GEOMORPHIC ASSESSMENT

MIDDLE FORK SNOQUALMIE RIVER
TANNER TO THREE FORKS NATURAL AREA

King County
Department of Natural Resources and Parks
River and Floodplain Management Section

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TANNER TO THREE FORKS NATURAL AREA

Prepared for

King County

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River and Floodplain Management Section
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GLOSSARY OF TERMS

1 Percent Annual Chance Flood. The flood that has a 1 percent chance of being equaled or exceeded in any given year.

Aquatic Area. Any non-wetland water feature including all shorelines of the state, rivers, streams, marine waters, inland bodies of open water including lakes and ponds, reservoirs, and conveyance systems and impoundments of these features if any portion of the feature is formed from a stream or wetland and if any stream or wetland contributing flows is not created solely as a consequence of stormwater pond construction. "Aquatic area" does not include water features that are entirely artificially collected or conveyed storm or wastewater systems or entirely artificial channels, ponds, pools or other similar constructed water features.

Alluvial Fan. A radially symmetric geomorphic surface created by an alluvial sedimentation. Alluvial fans are usually characterized by active and sometimes unpredictable channel movement and channel avulsions.

Anabranching River. A river that contains multiple mid-channel bars, vegetated islands, and multiple channel courses. In many gravel bed rivers, anabranching rivers experience relatively frequent and somewhat unpredictable changes in channel position as mid channel bars form and erode. They are thus sometimes referred to as wandering rivers.

Armor. A relatively coarse layer at the surface of a sedimentary deposit that results from the winnowing of fine material out of the underlying deposit.

Avulsion. A rapid change in channel course that results in the abandonment of the original channel. Avulsions can result in the creation of a new channel or, more frequently, in the reoccupation of an old channel that was abandoned by a previous channel avulsion.

Bank Erosion. Fluvial erosion of a river bank.

Bar. An in-channel sedimentary structure that is elevated relative to the rest of the channel bed and generally has horizontal dimensions that are not significantly larger or smaller than the width of the channel.

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

Bed Material. Sediment with a size gradation similar to that found on the channel bed. In the study area, bed material consists of sand, gravel, cobble, and boulder-size material.

Bed/Bar Material. Sediment with a size gradation similar to that found on the channel bed or in channel bars. In the study area, bed/bar material probably contains more sand than bed material.

Bedload. Sediment that moves near the channel bed and not high in the water column.

Channel Migration. Change in channel position through bank erosion on one side of a channel and deposition on the opposite bank.

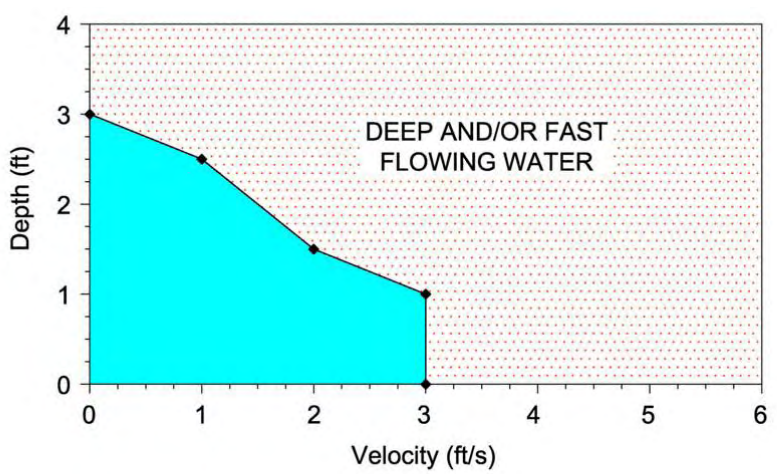
Corridor. The area of a river and surrounding lands that is essential to the storage and conveyance of floodwaters and is integral to natural riverine processes. A river corridor is a larger geographic area that includes one or more river segments (see **River Segment**), which are made up of one or more river reaches (see **River Reach**).

Debris Flow. A fast-moving slurry of sediment and water and sometimes plant material.

Debris Flow Fan. An alluvial fan formed by debris flow processes. Debris flow fans are present where steep colluvial channels divulge sediment onto a relatively flat alluvial floodplain or terrace. One debris flow fan occurs in the study area, at the base of a steep channel on the west side of Mount Si. Because the debris flow fan is forested, it is not clear how active the fan has been during the historic period.

Delta. A sedimentary structure formed at the transition between a river and standing water such as a lake or the ocean.

Deep and/or Fast Flowing Water – Areas of public safety hazard characterized by water depths greater than 3 feet, flow velocities greater than 3 feet per second, or a combination of depth and velocity greater than a threshold as shown on the figure below (from USBR 1988 as modified by Pierce County):



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

Digital Elevation Model (DEM). A three-dimensional digital representation of the ground (or other) surface based upon a regularly spaced grid of elevation data points.

Distal Floodplain/Fan. Relatively low elevation areas near and potentially below the lower limit of an alluvial fan that are either potentially inundated during a flood or exhibit evidence of past overbank deposition of sediment.

Distributary Channel: A channel that conveys flow away from the main channel, usually on an alluvial fan or fan delta.

Embankment. A large glacially-derived sedimentary structure. Near the study area embankment moraines block all or part of the valleys of the Middle Fork Snoqualmie River, South Fork Snoqualmie river, and the Cedar River.

Erosion. The wearing away of ground surface as the result of the movement of wind, water or ice.

Extent. The size of an area affected by a hazard.

Fan Delta. An alluvial fan whose lower limit is a delta.

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

Flood Protection Infrastructure. Structures that provide protection from flood damage, including but not limited to the following:

- Dams or water diversions, regardless of primary purpose, if the structures provide flood protection benefits
- Flood containment structures such as levees, dikes, berms, walls and raised banks, including pump stations, flood closure devices, and other supporting structures
- Bank stabilization structures, often called revetments

Flood Risk Reduction. An action taken to decrease exposure of people and property to flood or channel migration hazards.

Floodplain. The area potentially subject to inundation due to high river levels. The floodplain encompasses geomorphically active areas near the channel, alluvial fans (whether active or inactive), and low-elevation surfaces which may be flooded by the river. As used in this report, the term does not necessarily distinguish between land surfaces that are currently protected from flooding by flood protection infrastructure and surfaces that have no such protection.

Floodplain Swale. A channel that is usually smaller than the main river channel and crosses a floodplain surface. Floodplain swales are typically mantled by fine-grained silt/clay sediment.

Geomorphology. The study of landforms.

Glacial Outwash. Glacially-derived sediment deposited by a fluvial action, usually by meltwater flowing out of the glacier.

Glacial Till. Unsorted sediment deposited directly by a glacier. Usually includes a wide range of sediment sizes ranging from boulders down to clay. The weight of overlying glacial ice usually consolidates glacial till so that it is relatively resistant to erosion.

Glide. Glide habitats are characterized by moderately shallow water with an even flow that lacks pronounced turbulence. Glides are most frequently located at the transition between a pool and the head of a riffle. The typical substrate is gravel and cobble. Glides are commonly referred to as "runs."

Groundwater Channel. Groundwater channels are often relict river and/or flood channels fed by groundwater, although surface flow from higher terraces can also contribute. They include several subtypes of channels that include, but are not limited to:

- Channels originating from the exfiltration of main channel surface water (i.e., very shallow groundwater associated with the main river); they are sometimes called backwater channels or sloughs
- Channels fed by the floodplain aquifer (hyporheic zone); they are sometimes called percolation channels
- Channels fed by lateral groundwater supplied from adjacent terraces; they are sometimes called wall-base channels

Some groundwater channels can also be classified as overflow channels. For the purposes of this study, they are classified as groundwater channels if the dominant source of hydrology is from groundwater. The size of groundwater channels will have some seasonal variation through tempered from the range of change associated with the hydrograph. Groundwater channels are typically vegetated and commonly contain upland forests or wetlands (forested, scrub-shrub, emergent, and aquatic bed).

Hazard. An event or physical condition that has the potential to cause fatalities, injuries, property damage, infrastructure damage, agricultural loss, damage to the environment, interruption of business, and other types of loss or harm.

Hazard Mitigation. Reduction or alleviation of the loss of life, personal injury, and property damage that could result from a disaster through long- and short-term strategies. Hazard mitigation involves strategies such as planning, policy changes, programs, projects, and other activities that could mitigate the impacts of hazards.

Headcut. An erosive landform that occurs where water spills across a locally steep drop. Headcuts can migrate upstream when material at the toe is removed by the highly erosive flow at the base of the headcut.

Hillslope. Hillslopes are comprised of the valley walls and convex surfaces at the toe of the valley slopes.

In-channel Island. In-channel islands are composed of floodplain benches that are entirely surrounded by the main channel and/or active side channels. They occupy an elevation at or above typical annual high flows and are commonly inundated by larger floods. They are indicative of active channel formation processes. In-channel islands are typically forested or dominated by shrubs and provide extensive riparian edge habitat.

Large Wood. Large pieces of wood including logs, pieces of logs, root wads of trees, and other large chunks of wood that are in or partially in the channel or floodplain of rivers and streams. The term does not include rooted, standing vegetation. Large wood can stabilize streambeds and riverbanks, provide cover and refuge for fish, and create complex in-stream habitat by forming pools, regulating sediments, and dispersing stream energy.

Lateral migration. Progressive, usually gradual change of position of a geomorphic feature. Channel migration is the lateral migration of a river channel.

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

Lidar. Shorthand for **li**ght **d**etection **a**nd **r**anging, which is a remote sensing method that uses light in the form of a pulsed laser mounted in aircraft to measure ranges (variable distances from the sensor) to the earth's surface. The resultant topographic mapping is typically precise, high resolution information that can be used cost-effectively in lieu of on-the-ground or other photogrammetric survey data for analysis encompassing large areas.

Meandering River. A sinuous single-thread river. Meandering rivers often are characterized by meander bends that migrate across the floodplain.

Meandering River Floodplain. Floodplain formed by a meandering river. Meandering river floodplains are usually characterized by lateral accretion of point bars and subsequent deposition of suspended sediment. They also usually contain abandoned meander bends or oxbow lakes.

Moraine. A geomorphic feature formed by deposition of sediment at the edge or front of a glacier.

Native Vegetation. Plant species indigenous to the Puget Sound region that reasonably could be expected to occur naturally on a site.

Natural Resource Lands. Lands designated under requirements of the Growth Management Act that include the following: 1) agricultural lands with long-term significance for the commercial production of food or other agricultural products; 2) forest lands with long-term significance for the commercial production of timber; and 3) mineral resource lands with long-term significance for the extraction of minerals. The King County Comprehensive Plan designates Agricultural Production Districts, Forest Production Districts, and Mineral Resource Sites.

Open Space. Areas left predominantly in a natural state to create urban separators and greenbelts, sustain native ecosystems, connect and increase protective buffers for environmentally sensitive areas, provide a visual contrast to continuous development, reinforce community identity and aesthetics, or provide links between important environmental or recreational resources.

Overflow Channel. Overflow channels represent flood swales, often an abandoned mainstem or side channel, carrying surface water and directly connected to the primary channel at its upstream end. Some side channels may have formed or at least been enhanced by headcutting that was initiated where the side channel reconnects with the main river at its downstream end. For purposes of this study, overflow channels are characterized as hydraulically connected to the primary channel at modeled flows corresponding to flows above 1-year floods, but at or below 2-year peak flows.

