elevation. All scalp scenarios in this study were purposefully configured to avoid excavation within a line at a slope of 3H:1V drawn from the levee top of bank down to the gravel bar, whereas the 1964 As-Built condition most likely had gravel bar excavation all the way back to the riprap on the new levee face, which were built at a 1.5H:1V slope. Comparison of Figures 4-1 and 4-4 illustrates differences between the past and any potential future excavation practices. Also, the freshly constructed levee project in 1964 had smoother bed and levee bank surfaces than present-day conditions, resulting in less flow resistance and therefore greater conveyance capacity. In addition, the present-day North Bend Blvd (Bendigo) Bridge was built more than a decade after the levees, so its backwater effects would not have been taken into account in channel capacity design considerations in the 1960s.

## 6.5 Conclusions

1. Under 2009 existing conditions, modeled channel conveyance capacity exceeds 15,000 cfs or greater along both banks everywhere in the upstream part of the study reach (RM 3.64 to RM 4.46) except the left bank at RM 3.99. The existing conditions right bank also has containment in excess of 15,000 cfs in the downstream part of the study reach except near North Bend Blvd (Bendigo) Bridge. Any increases in channel conveyance capacity resulting from gravel removal would manifest as increased freeboard along most of the upper part of the study reach and most of the downstream right bank.

2. Under 2009 existing conditions, modeled channel conveyance capacity in the downstream part of the study reach (RM 2.85 to RM 3.54) does not equal 13,000 cfs plus one foot of freeboard at various locations, primarily due to overtopping along the left bank. Gravel

removal would result in containment of 14,000 cfs at RM 3.54 and RM 3.51 where it does not occur under existing conditions. Gravel removal would decrease water surface elevations but would not contain 13,000 cfs plus one foot of freeboard along the left bank from RM 3.34 to RM 3.39.

3. Gravel removal would not have a significant effect on water surface elevations at RM 2.97 to RM 3.02, which is consistent with backwater conditions due to North Bend Blvd (Bendigo) Bridge. Hydraulic modeling in this study shows noticeable effects of gravel removal scenarios on water surface elevations at RM 3.15 and upstream, which suggests backwater conditions are diminishing or absent from that location upstream.

4. Gravel removal would decrease water surface elevations by as little as 0.2 feet to as much as 0.7 feet during the 13,000 cfs discharge (50-year flood) along the left bank at RM 3.34 to RM 3.39. Gravel removal would decrease water surface elevations by as little as 0.2 feet to as much as 0.8 feet during the 11,700 cfs discharge (30-year flood) along the left bank at RM 3.34 to RM 3.39.

5. None of the three gravel removal scenarios would contain 13,000 cfs plus one foot of freeboard throughout this study reach. Containment with certainty of 13,000 cfs plus one foot of freeboard (the flood reduction objective) throughout this study reach will require measures beyond gravel removal as evaluated in this study.

6. Gravel removal (by Scalp Scenario 2) would temporarily increase the channel conveyance capacity from 11,700 cfs to about 12,800 cfs along the left bank at RM 3.39, a location of past overtopping and damaging flood flows. This same increase in containment at this location would decrease the probability of overtopping by about 1 percent in any given year, for the duration of time through which the gravel removal remains effective.

7. Gravel removal by Scalp Scenario 1 or 2 would temporarily increase channel conveyance capacity from about 14,200 cfs to about 18,000 cfs along the left bank at RM 3.99.

8. Decreases in water surface elevations due to gravel removal by any of the three scalp scenarios would, to a greater or lesser extent, counteract the increases in water surface elevations that have occurred since 1992/95 along Berry Estates at RM 3.35 to RM 3.39. Scalp Scenario 1 or 2 would have similar results along gravel bar 6 at RM 3.95 to RM 4.04. Decreases in water surface elevations would vary throughout the rest of the study reach, depending on the scenario.

9. All flood hazard reduction benefits due to gravel removal described in this study would be temporary in nature. Calculations in this study indicate that the flood reduction effectiveness of gravel removal could persist for about a decade or so, depending on the gravel removal scenario implemented and the magnitudes and durations of the floods that occur after gravel removal. However, the full flood hazard reduction benefit of gravel removal would not persist through the full period of the calculated longevity because sediment will begin to fill in the locations where gravel bars were scalped as soon as there is a flood that moves and deposits sediment.

# 7. General description of potential adverse impacts and estimated costs of gravel removal scenarios on the South Fork Snoqualmie River

Three types of potential adverse impacts of gravel removal in the South Fork Snoqualmie River are described generally in this section: increased riverbed or bank erosion that could destabilize King County levees or existing public infrastructure, increased nearby flooding, and impacts to salmonid fish habitat. Providing a general assessment of these few key impacts is intended to inform the evaluation of the three bar scalping scenarios in the next report section, while assuming that if a gravel removal operation were to be pursued on this river, more specific characterization of a broader array of adverse impacts would be required as part of the permit process. The methods that were used to generate this general assessment of likely impacts were described in Section 3. A description of the types of further study that may be needed for a more detailed assessment of impacts is included at the end of this report.

## 7.1 Potential adverse impacts of gravel removal on the stability of existing levees or infrastructure

### 7.1.1 Information from the literature

Information summarized in Section 2.3.1 is drawn on to describe in this subsection the potential effects of gravel removal on erosion of riverbanks, levees or public infrastructure if gravel removal were to occur on the South Fork Snoqualmie River.

Kondolf et al. (2001) note that “Regardless of the [gravel] mining technique, the pre-existing channel morphology is disrupted and a local sediment deficit is produced.” Gravel removal from an active river channel “interrupts the continuity of sediment transport through the river system, disrupting the sediment mass balance in the river downstream and inducing channel adjustments (usually incision)” for a considerable distance both upstream and downstream (Kondolf et al. 2001).

The elements and effects of gravel removal directly relevant to potential destabilization of existing levees and infrastructure include:

- The interruption of coarse sediment transport to downstream areas can cause coarsening of the channel bed material, erosion of channel bed, bars and banks, a reduction of downstream gravel bars local scour or upstream or downstream propagation of incision of the channel bed (Kondolf and Matthews 1993; Norman et al. 1998).
- Channel incision can lead to potential channel instability (Dunne et al. 1981) and undercut the toe of the river banks or structures (Collins and Dunne 1990), including levees, revetments or infrastructure such as bridges.
- Gravel extraction far in excess of the average annual influx of coarse sediment is more likely to cause erosion problems than gravel removal in lesser amounts (Collins and Dunne 1990; Kondolf et al. 2001; NOAA 2004).
- The wider, more uniform channel formed by gravel bar scalping will alter channel hydraulics. Those changes in hydraulics can result in altered flow paths across the gravel

bar, leading to either greater or lesser impingement of flows on adjacent riverbanks, with increased or decreased potential for local scour (Collins and Dunne 1990).

A gravel removal operation on the South Fork Snoqualmie River could be expected to result in some or all of these effects to varying degrees.

As with any gravel removal operation, the downstream movement of coarse sediment would be diminished or interrupted, potentially resulting in downstream erosion, scour, or coarsening of the riverbed material, or other disruptions in channel process. Perkins (1996) found that there was a decrease in the channel migration rate on the South Fork Snoqualmie River downstream of this study reach following the extensive excavation (which appears to have been done by bar scalping) in the mid-1960s associated with construction of the South Fork Snoqualmie River levees. This observed decrease in channel migration would be consistent with the effect of interrupting a large portion of bed material being transported from upstream. If Scalp Scenario 2 were implemented (which would approximate the 1964 excavations in volume and extent), alteration of downstream channel migration could be expected.

South Fork Snoqualmie River gravel bar scalping could be expected to result in decreased confinement at the affected gravel bars, with resulting alterations to flow hydraulics, flow direction and sediment movement. Local increases in channel gradient at the upstream end of the scalped gravel bar could induce local scour (Collins & Dunne 1990; NOAA 2004). If scour occurred where the elevation of the existing channel bed was already close to the elevation of the adjacent levee toe, then erosion, undermining or levee destabilization could occur.

The altered hydraulics of wide, flat bar surfaces resulting from bar scalping likely would also locally decrease channel gradient and depth along the middle of the scalped gravel bar (Kondolf et al. 2001; NOAA 2004), which are conditions that enhance sediment deposition. Sequential surveys of South Fork Snoqualmie River cross sections following bar scalping operations suggest this to have occurred after the bar scalping of the early 1990s (e.g., as seen in Figure 5-9B on the right bank gravel bar 3 at RM 3.39, from 1992 to 1999). The same conditions that favor deposition in the middle of scalped gravel bars, and relatively higher rates of deposition such as those observed from 1992/95 to 1999, could be expected along future scalped bars.

Channel instability (Collins and Dunne 1990) or channel shifting (Dunne et al. 1981) could occur due to any future gravel removal, as suggested by channel changes within this reach during and after the various past gravel removal operations, although channel shifting would be limited due to the planform configuration that is imposed by levee constraints. There was a channel shift at RM 3.15 that cut off a left bank point bar (gravel bar 2) to form an island in about 1993, after the bar scalping in that area in 1991. This may be an example of a channel shift resulting from shortening of the main high flow path due to scalping of the left bank point bar, as described by Dunne et al. (1981). There also was left bank erosion damage to the levee at RM 3.65 in the floods of 1995-96 after bar scalping at adjacent gravel bar 5 in 1994 and bar scalping of gravel bar 4 (about 0.15 river miles downstream) in 1991. These examples and other in-channel erosion that occurred at places throughout this study reach in the mid- to late-1990s may have been affected by the gravel extractions in 1991 and 1994, in combination with the high flows of 1995-

96, but there is insufficient data to demonstrate a direct relationship between gravel removal and observed erosion.

As emphasized in the literature, the extent to which these effects would occur appears to vary with the amount of extraction that would occur with each scenario, where extraction far in excess of the average annual influx of coarse sediment from upstream is more likely to result in erosion problems, both upstream and downstream. The effects of bar scalping scenarios on coarse sediment movement through the South Fork Snoqualmie River study reach, and potential erosion problems, could be expected to vary based on extraction volumes.

### 7.1.2 Available information, studies and observations relevant to this reach

#### 7.1.2.1 Excavation relative to average annual influx of coarse sediment

Dunne et al. (1981) identify potential adverse effects of gravel removal such as channel instability, channel abandonment and shifting, damage to structures and to spawning areas, particularly if extraction volumes exceed the influx of sediment to the site: “For this reason, gravel harvesting should be conducted in such a way that a considerable fraction of bedload arriving at a site is allowed to pass on to the downstream bars.” Dunne et al. (1981) assert that if gravel removal were done as "careful scalping" it would not likely result in increased erosion within the study reach and that “excessive harvesting" could cause shortened flow paths or redirected flows that can result in toe scour and bank erosion, but do not provide details as to what constitutes careful versus excessive extraction. If the amount of excavation compared to the average annual volume of coarse sediment influx is considered an absolute criterion, then none of the three South Fork Snoqualmie River bar scalping scenarios in this study would be considered “careful scalping” as all would exceed the annual influx. If the bar scalping scenarios are considered relative to each other, then those with less excavation (e.g., Scalp Scenario 1 or Scalp Scenario 3) would be considered less likely to result in problematic erosion than a scenario with larger excavation (e.g, Scalp Scenario 2).

The bedload sediment transport model constructed by Booth et al. (1991) (Section 5.3.3) includes a model reach (Reach 23) that corresponds closely to the study reach for the present study. The average annual influx of coarse sediment into their Reach 23 was calculated by Booth et al. (1991) as 4,400 cubic yards per year. If average annual influx is used as a guideline, any extraction far in excess of 4,400 cubic yards per year could be considered problematic. By this metric, Scalp Scenario 1 and 3 each would excavate about five times the average annual influx and Scalp Scenario 2 would excavate about 12 times the average annual influx.

Some existing information does not emphasize the relation between excavation volume and average annual influx of coarse sediment. Shannon & Wilson (1993) evaluated existing levee conditions and potential alternatives for flood reduction, including gravel removal. They observed few changes in overall bar location following the large excavation in the mid-1960s for levee construction, which they estimated as 63,000 cubic yards scalped from the existing gravel bars. Shannon & Wilson (1993) therefore assert that the gravel bar configuration within the levees probably would not be altered by a present-day gravel removal operation and that an extensive gravel bar scalping operation (on the scale and extent of Scalp Scenario 2 in this study)

could be implemented without downstream impacts to sediment movement and deposition. While it is true that an extensive bar scalping operation may not cause significant downstream impacts in terms of sediment regime and channel morphology because the river downstream of this study reach is a depositional reach (Booth et al. 1991), the potential for extensive excavation to destabilize existing levees or infrastructure within this study reach appears to be considerable, as described below (Section 7.1.2.2).

Further information on gravel removal in this study reach comes from the commercial bar scalping operation that removed approximately 1,000 cubic yards per year on an ongoing basis from 1956 to 1998 at gravel bar 6 (aka Churchill Bar; approx. RM 3.95 to RM 3.99). That operation annually extracted less than the estimated average annual influx (4,400 cubic yards) of coarse sediment and less than the estimated average annual deposition volume for this reach (2,700 cubic yards). As such, the now-ceased annual extraction at the Churchill Bar might be considered an example of the "replenishment rate" approach (Section 4.5), i.e., gravel removal conducted on a regular basis at a level less than the annual influx. The cumulative volume removed over a period of more than 40 years is not insignificant to the extent that it diminished ongoing aggradation at and possibly downstream of the extraction site, and the extraction probably had some net benefit to flood containment capacity at and for some distance upstream of the extraction site, though the magnitude and extent of this benefit is not known. Although that operation was conducted for commercial purposes, it is similar to the replenishment rate approach, and as such could inform potential flood hazard reduction efforts.

#### 7.1.2.2 Potential erosion or scour of riprap along the existing levees and bridge

The 1964 levee design plans and subsequent As-Built sketches provide information on the maximum depth of the toe of the levees at various locations. Comparison of the full channel cross sections in the 1964 design plans to 1992 and 2009 existing conditions (Figure 7-1 and Figure 7-2) suggest that the present-day thalweg elevation is close to the bottom of the levee toe at these two locations, both of which are located along present-day gravel bar 1. No other full channel cross sections have been found in either the design plans or As-Built information.

The conditions at these two cross sections appear to be representative of other locations, as indicated in existing South Fork Snoqualmie River geotechnical studies (Shannon & Wilson 1993, 2009), which found several areas of inadequate toe protection or riprap erosion on along both river banks in this same study reach. The situation would be further exacerbated than depicted in Figures 7-1 and 7-2 during higher flows when the depth of active scour would go deeper than the channel bottoms plotted in these figures, which were surveyed in low flow conditions. This information suggests that the potential already exists for widespread lack of protection against scour erosion and levee undermining and that any gravel removal scenario that would increase the likelihood of scour along the levee toes likely would exacerbate this condition.

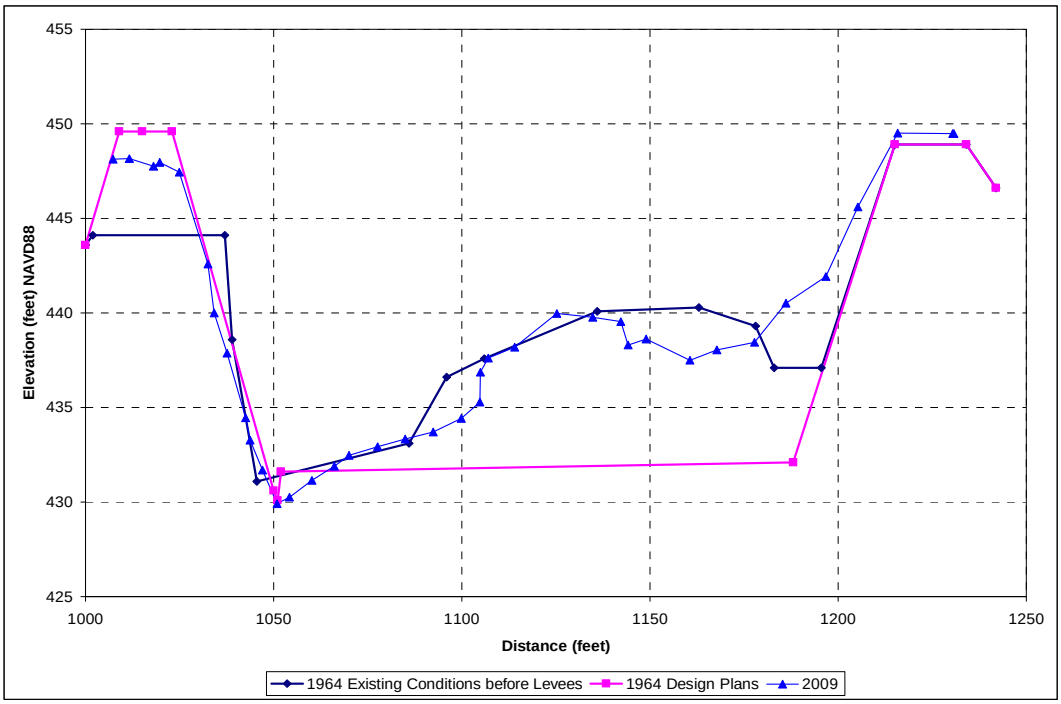


**Figure 7-1: South Fork Snoqualmie River cross section 45+41 from 1964 existing conditions before levee construction and 1964 plan set dimensions, compared to present-day RM 2.97 in 2009**

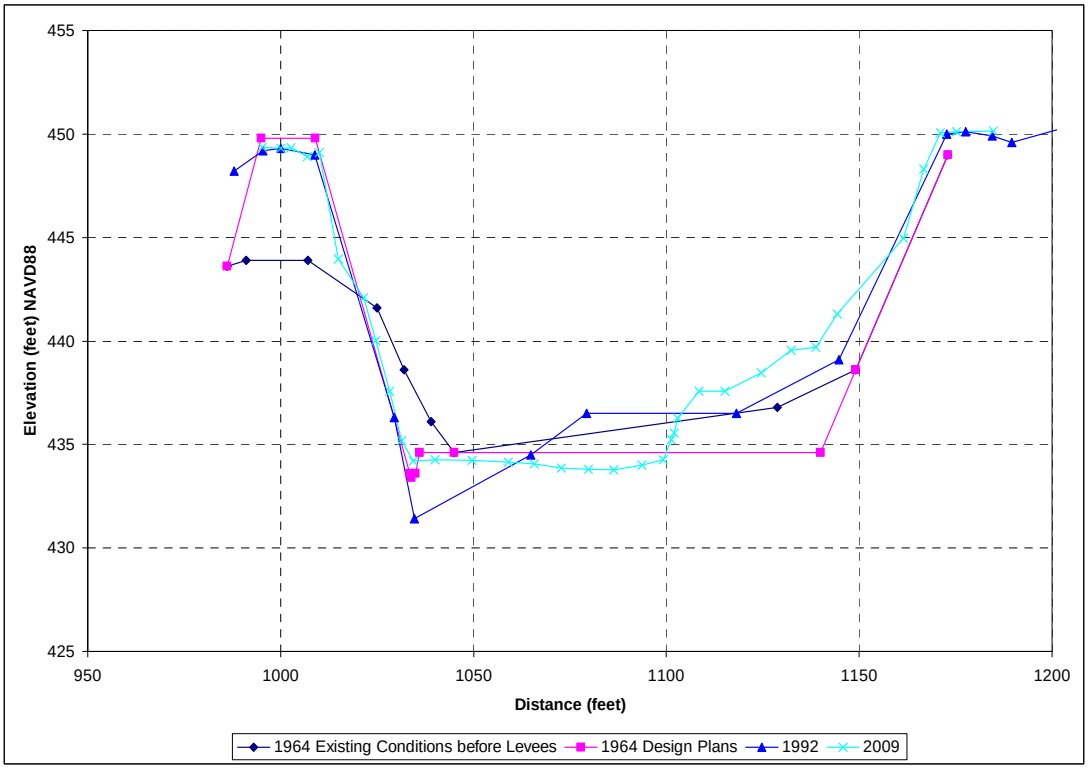


**Figure 7-2: South Fork Snoqualmie River cross section 43+00 from 1964 existing conditions before levee construction and 1964 plan set dimensions, compared to present-day RM 3.02 in 1992 and 2007**

Repeated surveys of the cross section at the downstream face of North Bend Blvd Bridge (Figure 7-3) plot the channel bottom elevations at this location several times from 1992 to 2009. Figure 7-3 indicates that there has been some erosion at this cross section from 1999 to 2009, with a total net lowering of the thalweg by about three feet and some erosion across most of the channel bed during that period. While this net erosion may seem relatively minor, or locally moderate, it is progressing through this time series. It should be noted again that the survey data were collected during low flow and the actual scour depth that occurs during high flows will be greater than indicated in these plots, which reflect the condition after the scoured areas partially refill with gravel during the receding flows of a flood. Therefore, the present condition of progressing scour calls for caution regarding any in-channel management that could increase downcutting under this bridge. Other data at this location such as bridge plans, earlier surveys, or USGS flow measurements (at USGS Gage 12144000) could further inform the situation.

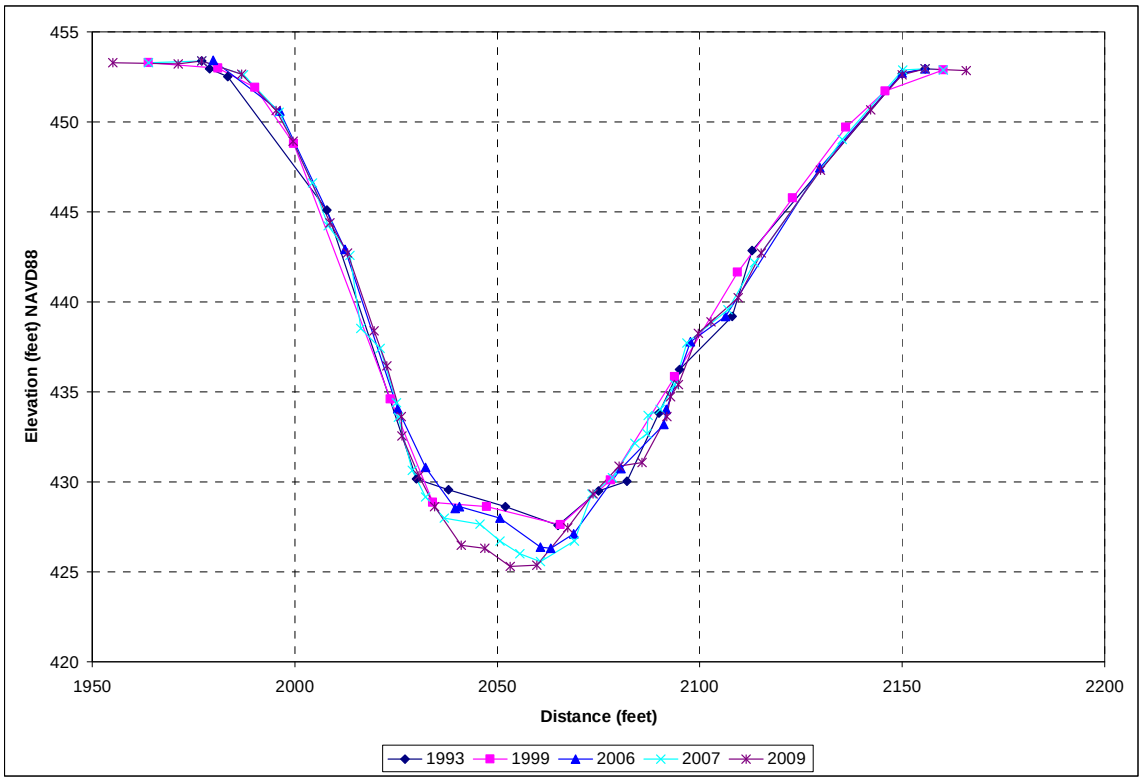


**Figure 7-3: South Fork Snoqualmie River surveyed cross sections at RM 2.84, the downstream face of North Bend Blvd (Bendigo) Bridge**

The North Bend Blvd (Bendigo) Bridge appears to have been designed with an opening that would convey 10,900 cfs, estimated to be a 50-year flood calculated for bridge designs in 1976 but which is about a 20-year event today; this discrepancy between historic and present day peak flow estimates may imply that the bridge opening is under-designed (Kato and Warren, Inc. 2000). The same study by Kato and Warren, Inc. (2000) found that if levee system improvements were made and flows that currently overtop the levees in a 100-year flood were kept in-channel, the erosive forces on the existing riprap that protects the bridge abutments would increase such that the stability of the riprap would decrease appreciably. These findings from Kato and Warren, Inc. (2000) are not predictive with regard to the potential for gravel

removal to cause erosion impacts at this bridge, but they provide relevant information for this study: the North Bend Blvd Bridge conveyance capacity is limited and an increase in flow within the channel due to greater containment upstream could increase riprap scour along the bridge.

Based on available information, the potential for gravel removal to result in scour or destabilization of riprap along the South Fork Snoqualmie River levees or North Bend Blvd (Bendigo) Bridge is a real concern. Therefore, the following findings are offered regarding potential scour associated with any gravel removal operation:

- Further information relevant to North Bend Blvd (Bendigo) Bridge stability should be obtained, including As-Built bridge plans, USGS measurements and any other surveys.
- Any gravel removal proposal should include preparation of scour calculations for existing conditions and proposed post-gravel removal conditions.
- A geotechnical assessment should be conducted of the present-day depth and stability of levee toes throughout this study reach, particularly in the vicinity of any proposed excavation. (As of late 2010, King County is in the process of contracting for geotechnical analyses that should address these concerns about the South Fork Snoqualmie River levee stability.)
- Any gravel removal operation must not increase the likelihood of scour and undermining of levees or infrastructure.
- Even without further investigation, the information in this study and in previous studies regarding levee toe elevations and bridge conditions suggests that any large or extensive gravel removal operation may not be possible without extensive adverse effects in terms of levee toe and bridge scour.
- Any excavation that is close to or lower than the toe of the existing levees, or which could result in scour to those elevations, would threaten the stability of the levees and would not be acceptable as a gravel removal scenario.

Factors that have the potential to threaten the stability of existing levees and infrastructure are considered in the rating of each scenario.

### 7.1.3 Ratings of each gravel removal scenario for its likely avoidance of destabilizing existing King County flood protection facilities or public infrastructure

This subsection provides a qualitative rating of each bar scalping scenario's likelihood to avoid bank erosion or undermining of levees or bridge infrastructure. Information from subsections 7.1.1 and 7.1.2 and reconnaissance-level field observations was used to evaluate potential physical effects likely to result from each scenario. The primary elements and physical effects of gravel removal that were considered in evaluating the potential for each scenario to destabilize existing levees or infrastructure are: excavation on a gravel bar or reach scale that results in channel incision within the study reach or propagation of incision upstream or downstream, extraction in excess of influx with resultant channel degradation, and the overall configuration of the scenario. The existing conditions within the study reach also are a primary factor. The alteration of channel geometry and associated alteration of channel hydraulics was considered secondarily, because altered hydraulics may result in greater or lesser impingement of flow on

levees with increased or decreased potential for local scour. Most of these factors are drawn directly from the elements relevant to destabilization in the bulleted list in Section 7.1.1.

Scalp Scenario 1:

Scalp Scenario 1 is configured to minimize impacts to instream habitat by limiting excavation and minimizing alteration of existing hydraulics. It would do so by keeping excavation two feet vertically above the low flow water elevation and by leaving untouched the upstream third of the gravel bar and areas of woody vegetation. The five gravel bars that would be scalped in this scenario are spread out through the reach.

The fact that the scalped gravel bars are spread out in Scalp Scenario 1 may allow any interruption of sediment transport and local sediment deficit that does result from this scenario to be compensated for by erosion of the nearby riverbed or un-scalped gravel bars within this reach, and thereby decrease the likelihood of incision propagating upstream or downstream of the study reach. That same compensation of a local sediment deficit would, however, manifest as channel degradation or scour within the study reach.

The emphasis of Scalp Scenario 1 on minimizing excavation and alteration of hydraulics would make it least likely of the three scenarios to result in adverse flow impingement and increased local scour of levee toes.

Relative to the other two scenarios, Scalp Scenario 1 should have a lower potential to destabilize levees or infrastructure due to its shallower excavation depth and areal extent and because it would excavate the least volume, at 22,000 cubic yards. However Scalp Scenario 1 still would excavate five times the average annual bedload influx, and do so throughout a river reach where the thalweg is already lower than the levee toes, and the channel under the North Bend Blvd Bridge is progressively downcutting. Therefore, Scalp Scenario 1 gets a rating of moderate avoidance of destabilizing existing King County levees or public infrastructure.

Scalp Scenario 2:

Scalp Scenario 2 would remove the largest sediment volume of the three scenarios by excavating to within one foot of low flow along the full width and length of every non-island gravel bar in this study reach. The Scalp Scenario 2 excavation of 51,000 cubic yards would be about 12 times, and far in excess of, the average annual influx of coarse sediment. This scenario would likely result in an interruption of coarse sediment transport through this study reach and a sediment deficit that likely would be compensated for by channel degradation within this study reach and propagation of incision outside of the reach. Such erosion, coupled with the existing thalweg being at nearly the same elevation as the levee toe throughout much of the reach, could result in scour of the levee toe and levee destabilization. The amount and extent of excavation in Scalp Scenario 2 likely constitutes “excessive harvesting” (Dunne et.al. 1981), with its potential resultant channel shifts, incision or instability.

Scalp Scenario 2 would alter channel geometry and hydraulics at every gravel bar and cumulatively throughout the reach, giving it the highest likelihood of the three scenarios to alter

flow paths and thereby either increase or decrease flow impingement on existing levees, which may cause increased local scour at some locations.

Because of its extensive excavation along the width, depth and length of every non-island gravel bar, its excavation far in excess of the average annual influx of coarse sediment, and also its likely widespread alteration of channel hydraulics, Scalp Scenario 2 would have the greatest potential of the three scenarios to adversely affect the stability of existing levees and infrastructure. Scalp Scenario 2 gets a rating of low avoidance of destabilizing existing King County levees or public infrastructure.

Scalp Scenario 3:

Scalp Scenario 3 would scalp the downstream four gravel bars to an identical planview extent and depth as Scalp Scenario 2, so its adverse effect on existing levees and infrastructure would be the same as or similar to Scalp Scenario 2 in the downstream area. This scenario would leave the upstream five gravel bars in the study reach untouched and would scalp 24,000 cubic yards from the four downstream gravel bars using deep and extensive excavation.

The total excavation volume, which would equal about five times the average annual influx of coarse sediment, is similar to Scalp Scenario 1 and less than half that of Scalp Scenario 2. This excavation may not completely interrupt coarse sediment transport sufficient to propagate incision upstream or downstream of this study reach, but it probably would be sufficient to result in a local sediment deficit within the reach. That deficit probably would be compensated for within this study reach which would manifest as erosion of bed and gravel bars, channel degradation, or local scour.

Scalp Scenario 3 would alter channel geometry and hydraulics in the downstream area as in Scalp Scenario 2, which may result in increased local scour in some locations. However, the backwater effects of North Bend Blvd (Bendigo) Bridge may diminish the potential for local scour upstream of the bridge (see below).

Relative to the other two scenarios, Scalp Scenario 3 should result in a lesser threat to levee or infrastructure stability than Scalp Scenario 2 but more than Scalp Scenario 1. With its deep, extensive and sequential scalping of the downstream four gravel bars in an area where there is evidence that the thalweg is lower than the existing levee toes and the channel under the North Bend Blvd (Bendigo) Bridge is progressively downcutting, Scalp Scenario 3 gets a rating of low to moderate for avoidance of destabilizing King County levees or public infrastructure.

Potential effect of backwater conditions:

Findings of this study indicate that the North Bend Blvd (Bendigo) Bridge causes backwater conditions upstream to about RM 3.02 at various flows and Kato and Warren, Inc. (2000) describe backwater as far upstream as RM 3.23. While backwater conditions essentially negate the flood reduction effectiveness of gravel removal, they also may decrease the extent to which gravel removal would induce local scour of the levees, and thereby diminish the potential threat of gravel removal to levee stability.

The extent to which backwater conditions alter the potential for gravel removal to induce scour or erosion is not quantified here, but it can be stated qualitatively that the North Bend Blvd Bridge backwater conditions probably would have the greatest effect on the scour potential of Scalp Scenario 3 because that scenario is focused on the downstream four gravel bars in the study reach. The same bridge backwater conditions probably would have lesser influence on Scalp Scenarios 1 and 2 because most of their scalped bars are upstream of the area of backwater influence. The ratings of the three scalp scenarios, above, include this qualitative consideration of the influence of backwater conditions on scour potential.

Any potential decrease in scour within backwater conditions upstream of the bridge should not be assumed to occur in the channel underneath the bridge, where constricted flows would tend to favor scour, as evidenced in Figure 7-3.

These ratings of the three scenarios with regard to their potential destabilization of existing King County levees and public infrastructure are used in evaluation of the gravel removal scenarios in Section 8. If any gravel removal proposal is to be pursued, a thorough and quantitative evaluation of impacts would need to be conducted, including an analysis of the effects of North Bend Blvd (Bendigo) Bridge backwater.

## 7.2 Potential for gravel removal to increase nearby flooding

Gravel removal from a river can increase channel conveyance capacity and can enable containment of floodwaters that otherwise would flow out of the channel into the overbank floodplain area. Because the floodwaters are no longer stored in the overbank areas, they are conveyed downstream within the channel more quickly relative to existing conditions. Such increased in-channel conveyance of floodwaters can adversely affect downstream areas by increasing the downstream flow rate. Results from this study can inform this issue qualitatively, but if gravel removal is to occur on the South Fork Snoqualmie River, its potential impacts on downstream flooding will need to be addressed more comprehensively than can be done in this study.