Plane Bed Channel. Plane bed channels generally lack regularly repeating bedforms and are characterized by long stretches of relatively featureless bed encompassing glide, riffle, and rapid morphologies. Plane bed channels lack discrete bars, a condition associated with low width-to-depth ratios. Plane bed channels typically exhibit armored bed surfaces dominated by gravel and cobble.

Point Bar. A bar located on the inside of a meander bend.

Pool. Pool habitats are topographic depressions within the channel that include several types formed under a variety of different conditions. Within the main channel of the river, pool-riffle channels are typical, where pools are rhythmically spaced between riffles. Pools are also found in association with bars generated by flow convergence and divergence either freely formed by cross-river flow and sediment transport, or forced by channel bends and obstructions (e.g., large woody debris). Pool types affected by obstructions include backwater pools, trench pools, and lateral scour pools. Substrate size in pools varies from sand to cobble, but it typically is gravel-sized in pool-riffle channels.

Regulatory Floodplain. An area regulated by King County as floodplain through its land-use regulations. It includes, but is not limited to, areas identified by FEMA and published on Flood Insurance Rate Maps and additional areas identified by King County as being susceptible to flooding using best available flood information.

Relict Channel. Former river channels, side channels, or floodplain swales that are disconnected from frequent flooding. For the purposes of this study, relict channels are characterized as only showing signs of inundation at modeled flows corresponding to greater than 2-year flood events. Relict channels occur in historic floodplains at higher elevations that are no longer flooded except at extreme flows. These channels are typically entirely vegetated and lack visible signs of flow (e.g., no scour evident).

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

Riffle. Riffle habitats are characterized by shallow reaches with moderate current velocity and moderate turbulence. Substrate is usually composed of gravels, cobbles, and boulders. The upper gradient limit for this habitat is approximately 4 percent.

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

River Reach. A length of river through which similar physical or geomorphic conditions exist.

Riverine. Of or produced by a river. Riverine floodplains have readily identifiable channels.

River and Floodplain Management Section. A section within King County's Water and Land Resources Division, Department of Natural Resources and Parks, and funded by the King County Flood Control District and Inter-County River Improvement Fund to conduct the following activities:

- Structural capital improvement projects
- Relocation and elevation projects
- Maintenance and monitoring
- River planning
- Flood hazard education
- Flood warning and emergency response
- Complaint response and enforcement
- Interlocal coordination

Salmonid. Members of the fish family *Salmonidae*, including, but not limited to:

- Chinook, coho, chum, sockeye and pink salmon
- Rainbow, steelhead and cutthroat salmon, which are also known as trout
- Brown trout
- Brook, bull trout, which is also known as char, and Dolly Varden char
- Kokanee
- Pygmy whitefish

Sediment. Mineral and rock materials that are eroded, transported and deposited by rivers, in sizes that range from clay and silt through sand and gravel to cobble and boulders. Sediment may also include waterlogged organic debris.

Sediment Yield. The amount of sediment supplied by a watershed to a given location.

Sediment Transport Capacity. The rate at which a channel could transport sediment without leading to significant net sediment deposition, assuming sediment supply is sufficiently high.

Sedimentation. The deposition of sediment.

Setback Levee. A levee that is set away from a river in a manner to allow the river channel to migrate, increasing the connection between the river and floodplain to accommodate a floodplain that can store and convey flood flows.

Side Channel. Side channels contain a portion of the riverflow from the main or primary river channel at flows less than 1-year floods, and are partially or entirely surrounded by vegetated or stable island(s). The channel may remain connected at its upstream end through all flows less than bankfull, or it may become disconnected at some point as flows decline. When flowing, the channel is connected to the main channel at its upstream and downstream ends. The primary channel carries the greatest volume of water when there is one (or more) secondary channel with flowing surface water. Side channels can contain a variety of sub-habitats including riffles, pools, glides, and bars. They have an un-vegetated substrate indicative of regular scour.

Single-thread River. A river channel that ordinarily is characterized by single main channel course.

Sinuosity. Total channel length divided by straight-line distance (or sometimes along-valley distance) between two points.

Structural Solution. Reducing flood hazard through physical means, such as dams, levees, revetments or channelization of rivers and streams.

Suspended Sediment. Sediment that is mixed throughout the water column.

Terrace. Terraces are relatively planar surfaces that do not show evidence of recent reworking by the main river channel and are elevated above any adjacent floodplain.

Tributary. Tributaries are defined as stream systems that flow into the main river channel. Tributaries often flow through side channels of the main stem as they approach their confluence.

Vashon Ice Sheet. The large ice sheet that advanced through the Puget Sound area approximately 17,000 years ago.

Wandering River. See **anabranching river**.

Wandering River Floodplain. Floodplain formed by a wandering river. Wandering river floodplains typically contain multiple abandoned channel bars and abandoned channels. In the study area, the transition between wandering river floodplain and distal floodplain/fan surfaces is not always distinct.

Water Resource Inventory Area (WRIA). Area designations formalized under WAC 173-500-040 and authorized under the Water Resources Act of 1971, RCW 90.54. The original WRIA boundary agreements and judgments were jointly reached in 1970 by Washington's Departments of Ecology, Natural Resources, and Fish and Wildlife. The Washington Department of Ecology is responsible for developing and managing these administrative and planning areas.

Watershed. A land area that drains to a single outlet and is separated from other watersheds by a divide.

EXECUTIVE SUMMARY

King County is responsible for several flood and erosion protection facilities in the Middle Fork Snoqualmie River between the community of Tanner (upstream) and the Three Forks Natural Area (downstream) near North Bend, Washington. The County is developing a comprehensive corridor management plan to prioritize and implement future actions to reduce flood and erosion hazards in this 5-mile reach of the river. This report focused on geomorphic processes that influence flood and erosion hazards and aquatic habitat conditions, and that are influenced by flood and erosion protection facilities that were mostly built in the 1950s and 1960s.

The report presents a detailed description of the natural processes that shaped the river valley and summarizes key historic events that have influenced the evolution of the system. Rates of geomorphic change measured using aerial photography, repeat cross-section surveys, and two lidar flights are used to develop a sediment budget that estimates the rate at which sediment has been supplied to or removed from the study reach over the past several decades. Understanding the history of the river's interaction with a broad floodplain between the Middle Fork and South Fork Snoqualmie River is enhanced with radiocarbon dating of soil samples collected at several locations on the floodplain. These dates help in estimating the rate at which the channel has reworked the valley floor.

The study area has been strongly influenced by the legacy of Pleistocene glaciation. The major glacial impact on the landscape occurred during and immediately after the formation of the Vashon Ice Sheet around 17,000 years ago, after alpine glaciers had retreated far upstream of the study area. At its maximum extent, the Vashon Ice Sheet blocked the mouths of many east-west trending Cascade Range valleys, resulting in the formation of large pro-glacial lakes that extended eastward into the Cascades. Glacial outwash at the edge of the ice sheet formed a large embankment moraine that blocked the valleys of the Cedar River and the Middle and South Forks of the Snoqualmie River. Much of the embankment remains in place in the Middle Fork valley upstream of Tanner and is referred to in this report as the Middle Fork Embankment. Retreat of the ice sheet allowed the Middle Fork to cut through the embankment, resulting in the formation of a series of alluvial fans near the upstream end of the study area. Further ice retreat allowed the emergence of Snoqualmie Falls, which initially formed the lower end of a lake that probably inundated the downstream parts of the study area. Subsequent sedimentation filled this lake, eventually allowing the Snoqualmie River to develop its present meandering course between the base of Mount Si and Snoqualmie Falls.

A timeline was developed as part of this study to summarize potentially important historic events that could have influenced the geomorphic evolution of the Middle Fork channel. The timeline includes approximate dates of major fires, timber harvests, floods, droughts, and construction of major flood and erosion protection facilities. Perhaps the most significant regional impact was forest clearing, which began in the study area around 1900 and affected the upstream watershed most significantly during the 1940s. Logging was focused on low elevation parts of the Middle Fork watershed. The Alpine Lakes Wilderness now protects a major part of the watershed from logging, but timber production continues in places, mainly on private lands outside the boundary of Mount Baker-Snoqualmie National Forest.

In general, logging alters watershed hydrology by changing snowmelt dynamics and evapotranspiration rates and because the road network associated with timber harvest changes runoff patterns. It also results in a decrease in the strength of roots that play an important role in stabilizing near-surface soils, particularly in sloped terrain. This, in combination with slope failures associated with forest roads, tends to lead to an increase in sediment supply when logging occurs on steep slopes. However, because runoff from many upland catchments must pass across relatively flat terraces before reaching the Middle Fork upstream of the Middle Fork Embankment, and because a relatively low gradient reach upstream of the Embankment probably serves to store and slowly release any large pulses of bed material sediment, timber harvest may have had less impact on the dynamics of the Middle Fork than on other Pacific Northwest rivers.

Because of the complicated geomorphic history of the area, the Middle Fork undergoes several significant geomorphic transformations as it passes through the study area. Both slope and sediment size decrease significantly in the downstream direction, with the most rapid change occurring where the channel begins to flow westward across the alluvial valley away from Mount Si, near River Mile (RM) 1.0 (referenced relative to RM 0.0 being at the confluence with the North Fork). Floodplain formation processes also change through the study reach. Near the upstream end of the reach, the channel is incised into an alluvial fan that probably formed during Pleistocene deglaciation. Rates of channel migration in this area are generally low. Further downstream, where the channel runs along the base of Mount Si, the channel has a wandering or anabranching planform morphology characterized by several large mid-channel bars. The near-channel floodplain in this area probably consists mainly of abandoned bars and probably has been reworked several times. Further downstream, near and below the confluence with the North Fork, the channel develops a single-thread meandering pattern. The large floodplain in this area has been reworked regularly by meander bend migration, and several abandoned channel courses of the Middle Fork are preserved in the floodplain. Previous studies split the study reach into three subreaches with boundaries corresponding relatively closely with these geomorphic zones, although the transition in floodplain-forming processes was probably historically somewhere in the middle of the three subreaches, near RM 1.0, and may have been pushed downstream by historic channel engineering projects.

Large wood plays an important role in controlling channel evolution and maintaining in-stream habitat in forested landscapes. Several historical factors significantly reduced the amount of in-channel wood within the study area. These include timber harvest, bank armoring that reduced the rate at which the channel eroded floodplain forest, and direct removal of in-channel wood. However, in-channel wood is still present in places as individual pieces and in several large log jams. The formation and longevity of log jams depends on the presence of large "key piece" logs. Potential sources of large wood in the study reach were characterized by developing a canopy height map and computing the difference between first and last returns in 2010 lidar survey data. One of the primary sources of large wood in the reach is a mature forest of black cottonwood near the downstream end of the study area, where recent erosion has recruited several exceptionally large trees into the channel. Additional erosion in this area is likely, so it will probably remain an important source of large wood for the foreseeable future. Revetments on the river banks upstream of this cottonwood forest area probably limit the number of exceptionally large "key piece" logs that can be recruited into the channel in the upstream parts of the study reach.