Table 7-1 lists the difference at each cross section between the channel conveyance capacity for 2009 existing conditions and each of the three gravel removal scenarios. (As stated previously, the right bank elevation is greater than the left bank at every cross section in this reach, so channel conveyance capacity is equivalent to the maximum flow contained by the left bank.) For example, Scalp Scenario 1 would increase channel conveyance capacity relative to the 2009 existing conditions by 1,000 cfs at RM 3.54 and Scalp Scenarios 2 and 3 would increase channel conveyance capacity by 1,500 cfs at RM 3.54. The modeled increase in channel conveyance capacity at each cross section is equivalent to the amount of increased containment at that cross section. But modeled increases in channel conveyance capacity at each cross section cannot be simply summed through the study reach to represent the cumulative reach-scale increase in channel conveyance to downstream areas because the HEC-RAS model configured for this study calculates hydraulic conditions at every cross section using the full given flood discharge, even if part of that discharge was calculated to have gone overbank at an upstream or downstream cross

section. This is evident in the three Table 7-1 columns that list "Increased Channel Capacity" values. A differently configured HEC-RAS one-dimensional model or a different hydraulic model, such as a two-dimensional model, that considers split flows (as well as the influence of other floodwater sources) is needed in order to quantitatively address potential adverse impacts of gravel removal on downstream flooding. The results in Table 7-1 demonstrate qualitatively that there would be some level of increased in-channel conveyance of floodwater to areas downstream of the study reach with increased containment and conveyance capacity due to gravel removal, and give a general indication of the relative differences between scenarios.

Table 7-1 indicates that there would be some amount of increased channel conveyance capacity at almost every cross section for each of the three scenarios, and that some of those increases would be large enough to potentially create a measureable downstream effect relative to existing conditions. A typical flood hydrograph of this river (not shown here) suggests that such an effect would be of relatively short duration. A moderate magnitude and short duration effect fits the description for a "moderate" level of avoiding an impact described in Section 4 (Table 4-1). The differences between the three scalp scenarios in the amount of flow that would be kept in channel appear to be relatively minor, so all three scenarios would get a moderate rating for avoiding potential increases to nearby or downstream flooding.

The potential flooding impacts to downstream areas due to increased in-channel conveyance resulting from gravel removal warrant further analysis if it is decided that gravel removal is to be pursued. That further analysis of the potential downstream effects of gravel removal on downstream flooding should take into consideration the other sources of floodwaters in this area, including stormwater flooding, groundwater flooding and the influence of Clough, Ribary and Gardiner Creeks, and should recognize the presence of existing flooding problems in downstream areas in the City of North Bend and City of Snoqualmie and unincorporated King County.

**Table 7-1: Increased channel conveyance capacity of the South Fork Snoqualmie River with bar scalping scenarios implemented, relative to 2009 existing conditions**

| River Mile | 2009 Existing Conditions Channel Conveyance Capacity (cfs) | Scalp Scenario 1 Channel Conveyance Capacity (cfs) | Increased Channel Capacity with Scalp 1 Relative to 2009 Existing Conditions (cfs) | Scalp Scenario 2 Channel Conveyance Capacity (cfs) | Increased Channel Capacity with Scalp 2 Relative to 2009 Existing Conditions (cfs) | Scalp Scenario 3 Channel Conveyance Capacity (cfs) | Increased Channel Capacity with Scalp 3 Relative to 2009 Existing Conditions (cfs) | |
|---|---|---|---|---|---|---|---|---|
| | Upstream end of study reach | | | | | | | |
| 4.46 | > 19,700 | >19,700 | A | >19,700 | A | >19,700 | A | |
| 4.34 | > 19,700 | >19,700 | A | >19,700 | A | >19,700 | A | |
| 4.17 | 16,600 | 17,700 | 1,100 | 18,700 | 2,100 | 16,600 | 0 | |
| 4.11 | 15,700 | 16,800 | 1,100 | 18,300 | 2,600 | 15,700 | 0 | |
| 4.04 | 18,000 | >19,700 | >1,700 | >19,700 | >1,700 | 18,400 | 400 | |
| 3.99 | 14,200 | 18,300 | 4,100 | 17,800 | 3,600 | 14,300 | 100 | |
| 3.95 | 17,100 | 18,000 | 900 | 18,200 | 1,100 | 17,300 | 200 | |
| 3.86 | > 19700 | >19,700 | A | >19,700 | A | >19,700 | A | |
| 3.72 | 18,700 | 19,200 | 500 | >19,700 | A | 19,610 | 910 | |
| 3.65 | 15,800 | 16,500 | 700 | 17,000 | 1,200 | 17,000 | 1,200 | |
| | Approx split between upper and lower parts of study reach | | | | | | | |
| 3.54 | 13,100 | 14,100 | 1,000 | 14,600 | 1,500 | 14,600 | 1,500 | B |
| 3.51 | 14,000 | 14,500 | 500 | 15,000 | 1,000 | 15,000 | 1,000 | B |
| 3.39 | 11,700 | 12,500 | 800 | 12,800 | 1,100 | 12,800 | 1,100 | B |
| 3.35 | 11,900 | 12,200 | 300 | 12,600 | 700 | 12,600 | 700 | B |
| 3.34 | 11,300 | 11,600 | 300 | 12,000 | 700 | 12,000 | 700 | B |
| 3.23 | 14,500 | 14,600 | 100 | 14,700 | 200 | 14,700 | 200 | B |
| 3.15 | 13,300 | 13,500 | 200 | 13,700 | 400 | 13,700 | 400 | B |
| 3.02 | 14,300 | 14,400 | 100 | 14,400 | 100 | 14,400 | 100 | B |
| 2.97 | 12,000 | 12,300 | 300 | 12,300 | 300 | 12,300 | 300 | B |
| 2.85 | North Bend Blvd Bridge<br>Downstream end of study reach | | | | | | | |

Notes:
A: No difference is calculated when existing conditions channel conveyance capacity is listed as greater than (>)19,700 cfs.
B: Scalp Scenarios 2 and 3 are configured identically in the downstream part of the study reach.

## 7.3 Potential adverse impacts to salmonid habitat in the South Fork Snoqualmie River study reach

### 7.3.1 Evaluations of gravel removal scenarios

During summer of 2008, reconnaissance-level field observations of riparian and channel conditions were conducted in the study reach of the South Fork Snoqualmie River. Information from the literature, existing studies and data on the South Fork and the reconnaissance-level field observations are the basis for the evaluation of effects that follows. The effects are discussed for each of the three bar scalping gravel removal scenarios detailed in previous sections and follow the four categories of effect discussed in Section 2.3.3. The four categories of physical effects are drawn directly from NOAA (2004).

The assessment that follows covers the entire study reach and is not specific to any single habitat unit or feature. This analysis should not be considered complete or even sufficient to assess all the likely impacts of a particular gravel removal scenario. These are preliminary results and conclusions based on the literature, existing information and field observations and conditions at the time of the field reconnaissance and are for advisory purposes. Nevertheless, the evaluations are based on well-studied linkages between physical effects and biological outcomes to characterize the likely effect of the three gravel removal scenarios on the existing salmonid habitat in the study reach. The focus of this impact analysis is on salmonid habitat, given the ESA requirements discussed in Section 1.4.1 and the regional importance of salmon habitat recovery efforts, as indicated in Section 3.4. However, it should be noted there may be other aquatic habitat impacts as well, and these may need to be more fully assessed if a decision is made to pursue a gravel removal action in this reach of the South Fork Snoqualmie River.

Because the bar scalping scenarios do not involve any gravel removal from the wetted channel, there are likely to be no *direct* effects on spawning substrates unless heavy equipment is staged in the wetted channel. Given the configuration of the bar scalping scenarios, a direct effect would be expected only if the bar surfaces were used as spawning sites when the flow was sufficiently high to cover them. Spawn timing for each of the species likely to be present in the reach, coupled with substrate preferences and velocity preferences, suggest that the bar surfaces are probably not preferred spawning habitat. *Indirect effects* on spawning habitats from the bar scalping activity are of some concern, however. The literature suggests that the following physical effects are important in the evaluation of this overall habitat effect: propagation of degradation away from the removal area, including scour of upstream riffles and reduced pool areas; increased channel uniformity and reduced prominence of the pool-riffle sequence; reduced sediment supply to downstream areas; and release of fine sediments to downstream areas. In general, a high likelihood of avoidance of these effects would suggest a similar likelihood of avoiding effects on the current habitat structure.

Note that the evaluation of each of the scenarios with regard to its reduction in riparian vegetation and woody debris considers only the effects within the footprint of the scenario on the gravel bar itself. The potential effect of the scenario due to vegetation clearing to create access

to the gravel bar also would need to be considered thoroughly as part of the permit process, if gravel removal were to be pursued.

Scalp Scenario 1:

This gravel removal scenario would affect gravel bars 1, 3, 4, 6, and 7 for a total excavation volume of 22,000 cubic yards. In this scenario, the lowermost two-thirds of five gravel bars would be scalped to within two vertical feet of the low flow wetted channel. The upstream third of the bars would remain in place as a hydraulic control to reduce some of the potential adverse effects on the channel, particularly to avoid or minimize scour of riffles.

*Modification of riffle substrates*

Our evaluation revealed that this scenario has a high likelihood of avoiding most of the physical effects that would lead to habitat degradation throughout the reach and downstream. Two effects may be problematic, however: the scalping of the bars, though limited in both extent and volume, is likely to produce a more uniform channel cross section with somewhat less later variation in depth. This could alter the depth and velocity profile across the channel bed and affect the suitability of the affected areas for spawning. Leaving the upstream third of each bar in place leaves an important hydraulic control in place, however, and could reduce the rate and extent of channel changes in the vicinity of the bars. The limited extent of gravel removal under Scalp Scenario 1, coupled with the current condition of the habitat and the potential distribution of spawning activity within the reach indicates that there is a moderate to high likelihood that these habitat effects will be avoided.

The second effect may be a bit more problematic insofar as it has the potential to affect the river channel downstream of the study reach, which is an area without extensive levees and where spawning activity has been noted as recently as 2006 (N.C. Overman, personal communication 2009). The mobilization of fine sediments is a likely result of any scalping scenario. Once a gravel bar is scalped, this fine sediment will be exposed to flows that will entrain it into the water even at non-flood volumes. For the reach-scale effect, however, gravel will be removed from only five of the nine bars in this study reach. Therefore our evaluation indicates that there is a moderate to high likelihood that the effect on downstream habitats will be avoided. (A more detailed consideration of downstream effects than is included here should be included in any more detailed assessment of impacts, if gravel removal were to be pursued. See also Section 9.2.2.)

*Reduction in pool depth, frequency, and number of pools*

Because there are so few pools in the entire study reach in its current condition, none of the scenarios is expected to affect these pool characteristics strongly. Scalp Scenario 1 may have the least effect and therefore gets a high rating on likely avoidance of this impact. The largest pool in the reach sits on the curve opposite gravel bar 2 and is a long scour pool, maintained by the erosive force of the current against the hardened bank. The scalp at the immediate upstream gravel bar (bar 3) and at gravel bar 4 is likely to mobilize sediments that could deposit in the

lowermost portions of the pool where velocities are reduced. Higher winter flows are just as likely to re-scour the deposited material, however, and re-form the pool.

*Reduction in overall channel complexity*

In Scalp Scenario 1, the width of the scalped area is relatively narrow and the scalped length is shorter than with the other scenarios, which likely will limit the hydraulic effects of the gravel removal on the channel, particularly at low to moderate flows. Nevertheless, the removal of gravel from the bars will reduce the variation in the channel cross section at those locations and will produce a more uniform channel with less variation in depth, an effect most noticeable during high flows. Our evaluation suggests that this scenario has a moderate to high likelihood of avoiding this effect at the reach scale, mainly due to the limited removal of material at the scalped bars and the avoidance of any removal at four of the bars.

*Reduction in riparian vegetation and woody debris*

In this scenario, the removal of riparian vegetation is generally avoided except for the vegetation on gravel bar 4, one of only three heavily vegetated bars in the study reach. In this case, more than half of the vegetation on the bar is likely to be removed by the scenario with the concomitant loss of cover, leaf and wood litter, and a future source of woody debris. Most of the vegetation to be removed would be willow, alder, and young cottonwood, most of which presently are less than 20 feet tall. Vegetation on the back portion of the bar—the larger cottonwood and alder—would remain, along with the few pieces of woody debris that are found in the lower portion of the bar. The remaining heavily vegetated gravel bars—bar 2 and bar 5—are not affected in this scenario. Overall, this scenario would avoid the greatest loss of riparian vegetation of any of the gravel removal scenarios and so gets a high rating.

Scalp Scenario 2:

This is a more extensive gravel removal scenario where 51,000 cubic yards would be removed from all nine gravel bars in the study reach. Vegetation would be removed along with gravel. Excavation would be taken down to within one vertical foot of the low flow water edge and, except for the gravel bar area within one vertical foot of low flow, no portion of the gravel bar would be left untouched.

*Modification of riffle substrates*

Because this scenario would remove large volumes of material from all bars in the reach, we should expect that the likelihood of avoiding the same indirect effect described above will be lower. For the propagation of degradation away from the removal area, including scour of upstream riffles and reduced pool areas, the evaluation arrives at a moderate likelihood that the physical effects can be avoided. A wider and more uniform channel is almost assured in this scenario and the likelihood of avoiding that effect is low. It is unlikely, however, that the pool-riffle sequence will be altered much since the reach does not exhibit that structure presently. The likelihood of reducing the sediment supply to downstream areas is higher than in Scalp Scenario 1 and the probability that such an effect will be avoided in this scenario is only moderate. The

release of fine sediments to downstream areas is assigned only a low to moderate probability of avoidance. It is unlikely that the cumulative outcomes of these physical effects on habitats can be successfully avoided in the study reach or in the downstream reach of the river. We conclude that there is a low to moderate likelihood that deleterious modification of riffle substrates will be avoided in this scenario.

*Reduction in pool depth, frequency, and number of pools*

Because Scalp Scenario 2 would affect the full extent of every gravel bar in this reach, it is most likely of the three scenarios to expose finer subsurface substrate that would be mobilized by flood flows and potentially deposited in the bottom of pools in this study reach. However, as described earlier, well-defined pools are infrequent and small in this reach. Therefore, because of the relatively uniform depth and the paucity of well-defined pools in the reach, Scalp Scenario 2 is rated as a moderate likelihood of avoiding further reductions in pool depth frequency or number.

*Reduction in overall channel complexity*

The evaluation suggests that, under Scalp Scenario 2, there is a low likelihood that a reduction in overall channel complexity (as measured by variation in depth across the channel) would be avoided. Moreover, given the volumes that would be removed, the effect is likely to persist for much longer than with either Scalp Scenario 1 or Scalp Scenario 3. Gravel removal under this scenario would create a much wider and flatter cross section throughout the reach. This can reduce or eliminate the prominence of any defined low flow channels.

*Reduction in riparian vegetation and woody debris*

Through the study reach, this scenario would remove most of the riparian vegetation that now occurs adjacent to the channel. Although the vegetation along this reach is poorly developed, where it does occur it has some value for shade, for inputs of woody debris (in the future), and for leaf and woody litter (which forms much of the basic elements of the food web in rivers). The likelihood of avoiding the ecological effects associated with this reduction in riparian vegetation is low to moderate, mainly due to the overall scarcity of vegetation in the current condition and to the retention of the riparian trees on gravel bars 5 and 6. This scenario would remove virtually all of the woody debris now found on the bars also. However, there is very little large wood to be found in the study reach and, except for gravel bar 5, none of the pieces observed were in contact with, or forming, habitats. This current scarcity of large wood limits the potential impact of this scenario.

Scalp Scenario 3:

Scalp Scenario 3 would remove 24,000 cubic yards from gravel bars 1, 2, 3 and 4. This is a focused scalp at particular places within the study reach where overbank flow has occurred previously. In the localized areas where the gravel is to be removed, we expect that the physical effects would be relatively severe. But given that the scenario is localized, and the volumes

equivalent to Scalp Scenario 1, the overall reach-scale evaluation for this scenario suggests that there is a moderate to high likelihood that the effects from this scenario will be avoided.

*Modification of riffle substrates*

The most severe physical effects are likely to be a wider and more uniform channel form in the vicinity of the removal. This effect could propagate both upstream and downstream from the removal sites. The release of fine sediments is also problematic with this scenario, with a low to moderate likelihood of avoidance in the vicinity of the scalped locations. But given that five bars will remain untouched in this scenario, the evaluation gives a moderate to high avoidance rating with regard to modification of riffle substrates on the reach scale. Habitats in the local areas of the scalped bars are likely to decrease in quality for a limited time, due to changes such as the intrusion of fine sediments into the gravel matrix. This effect could extend some distance into the habitats immediately downstream of the study reach but, given the depositional character of the downstream reaches, it may be difficult to detect a measurable change.

*Reduction in pool depth, frequency, and number of pools*

The lack of well-developed pools in the study reach provides a basis for determining that there is likely to be little change in the overall characteristics of the study reach as a result of this scenario. As discussed in the habitat characterization, the longitudinal profile of the reach shows little variation in depth and few outstanding pools at low flow. Both physical effects—reduced pool area and reduced prominence of a pool sequence—have a high likelihood of being avoided by this scenario. Nevertheless, the location of this gravel removal scenario could have a disproportionate effect on the large pool opposite gravel bar 2. Even though this pool accounts for a very small proportion of the habitat types in the reach, it remains the largest and most well-defined pool in the study reach. With all factors considered, this scenario is rated moderate with regard to its reach-scale effects on pool depth, frequency and number.

*Reduction in overall channel complexity*

As indicated by the width and variation in depth across the channel, this scenario is likely to cause a reduction in channel complexity in the vicinity of the four gravel bars that would be scalped. In fact, only at gravel bar 2 where the footprint of the removal is relatively narrow, does the evaluation suggest that the loss of variation can successfully be avoided (rating = high). At the other three gravel bars that would be affected by this scenario, the scalping of the bar would widen the active channel and, as a result, decrease the lateral variation in depth (rating = low). The overall reach-scale rating is moderate to high since the five upstream gravel bars will remain intact.