Several channels that are relatively small in comparison to the Middle Fork cross the alluvial fan/floodplain surface between the Middle and South Forks. These are referred to in this report as relict channels or floodplain swales. While the age of these channels is not well known, they probably formed through upstream headcut propagation during floods. Some may also represent historic courses of either the main channel of the Middle Fork or smaller distributary channels that may have crossed the alluvial fan. Two such channels were identified in a previous study (Perkins 1996) as being at risk for rapid enlargement during a large flood. Potential mechanisms for activation of these channels are not well understood but would probably require the diversion of significant high-velocity flow onto the floodplain.

To help characterize the age of the floodplain surfaces in the study area and particularly to help estimate the age of relict floodplain channels, soil samples were collected at several locations using a hand auger and in pits excavated by hand or using a backhoe. Wood fragments, charcoal, or soil carbon from the samples were dated using radiocarbon techniques. Results show that an abandoned meander bend near the edge of the meandering river floodplain in the lower part of the study area was probably abandoned only a few hundred years ago. This indicates that the lower (northern) part of the study area probably underwent rapid channel migration even prior to forest clearing. However, sample dates from floodplain swales are generally older, ranging from several hundred to over 2,000 years. In places, the swales in the floodplain are mantled by up to 4 feet of fine-grained silt/clay sediment most likely deposited in a relatively quiescent floodplain environment. This implies that the floodplain swales may be relatively old geomorphic features that did not actively enlarge over the past several hundred years.

Sediment yield to the study reach was estimated based on literature values for nearby watersheds and by using an empirical equation that was developed from a large database of sediment transport rates from around the globe (Syvitski et al. 2003). Literature-based estimates of bed material yield estimates range from 14,500 tons per year (average for similar watersheds in Washington state) to 17,300 tons per year (a published value for the Middle Fork watershed by Nelson [1971]). The global yield equation of Syvitski et al. (2003) resulted in a bed material yield estimate of 58,200 tons per year. Bed material sediment transport capacity was estimated for a depositional area in the lower part of the study area using the BAGS computer model (Pitlick et al. 2009). Results of the BAGS computation vary widely, with average bed material transport capacity estimates ranging from 400 to 12,600 tons per year, depending on the equation used and the input parameters.

A sediment budget was developed using cross-section surveys performed by King County in 1993 and 2010 and lidar surveys performed in 2002 and 2010. Cross-sections were used to characterize geomorphic change below the water surface, and lidar was used to characterize changes above the water surface. The sediment budget shows that sediment accumulation is focused near RM 1 where the slope of the channel drops significantly. Rates of bed material accumulation may be similar to the transport capacity computed for the nearby channel. The sediment budget shows that net evacuation of large amounts of sediment may have occurred over the past few decades in the downstream-most part of the study reach. This may be associated with an increase in sinuosity associated with long-term evolution of the channel in response to meander bend cutoff that occurred sometime between 1942 and 1961. However, several assumptions in the sediment budget are subject to large uncertainty, particularly the fraction of the exported material consisting of bed/bar material. A sensitivity analysis shows that it is plausible that even the furthest downstream part of the study reach may be experiencing net storage of bed material sediment.

Several flood and erosion protection facilities (including the Mason Thorson Ells and Mason Thorson Extension Levees) presently serve to limit the amount of flow that can enter floodplain channel and swales. While hydraulic modeling shows that both of the floodplain channels of concern identified by Perkins (1996) as potentially at risk of enlargement would likely contain flow during large floods, the estimated flow velocities and shear stresses are relatively low. Coupled with the findings regarding the age of sediment collected from floodplain channels, the modeling results indicate that the risk of a major avulsion resulting in the Middle Fork occupying one of them is likely to be low. Large mid-channel bars have formed near the Mason Thorson Ells and Mason Thorson Extension levees and near the Upper and Lower Norman levees. Hydraulic model results of WSE (2013) show that the backwater created upstream from flood protection facilities reduces flow velocities and could partly explain the sedimentation in these areas. In addition, particularly for the Norman Levee, this may be associated with the reduction in lateral channel movement caused by the bank armoring. Prevention of lateral movement at this location, which is near the point where channel slope drops and the channel historically transitioned to a meandering river planform, probably reduces the rate at which coarse bed material sediment is transferred to the floodplain. This could be exacerbating the natural accumulation of bed material at this location. Further downstream, the Middle Fork Bridge prevents the channel from accessing part of the historic meandering floodplain. However, because the channel experiences active lateral migration further downstream, the effect of the bridge is probably limited to the straight reach immediately downstream of the bridge.

Geomorphic processes in the study area influence both ecological resources and hydraulic characteristics of the study reach. A full characterization of the relationship between these is provided in two companion reports to this study, WSE (2013) and Herrera (2013).

INTRODUCTION

This report presents a description of the geomorphic processes that have influenced and continue to influence the evolution of the Middle Fork Snoqualmie River from the confluence of the three river forks upstream to the community of Tanner, Washington. The geomorphic characterization is part of a larger work plan that incorporates hydraulic, geomorphic, and ecological assessments into a comprehensive flood and erosion hazard management strategy for this river reach. This report provides a general overview of relevant processes and geomorphic history at the watershed scale and then focuses on geomorphic processes occurring within the study reach itself.

The material presented here draws upon several previous studies that have been performed for the Middle Fork Snoqualmie River watershed or the Three Forks area. These include a watershed-wide assessment report prepared by the US Forest Service (Mount Baker Snoqualmie National Forest 1998) and a King County study focused on watershed-wide geomorphic processes (Bethel 2004). The characterization of river channel behavior also relies on a set of King County-sponsored studies of channel position within and adjacent to the study reach (Perkins 1996; Tetra Tech 2011). New analysis of reach-scale geomorphic activity is presented, augmenting, where relevant, the channel shifting analysis documented by Perkins (1996) and presenting the results at a finer scale and in a manner that allows direct comparison with channel change that occurred after 1996. In order to improve the understanding of the geomorphic history of the study area, 11 floodplain sediment samples were collected as part of the study and dated using radiometric techniques. The dates help in estimating the age of floodplain deposits between the Middle and South Forks of the Snoqualmie River. This report also presents a sediment budget for the study reach that is based on published observations of sediment load as well as on channel cross section surveys performed in 1993 and 2010 and lidar surveys from 2002 and 2010.

This report describes the relationship between past and existing geomorphic processes, the risk to human development represented by ongoing geomorphic trends, and the role that existing infrastructure has played in the natural progression of these processes. The discussion often refers to flood-protection facilities, other infrastructure, and major transitions in geomorphic processes using an along-channel coordinate system. The standard King County Middle Fork Snoqualmie River Mile reference system has been selected for this purpose. This coordinate system is based on the 1993 channel centerline and progresses upstream from an origin at the position of the 1993 confluence of the Middle and North Forks of the Snoqualmie River. A coordinate system with its origin located in the middle of the study area necessarily results in channel coordinates that are below zero for part of the study reach. Negative river mile (RM) coordinates in this study are thus used to represent the small portion of the study area that is located downstream of the confluence with the North Fork.

GEOGRAPHIC SETTING AND GEOLOGIC HISTORY OF THE WATERSHED

The Middle Fork Snoqualmie River has its headwaters in the central Cascade Mountains of Washington State, roughly 50 miles east of Seattle (Figure 1). Precipitation rates in the watershed are high, particularly near the crest of the Cascade Range where precipitation can be over 160 inches per year. Elevations within the watershed range from roughly 400 feet at the confluence with the South Fork Snoqualmie River to 7,492 feet at Mount Hinman. Land use within the watershed is primarily forest, with approximately 80 percent of the area administered by the US Forest Service.

Figure 2 illustrates the geology of the watershed. At higher elevations and to the east, the Middle Fork watershed is dominated by hard, intrusive igneous bedrock. The granitic rocks of this region are generally relatively resistant to erosion. Further west and lower in the watershed, the bedrock geology also includes sedimentary and metamorphic deposits, many of which are more easily eroded than the igneous rocks near the Cascade crest. This region, known as the western mélange belt, extends all the way to Mount Si, immediately adjacent to the study reach. Mount Si itself is composed primarily of erosion-resistant metamorphosed gabbro and volcanic rocks.

The river and tributary creek valleys within the watershed are mantled by extensive deposits of glacially derived material and post-glacial alluvium. Most of this material was deposited during and after the most recent Pleistocene glaciation. During the Pleistocene, both local alpine glaciers and continental ice sheets advanced into various parts of the Middle Fork valley. The advances were not synchronous, with alpine glaciers having retreated far up the Middle Fork valley prior to the most recent advance of the Puget lobe of the Cordilleran ice sheet. Alpine glacial deposits occur primarily in the upper sections of the river valleys in the watershed.

Continental glaciation reached its maximum in the Puget Sound area approximately 17,000 years ago (Porter and Swanson 1998). At its maximum extent, the continental ice blocked the valley of the Middle Fork, causing the formation of a pro-glacial lake extending upstream through much of the valley. Similar ice dams occurred in other alpine valleys in the Cascade Range north of the Middle Fork, generally resulting in focused sedimentation near the edge of the ice sheet (Booth 1986). During the period of glacial maximum and as ice began to recede, meltout from the bottom of floating ice near the grounding line (the point where ice begins to float on the impounded water) and eventually outwash supplied by the melting glacier created large embankments that choked the lower end of the Middle Fork valley. This area is represented in Figure 2 as the large area of continental glacial outwash between RM 5 and RM 12. Grouse Ridge and the large terrace on the north side of the valley that is referred to as the Middle Fork Embankment represent the remnants of this feature. Similar delta moraines, with essentially the same top elevation, are present along the mouths of the glacial South Fork Snoqualmie River and the Cedar River (Mackin 1941; Booth 1986). These features are easily identified on a regional digital elevation model (DEM), as shown in Figure 3. The material in the embankments is characterized by relatively high permeability and represents an important recharge zone for the Middle Fork Snoqualmie aquifer (Golder Associates 2007). Fine-grained silt and clay-rich material was deposited on the lake bed upstream of the embankment. Such deposits are presently exposed in river banks at many places along the Middle Fork upstream of Tanner.

Erosion that occurred during the subsequent ice retreat, which extended over a period of several hundred years (Porter and Swanson 1998), resulted in the creation of terraces that are still present on the west face of the Middle Fork Embankment. Outwash from the receding ice sheet was deposited during this time in the lower Middle Fork valley area, possibly in a muted, fan-shaped outwash surface referred to by Mackin (1941) as the Sallal moraine. This feature is located within the area of Sallal Prairie, downstream of the large embankment moraines and immediately upstream of the study area.

A large pro-glacial lake at the edge of the ice sheet known as glacial Lake Snoqualmie (Mackin 1941) played a major role in controlling geomorphic evolution of the Snoqualmie River valley during deglaciation. As the ice sheet retreated, meltwater gained access to outlet valleys with increasingly lower elevation. When such a pathway opened, water levels in glacial Lake Snoqualmie would have dropped rapidly and then stabilized at the level of the newly-open outlet. While subsequent erosion at the newly open outlet may have caused modest adjustments in lake level, lake elevation would have remained relatively constant until a new spillway opened. The primary spillways that controlled lake level when it inundated the Middle Fork valley are the Cedar spillway, presently at elevation 920 feet, and the Raging River spillway, presently at elevation 520 feet. Differential vertical uplift occurred after the ice sheet melted, with the highest rates of uplift occurring where the ice sheet was thickest. Because of differential uplift, the elevations at these spillways are probably 10 to 20 feet above corresponding historic lake shoreline elevations in the study area. This is based on an assumed differential uplift rate of 4.8 feet per mile (0.9 meters per kilometer) along a northward-oriented line, as proposed by Thorson (1979).