*Reduction in riparian vegetation and woody debris*

In this scenario, the vegetation on gravel bars 2 and 4 would be removed during the bar scalping work. Both gravel bars are entirely covered by trees and shrubs and gravel bar 2 has some of the largest trees in the study reach at 20-30 feet in height and greater than 12 inches in diameter. The loss of this vegetation will have a large effect on the local habitat but only a relatively small

effect on the reach since the bars are so near the downstream end of the study reach. However, the loss of existing and potential woody debris and leaf litter could affect the reaches immediately downstream of the study reach. Ten of the 23 pieces of large wood observed throughout the study reach occur on these four gravel bars. The likelihood of avoiding the effects associated with the loss of riparian vegetation and woody debris are low for gravel bars 2 and 4 but moderate and high for gravel bars 1 and 3, respectively. At the reach scale, the likelihood of avoiding the effects associated with loss of riparian vegetation is moderate to high. Upstream gravel bars 5 and 6, both well-vegetated, would not be modified in this scenario.

### 7.3.2 Discussion regarding impacts to salmonid habitat

The present condition of the instream salmonid habitat throughout the study reach tends to mitigate many of the expected severe negative effects associated with the three gravel removal scenarios. The present lack of structure and complexity in the study reach probably has many causes but the most prominent are likely the lasting effects of several past management practices. The levees that were built to contain the floodwaters of the river also act to constrain the lateral movement of the channel, reducing the lateral variation in depth and the formation of habitat heterogeneity (Spence et al 1996). Even within the general pattern of meanders, a normal river channel may braid and converge, forming mid-channel bars and side channels that add habitat variation. Also, the past practice of gravel removal, including the bar scalping carried out in the early 1990s, tended to smooth the channel by reducing lateral variations in depth and slope, reducing the variation in velocity so important to habitat variation. In addition, there appears to have been constant and regular removal of woody debris that enters the study reach, perhaps by agencies or by riverside residents who are concerned about damage to levees and bridges, and who may consider this debris an impediment to the efficiency of flowing water.

In sum, these past practices have led to a reach with little lateral or longitudinal variation, sparse and immature riparian vegetation, and a woody debris load that is likely much lower than historic volumes. As the reach is almost devoid of complex habitat structure, the adverse effects of any of the three bar scalping scenarios would likely be less significant in this reach than in a river reach with more complex existing habitat conditions. The 2009 existing conditions of the study reach were considered as part of the evaluation and ratings as to the extent to which each of the gravel removal scenarios likely would avoid adverse impacts to salmonid habitat, as summarized in the next subsection.

Potential adverse effects on salmonid habitat of repeated gravel removal:

As described in Section 2 and this section so far, a gravel removal operation can be expected to have immediate adverse impacts on channel geomorphology, hydraulics, and sediment transport, and fish habitat. Depending on its methods and scale, e.g., relative to the channel geometry and annual influx of sediment, the adverse effects may last for one to many years (USFWS et al. 2006). The inference is that the resilience of the natural system will allow recovery from the impacts of a gravel removal operation, given enough time.

If gravel removal occurs repeatedly, adequate recovery between operations likely would not occur. “Distinct geomorphic features (e.g., pools and riffles) within stream channels can recover

from natural and anthropogenic disturbances given adequate time, sufficient flow magnitude and sediment supply. Alternate bars may be partially restored from scalping during an average flow, leading the general perception that bar scalping is a sustainable harvest of a renewable resource. Repeated sediment extraction not only depletes sediment sources and habitats downstream, frequently scalped bars are incapable of driving the pool maintenance and sediment sorting processes that create valuable salmonid habitat such as pools, riffles and spawning beds. Thus there tends to be diminishment of habitat even when relatively conservative sediment removal restrictions are followed. This is particularly true in cases of industrial sediment harvesting on multiple adjacent bars, and where flood security maintenance operations disturb multiple bars" (NOAA 2004).

The long-term effects of repeated gravel removal described above would apply to the South Fork Snoqualmie River, where this study reach would have a relatively low probability of recovering significant complex habitat structure for 20 to 30 years after any of the gravel removal scenarios. Even if the immediate habitat effects of the proposed work are somewhat less than severe, this reach of the river would be likely to remain in its current state for some time to come. Repeated removal operations likely would perpetuate that condition.

### 7.3.3 Ratings of each gravel removal scenario with regard to its avoidance of causing adverse impacts to salmonid habitat

Table 7-2 summarizes the extent to which the gravel removal scenarios likely would avoid each of the adverse impacts to salmonid habitat described in previous subsections**.** The rating of each scenario relative to each of the four individual adverse impacts also is combined into an overall rating for each scenario throughout the overall study reach at the bottom of the table. As stated in Section 4.2, each scenario is evaluated for its likely avoidance of adverse impacts, whereby a Low (L) in this table indicates a less favorable rating and a High (H) indicates a more favorable rating. These ratings are used in the overall evaluation of the gravel removal scenarios in Section 8.

In Scalp Scenario 1, the combined reach-scale rating for avoidance of impacts is moderate to high, as there is a good likelihood that the proposed gravel removal by this scenario would avoid many if not most of the effects discussed above. The channel is likely to remain in the current condition until the riparian vegetation matures sufficiently to be recruited into the channel and exert some influence on gravel storage, erosion, and habitat form. Scalp Scenario 2 is rated with a combined, reach-scale low to moderate likelihood of avoiding the adverse habitat impacts. This scenario essentially would recreate the condition prior to the development of the riparian vegetation and reset the channel to a simpler form throughout the study reach. Scalp Scenario 3, because it is limited to the downstream portion of the study reach, is rated with a combined, reach-scale moderate likelihood of avoiding adverse habitat impacts. In Scalp Scenarios 1 and 3, some portions of the study reach would be left untouched and further maturation and development of the riparian community is likely to occur, albeit within the constraints of the levees. The length of time that this process of riparian development will continue is uncertain if gravel removal is carried out repeatedly.

**Table 7-2 Ratings of each gravel removal scenario on the South Fork Snoqualmie River for its likely avoidance of causing adverse impacts to salmonid habitat**

| Adverse impact to be avoided | Scalp Scenario 1 | Scalp Scenario 2 | Scalp Scenario 3 |
|---|---|---|---|
| Avoid modification of riffle substrates | M-H | L-M | M-H |
| Avoid reduction in pool depth, frequency and number of pools | H | M | M |
| Avoid reduction in overall complexity | M-H | L | M-H |
| Avoid reduction in riparian vegetation and woody debris | H | L-M | M-H |
| **Avoid or minimize adverse impacts to salmonid habitat** | **M-H** | **L-M** | **M-H** |

If gravel removal is to be pursued as flood hazard reduction measure, it is assumed that a more detailed assessment of the specifically proposed gravel removal project would be conducted as part of the design and permit process. It would be appropriate to evaluate the potential adverse effects of repeated or ongoing gravel removal operations on salmonid habitat as part of that process and to include the elements listed below, which are based on USFWS et al. (2006). This study addresses many of these elements but the evaluation of an actual gravel removal proposal should cover greater detail. In addition—while salmonid habitat is a good indicator of a river's overall ecological condition—such an evaluation should consider looking at the broad range of river and riparian functions that contribute to habitat for other species as well.

1. Identify appropriate sediment harvest locations
2. Identify species, life stages present, and habitat elements needed
3. Identify physical processes that create or maintain habitat elements
4. Select alternatives that minimize habitat disturbance and disruption of physical processes that create and maintain habitat.

## 7.4 Summary of ratings of potential adverse impacts of gravel removal scenarios

Based on the general assessment of likely adverse impacts described in this section, the bar scalping gravel removal scenarios are rated in Table 7-3 for avoidance of adverse impacts.

**Table 7-3: Summary of the evaluation of South Fork Snoqualmie River gravel removal scenarios for their avoidance of adverse impacts**

| Avoidance of Potential Adverse Impact | Scalp Scenario 1 | Scalp Scenario 2 | Scalp Scenario 3 |
|---|---|---|---|
| Avoid destabilizing existing King County flood protection facilities or public infrastructure | M | L | L-M |
| Avoid impacts to nearby flooding | M | M | M |
| Avoid impacts to salmonid habitat | M-H | L-M | M-H |

Each scenario is evaluated for its likely avoidance of adverse impacts, so that a Low (L) in this table indicates a less favorable rating and a High (H) indicates a more favorable rating. These ratings are used to evaluate the gravel removal scenarios in Section 8.

## 7.5 Estimated costs of gravel removal scenarios

An estimated cost of each gravel removal scenario is presented in this subsection based on the assumption that King County would conduct the gravel removal operation outright, or would hire contractors to conduct the operation. These cost estimates are based on standard unit costs of project components, with component and total costs of the three bar scalping gravel removal scenarios summarized in Table 7-4.

**Table 7-4: Estimated costs of South Fork Snoqualmie River gravel removal scenarios, assuming that King County would conduct the gravel removal or manage a contract for its removal**

| Component | Scalp Scenario 1 | Scalp Scenario 2 | Scalp Scenario 3 |
|---|---|---|---|
| Est. Excavation Volume (cu yd) | 22,000 | 51,000 | 24,000 |
| **Construction Component** | | | |
| Excavation, disposal (A) | $770,000 | $1,785,000 | $840,000 |
| Mobilization, ramps, etc (B) | $77,000 | $179,000 | $84,000 |
| **Rounded Sub Total:** | **$850,000** | **$1,960,000** | **$920,000** |
| **Other components** | | | |
| Planning, design (note C) | $300,000 | $690,000 | $320,000 |
| Construction management (note D) | $170,000 | $390,000 | $180,000 |
| Mitigation (E) | $90,000 | $290,000 | $90,000 |
| Monitoring (E) | $90,000 | $290,000 | $90,000 |
| **Rounded Sub Total:** | **$650,000** | **$1,660,000** | **$680,000** |
| **Rounded Total:** | **$1,500,000** | **$3,600,000** | **$1,600,000** |

**Notes:**
A: Assumed to cost $35 per cubic yard.
B: Assumed to cost 10% of excavation and disposal.
C: Assumed to cost 35% of Construction subtotal.
D: Assumed to cost 20% of Construction subtotal.
E: Assumed to cost from 10% to 15% of Construction subtotal, depending on excavation volume, areal extent and likely impacts of project.
Numbers may not add up exactly due to rounding.
Cost estimates are conceptual level for comparison between scenarios.
Actual costs may differ significantly from these conceptual level estimates.
Estimates are based on 2010 dollars.

The construction component includes excavation and disposal, which is calculated at $35 per cubic yard of excavation, and mobilization, which is assumed to cost 10 percent of excavation and disposal. Other project components include planning and design, mitigation and monitoring; their costs are estimated as a percentages of the construction component subtotal (explained in Table 7-4). Estimated component costs are based on examples from recent repair or construction projects on King County flood protection facilities and assume that the county would implement the project. The estimated costs can be rounded to $1.5M for Scalp Scenario 1, $3.6M for Scalp Scenario 2, and $1.6M for Scalp Scenario 3. These cost estimates are used in the evaluation of the scenarios in Section 8.

# 8. Evaluation of South Fork Snoqualmie River gravel removal scenarios

The three bar scalping gravel removal scenarios are evaluated in this section against the evaluation criteria identified in Section 4.2. The evaluation ratings are summarized in the following tables with regard to flood hazard reduction effectiveness (Table 8-1 and 8-2) and potential adverse impacts and costs (Table 8-3). The analyses throughout this study that were used to rate the scenarios against each criterion are also noted in the tables.

## 8.1 Evaluation of gravel removal scenarios

A flood hazard reduction objective of 13,000 cfs plus one foot of freeboard was identified in Section 4. Hydraulic modeling plus actual flood events indicate that this objective is met under existing conditions (Section 5) in the upstream part of the study reach along both banks except at left bank RM 3.99 and most of the downstream area along the right bank except near North Bend Blvd (Bendigo) Bridge. Hydraulic modeling (Section 6) indicates that the gravel removal scenarios would increase channel conveyance capacity by various amounts but the flood reduction objective would continue not to be met in the downstream part of the reach along the left bank. The locations where channel conveyance capacity is adequate to meet this flood hazard reduction objective are listed in Table 8-1.

**Table 8-1: Evaluation of three South Fork Snoqualmie River bar scalping gravel removal scenarios against evaluation criterion 1.1, "Does the scenario meet the flood hazard reduction objective of containing 13,000 cfs plus one foot of freeboard"?**

| RM | Does this scenario or condition meet the flood hazard reduction objective of 13,000 cfs plus one foot of freeboard? | | | | Source of information used to make this determination |
|---|---|---|---|---|---|
| | 2009 Existing Conditions | Scalp Scenario 1 | Scalp Scenario 2 | Scalp Scenario 3 | |
| 4.46 | Yes | Yes | Yes | Yes | Table 6-3 |
| 4.34 | Yes | Yes | Yes | Yes | Table 6-3 |
| 4.17 | Yes | Yes | Yes | Yes | Table 6-3 |
| 4.11 | Yes | Yes | Yes | Yes | Table 6-3 |
| 4.04 | Yes | Yes | Yes | Yes | Table 6-3 |
| 3.99 | No | Yes | Yes | Yes | Table 6-3 |
| 3.96 | Yes | Yes | Yes | Yes | Table 6-3 |
| 3.86 | Yes | Yes | Yes | Yes | Table 6-3 |
| 3.72 | Yes | Yes | Yes | Yes | Table 6-3 |
| 3.65 | Yes | Yes | Yes | Yes | Table 6-3 |
| 3.54 | No | No | Yes | Yes | Table 6-3 |
| 3.51 | No | No | Yes | Yes | Table 6-3 |
| 3.39 | No | No | No | No | Table 6-3 |
| 3.35 | No | No | No | No | Table 6-3 |
| 3.34 | No | No | No | No | Table 6-3 |
| 3.23 | Yes | Yes | Yes | Yes | Table 6-3 |
| 3.15 | No | No | No | No | Table 6-3 |
| 3.02 | Yes | Yes | Yes | Yes | Table 6-3 |
| 2.97 | No | No | No | No | Table 6-3 |

Because the right bank elevations exceed those on the left bank throughout the study reach, all Table 8-1 determinations refer to the left bank. The right bank contains 13,000 cfs plus one foot of freeboard throughout the reach except at and near RM 2.97, which is within the area of backwater conditions created by the North Bend Blvd (Bendigo) Bridge where gravel removal would be ineffective in reducing flood water levels.

Table 8-2 focuses on the channel adjacent to Berry Estates (RM 3.34 to RM 3.39) where the flood hazard reduction objective is not met and which also appears to be upstream of backwater conditions. Table 8-2 lists the change in water surface elevations (WSELs) during a discharge of 13,000 cfs (50-year flood). Note that the changes in water surface elevations due to gravel removal during a discharge of 11,700 cfs (30-year flood) are similar in magnitude (as listed in Table 6-6). The ranges of longevity of flood hazard reduction result from calculating it based on either the average annual coarse sediment influx rate or the average annual deposition rate.

**Table 8-2: Evaluation of flood hazard reduction along the South Fork Snoqualmie River for three bar scalping gravel removal scenarios**

| Crit-eria No. | Evaluation Criteria (abbreviated) | Response units | 2009 Existing Conds. | Scalp Scen-ario 1 | Scalp Scen-ario 2 | Scalp Scen-ario 3 | Source of info. |
|---|---|---|---|---|---|---|---|
| 1.2 | Channel conveyance capacity relative to 2009 existing conditions | Channel capacity at RM 3.34: RM 3.35: RM 3.39: (cfs) | 11,300 11,900 11,700 | 11,600 12,200 12,500 | 12,000 12,600 12,800 | 12,000 12,600 12, 800 | Table 6-2 |
| 1.3 | Change in WSELs during a flow of 13,000 cfs relative to 2009 conditions | Change in WSELs (feet) | RM 3.34: RM 3.35: RM 3.39: | -0.2 -0.2 -0.5 | -0.4 -0.4 -0.7 | -0.4 -0.4 -0.7 | Table 6-4 |
| 1.4 | Estimated longevity of flood hazard reduction | Years | n/a | 5 to 8 yrs | 12 to 19 yrs | 6 to 9 yrs | Table 6-7 |

Table 8-3 lists the likely adverse impacts in terms of the degree of avoidance of impacts and the estimated costs of each gravel removal scenario in terms of minimization of long term costs. Evaluation criterion 3.1 restates gravel removal goal 3 (Section 4.1), which in turn is based on the Flood Hazard Reduction Plan Goal 3, to reduce the long term costs of flood hazard management. It must recognized in this evaluation that none of the gravel removal scenarios would result in a permanent or long term reduction in flood hazards that affect this area, because excavated gravels will fill in again within a matter of years (Table 8-2). Therefore, the cost estimates in Table 8-3 can be used for relative comparison between the gravel removal scenarios, but in an absolute sense none of the gravel removal scenarios should be rated highly as a strategy for minimizing long term costs. The temporary nature of flood hazard/risk reduction by gravel removal would become apparent if gravel removal were being considered along with other potential flood risk reduction projects, such as home acquisition or elevations, levee setbacks, etc. That process of more comprehensively evaluating a variety of potential flood risk reduction strategies is described in Section 9 of this report.

**Table 8-3: Evaluation of potential adverse impacts and costs along the South Fork Snoqualmie River for three bar scalping gravel removal scenarios**

| Crit. No. | Evaluation Criteria (abbreviated) | Response, Range | Scalp Scenario 1 | Scalp Scenario 2 | Scalp Scenario 3 | Source of info. |
|---|---|---|---|---|---|---|
| 2.1 | Avoid destabilizing King County flood protection facilities or public infrastructure | **L/M/H** | M | L | L-M | Section 7.1 |
| 2.2 | Avoid or minimize impacts to nearby flooding | **L/M/H** | M | M | M | Section 7.2 |
| 2.3 | Avoid or minimize impacts to salmonid habitat | **L/M/H** | M-H | L-M | M -H | Section 7.3 |
| 3.1 | Minimize long term costs | **Estimated costs ($)** | $1.5M | $3.6M | $1.6M | Section 7.6 |

Scalp Scenario 1 would result in the channel conveyance capacity increasing from 11,300 cfs for the 2009 existing conditions to 11,600 cfs for this scenario at RM 3.34 and from 11,700 cfs to 12,500 cfs at RM 3.39. Scalp Scenario 1 would result in a decrease in water surface elevations ranging from as little as 0.2 feet to as much as 0.5 feet along RM 3.34 to RM 3.39 for a flood of 13,000 cfs (50-year). The calculated longevity of the increased containment due to Scenario1 is an estimated five years when based on the average sediment influx and eight years when based on average deposition rate, although the flood reduction benefits of any gravel removal will decrease as soon as there is a flood that moves in sediment and it deposits in the scalped area.

Scenario 1 was rated with a moderate level for its avoidance of destabilizing existing King County levees and public infrastructure (Section 7.1), as a moderate level of avoiding adverse impacts to nearby flooding (Section 7.2), and as moderate to high level of avoiding impacts to salmonid habitat (Section 7.3). The estimated cost of Scalp Scenario 1 is $1.5M.

Under Scalp Scenario 2, the channel conveyance capacity would increase from 11,300 cfs under 2009 existing conditions to 12,000 cfs at RM 3.34 and from 11,700 cfs to 12,800 cfs at RM 3.39. Scalp Scenario 2 would result in a decrease in water surface elevations ranging from as little as 0.4 feet to as much as 0.7 feet along RM 3.34 to RM 3.39 during a flood of 13,000 cfs (50-year). The calculated longevity of the increased containment due to Scenario 2 is an estimated 12 to 19 years.

Scenario 2 was rated as low for its avoidance of destabilizing levees and infrastructure; as moderate for avoiding adverse impacts to nearby flooding; and as low to moderate for avoiding impacts to salmonid fish habitat. The estimated cost of Scenario 2 is $3.6M.

Scalp Scenario 3 would have the same flood reduction benefit as Scalp Scenario 2 along the left bank near Berry Estates because the two scenarios are configured identically in the downstream part of the study reach. Scalp Scenario 3 would increase the channel conveyance capacity to from 11,300 cfs to 12,000 cfs at RM 3.34 and from 11,700 cfs to 12,800 cfs at RM 3.39. Scalp Scenario 3 would result in a decrease in water surface elevations ranging from as little as 0.4 feet to as much as 0.7 feet along the left bank at RM 3.34 to RM 3.39 during a flood of 13,000 cfs (50-year). The calculated longevity of increased containment due to Scalp Scenario 3 is an estimated six to nine years.

While Scalp Scenarios 2 and 3 have an identical configuration at these locations of interest along the left bank, their configuration and extraction volumes differ elsewhere throughout the study reach, which is why they differ with regard to periods of longevity, likely impacts and estimated costs.

Scalp Scenario 3 was rated as low to moderate for its avoidance of destabiliziing levees and infrastructure, as moderate for avoiding adverse impacts to nearby flooding, and as moderate to high for avoiding impacts to salmonid fish habitat. The estimated cost of Scalp Scenario 3 is $1.6M.

## 8.2 Discussion

Results from this study indicate that backwater conditions from North Bend Blvd (Bendigo) Bridge exist upstream to about RM 3.02 and that gravel removal would be ineffective in those backwater areas. Kato and Warren, Inc. (2000) identify backwater effects as far as upstream as RM 3.23 in large flood events. It is generally accepted and can be demonstrated with hydraulic calculations that gravel removal for flood reduction purposes is ineffective in areas controlled by existing backwater effects regardless of the amount and frequency of gravel extraction.

None of the three bar scalping gravel removal scenarios analyzed in this study would meet the flood reduction objective of containing 13,000 cfs plus one foot of freeboard throughout the study reach, although that discharge is contained under existing conditions along most of both banks in the upstream part of the study reach and most of the right bank through the downstream part. The several reasons that these three bar scalp scenarios would not contain the estimated original channel capacity of 13,000 cfs plus one foot of freeboard are described in Section 6.4, but generally result from greater depths and widths having been excavated during the 1960s bar scalping and levee construction than could be done under present-day regulatory and physical constraints. In addition, the North Bend Blvd (Bendigo) Bridge was completed a decade after the levees were built, so its influence on channel capacity was not considered when the levees were completed in the 1960s.

Though 13,000 cfs plus one foot of freeboard would not be contained adjacent to Berry Estates (RM 3.34 to RM 3.39 along the left bank) due to gravel removal, a flow of about 12,000 cfs would be contained along that same area with gravel removal implemented. Gravel removal by any of the three scalp scenarios would result in vertical decreases in water surface elevations that would approximately and temporarily counteract or more than counteract the vertical increases in

water surface elevations that have occurred since 1992/95 under existing conditions along RM 3.34 to RM 3.39. Scalp Scenario 1 or 2 would have similar results at RM 3.35 to RM 4.04.

The flood hazard reduction benefits of Scalp Scenario 1 would be less than those of the other two scenarios, whether considering its decrease in flood water surface elevations (e.g., a drop of 0.2 feet in the 13,000 cfs flood at RM 3.34), an increased channel conveyance capacity of only 300 cfs (from 11,300 cfs to 11,600 cfs), or longevity of benefit (between five and eight years). Scalp Scenario 1 does have the least impacts, because it was configured to do so (and as such might be the most feasible to obtain permits for), but the minimization of scalped areas and gravel bars in this scenario also minimizes its flood hazard reduction effectiveness. The cost of Scalp Scenario 1 is similar to that of Scalp Scenario 3.

Scalp Scenarios 2 and 3 are configured identically in the downstream part of the study reach and so would have identical effectiveness near Berry Estates in terms of resulting channel conveyance capacity (12,000 cfs, compared to the 11,300 cfs under 2009 conditions). Both Scalp Scenarios 2 and 3 would lower the water surface elevation of the 13,000 cfs (50-year) flood by as little as 0.2 feet to as much as 0.7 feet near Berry Estates (RM 3.34 to RM 3.39). Neither Scalp Scenario 2 nor Scalp Scenario 3 would result in containment of 13,000 cfs plus one foot of freeboard at the left bank adjacent to Berry Estates.

The estimated longevity of flood hazard reduction benefits of Scalp Scenario 2 is about twice as long as Scalp Scenario 3 due to about twice as much sediment volume that would be extracted throughout the reach. Scalp Scenario 2 also would cost more than twice as much as Scalp Scenario 3 due primarily to the sediment volume extracted, and would have greater impacts than Scalp Scenario 3 due to a much greater areal extent (affecting more gravel bars and habitat) and more pervasive and longer lasting effects on hydraulics and sediment movement through the reach. Because its excavation volume far exceeds the average annual influx and because it would excavate at every non-island gravel bar in the reach, Scalp Scenario 2 likely would interrupt gravel transport significantly, produce a sediment deficit, and induce erosion and incision of the channel within this study reach. Those factors, coupled with the available information on levee toe elevations, strongly suggest that Scalp Scenario 2 could result in erosion at levee toes and destabilization of levee banks. The reach-scale sediment deficit that Scalp Scenario 2 could induce potentially could aggravate the scour already indicated by cross section measurements under the North Bend Blvd (Bendigo) Bridge.

In all, Scalp Scenario 2 has the potential to cause erosion damage to the existing levees, increased scour at North Bend Blvd (Bendigo) Bridge and widespread adverse impacts to salmonid habitat, all at a very high estimated cost. At the same time, there is flood containment under existing conditions that exceeds the design capacity of the channel in the upstream part of the study reach except at the left bank at RM 3.99. Taken together, these factors appear to eliminate Scalp Scenario 2, with its extensive and deep excavation, from further consideration as a viable gravel removal scenario.

The flood reduction effectiveness of Scalp Scenario 3 would be focused at the areas of past overtopping, and result in the same channel conveyance capacity at RM 3.34 to RM 3.39 as with Scalp Scenario 2 implemented. Its impacts would be focused in the downstream area, directly

affecting only the downstream four gravel bars in this study reach. Also, Scalp Scenario 3 should be less likely to interrupt gravel flux through the overall reach because its excavated volume would be less than half that of Scalp Scenario 2. Similarly, the anticipated impacts to salmonid habitat would be locally adverse but moderate on the reach scale. The cost of Scalp Scenario 3 would be similar to Scalp Scenario 1. When flood reduction benefits are compared to potential adverse impacts and long term costs, this evaluation process indicates that Scalp Scenario 3 (or some variation thereof) would best meet the evaluation criteria. However, the potential for Scalp Scenario 3 to induce channel degradation or local scour and threaten levee or bridge stability is a real concern that would need to be addressed in a geotechnical analysis.

If it is determined that gravel removal should be pursued for flood hazard reduction purposes, some variation of one of the scenarios or a hybrid combination of elements from the three gravel bar scalping scenarios may be appropriate. Such refinements in scalping scenarios could be accomplished readily using the models created in this study as part of a design process if it is decided to pursue gravel removal. However, it should be noted that the depth and width of excavation simulated in Scalp Scenarios 2 and 3 may not be permitted as currently configured. If regulations would only allow excavation similar to that in Scalp Scenario 1 (which was configured to meet anticipated permit requirements), then the resulting flood hazard reduction effectiveness would be about equal to that of Scalp Scenario 1. Such a revision may call into question whether gravel removal would be worth pursuing because the flood hazard reduction effectiveness of Scalp Scenario 1 is somewhat limited, as described above. These factors would need to be considered in any project design process, which is described in more detail Section 9.

Whether or not a gravel removal project is pursued, channel monitoring of the South Fork Snoqualmie River will continue in this reach so as to inform the ongoing flood management program both with regard to sediment management as well as various other flood risk reduction efforts relevant to the South Fork Snoqualmie River.

## 8.3 Conclusions

1. The effectiveness of the three analyzed bar scalping gravel removal scenarios varies among the scenarios and throughout the study reach.
2. Results from this study indicate that backwater conditions from North Bend Blvd (Bendigo) Bridge exist upstream to about RM 3.02 and that gravel removal would be ineffective in those backwater areas. Kato and Warren, Inc. (2000) identify backwater effects as far as upstream as RM 3.23 in large flood events. Any effective flood hazard reduction strategy for this part of the river would need to address the backwater effects of the North Bend Blvd Bridge.
3. For the downstream part of the study reach that is upstream of backwater influence, the results of this study and past overtopping floods point to the left bank in the area of RM 3.34 to RM 3.39 as being the main area of existing and future flooding. Any flood hazard reduction management strategies or actions for this study reach would best focus on this left bank location as an area of primary concern.

4. Gravel removal by bar scalping would temporarily improve channel conveyance capacity at RM 3.34 from 11,300 cfs under 2009 existing conditions to 12,000 cfs with Scalp Scenario 2 or 3 implemented.
5. The existing channel conveyance capacity continues to exceed 13,000 cfs plus one foot along both banks in the entire upstream part of the study area except at RM 3.99 on the left bank. Increased channel conveyance capacity due to gravel removal in this upstream area would manifest as increases in freeboard.
6. Implementation of Scalp Scenario 1 or 2 would increase the channel conveyance capacity from 14,200 cfs under 2009 existing conditions to about 18,000 cfs, in the area of RM 3.99. This increased channel conveyance capacity could be expected to persist for eight to 19 years, although the full 3,800 cfs increase in channel conveyance capacity would persist only until the first flood deposits sediment at this location.
7. Containment with certainty of 13,000 cfs plus one foot of freeboard (the flood reduction objective) throughout this study reach will require measures beyond gravel removal as evaluated in this study. Such measures could include levee setbacks or other modifications to existing infrastructure, any of which would require further evaluation.
8. Decreases in water surface elevations due to gravel removal by any of the three scalp scenarios would, to a greater or lesser extent, temporarily counteract or more than counteract the increases in water surface elevations that have occurred since 1992/95 at RM 3.35 to RM 3.39. Scalp Scenario 1 or 2 would have similar results at RM 3.95 to RM 4.04. Decreases in water surface elevations due to gravel removal would vary throughout the rest of the study reach, depending on location and gravel removal scenario.
9. Each of the gravel removal scenarios evaluated would likely cost in excess of $1 to 3 million for King County to implement, and all would be challenging to obtain permits for. The most feasible alternatives have flood hazard reduction benefits that likely would persist for ten years or less based on average rates of sediment influx.
10. Even with a decade of estimated longevity, the flood hazard reduction benefits of any gravel removal scenario would be temporary in nature, not only at a decade timeframe but because the full flood hazard reduction benefit only would last until the first flood that moves and deposits coarse sediment. None of the gravel removal scenarios truly would minimize or reduce the long-term cost of flood hazard management (gravel removal criterion 3.1 and 2006 King County Flood Plan overall goal 3).
11. No anadromous salmonids inhabit the South Fork Snoqualmie River, which is upstream of Snoqualmie Falls, but the South Fork Snoqualmie River supports other salmonid species. In this study reach where existing habitat is of limited quality and homogeneous in nature, the likely adverse impacts to salmonid habitat due to gravel removal would be relatively muted, although continued gravel removal likely would prevent any future improvement in salmonid habitat in this reach. If gravel removal is to occur, a more quantitative assessment of impacts to a full range of aquatic habitats and species would be needed.
12. Each of the analyzed gravel removal scenarios would result in some increase in channel conveyance capacity, which would translate to an increased magnitude or more rapid delivery of floodwaters to areas downstream of this study reach. If gravel removal is going to be pursued for flood reduction purposes in this study reach, a more complete assessment of potential impacts to downstream flooding would be needed.
13. Destabilization of King County levees or public infrastructure is a real concern based on the existing deficient conditions of the levees (Shannon & Wilson 1993, 1999) and the design

capacity of the North Bend Blvd (Bendigo) Bridge (Kato and Warren, Inc. 2000). Because Scalp Scenario 2 likely would result in reach-scale channel degradation or local scour, or both, it should be eliminated from further consideration as a viable gravel removal scenario.

14. If gravel removal is to be implemented, this evaluation indicates that Scalp Scenario 3 (or some variation thereof) would be the most acceptable of the three bar scalping gravel removal scenarios in this study in striking a balance between flood hazard reduction benefits and its likely adverse impacts and estimated costs. Any further consideration of Scalp Scenario 3 would need to include a geotechnical analysis of its effects on levee and bridge stability.
15. Whether or not a gravel removal project is pursued, channel monitoring of the South Fork Snoqualmie River will continue in this reach so as to inform the ongoing flood management program.

# 9. Summary of findings and next steps

## 9.1 Summary of findings

This report documents the existing conditions in the South Fork Snoqualmie River channel within the study reach with regards to sediment accumulation and its effect on water surface elevations, and evaluates the effectiveness of gravel removal for flood hazard reduction purposes. Key findings presented in this report include the following, which are listed in no particular priority.

Existing Conditions:

1. The study reach is depositional due to its location at the downstream end of a sediment-rich basin, in an area of decreasing channel gradient that is constrained laterally by levees and confined at the downstream end by a bridge that causes backwater conditions (Kato and Warren, Inc. 2000). The estimated average annual sediment deposition rate from 1992/95 to 2009 and over the full study reach is 2,700 cubic yards per year, with much annual variability, which translates to a vertical infilling of the channel bed of approximately 0.4 feet per decade. These rates are consistent with previous studies of this same study reach and with other similar rivers in the region.
2. The amount of deposition during any of the four individual study periods (1992/95-1999, 1999-2006, 2006-2007, and 2007-2009) appears to have been influenced primarily by the magnitude and duration of the flood flows that occurred during that period and possibly by the magnitude and extent of any gravel removal that had been performed in the recent past.
3. The original design capacity of the channel is estimated at 13,000 cfs plus one foot of freeboard. Under existing conditions, levees in the upstream part of the study reach continue to meet or exceed this channel conveyance capacity along both banks, except the left bank at RM 3.99. This original channel capacity also is met along the downstream right except at RM 2.97 to RM 3.02, where backwater conditions dominate. Under existing conditions, the left bank along most of the downstream part of the reach does not contain 13,000 cfs plus one foot of freeboard.
4. This study found that North Bend Blvd (Bendigo) Bridge backwater conditions extend upstream to about RM 3.02; findings from Kato and Warren, Inc. (2000) indicate that backwater conditions may extend further upstream during flows of 13,000 cfs and greater. Water surface elevations within the area of backwater influence have not changed significantly over the full study period regardless of ongoing sediment deposition within that area.
5. Trends in modeled water surface elevations varied through the four individual study periods and in the upstream and downstream parts of the study reach. Cumulatively through the full study period (1992/95 to 2009), modeled water surface elevations have increased at almost every cross section in the study reach at each of the analyzed flows. These increases are clearest in the upstream part of the study reach (RM 3.65 to RM 4.46) where there was a mean increase of about 0.8 feet in modeled water surface elevations through the through the full study period. In the downstream part of the study reach, modeled water surface

elevations showed a mean increase of about 0.3 feet in the analyzed flows through the full study period.