As deglaciation progressed and lake level fell, the Middle Fork was able to incise into the embankment blocking its valley. This erosion probably provided much of the material that formed the Sallal Prairie and other alluvial surfaces seen within the study area today. Subsequent erosion most likely associated with the opening of the Raging River spillway caused incision through the Sallal Prairie surface, leaving behind a set of terraces between the embankment and the upper end of the study area. Some of these terraces preserve relict channels with geometries that are similar to the existing Middle Fork channel. Downstream from Sallal Prairie, at the head of the study reach, the Middle Fork passes across a radially symmetric alluvial fan surface with elevations ranging from approximately 450 to 520 feet. The alluvial fan runs from approximately the upstream end of the study reach to a point roughly 1.2 miles upstream of the confluence with the North Fork. The age of this alluvial fan is not well documented in the literature, but its elevation implies that it formed after the abandonment of the Raging River spillway, when glacial Lake Snoqualmie would have dropped to below the crest elevation of Snoqualmie Falls (now approximately 400 feet above sea level) and the falls themselves began to control the upstream water level.

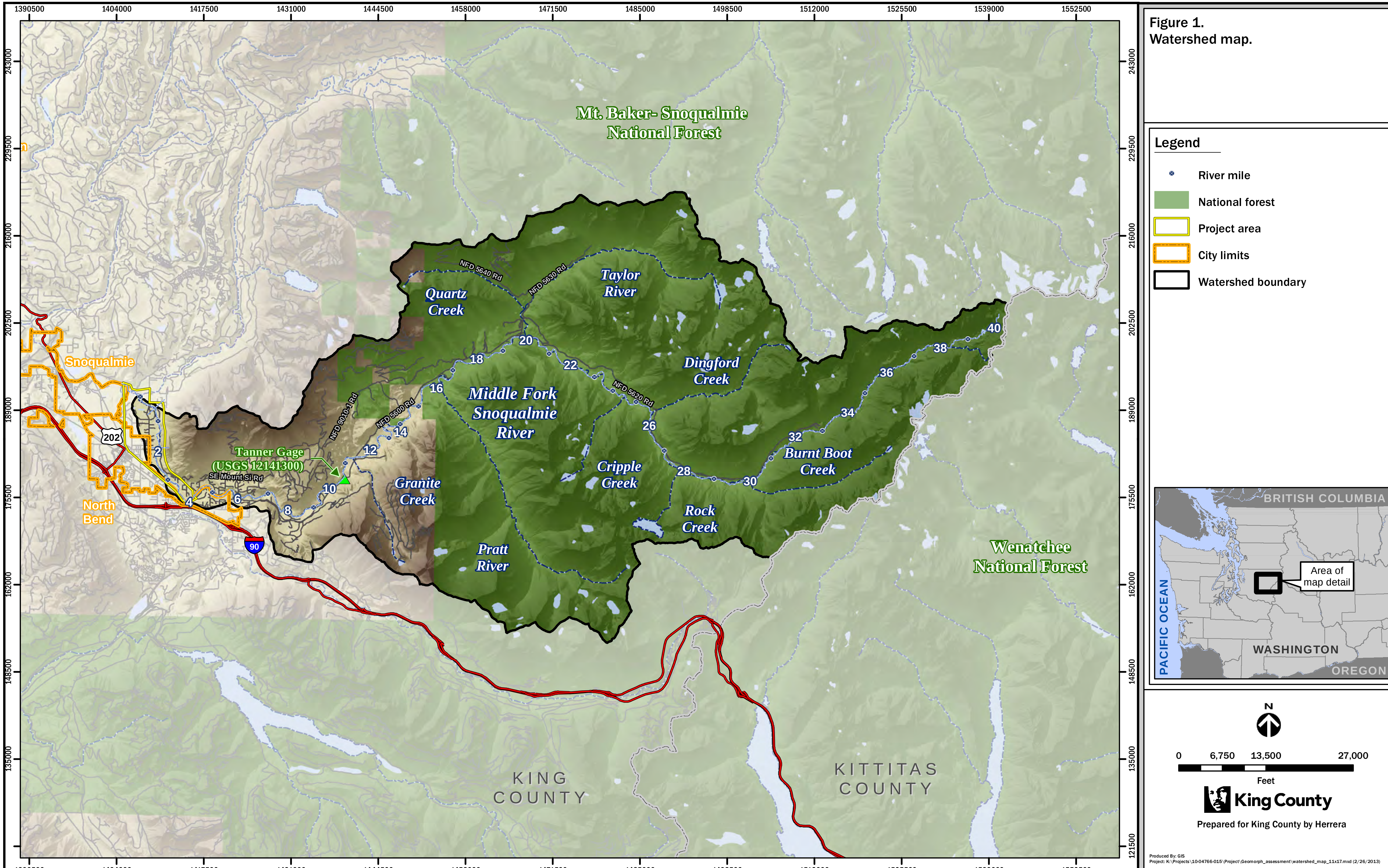
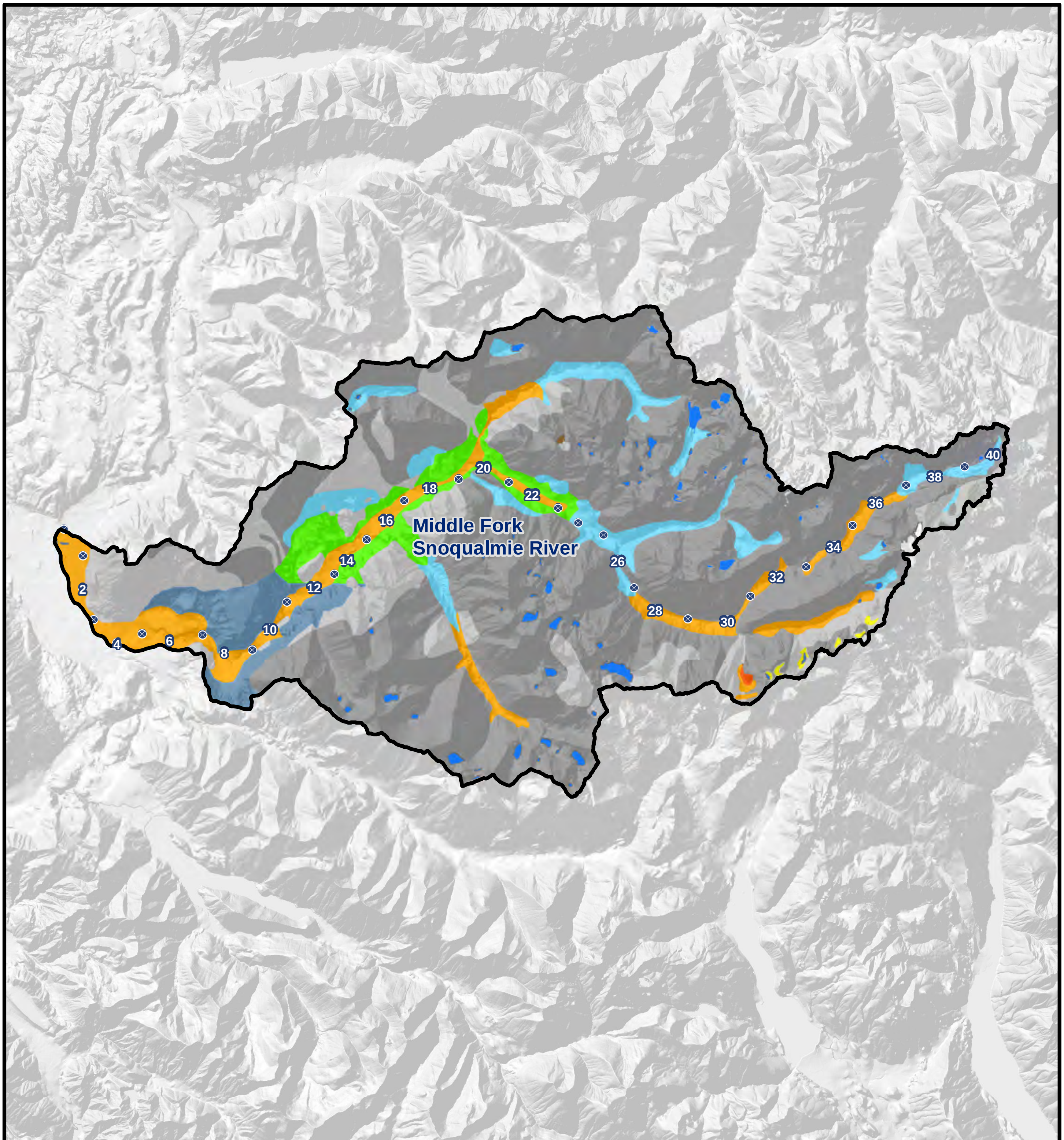


Figure 1.
Watershed map.



Bedrock or Deposit Type

- Metamorphic or Sedimentary Rock
- Igneous Rock
- Alpine Glacial Deposit
- Continental Glacial Outwash
- Glacial Lake Deposit
- Alluvium
- Tallus
- Landslide
- Water

Figure 2. Simplified Watershed Geology.

N

0 10,000 20,000 40,000

Feet

King County

Prepared for King County by Herrera

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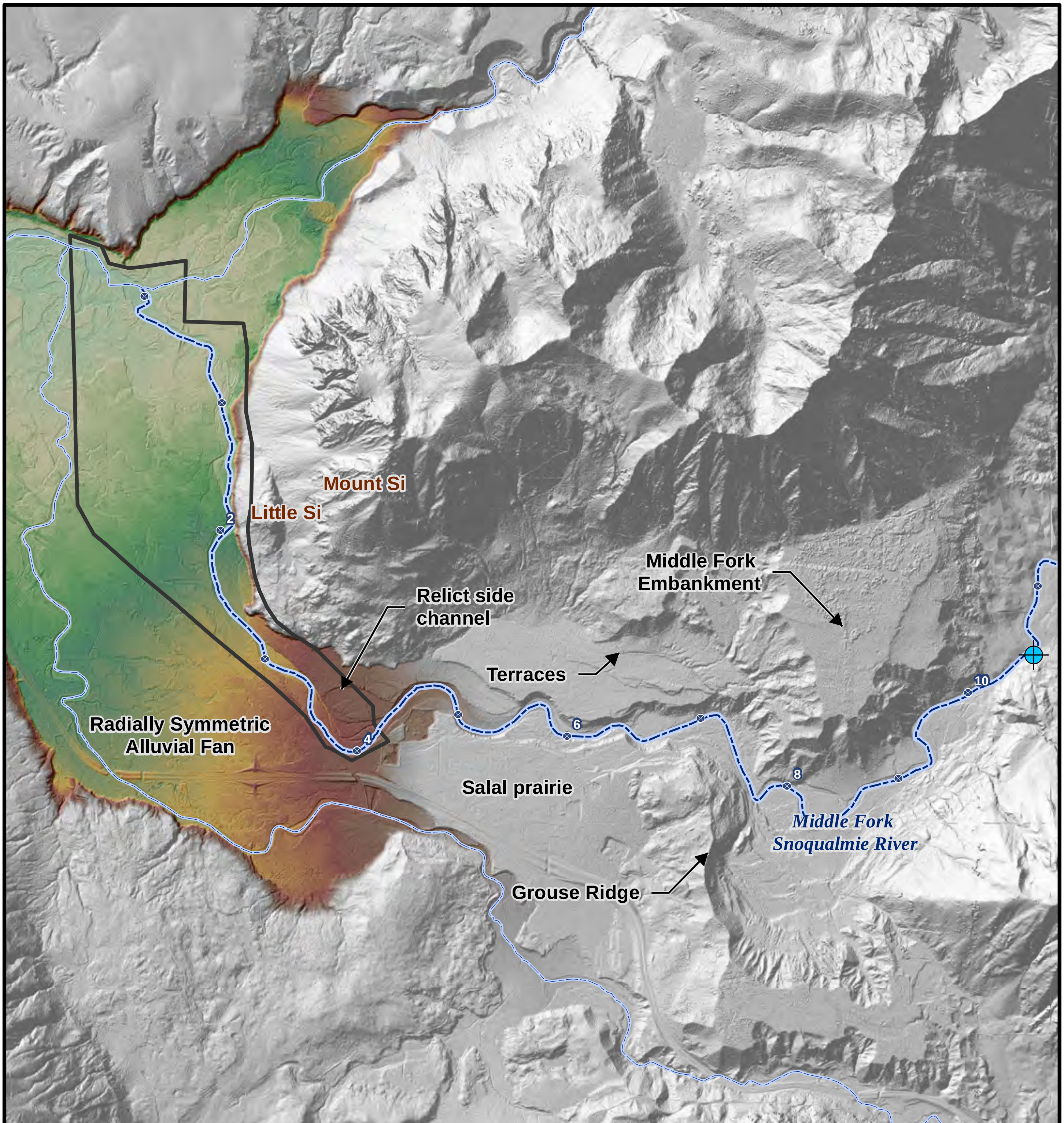

Legend

Tanner stream gage

River mile

River

Project area

Elevation (ft)

High : 600

Low : 400

Figure 3. Regional DEM.

N

0 2,500 5,000 10,000

Feet

King County

Prepared for King County by Herrera

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Golder Associates (2007) present a stratigraphic cross section of the Middle Fork valley between the confluence of the forks and the Middle Fork Embankment that characterizes the thickness of post-glacial deposits. The section (presented as Figure 3-2 in the Golder Associates report) begins near the lower end of the study reach, at a well drilled near RM 0.5 into silty and sandy material that is interpreted as recessional glacial outwash (see discussion below). Upstream, on the alluvial fan, the Golder Associates well logs show sand and gravel deposits that extend to depths that are on the order of 100 to 200 feet below the existing ground surface. Sand tends to underlie these relatively coarse sedimentary deposits. Further upstream, between Sallal Prairie and the Middle Fork Embankment, the Golder Associates section shows glacial till and advance outwash deposits underlying recessional outwash at depths of around 100 feet. Because much of the study area was historically submerged by glacial Lake Snoqualmie during glacial recession, much of the material characterized by Golder Assocates as recessional outwash was presumably deposited in deltas or on alluvial fans upstream from deltas.

The timescale for placement of sediment in the lower part of the study area is not well understood. Recent geological mapping classifies valley fill immediately above Snoqualmie Falls as alluvium that is much younger than Pleistocene in age. Dragovich et al. (2009b) report two radiocarbon dates for material sampled in the middle of the valley downstream of the confluence with the South Fork. Sample B289B, taken from a borehole located roughly 2,800 feet southeast of Snoqualmie Falls at a depth of 25 feet (elevation 392 feet), only a few feet below the crest elevation of the falls, was dated using radiocarbon techniques to 3,040 +- 80 years old. Another deeper sample, W80, was collected from a borehole near the south bank of the Snoqualmie River due south of Borst Lake at a depth of approximately 118 feet (elevation approximately 320 feet). Radiocarbon dating of this sample indicated an age of 5,720 years (with no precision given by Dragovich et al. [2009b]). The higher elevation sample probably represents alluvium that was reworked by the river through natural meander migration processes, supporting the idea that the valley had aggraded to roughly its present configuration thousands of years ago. However, the lower elevation sample is below any plausible river channel reworking depth and is significantly below the crest elevation of the falls. If this older date is correct, it is possible that a lake immediately above Snoqualmie Falls may have persisted well into Holocene time. The downstream-most well log presented in the Golder Associates (2007) transect, located near the confluence of the Middle and North Forks near RM 0, shows an upward-coarsening sequence of silt and sand that extends from the base of the borehole at elevation 158 feet upward to elevation 388 feet. This deposit is capped by a 5-foot-thick layer of silty clay and then by 23 feet of sand and gravel. This well log is broadly consistent with the hypothesis that a delta prograded through the lower part of the study area into a lake, the surface elevation of which was controlled by Snoqualmie Falls. This must have occurred at some time after deglaciation, but it is not clear precisely when.

In any case, of the five well logs presented in the Golder Associates stratigraphic section, none show anything looking like a buried soil horizon similar to the surface soils present in the study area today (although vegetation fragments are reported at depths of several hundred feet in one well log, presumably representing lake bed or pre-Vashon alluvial deposits). While soil horizons are not always recorded in well logs, their absence is consistent with the hypothesis that the valley fill developed rather quickly at the end of the Pleistocene and that the valley floor has not aggraded vertically by more than a few feet during most of the Holocene.

Possible Tectonic Control at Snoqualmie Falls

Snoqualmie Falls represents a long-term control on the elevation profile of the Middle Fork Snoqualmie River. Relatively low channel gradients upstream of the falls and downstream of the majority of the study reach presently act to trap much of the bed material that is transported through the study reach (Booth et al. 1991). The mechanism behind the presence of this low slope reach has not been fully explained. While the common explanation for the storage of sediment above the falls is the continued evolution of the system in response to deglaciation, it is also possible that the elevation of the falls themselves may change vertically because of tectonic movement in the Rattlesnake Mountain Fault Zone (Dragovich et al. 2009a). Additional geophysical exploration is required to fully evaluate this possibility.

Effect of Glacial Deposits on River Profile

In general, rivers draining to the Puget Sound remain strongly influenced by glacial history and are still responding to the slopes and valley widths that were formed by glacial processes (Collins and Montgomery 2011). Discontinuities in channel profiles often mean that near-channel sediment sources (e.g., bank erosion, mass wasting from near-channel deposits) can dominate the sediment load within a given channel reach, particularly for coarser bed material sediment (Church and Slaymaker 1989). Collins and Montgomery (2011) make a distinction between rivers that occupy valleys incised into glacial sediments after glaciation ended ("post-glacial valleys") and rivers that occupy valleys that were carved by sub-glacial flow and have since filled with alluvium ("glacial valleys"). In general, rivers in glacial valleys have lower slopes and higher sinuosities than rivers in post-glacial valleys. In addition, rivers in glacial valleys are usually characterized by a single thread meandering planform geometry, while rivers in post-glacial valleys or those crossing alluvial fans that have been built into glacial valleys are more likely to be characterized by a wandering or anabranching planform geometry associated with multiple flow pathways around vegetated bars or islands. The study area is located at the transition between these two valley types, with the upstream end incised into the lower parts of the Sallal Prairie outwash/alluvial fan deposit and the downstream end underlain by sediments most likely deposited in a lake that had an outlet controlled by Snoqualmie Falls. While the entire study reach is in some senses transitional, the most distinct change occurs near RM 1.0, within the reach that Perkins (1996) and Tetra Tech (2011) call the Middle Fork 1 (MF1) reach. Below this transition, the channel historically migrated across an alluvial floodplain containing numerous abandoned meander loops. Upstream of this transition, the channel slope is much higher and the river contains several island bars that split the channel into multiple threads. Because the transition is relatively distinct, the MF1 reach is split in this report into a section downstream of the transition (MF1a) and a section upstream of the transition (MF1b).

Figure 4 shows the longitudinal profile of the Middle Fork from the Three Forks Area upstream to Burnt Boot Creek, near RM 30. The profile clearly retains the imprint of glaciation. Glacial features include hanging tributary valleys (the Middle Fork itself may cross a glacially—carved break in slope above Dingford Creek),as well as a steep section in the lower reach between RM 6 and RM 10, where the channel cuts through the delta moraine deposits of the Middle Fork Embankment and Grouse Ridge. The anomalously steep zone extends downstream through the dissected terraces of the Sallal Prairie area and into the upstream end of the study reach. Above the Middle Fork Embankment, the slope is far lower, with a very flat region between the upper limit of the moraine/embankment and the Pratt River confluence. Several abandoned meander loops are present on the floodplain in this area. Because the embankment and terraces buffer the river from sediment supplied from the valley walls for much of its length upstream of the moraine, a significant fraction of any coarse sediment mobilized from the valley walls is likely to be retained on hillslopes or in the upper Middle Fork valley. Therefore, the supply of coarse gravel and cobble to the river channel in the study reach is probably primarily associated with mobilization of material from slopes that are adjacent to the channel downstream of about RM 10.

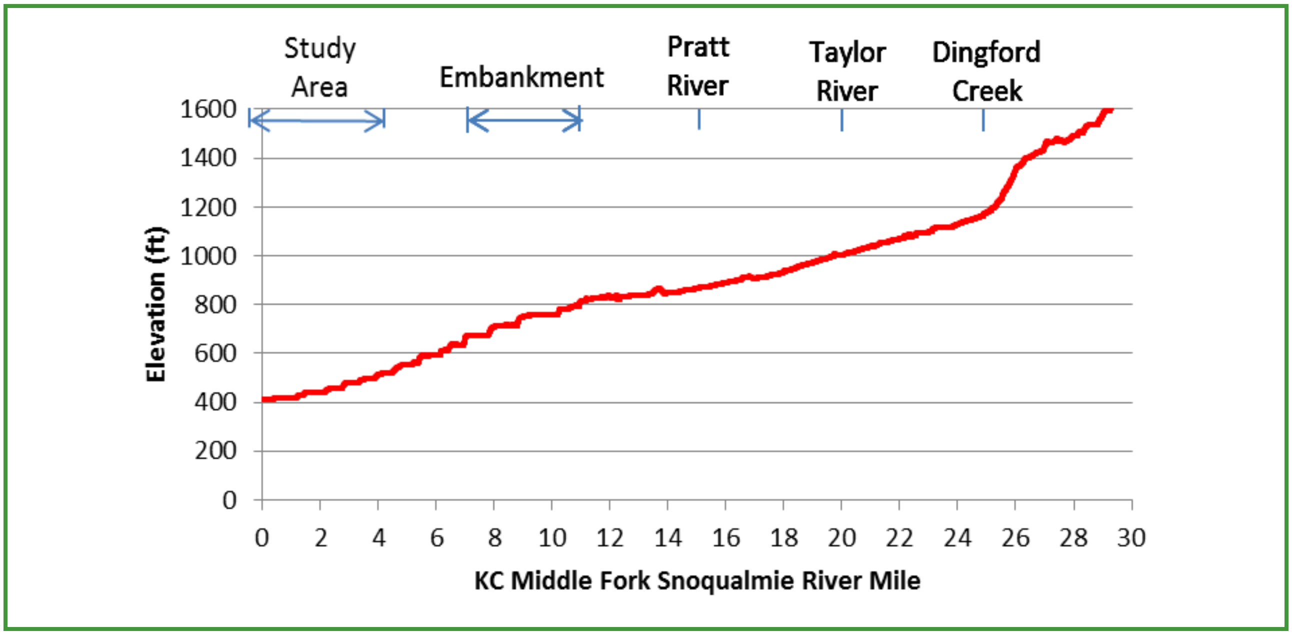


Figure 4. Longitudinal Profile of Middle Fork Snoqualmie River.