6. The 2007 to 2009 period saw increases in water surface elevations of about 0.2 feet along RM 3.34 to RM 3.39, which is adjacent to Berry Estates, the location of previous overtopping and damaging flood flows. From 2006 to 2009 there have been increases in water surface elevations of about one foot along RM 3.95 to RM 4.04. These recent, marked increases in water surface elevations, which are likely a result of gravel deposition due to the size and cumulative duration of the three flooding events that occurred during this timeframe, warrant continued attention.
7. Increases in water surface elevations throughout the study reach from 1992/95 to 2009 are attributed to sediment deposition. Therefore, it was appropriate to consider gravel removal in this study as a potential sediment management action (King County 2006) for this study reach.
8. No anadromous salmonids inhabit the South Fork Snoqualmie River, which is upstream of Snoqualmie Falls. This reach of the South Fork Snoqualmie River supports two native salmonid species, the western cutthroat trout and the mountain whitefish, and two non-native salmonid species, the rainbow trout and Brook trout. Bull trout, which are listed as "threatened" under the ESA, have not been detected in this part of the South Fork Snoqualmie River.

Gravel removal scenarios:

9. The effectiveness of the three analyzed bar scalping gravel removal remedies varies among the scenarios and throughout the study reach.
10. There were negligible decreases in modeled water surface elevations due to gravel removal within the area affected by the North Bend Blvd (Bendigo) Bridge backwater. It is generally accepted and can be demonstrated with hydraulic calculations that gravel removal is ineffective in backwater areas. Any effective flood hazard reduction strategy for this part of the river would need to address the backwater effects of the North Bend Blvd (Bendigo) Bridge.
11. For the downstream part of the study reach that is upstream of backwater conditions, the results of this study and previous overtopping floods point to the left bank in the area of RM 3.34 to RM 3.39 as being the main area of existing and future flooding. Any flood hazard reduction management strategies or actions in this study reach would best focus on this left bank location. Gravel removal by bar scalping would temporarily improve channel conveyance capacity along the left bank at RM 3.34 from 11,300 cfs under 2009 existing conditions to 12,000 cfs with either Scalp Scenario 2 or 3 implemented.
12. The 2009 existing conditions channel conveyance capacity exceeds 13,000 cfs plus one foot in the entire upstream area except along the left bank at RM 3.99. The marked decrease in channel conveyance capacity from 2006 to 2009 makes this location is an area of concern. Gravel removal by bar scalping on gravel bar 6 at and near RM 3.99 would temporarily increase containment along the left bank from about 14,200 cfs under 2009 existing conditions to about 18,000 cfs in the area of RM 3.99 with Scalp Scenario 1 or 2 implemented.
13. Containment with certainty of 13,000 cfs plus one foot of freeboard (the flood hazard reduction objective) throughout this study reach would require measures beyond the gravel

removal actions as evaluated in this study, e.g., modifications to levees and other infrastructure.

14. Decreases in water surface elevations due to gravel removal by any of the three scalp scenarios would, to a greater or lesser extent, temporarily counteract the increases in water surface elevations that occurred under existing conditions from 1992/95 to 2009 along Berry Estates (RM 3.34 to RM 3.39). Scalp Scenario 1 or 2 would have similar results along gravel bar 6 (RM 3.95 to RM 4.04). The effectiveness of the scenarios in this regard varies throughout the rest of the study reach.
15. The three scenarios that were evaluated would range in cost from approximately $1.5M to $3.6M. Scenario 2 has likely impacts to the stability of the South Fork Snoqualmie River levee system and possibly to the North Bend Blvd (Bendigo) Blvd Bridge stability and therefore should not be pursued. Scenarios 1 and 3 are more feasible and would result in less impacts, but obtaining the necessary permits to implement them would still be very challenging. The flood hazard reduction benefits of Scenarios 1 and 3 would persist for less than ten years based on average rates of coarse sediment influx.
16. Implementation of either Scalp Scenario 2 or Scalp Scenario 3 would result in about a one percent decrease in the probability of overtopping in any given year at RM 3.39 (adjacent to Berry Estates) for the duration of time through which gravel removal remains effective.
17. A permanent or long-term solution to flooding along the South Fork Snoqualmie River in this study reach will require implementation of flood risk reduction measures, e.g., acquisition of at-risk structures, home elevations, modifications to levees or other infrastructure, that would go beyond gravel removal actions.
18. If gravel removal were to be implemented, this evaluation indicates that Scalp Scenario 3 (or some variation thereof) would be the most acceptable of the three bar scalping gravel removal scenarios in this study in striking a balance between flood hazard reduction benefits and its likely adverse impacts and estimated costs. Further consideration of any scenario, including Scalp Scenario 3, would need to include a geotechnical analysis of its effects on levee and bridge stability.
19. Whether or not a gravel removal project is pursued, channel monitoring of the South Fork Snoqualmie River will continue in this reach so as to inform the ongoing flood management program.

## 9.2 Next steps

This study has demonstrated that gravel removal could be used to reduce flood hazards at certain locations in this study area, which would have some degree of effectiveness over a limited amount of time. Flood risk reduction, which takes into consideration the consequences, or damages, that result from flood hazard, was not addressed quantitatively in this study. Other flood hazard and flood risk reduction alternatives need to be evaluated for this same study reach and compared to the potential flood hazard reduction of gravel removal.

This comprehensive perspective of potential flood risk reduction projects is being coordinated on a regional scale via various flood management initiatives for the South Fork Snoqualmie River and Middle Fork Snoqualmie River, through efforts of King County on behalf of the

KCFCD. As other alternatives are considered, individually or in combinations, such a comprehensive assessment of solutions should include consideration of gravel removal actions for this area. A decision as to whether to pursue gravel removal should be based on this comprehensive evaluation, in accordance with Policy RCM-3 of the 2006 Flood Hazard Management Plan.

If a decision were made to further consider a gravel removal project, the project proposal would be evaluated and rated for relative priority amongst all other flood risk reduction projects proposed by the KCFCD through an evaluation process including review by a Basin Technical Committee and an Advisory Committee, which together include input by staff and elected officials from all King County jurisdictions. This process rates each project proposal by considering both its flood risk reduction benefits and its implementation opportunity. The flood risk reduction benefits are based on the likely consequence, severity, and urgency of the flood risk, including impacts to the regional economy. Capital project priorities are then sequenced based on an evaluation of implementation factors such as:

a. Readiness to proceed, such as landowner willingness and the status of project design and permits
b. Leveraging of external resources
c. Support for multiple floodplain objectives
d. Long-term maintenance needs associated with the proposed action

If this evaluation led to a conclusion that a South Fork Snoqualmie River gravel removal project should be implemented, then it would be recommended to the KCFCD Board of Supervisors, who would consider it as part of their adoption of the KCFCD annual capital budget.

Any flood risk reduction project, including gravel removal, also must satisfy all regulatory and permit requirements associated with the riverine environment, including provisions of the ESA.

## 9.3 Information gaps; further study

### 9.3.1 Further study for general flood management purposes

Channel monitoring will continue in this South Fork Snoqualmie River study reach so as to inform ongoing flood management efforts.

This report focused just on flood hazard associated with sediment accumulation in the South Fork Snoqualmie River channel in this study reach. In recognition that there are multiple sources of flood hazard that affect the South Fork Snoqualmie River along the study reach (e.g., stormwater flooding, groundwater flooding, tributary flooding, backwater conditions) it would be helpful to characterize the extent to which in-channel sediment accumulation contributes to the overall flood hazard in this area. Such an assessment is being carried out as part of the comprehensive coordination of potential flood risk reduction projects for the South Fork Snoqualmie and Middle Fork Snoqualmie rivers described in the previous subsection.

### 9.3.2 Further study of potential impacts if a permit process were initiated:

If a specific gravel removal operation were to be proposed, more detailed assessments of potential impacts will be necessary as part of the permit process. Listed here are further analyses that likely would be required, although the actual required analyses would be determined in the permit process.

Likely impacts of gravel removal on bank erosion, levee stability, and bridge infrastructure:

- Further information relevant to North Bend Blvd (Bendigo) Bridge stability should be obtained, including As-Built bridge plans, surveys, etc.
- Any gravel removal proposal should include preparation of scour calculations for existing and proposed post-gravel removal operation.
- A geotechnical assessment should be conducted of the present-day depth and stability of levee toes, particularly in the vicinity of any proposed excavation.

Likely impacts of gravel removal on downstream flooding:

- Recognize existing flooding problems in downstream areas in the City of North Bend and the City of Snoqualmie, as well as unincorporated King County.
- An unsteady hydraulic model, to characterize the relative influences and different timing of flood flows from the mainstem South Fork Snoqualmie River and the three tributary channels.

Likely impacts of gravel removal on the aquatic habitat:

- Identify species and life stages of salmonids present and habitat elements needed.
- Identify physical processes that create or maintain habitat elements.
- Extend the evaluation beyond the effects on salmonid habitat and include an evaluation of the effects of gravel removal on salmonid species and populations.
- Extend the evaluation to include effects on other species and habitat types that may be present in the South Fork Snoqualmie River.
- Extend the evaluation to include parts of the South Fork Snoqualmie River downstream and upstream of the present study reach, as appropriate.

See US Fish and Wildlife Service et al. (2006) for further details on the evaluation of salmonid fishes and habitat.

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# Appendix A

## Sediment volume calculation tables and surveyed cross section plots

**Table A-1: South Fork Snoqualmie River surveyed cross sections used in gravel removal study calculations**

| See Note | Cross Section at River Mile (RM) | Year Cross Section was surveyed or estimated for this study | | | | | Cross Section Location, Description | Gravel Bar Number: Note C |
|---|---|---|---|---|---|---|---|---|
| | | 1992/95 | 1999 | 2006 | 2007 | 2009 | | |
| | | Downstream end of study reach | | | | | | |
| A | 2.80 | 1993 | 1999 | 2006 | 2007 | 2009 | ~250 feet downstream of North Bend Blvd Bridge | |
| A | 2.84 | 1993 | 1999 | 2006 | 2007 | 2009 | Downstream face of North Bend Blvd Bridge | |
| B | 2.97 | 1992 est. | 1999 | 2006 est. | 2007 | 2009 | ~1000 feet upstream of North Bend Blvd Bridge | Bar 1 |
| A | 3.02 | 1992 | 1999 | 2006 | 2007 | 2009 | Adjacent to Shamrock Park | Bar 1 |
| A | 3.15 | 1992 | 1999 | 2006 | 2007 | 2009 | Adjacent to Shamrock Park. Island bar | Bar 2 |
| A | 3.23 | 1992 | 2000 | 2006 | 2007 | 2009 | Narrow channel | Bar 2 |
| B | 3.34 | 1992 est. | 1999 est. | 2006 | 2007 | 2009 | Adjacent to Berry Estates | Bar 3 |
| B | 3.36 | 1992 est. | 1999 | 2006 | 2007 | 2009 | Adjacent to Berry Estates | Bar 3 |
| A | 3.39 | 1992 | 1999 | 2006 | 2007 | 2009 | Adjacent to Berry Estates | Bar 3 |
| B | 3.51 | 1992 est. | 1999 | 2006 | 2007 | 2009 | Middle of left bank bar | Bar 4 |
| A | 3.54 | 1993 | 1999 | 2006 | 2007 | 2009 | 100 feet downstream of rock falls | Bar 4 |
| A | 3.66 | 1992 | 2000 | 2006 | 2007 | 2009 | Through gravel bar at hard right bend | Bar 5 |
| A | 3.72 | 1992 | 1999 | 2006 | 2007 | 2009 | Adjacent to Log Cabin Creations | Bar 5-6 |
| A | 3.80 | 1992 | 2000 | 2006 | 2007 | 2009 | Downstream end of large left bank bar | Bar 6 |
| B | 3.95 | 1992 est. | 1999 est. | 2006 est. | 2007 | 2009 | Middle of large left bank bar | Bar 6 |
| B | 3.99 | 1992 est. | 1999 est. | 2006 | 2007 | 2009 | Upstream end of large left bank bar | Bar 6 |
| A | 4.04 | 1992 | 1999 | 2006 | 2007 | 2009 | Between gravel bars | Bar 6-7 |
| B | 4.11 | 1995 est. | 1999 est. | 2006 est. | 2007 | 2009 | Middle of right bank bar | Bar 7 |
| A | 4.17 | 1995 | 2000 | 2006 | 2007 | 2009 | Upstream end of right bank bar at bend | Bar 7 |
| B | 4.34 | 1995 | 1999 | 2006 | 2007 | 2009 | Left bank bar near upstream end | Bar 8 |
| A | 4.46 | 1992 | 1999 | 2006 | 2007 | 2009 | Right bank bar near upstream end | Bar 9 |
| | | Upstream end of study reach | | | | | | |

**Notes:**

A: Cross section exists in the South Fork Snoqualmie River Flood Insurance Study (FEMA 2005).

B. Cross section was added for channel monitoring and hydraulic modeling purposes.

C: Gravel bars are numbered sequentially going upstream from North Bend Blvd (Bendigo) Bridge (per Shannon & Wilson 1993).

Est. = cross section geometry was estimated, using information from adjacent topography in that same year.

Left bank or right bank are viewed looking downstream.

**Table A-2:**
**South Fork Snoqualmie River**
**Changes in sediment volumes and levels from 1992/95 to 1999**

| River Mile | Distance between cross sections (feet) | Change in cross sectional area [A] at each xsec (sq ft) | Average change in xsectional area, from xsec to xsec (sq ft) | Change in storage volume, from xsec to xsec (cu yd) | Channel Width [B] (feet) | Change in sediment level from 1992/95-1999 at each xsec [C] (feet) | Average annual rate of change in sediment level at each cross section (feet/year) |
|---|---|---|---|---|---|---|---|
| | Downstream end | | | | | | |
| 2.80 | | 64 | | | 105 | 0.6 | 0.10 |
| 2.84 | 252 | 12 | 38 | 358 | 136 | 0.1 | 0.01 |
| 2.97 | 670 | 140 | 76 | 1,890 | 160 | 0.9 | 0.13 |
| 3.02 | 250 | -32 | 54 | 504 | 172 | -0.2 | -0.03 |
| 3.15 | 710 | 94 | 31 | 822 | 205 | 0.5 | 0.07 |
| 3.23 | 420 | -31 | 32 | 492 | 142 | -0.2 | -0.03 |
| 3.34 | 545 | 121 | 45 | 915 | 157 | 0.8 | 0.11 |
| 3.35 | 90 | 385 | 253 | 543 | 184 | 2.1 | 0.30 |
| 3.39 | 180 | 225 | 305 | 2,034 | 247 | 0.9 | 0.13 |
| 3.51 | 637 | 182 | 204 | 4,603 | 258 | 0.7 | 0.10 |
| 3.54 | 180 | -5 | 89 | 593 | 200 | 0.0 | 0.00 |
| 3.65 | 588 | -208 | -107 | -2,319 | 280 | -0.7 | -0.11 |
| 3.72 | 365 | -112 | -160 | -2,158 | 237 | -0.5 | -0.07 |
| 3.86 | 705 | -200 | -156 | -4,077 | 250 | -0.8 | -0.11 |
| 3.95 | 470 | 118 | -41 | -713 | 192 | 0.6 | 0.09 |
| 3.99 | 240 | 59 | 88 | 787 | 218 | 0.3 | 0.04 |
| 4.04 | 260 | 37 | 48 | 461 | 166 | 0.2 | 0.03 |
| 4.11 | 375 | 44 | 41 | 564 | 140 | 0.3 | 0.08 |
| 4.17 | 310 | 132 | 88 | 1,012 | 220 | 0.6 | 0.15 |
| 4.34 | 890 | 121 | 126 | 4,165 | 227 | 0.5 | 0.13 |
| 4.46 | 620 | 94 | 107 | 2,466 | 213 | 0.4 | 0.06 |
| | Upstream end | | | | | | |
| Total change in storage volume (cu yd) | | | | 13,427 | Reach-wide average annual rate of change in sediment level (feet/year) | | 0.05 |
| | | | | 7,000 | Total extraction 1992-1999 (cu yd) [D] | | |
| | | | | 20,427 | Total volume deposited (cu yd) [E] | | |
| | | | | 20,400 | Rounded Total volume deposited (cu yd) | | |
| | | | | 2,918 | Average annual deposition (cu yd/yr) [F] | | |
| | | | | 2,900 | Rounded average annual deposition (cu yd/yr) | | |

**Notes**
'xsec' means cross section
A: Only changes in cross sectional area along the channel bed and gravel bars are reported here.
B: Channel width was measured along the change in cross sectional area only.
C: Change in sediment level equals change in cross sectional area divided by channel width.
D: Assumes 7 years times 1,000 cu yd/yr extraction at gravel bar 6.
E: Total volume deposited equals change in storage volume plus extracted volume
F: Average annual deposition is total volume deposited divided by 7 years

**Table A-3:**
**South Fork Snoqualmie River**
**Changes in sediment volumes and levels from 1999 to 2006**

| River Mile | Distance between cross sections (feet) | Change in cross sectional area [A] at each xsec (sq ft) | Average change in xsectional area, from xsec to xsec (sq ft) | Change in storage volume from xsec to xsec (cu yd) | Channel Width [B] (feet) | Change in sediment level from 1997/98-1999 at each xsec [C] (feet) | Average annual rate of change in sediment level at each cross section (feet/year) |
|---|---|---|---|---|---|---|---|
| | Downstream end | | | | | | |
| 2.80 | | 49 | | | 105 | 0.5 | 0.07 |
| 2.84 | 252 | -19 | 15 | 140 | 136 | 0.1 | -0.02 |
| 2.97 | 670 | 42 | 11 | 283 | 160 | 0.3 | 0.04 |
| 3.02 | 250 | -4 | 19 | 174 | 172 | 0.0 | 0.00 |
| 3.15 | 710 | -115 | -60 | -1,569 | 205 | -0.5 | -0.08 |
| 3.23 | 420 | 4 | -56 | -869 | 142 | 0.0 | 0.00 |
| 3.34 | 545 | 69 | 35 | 736 | 157 | 0.4 | 0.06 |
| 3.35 | 90 | -117 | -24 | -80 | 184 | -0.5 | -0.09 |
| 3.39 | 180 | -3 | -60 | -399 | 247 | 0.0 | 0.00 |
| 3.51 | 637 | -56 | -29 | -689 | 258 | -0.2 | -0.03 |
| 3.54 | 180 | 4 | -26 | -174 | 200 | 0.0 | 0.00 |
| 3.65 | 588 | 47 | 25 | 548 | 280 | 0.2 | 0.02 |
| 3.72 | 365 | -156 | -55 | -740 | 237 | -0.7 | -0.09 |
| 3.86 | 705 | 66 | -45 | -1,183 | 250 | 0.3 | 0.04 |
| 3.95 | 470 | 70 | 68 | 1,175 | 192 | 0.4 | 0.05 |
| 3.99 | 240 | 25 | 47 | 419 | 218 | 0.1 | 0.02 |
| 4.04 | 260 | 41 | 33 | 316 | 168 | 0.2 | 0.03 |
| 4.11 | 375 | 42 | 41 | 576 | 140 | 0.3 | 0.04 |
| 4.17 | 310 | 50 | 46 | 526 | 220 | 0.2 | 0.03 |
| 4.34 | 890 | 54 | 52 | 1,707 | 227 | 0.2 | 0.03 |
| 4.46 | 620 | 10 | 32 | 737 | 213 | 0.0 | 0.01 |
| | Upstream end | | | | | | |
| Total change in storage volume (cu yd) | | | | 1,636 | Reach-wide average annual rate of change in sediment level (feet/year) | | 0.006 |
| | | | | 0 | Total extraction 1999 -2006 (cu yd) [D] | | |
| | | | | 1,636 | Total volume deposited (cu yd) [E] | | |
| | | | | 1,600 | Rounded Total volume deposited (cu yd) | | |
| | | | | 234 | Average annual deposition (cu yd/yr) [F] | | |
| | | | | 200 | Rounded average annual deposition (cu yd/yr) | | |

**Notes**
"xsec" means cross section
A: Only changes in cross sectional area along the channel bed and gravel bars are reported here.
B: Channel width was measured along the change in cross sectional area only.
C: Change in sediment level equals change in cross sectional area divided by channel width.
D: There was no extraction during this period.
E: Total volume deposited equals change in storage volume plus extracted volume.
F: Average annual deposition is total volume deposited divided by 7 years.

**Table A-4:**
**South Fork Snoqualmie River**
**Changes in sediment volumes and levels from 2006 to 2007**

| River Mile | Distance between cross sections (feet) | Change in cross sectional area [A] at each xsec (sq ft) | Average change in xsectional area, from xsec to xsec (sq ft) | Change in storage volume, from xsec to xsec (cu yd) | Channel Width [B] (feet) | Change in sediment level from 1996/98-1998 at each xsec [C] (feet) | Average annual rate of change in sediment level at each cross section (feet/year) |
|---|---|---|---|---|---|---|---|
| | Downstream end | | | | | | |
| 2.80 | | -28 | | | 105 | -0.3 | -0.27 |
| 2.84 | 252 | -32 | -30 | -283 | 136 | -0.2 | -0.24 |
| 2.97 | 670 | 15 | -9 | -214 | 160 | 0.1 | 0.09 |
| 3.02 | 250 | 12 | 13 | 124 | 172 | 0.1 | 0.07 |
| 3.15 | 710 | 16 | 14 | 359 | 205 | 0.1 | 0.08 |
| 3.23 | 420 | -30 | -7 | -110 | 142 | -0.2 | -0.21 |
| 3.34 | 545 | 22 | -4 | -82 | 157 | 0.1 | 0.14 |
| 3.35 | 90 | 63 | 43 | 141 | 184 | 0.3 | 0.34 |
| 3.39 | 180 | 66 | 65 | 432 | 247 | 0.3 | 0.27 |
| 3.51 | 637 | 51 | 58 | 1,378 | 258 | 0.2 | 0.20 |
| 3.54 | 180 | 3 | 27 | 177 | 200 | 0.0 | 0.01 |
| 3.65 | 588 | 8 | 5 | 109 | 280 | 0.0 | 0.03 |
| 3.72 | 365 | -40 | -16 | -222 | 237 | -0.2 | -0.17 |
| 3.86 | 705 | 101 | 32 | 828 | 250 | 0.4 | 0.42 |
| 3.95 | 470 | 164 | 134 | 2,327 | 192 | 0.9 | 0.85 |
| 3.99 | 240 | 72 | 118 | 1,049 | 218 | 0.3 | 0.33 |
| 4.04 | 260 | 21 | 46 | 447 | 168 | 0.1 | 0.12 |
| 4.11 | 375 | 24 | 22 | 310 | 140 | 0.2 | 0.17 |
| 4.17 | 310 | 59 | 41 | 474 | 220 | 0.3 | 0.27 |
| 4.34 | 890 | -56 | -14 | -452 | 227 | -0.4 | -0.36 |
| 4.46 | 620 | 70 | -8 | -181 | 213 | 0.3 | 0.33 |
| | Upstream end | | | | | | |
| Total change in storage volume (cu yd) | | | | 6,611 | Reach-wide average annual rate of change in sediment level (feet/year) | | 0.12 |
| | | | | 0 | Total extraction 2006-2007 (cu yd) [D] | | |
| | | | | 6,611 | Total volume deposited (cu yd) [E] | | |
| | | | | 6,600 | Rounded Total volume deposited (cu yd) | | |
| | | | | 6,611 | Average annual deposition (cu yd/yr) [F] | | |
| | | | | 6,600 | Rounded average annual deposition (cu yd/yr) | | |

**Notes**
"xsec" means cross section
A: Only changes in cross sectional area along the channel bed and gravel bars are reported here
B: Channel width was measured along the change in cross sectional area only.
C: Change in sediment level equals change in cross sectional area divided by channel width.
D: There was no extraction during this period.
E. Total volume deposited equals change in storage volume plus extracted volume
F: Average annual deposition equals the total volume deposited in this 1-year period.

**Table A-5:**
**South Fork Snoqualmie River**
**Changes in sediment volumes and levels from 2007 to 2009**

| River Mile | Distance between cross sections (feet) | Change in cross sectional area [A] at each xsec (sq ft) | Average change in xsectional area, from xsec to xsec (sq ft) | Change in storage volume, from xsec to xsec (cu yd) | Channel Width [B] (feet) | Change in sediment level from 1992/93-1999 at each xsec [C] (feet) | Average annual rate of change in sediment level at each cross section (feet/year) |
|---|---|---|---|---|---|---|---|
| | Downstream end | | | | | | |
| 2.80 | | -70 | | | 105 | -0.7 | -0.33 |
| 2.84 | 252 | -27 | -49 | -454 | 136 | -0.2 | -0.10 |
| 2.97 | 670 | 33 | 3 | 73 | 160 | 0.2 | 0.10 |
| 3.02 | 250 | 35 | 34 | 315 | 172 | 0.2 | 0.10 |
| 3.15 | 710 | 142 | 89 | 2,335 | 205 | 0.7 | 0.35 |
| 3.23 | 420 | 26 | 84 | 1,308 | 142 | 0.2 | 0.09 |
| 3.34 | 545 | 77 | 52 | 1,041 | 157 | 0.5 | 0.25 |
| 3.35 | 90 | 64 | 71 | 236 | 184 | 0.4 | 0.18 |
| 3.39 | 180 | -3 | 31 | 204 | 247 | 0.0 | -0.01 |
| 3.51 | 637 | 56 | 26 | 617 | 258 | 0.2 | 0.11 |
| 3.54 | 190 | 5 | 30 | 202 | 200 | 0.0 | 0.01 |
| 3.65 | 588 | 35 | 20 | 436 | 280 | 0.1 | 0.06 |
| 3.72 | 365 | 150 | 92 | 1,249 | 237 | 0.6 | 0.32 |
| 3.86 | 705 | 122 | 136 | 3,543 | 250 | 0.5 | 0.24 |
| 3.95 | 470 | 144 | 133 | 2,312 | 192 | 0.8 | 0.38 |
| 3.99 | 240 | 50 | 97 | 863 | 218 | 0.2 | 0.1[illegible] |
| 4.04 | 260 | 1 | 26 | 246 | 168 | 0.0 | 0.00 |
| 4.11 | 375 | 54 | 28 | 385 | 140 | 0.4 | 0.19 |
| 4.17 | 310 | -17 | 19 | 215 | 220 | -0.1 | -0.04 |
| 4.34 | 890 | 53 | 18 | 595 | 227 | 0.2 | 0.12 |
| 4.46 | 620 | 105 | 79 | 1,308 | 213 | 0.5 | 0.25 |
| | Upstream end | | | | | | |
| Total change in storage volume (cu yd) | | | | 17,529 | Reach-wide average annual rate of change in sediment level (feet/year) | | 0.11 |
| | | | | 0 | Total extraction 2007-2009 (cu yd) [D] | | |
| | | | | 17,529 | Total volume deposited (cu yd) [E] | | |
| | | | | 17,500 | Rounded Total volume deposited (cu yd) | | |
| | | | | 8,765 | Average annual deposition (cu yd/yr) [F] | | |
| | | | | 8,800 | Rounded average annual deposition (cu yd/yr) | | |

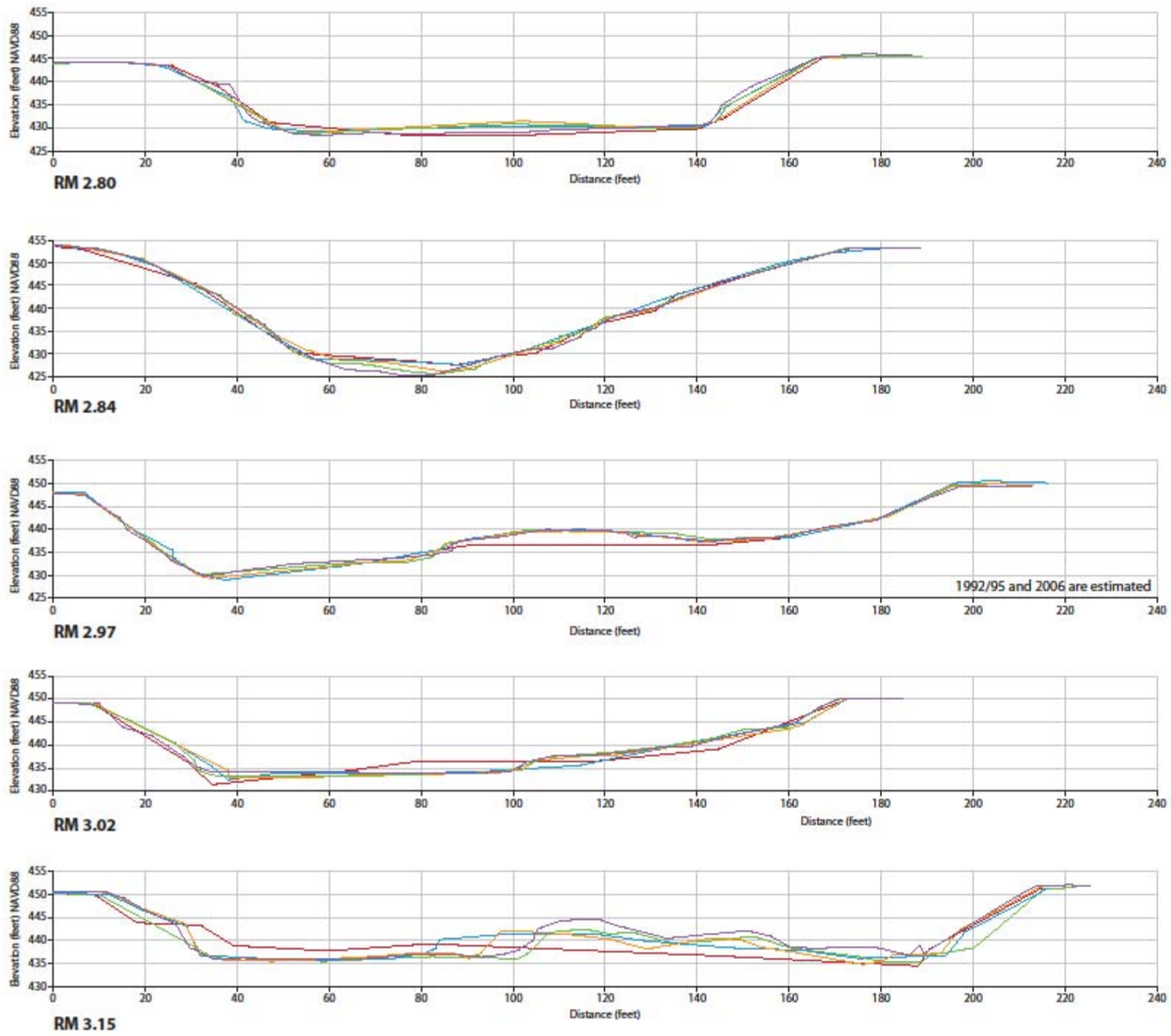
**Notes**
"xsec" means cross section
A: Only changes in cross sectional area along the channel bed and gravel bars are reported here.
B: Channel width was measured along the change in cross sectional area only.
C: Change in sediment level equals change in cross sectional area divided by channel width.
D: There was no extraction during this period.
E: Total volume deposited equals change in storage volume plus extracted volume.
F: Average annual deposition is total volume deposited divided by 2 years.

**Table A-6:**
**South Fork Snoqualmie River**
**Changes in sediment volumes and levels from 1992/95 to 2009**

| River Mile | Distance between cross sections (feet) | Change in cross sectional area [A] at each xsec (sq ft) | Average change in xsectional area, from xsec to xsec (sq ft) | Change in storage volume, from xsec to xsec (cu yd) | Channel Width [B] (feet) | Change in sediment level from 1992/95-1999 at each xsec [C] (feet) | Average annual rate of change in sediment level at each cross section (feet/year) |
|---|---|---|---|---|---|---|---|
| | Downstream end | | | | | | |
| 2.80 | | 15 | | | 105 | 0.1 | 0.01 |
| 2.84 | 252 | -75 | 30 | -281 | 136 | -0.6 | -0.03 |
| 2.97 | 670 | 225 | 75 | 1,851 | 160 | 1.4 | 0.08 |
| 3.02 | 250 | 34 | 129 | 1,197 | 172 | 0.2 | 0.01 |
| 3.15 | 710 | 126 | 80 | 2,105 | 205 | 0.6 | 0.04 |
| 3.23 | 420 | -30 | 48 | 745 | 142 | -0.2 | -0.01 |
| 3.34 | 545 | 290 | 130 | 2,617 | 157 | 1.8 | 0.11 |
| 3.35 | 90 | 358 | 324 | 1,078 | 184 | 1.9 | 0.11 |
| 3.39 | 180 | 281 | 320 | 2,132 | 247 | 1.1 | 0.07 |
| 3.51 | 637 | 227 | 254 | 5,996 | 258 | 0.9 | 0.05 |
| 3.54 | 180 | 13 | 120 | 798 | 200 | 0.1 | 0.00 |
| 3.65 | 585 | -56 | -42 | -909 | 280 | -0.3 | -0.02 |
| 3.72 | 365 | -138 | -117 | -1,560 | 237 | -0.6 | -0.03 |
| 3.86 | 705 | 105 | -16 | -428 | 250 | 0.4 | 0.02 |
| 3.95 | 470 | 496 | 300 | 5,225 | 192 | 2.6 | 0.15 |
| 3.99 | 240 | 222 | 359 | 3,193 | 218 | 1.0 | 0.06 |
| 4.04 | 280 | 90 | 156 | 1,506 | 168 | 0.5 | 0.03 |
| 4.11 | 375 | 165 | 128 | 1,772 | 140 | 1.2 | 0.08 |
| 4.17 | 310 | 210 | 188 | 2,153 | 220 | 1.0 | 0.07 |
| 4.34 | 890 | 152 | 181 | 5,960 | 227 | 0.7 | 0.05 |
| 4.46 | 620 | 285 | 220 | 5,042 | 213 | 1.4 | 0.08 |
| | Upstream end | | | | | | |
| Total change in storage volume (cu yd) | | | | 40,171 | Reach-wide average annual rate of change in sediment level (feet/year) | | 0.04 |

| | |
|---|---|
| 7,000 | Total extraction 1992/95-2009 (cu yd) [D] |
| 47,171 | Total volume deposited (cu yd) [E] |
| 47,200 | Rounded Total volume deposited (cu yd) |
| 2,775 | Average annual deposition (cu yd/yr) [F] |
| 2,800 | Rounded average annual deposition (cu yd/yr) |