Field Observations of the Role of Pleistocene Deposits

Over the course of the present study, glacially-derived material was observed at several locations in the study reach. Material with glacial or early post-glacial origin was most commonly observed upstream of approximately RM 2. Some of the most obvious relict sedimentary features observed in the field are shown in Figure 5.

Figure 5 panel A shows large boulders present in the bed of the Middle Fork near Tanner, at RM 4.3. While some granite bedrock is present in the Middle Fork watershed, it does not predominate, so the granitic lithology of these boulders is consistent with a continental glacial source (Booth 1990). While the Middle Fork Embankment and Sallal Prairie areas are known repositories for glacially-derived material with this lithology, the marginal mobility of boulders of this size makes it unlikely that they could have been transported to the reach from these upstream repositories by the modern river. They are only marginally mobile (if at

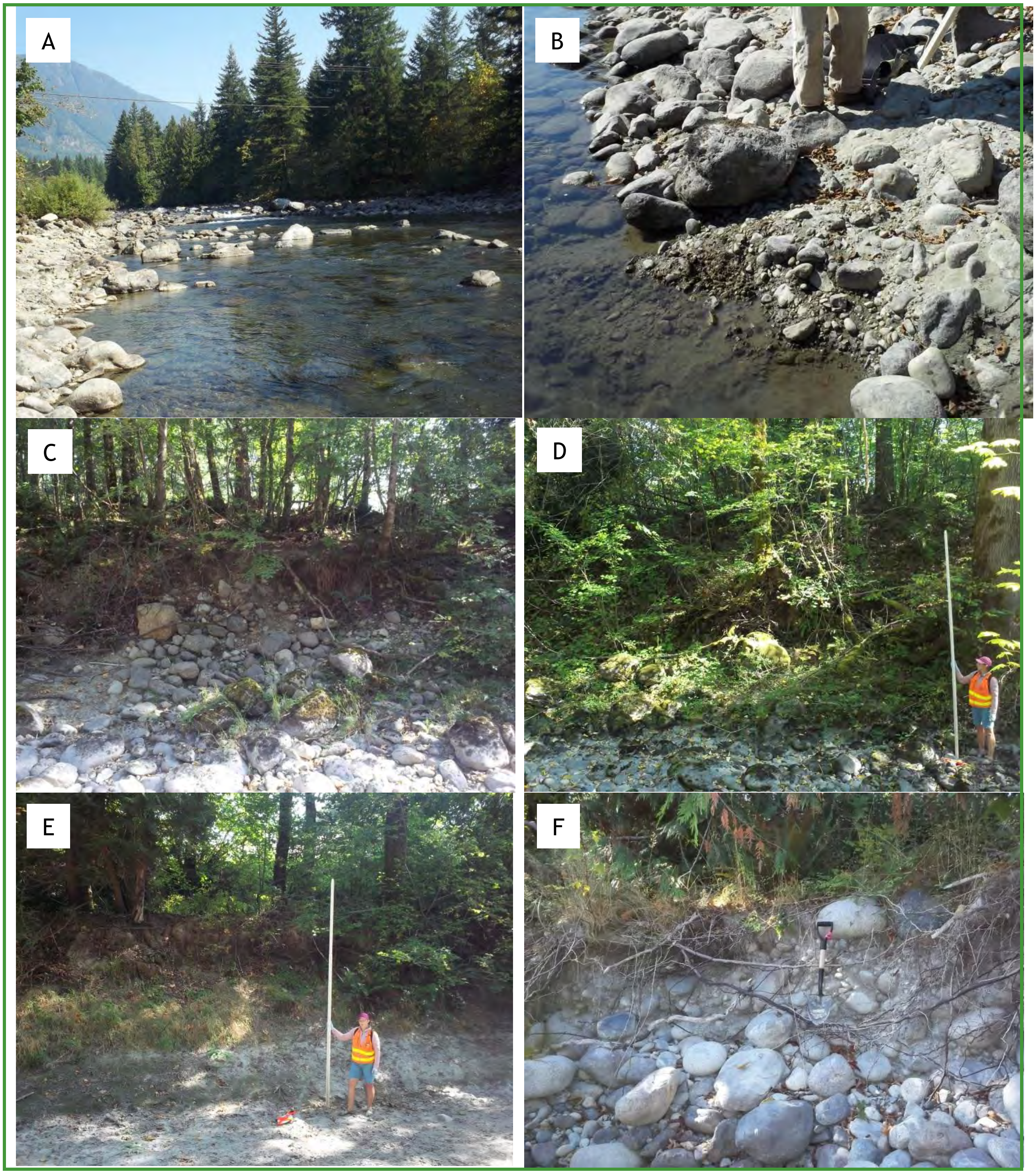


Figure 5. Relict Sedimentary Deposits in the Banks and Bed of the Middle Fork and Side Channels, Upper Study Reach.

all) even during large floods, so it is most likely that they were deposited within the study reach during or immediately after glaciation, either during the time when the Sallal Prairie alluvial fan was actively growing into glacial Lake Snoqualmie or during rapid lake drawdown associated with the abandonment of the Raging River spillway.

Figure 5 panel B shows a consolidated, erosion-resistant deposit of poorly-sorted sediment present near the toe of the right bank at RM 4.3 (see Figure 3 for regional context). The fines present in this deposit as well as the wide range of sediment sizes within it, along with its relatively low stratigraphic position beneath a Pleistocene fan, indicate that it probably formed in an extremely sediment-rich environment. It could be a glacial till or ice contact deposit that formed when the ice sheet was near its maximum extent (implying that the overlying fan subsequently formed on top of the till/ice contact surface). Alternatively, it could simply have beendeposited within the fan by a hyperconcentrated flow event during the deglacial period. In general, till and ice contact deposits are much denser than unconsolidated alluvial sedimentary deposits because they have been compressed by the weight of hundreds of feet of overlying glacial ice. In any case, the cohesion provided by the fine-grained matrix of the deposit reduces its erodibility, meaning that the deposit shown in Figure 5 panel B probably provides bank strength at this location.

Figures 5C and 5D show large boulders in the cut bank of a terrace that is located adjacent to the side channel that runs across the floodplain on river right between RM 4.2 and RM 3.4. While the presence of a relict channel at the top of this terrace (roughly at RM 3.5) implies that these boulders may have been reworked fluvially when the relict channel was active, the boulders clearly were not deposited at this elevated location by the modern river. Figure 5E shows the same bank at the point where it is bisected by the course of the relict channel. The fill within the relict channel is completely devoid of cobble and boulders. Where the modern side channel crosses this relatively fine-grained relict deposit, its bed is also free of cobble or boulders. Together, this implies that cobbles and boulders have remained immobile in the modern side channel since its formation, otherwise some would probably have come to rest at the toe of the relict channel. This also implies that the modern side channel in this area has never conveyed significant amounts of cobble as bedload, at least at the location of the photo in Figure 5E. The boulders and cobbles that are present on the bed of the modern side channel upstream and downstream of the relict channel probably represent an immobile lag deposit that consists entirely of coarse material eroded from the terrace bank or already present when the modern side channel formed through erosion of finer-grained floodplain material.

Figure 5F shows a relatively poorly sorted bank deposit on the left bank of the Middle Fork Snoqualmie River at RM 2.4, upstream of the Mason Thorson Ells Levee. In many places, this deposit contains a relatively large fraction of fine sand and silt-size material that is rather resistant to erosion when dry. The gravel and cobble in the deposit is often matrix supported, which suggests deposition in a sediment-rich fluid such as a debris flow or debris flood (not by normal riverine processes). Large cobbles and boulders are present at the top of bank in this area. While the origin of this deposit is not clear, it is located on a bank that has remained relatively stable over the photographic record (since 1942).

RECENT HISTORY OF THE WATERSHED

Table 1 presents a timeline summarizing major events that have effected geomorphic evolution of the Middle Fork Snoqualmie River. The discussion of these events is most easily organized by classifying them into categories related to a) climate and fire, b) timber and wood management, c) hydrology and geomorphology, and d) flood protection infrastructure construction and municipal history. Major datable events in each of these categories are discussed below, along with the geomorphic implications.

Climate and Fire History

Some of the earliest datable events include climatic shifts that occurred over the past millennia. During the period from 900 AD to 1,300 AD, the climate was generally warmer than during subsequent centuries and resulted in the colonization of higher-elevation areas by low-elevation forest species such as Western hemlock and Douglas fir (Mount Baker-Snoqualmie National Forest 1998). This was followed by a cooler and drier period during the little Ice Age, which lasted approximately from 1,400 AD to 1,850 AD.

Fire has played an important role in the landscape since pre-historic times. Native Americans intentionally burned large areas of the Snoqualmie Valley to maintain open areas that were used for various purposes including foraging for edible plants and grazing by elk (Hill 1970). Larger fires probably occurred periodically over much of the landscape. Large stand-replacing fires probably occurred in the 12th and 16th centuries AD across large portions of the Middle Fork watershed, and a smaller but still significant fire burned low elevation areas around the year 1,700 AD (Mount Baker-Snoqualmie National Forest 1998). Another large fire occurred in the Pratt River watershed in 1940 (Perkins 1996). Because logging also occurred in this watershed around this time, the impacts of the fire on geomorphic processes are difficult to separate from the effects of timber harvest.

Fires are known to significantly increase the down-slope transport rate of fine-grained soil particles (Jackson and Roering 2009), mainly by liberating particles previously buttressed by vegetation (Lamb 2011). Because such material is easily transported once supplied to the stream channel network through direct surface runoff or in shallow debris flows, it is likely that the initial downstream response to a large fire would be an increase in suspended sediment loads and probably in overbank sedimentation rates. Suspended sediment deposition rates have been shown to increase after fires in other parts of Western North America (Meyer and Pierce 2003; Calombaroli and Gavin 2012).