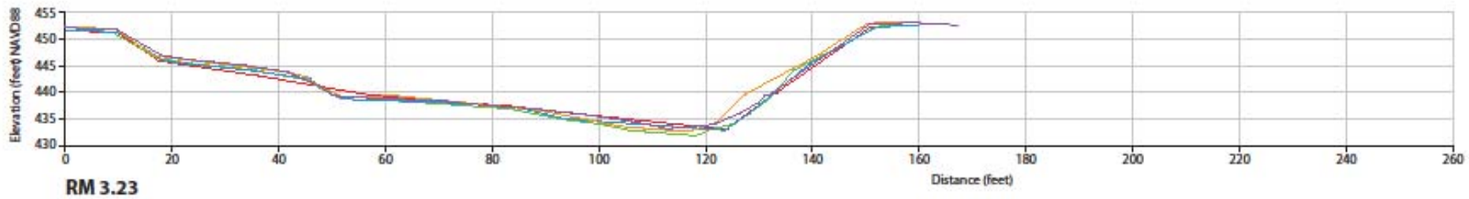
**Notes**
"xsec" means cross section
A: Only changes in cross sectional area along the channel bed and gravel bars are reported here.
B: Channel width was measured along the change in cross sectional area only.
C: Change in sediment level equals change in cross sections area divided by channel width.
D: Assume 7 years times 1000 cu yd/yr extraction at gravel bar 6.
E: Total volume deposited equals change in storage volume plus extracted volume.
F: Average annual deposition is total volume deposited divided by 17 years

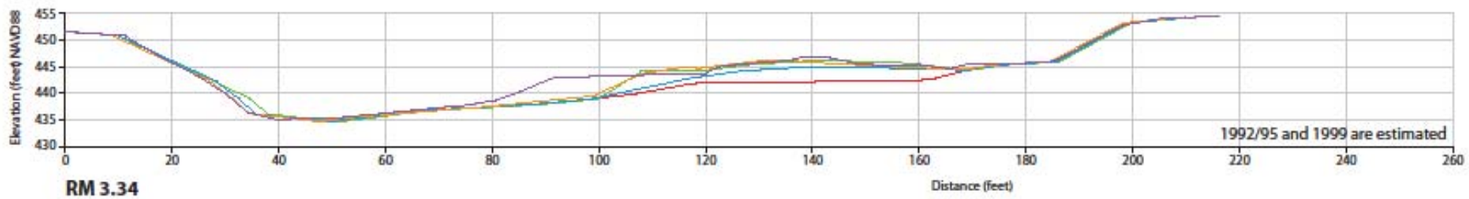


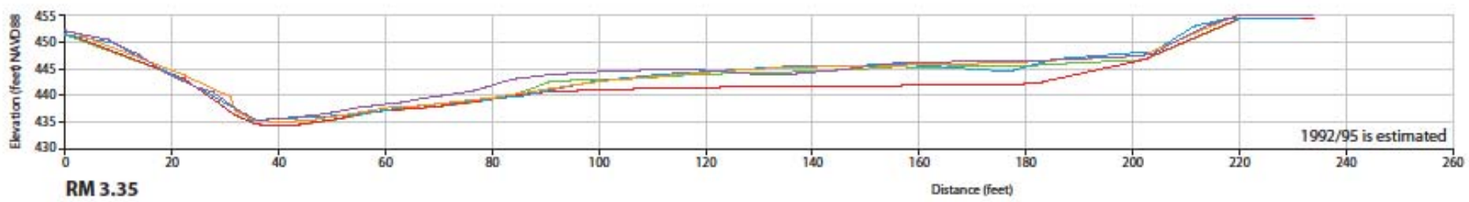

**South Fork Snoqualmie River Gravel Removal Study Appendix A: Surveyed Cross Sections, Viewed Looking Downstream**

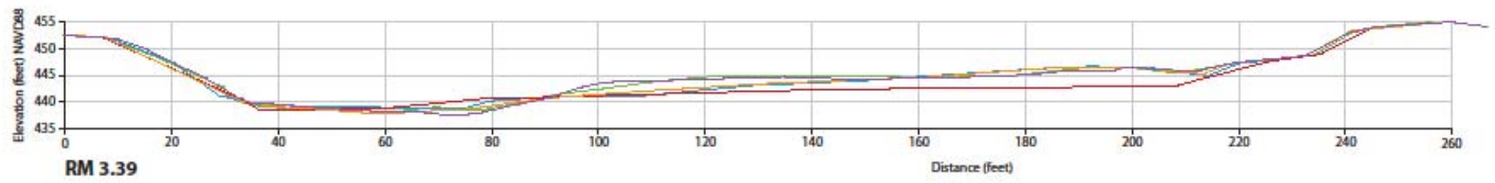
**Legend**
Surveyed Cross Sections
- 2009
- 2007
- 2006
- 1999
- 1992/95

**South Fork Snoqualmie River Gravel Removal Study Appendix A: Surveyed Cross Sections, Viewed Looking Downstream**

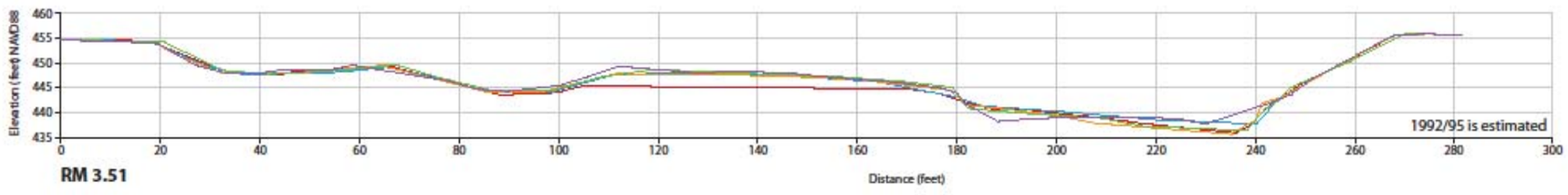


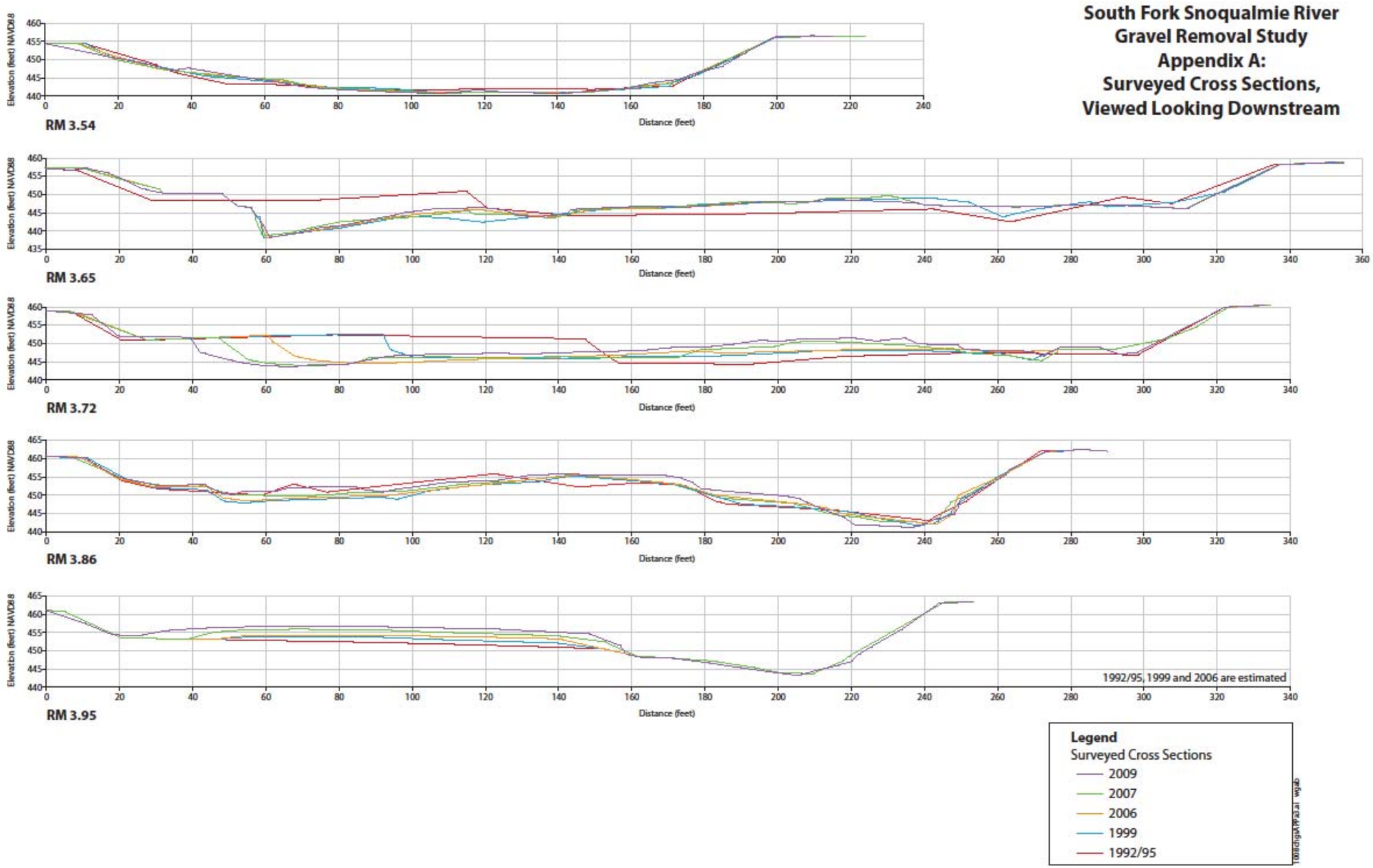



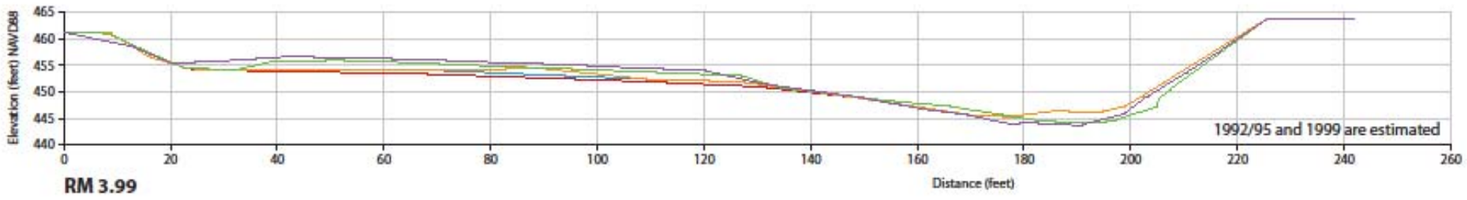




**Legend**
Surveyed Cross Sections
- 2009
- 2007
- 2006
- 1999
- 1992/95

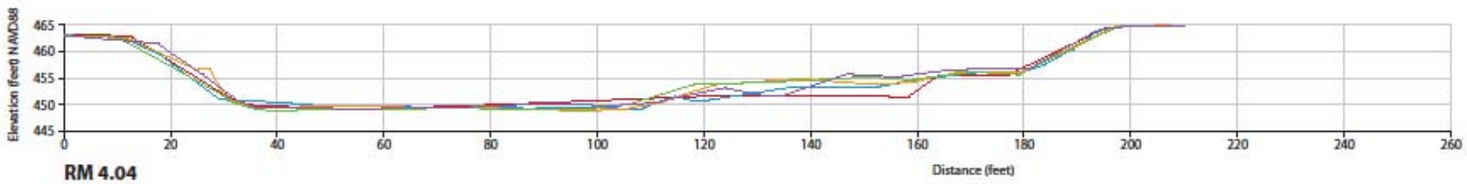



South Fork Snoqualmie River
Gravel Removal Study
Appendix A:
Surveyed Cross Sections,
Viewed Looking Downstream
Elevation (feet) NAVD88
Distance (feet)
RM 3.54
RM 3.65
RM 3.72
RM 3.86
RM 3.95
1992/95, 1999 and 2006 are estimated
Legend
Surveyed Cross Sections
2009
2007
2006
1999
1992/95

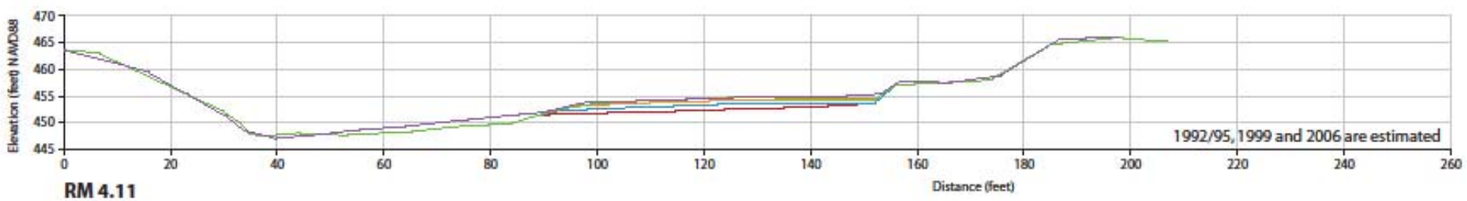
**South Fork Snoqualmie River Gravel Removal Study Appendix A: Surveyed Cross Sections, Viewed Looking Downstream**



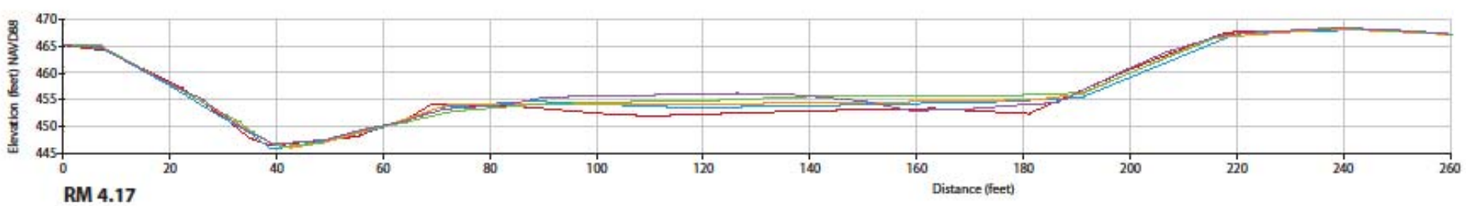

RM 3.99



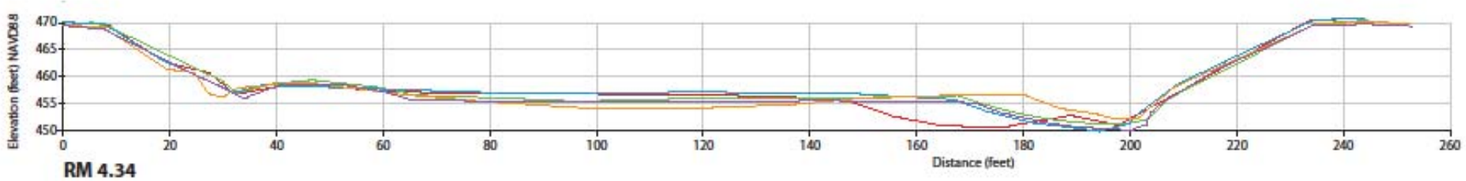

RM 4.04




RM 4.11



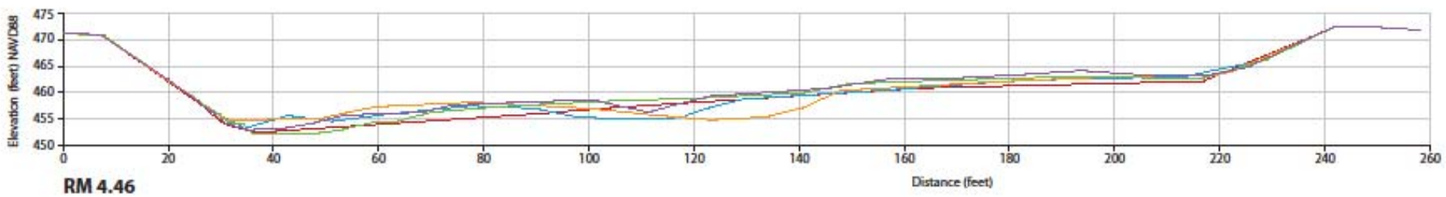

RM 4.17




RM 4.34

**Legend**
Surveyed Cross Sections
- 2009
- 2007
- 2006
- 1999
- 1992/95

**South Fork Snoqualmie River Gravel Removal Study Appendix A: Surveyed Cross Sections, Viewed Looking Downstream**




**RM 4.46**

**Legend**
Surveyed Cross Sections
- 2009
- 2007
- 2006
- 1999
- 1992/95