However, bed material supply could also have been affected by fire, particularly if landslide frequency increased because of the temporarily altered hydrology or through a decrease in the strength of the roots of fire-damaged plants (Jackson and Roering 2009). Root strength of near bank vegetation is particularly important with respect to bed material supply. Fires that kill banktop vegetation and thereby increase near-channel bank erosion can increase bed material supply without significantly increasing suspended sediment loads (Eaton et al. 2010). Since fire has been shown to induce landslides in steeply-sloping glaciolacustrine terraces (Sanborn et al. 2006), downstream impacts are particularly likely if the fire reduced vegetative cover on steep slopes immediately adjacent to the Middle Fork channel below the Pratt River confluence. Even fires occurring primarily at higher elevations, far from slopes that are directly connected to the lower reach of the river could have temporarily influenced the basin's hydrology and suspended sediment yield. However, because there are no data on fire-induced sedimentation in the Middle Fork Snoqualmie River watershed, the extent of the geomorphic impact of historic fires on the study area is not known.

Timber and Wood Management History

Historical timber and wood management in the Middle Fork watershed involved both forestry activities and the management of downed wood in the channel. Both types of activity probably began to have noticeable impacts in the Snoqualmie Valley in the last decades of the 19th century. Around this time and for several decades into the 20th century, the US Army Corps of Engineers (Corps) began removing snags and log jams from portions of the lower Snoqualmie River (Collins and Sheikh 2002; Collins et al. 2002). It is unknown whether these activities extended upstream of Snoqualmie Falls, though the likelihood seems low given the Corps was involved in wood removal for navigation purposes, and navigation above the falls would not have been a focus for the Corps.

In 1890, the W.C. Weeks shingle mill opened in North Bend, initiating a period when forestry played a major role in the local economy. A larger mill was constructed in 1906 by the North Bend Lumber Company along Boxley Creek, a tributary of the South Fork Snoqualmie River. At least one mill operated in North Bend into the 1980s. Photographic evidence from 1915 shows that significant forest clearing had occurred on the alluvial fan near North Bend, near the base of Mount Si. By 1929, much of the land adjacent to the Middle Fork downstream of the Middle Fork Embankment was owned by the Weyerhauser Logged Off Land Company, indicating it had been logged prior to this date.

Much of what is now Mount Baker-Snoqualmie National Forest was initially part of the Pacific Forest Reserve, which was designated in 1893 (Mount Baker-Snoqualmie National Forest 1998). While initially closed to settlement and resource use, this changed in 1897 with the creation of the Mt. Rainier Forest Reserve which allowed mining, agriculture, and timber uses. Logging within what is now the National Forest occurred first within the low elevation valleys during the 1920s and 1930s. Higher elevation tributaries were generally logged later. While logging is an ongoing activity in parts of the lower watershed, the total cleared area, particularly in the National Forest, peaked in the 1940s and has decreased since that time (Mount Baker-Snoqualmie National Forest 1998). This was partly because of the designation of approximately 46 percent of the watershed as part of the Alpine Lakes Wilderness, where logging is prohibited.

Recent Hydrologic and Geomorphic Events

Major hydrologic events in the Snoqualmie Valley are described by WSE (2013) and are included in Table 1. Major floods occurred in 1909, 1932, 1959, 1977, 1990, 2006, and 2009.

Table 1. Historic Timeline of Major Events in the Middle Fork Watershed.

Date	Climate and Fire	Timber and Wood Management	Hydrology and Geomorphology	Facility Construction and Municipal History	Source
900-1300	Medieval Climate Optimum, warmer climate. Western hemlock zone covers more of watershed to higher elevations than at present.				1
1400-1850	Little Ice Age, cooler and probably drier climate. Expansion of silver fir zone, downward movement of Douglas fir zone.				1
1308	Large fire(s) in Western Washington. Upper Middle Fork Snoqualmie River and Quartz Creek burned.				1
1508	Several fires in southern Pratt River and lower Middle Fork Snoqualmie and Quartz Creek watersheds.				1
1701	Fire in Western hemlock zone outside National Forest boundary, Middle Fork Snoqualmie watershed.				1
1887		Snag removal begins on Snoqualmie River below Snoqualmie Falls			2
~1890		W.C. Weeks shingle mill opens in North Bend			1
1893		Formation of Pacific Forest Reserve			1
1906		Construction of North Bend Lumber Company mill at Edgewick, in South Fork Snoqualmie River watershed. Mill was initially supplied with timber from near base of Mount Si.			3
1908		Large number of snags removed from Snoqualmie/Snohomish River system. Unclear whether removal occurred above Snoqualmie Falls.			2
1908		Formation of Snoqualmie National Forest			1
1909				Incorporation of Town of North Bend	3
1909				Norman Bridge built near site of existing Middle Fork Bridge	4
Nov-1909			Flood on Snoqualmie River. Ungaged on Middle Fork.		5
Apr-1915		Photographic evidence of cleared land on terrace/floodplain at base of Little Mount Si.			6
12/18/1918			Boxley Burst causes flood and sedimentation on South Fork. May have affected Middle Fork.		7, 8
1924				Norman Bridge replaced (near site of existing Middle Fork Bridge)	4
1929		Much of low elevation land adjacent to Middle Fork below Embankment is owned by Weyerhauser Logged Off Land Company, indicating it had been logged prior to 1929.			9
1930s				King County Flood Control Division in conjunction with Federal WPA, maintains staff of over 200 employees.	10
Feb-1932			Flood on Snoqualmie River. Ungaged on Middle Fork.		5
1930s and 1940s		Stand replacing logging begins inside National Forest boundary in Middle Fork watershed. Mostly consists of railroad logging of valley bottoms.			1
1940	Large fire, Pratt river drainage. Timber harvested after fire.				11
1940s		Period of maximum disturbance to canopy within National Forest in Middle Fork Snoqualmie watershed.			1
1940s and 1950s		Timber harvest in Taylor River watershed.			1
between 1942 and			Abandonment of bend above site of Middle Fork Bridge, at site of Norman Levee, RM 0.8 to RM 0.5.		12
between 1942 and 1961			Abandonment of bend below site of existing Middle Fork Bridge, ~1500 ft below confluence with North Fork. South Fork occupies part of this bend in 1961.		12
between 1942 and 1962			Major debris avalanche, Thunder Creek		1
1950				Wood truss bridge (Howe bridge) built near site of existing Middle Fork Bridge.	4
Late 1950s				King County Flood Control Division is reduced in size to 15 employees.	10
1959				River Improvement Fund (RIF) is established from Countywide levy.	10
Nov 1959 and Dec 1959			Two floods on Snoqualmie River. Ungaged on Middle Fork. Washout of 1400 feet of U.S. Highway 10 near North Bend where logjam caused South Fork to cut new channel.		5, 13
1959-1963				Middle Fork left and right bank and bridge revetments built	12
Feb-1961			USGS stream gage installed at Tanner.		14
1961-1962				Mount Si Bridge right bank revetment built.	15
1963				Mason Thorson Ells Levee built	15
1963				Mason Thorson Extension Levee built	12
1964				Mount Si Road protection revetment built.	15
1964				Mount Si Bridge built	15
1964-1965				Tanner Road Revetment installed	15
1965				Upper/Lower Norman Revetment built	15
1966				Reinig Road Revetment built	15
1969				Con Fury Revetment built	15
1969				Mason Thorson Ells Levee Extended	15
1970s		Last large-scale logging of uplands in National Forest (Taylor River)			1
1973				Duprells Revetment built	15
1976		Designation of Alpine Lakes Wilderness Area			
1977				Moskvin Revetment built	15
12/2/1977			3rd highest recorded discharge at Tanner gage, 30,200 cfs		14
1980s		Closure of last lumber mill in North Bend			1
October to November, 1987			Lowest 30-day average discharge on record for Tanner gage. Average discharge = 99.3 cfs.		14
11/24/1990			4th highest recorded discharge at Tanner gage, 30,100 cfs		14
1990s		County ends practice of burning snags. Last record of County involvement in wood burning was fall 1991 on right bank bar at RM 1.7.			15
July to September , 1998			Second lowest 30-day average discharge on record at Tanner gage. Average discharge = 129.2 cfs.		14
11/6/2006			Highest recorded discharge at Tanner gage, 31,700 cfs		14
2008				Mount Si Bridge replaced	15
1/7/2009			2nd highest recorded discharge at Tanner gage, 31,200 cfs		14
September to October, 2012			Third lowest 30-day average discharge on record at Tanner gage. Average discharge = 133.4 cfs.		14

Sources
[1] Mount Baker-Snoqualmie National Forest 1998; [2] Collins and Sheik 2002; [3] http://www.middleforkgiants.com/NBTC.html; [4] King County Department of Construction and Facilities Management 2000
[5] WSE 2013; [6] Ambrose 1915; [7] Mackin 1943; [8] Stein 2000; [9] Kroll Map Company, 1929; [10] King County Surface Water Management Division 1990; [11] Perkins 1996; [12] Air photo record;
[13] Hendricks 1964; [14] USGS Streamgage Record; [15] King County Staff

Events that occurred prior to the 1961 installation of the USGS stream gage at Tanner are inferred from records on nearby watersheds. The flood of record at the Tanner gage, 31,200 cubic feet per second (cfs), occurred on November 6, 2006. Table 1 also presents the dates of the three lowest 30-day average discharge periods in the study reach. These occurred near the end of summer in 1987, 1998, and 2012.

One of the most significant historic geomorphic events to affect the study area was the Boxley Burst, a groundwater-related outburst flood that occurred on December 18, 1918, from the base of the Cedar River Embankment (part of the same geomorphic feature as the Middle Fork Embankment but located in the valley of the Cedar River near the site of Seattle City Light's Cedar Dam). Seepage from Cedar Lake (impounded by Cedar Dam) occurred through the embankment around the time of the construction of a new spillway, causing the toe of the embankment to fail catastrophically and releasing a flood wave estimated at between 3,000 and 20,000 cfs. The flood wave mobilized 800,000 to 2,000,000 cubic yards of sediment from the site of the failure (Mackin 1943). The ensuing flood in Boxley Creek caused significant damage to the North Bend Timber Company's mill and the town of Edgewick. Flood water then entered the South Fork Snoqualmie River upstream of Tanner. The course of the flood wave is still visible 24 years later in 1942 aerial imagery, which shows large areas of exposed gravel along the South Fork downstream of the Boxley Creek confluence. The extent to which the Middle Fork was affected by the flood is not known.

Other documented geomorphic events include a major debris avalanche along Thunder Creek that occurred sometime between 1942 and 1962 (Mount Baker-Snoqualmie National Forest, 1998) and erosion of over 1,400 feet of US Highway 10 along the South Fork Snoqualmie River during the November 1959 flood event (USGS 1959). Several large meander bend cutoffs occurred in the lower part of the study area between 1942 and 1962. The implications of the meander cutoff events are discussed later in this report.

Flood Protection Infrastructure Construction and Municipal History

The town of North Bend was incorporated in 1909, about the time that the Norman Bridge was built near the site of the existing Middle Fork Bridge in the lower end of the study reach. This bridge has been replaced several times. Since the 1930s, King County has taken an active role in flood control and floodplain management along its major rivers. Major flooding in 1959 spurred the County to establish the River Improvement Fund that provided funding for design and construction of many new County levees and revetments. Planning efforts in the 1960s, including the King County Comprehensive Flood Control Plan, emphasized structural solutions to flooding issues. Most of the flood protection facilities along the Middle Fork Snoqualmie River originated in the 1960s. Over the next two decades, several severe floods caused extensive damages coincident with passage of Federal and State environmental legislation, including the State Shoreline Act of 1971, the National Flood Insurance Act of 1968, and the National Environmental Policy Act of 1969. The County adopted policies to comprehensively address flooding in the 1993 King County Flood Hazard Reduction Plan and subsequent 2006 King County Flood Hazard Management Plan (FHMP). In 2007, the King County Flood Control District was established to fund improvements to the County's flood protection facilities and to implement the 10-year action plan outlined in the 2006 FHMP. As of this writing, the 2006

FHMP was being updated to reflect new information on hazards, vulnerabilities, accomplishments, and proposed actions, and to introduce new policy issues that have emerged since it was adopted in 2007.

The dates of construction for each major flood protection facility in the study reach are provided in Table 1. A full description of each facility along with discussion of the associated geomorphic implications is provided later in this report.

Geomorphic Implications of Recent Watershed-scale History

While most of the Middle Fork watershed is presently managed by the US Forest Service, approximately 20 percent of the watershed is held privately or by State or local agencies (Mount Baker Snoqualmie National Forest 1998). Much of the State and private land continues to be managed for timber production. In general, logging is usually associated with an increase in sediment yield, particularly when done in areas with high relief (Croke and Hairsine 2006). The increase occurs for several reasons that may include altered runoff patterns or snowmelt dynamics (Jones and Grant 1998; Grant et al. 2008), or logging-induced changes to the stability of hillslopes. Particularly on steep slopes, logging can induce landslides by decreasing root strength and effective soil cohesion. This effect becomes most pronounced several years after logging and can last for several decades (Dragovich et al. 1993; Schmidt et al. 2001; Roering et al. 2003). Clearcut slopes consequently experience higher rates of mass wasting than unlogged sites (Swanson and Dyrness 1975; Pentec Environmental 1991; Montgomery et al. 2000; Imaizumi et al. 2008), particularly during large storms (Turner et al. 2010).

Forest roads play a major role in altered hydrology and initiation of landslides (Montgomery 1994), since road cuts often capture and channelize subsurface flow and the compacted roadways themselves are usually characterized by infiltration rates that are low relative to the forest floor. Local mass wasting at culvert crossings and elsewhere along the road network can also play an important role in sediment supply. Perhaps because of road-induced failures, forest harvest can result in pulses of sediment that are much larger than those associated with large stand-replacing fires (Colombaroli and Gavin 2012). However, the magnitude of logging-induced sediment production with respect to the downstream river system depends very strongly on the hydrologic connectivity within the watershed. In areas where increased runoff or landslides produced by a cleared forest have a direct pathway to the watershed's channel network, sediment production is likely to be strongly influenced by logging, particularly if the concentrated flow leads to mass wasting in ravines or on destabilized slopes. However, in areas where surface runoff has no connection to an open channel and is likely to infiltrate, the impacts are far lower, even if mass wasting occurs upstream (Croke and Hairsine 2006).

Modern forestry has probably influenced Middle Fork watershed hydrology to some extent. Several hydrologic modeling studies have shown increases of 10 to 30 percent in overall flood flow rates at the basin outlet for simulated clearing of all forest vegetation from the entire Snoqualmie basin (Storck et al. 1995) or the North Fork Snoqualmie River basin (Storck et al. 1998). While these simulations did not account for the hydrologic effect of the associated logging road network, which can be significant in other settings (Storck et al. 1998), the forest roads in the Middle Fork watershed are concentrated near the watershed outlet, as shown in Figure 1. This may have increased surface runoff production on slopes in the lower watershed. However, many of the slopes in this area run out onto the flat and highly permeable surface of the delta moraine and/or high terraces described previously. These flat areas adjacent to the channel buffer the channel from the hillslope drainage. This is illustrated in a satellite image of a recent mass wasting event that occurred between 2006 and 2009 (Figure 6). This mass wasting event, one of the largest prominent landslides visible in any of the recent aerial imagery of the lower Middle Fork watershed, apparently began at an abandoned road cut. However, the debris produced by the failure ran out across the flat, highly permeable surface of the Middle Fork Embankment and is unlikely to have entered the channel network.

It is difficult to say precisely how closely logging in the upper watershed has been related to sediment supply to the study reach. On the one hand, logging certainly occurred in the basin and would have increased sediment yield. Historical aerial imagery from 1942 shows particularly large impacts in the Pratt River watershed which experienced a large fire in 1940 (Perkins 1996) and was also logged around this time. By 1942, many debris flow channels connected directly to the Pratt River. Earlier logging of the riparian corridor may have directly destabilized streambanks. On the other hand, while erosion may have been extensive in places, the relatively large terraces and relatively low channel slopes upstream of the Middle Fork Embankment probably mean that bed material mobilized from the upper watershed would not have entered the study reach for many years. The main channel of the Pratt River is presently much wider and more braided than it was in the 1942 imagery, presumably due to the legacy of the sediment produced by the fire and logging. In addition, the fact that much of the logging that occurred along the Middle Fork was focused on the valley bottom and did not result in major road construction also implies that the effects of historic logging on basin-wide sediment supply may have been relatively small, at least within the study area.

The most likely location for a direct connection between a mass wasting event and the river channel is along the slopes of the Middle Fork Embankment itself, immediately adjacent to the channel. Both the north and south banks of the Middle Fork channel abut steep slopes in the reach between approximately RM 6 and RM 8. Slopes are especially steep on the north side of the channel, where topographic mapping presented in Figure 3 indicates that the slopes are cut by several ravines. Forest management activities that result in the mobilization of gravel and cobbles within this area are much more likely to have influenced river bed material sediment loads in the study reach than similar activities elsewhere in the watershed. Historical aerial imagery shows that some of these slopes were probably cleared prior to 1942. However, active slides are not common in the 1942 imagery in these areas or on the steep slopes east of Mount Si.

Historical logging and stream management activity has certainly affected in-channel recruitment of large wood. Logging activities in low elevation valleys often extended right up to the edge of the channel. As of 1998, 14 percent of stream miles within the watershed passed through forest classified as being at the sapling/pole stage of regeneration (diameter at breast height [dbh] less than 9 inches), and another 17 percent of stream miles passed through forest classified as immature (Mount Baker Snoqualmie National Forest1998). These areas are unlikely to provide large, geomorphically important large woody debris to the lower

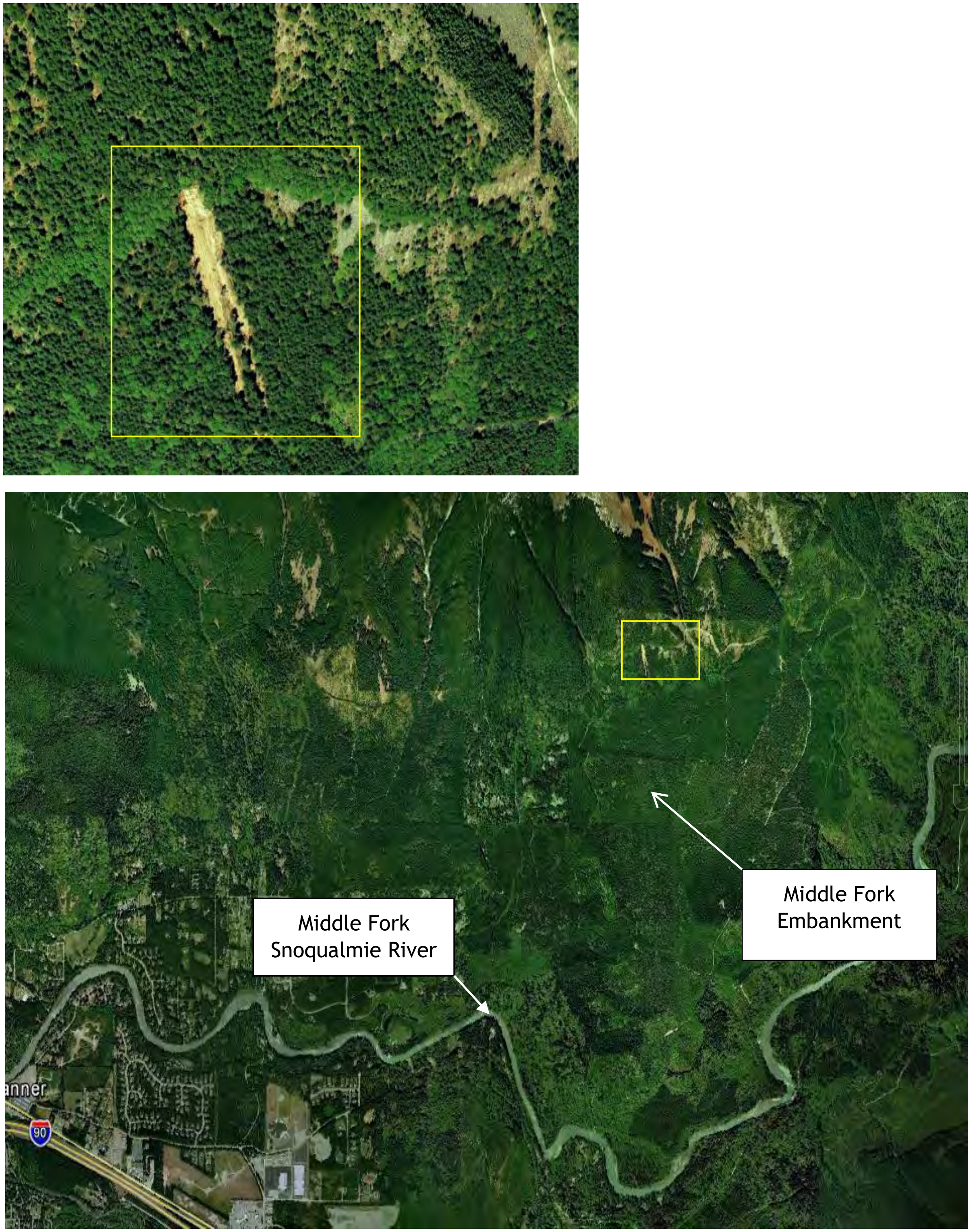


Figure 6. Mass Wasting Near Middle Fork Embankment.

river. Removal of in-channel wood was also commonly associated with logging and related land management during the early and middle parts of the 20th century and probably occurred within the Middle Fork watershed. These actions probably led to increased sediment mobility and reduced in-channel sediment storage capacity relative to pre-logging conditions, although the extent of these consequences is unclear because the aerial photograph record does not allow for direct evaluation of changes in wood density prior to the 1940s. Because wood removal tends to decrease overall channel roughness and increase flow velocities and sediment transport rates, modest channel incision and/or bed coarsening may have occurred in the reaches in which wood was removed. Sediment mobilized by wood removal would presumably have increased sediment supply to downstream reaches.

Landsliding

The Washington Department of Natural Resources (DNR) has mapped landslide hazard areas for a portion of the Middle Fork watershed, mainly downstream of the National Forest boundary (Washington Department of National Resources 2012). With the exception of a single deep-seated landslide on the lower slopes of Mount Si near RM 4, the predominant type of mass wasting hazard in the DNR inventory for the Middle Fork watershed is debris flows. In general, source areas for debris flows are mapped on steep upper slopes on both sides of the Middle Fork valley where they typically originate in bedrock hollows at the tip of the channel network. Debris flows and the channels that they carve can be an important source of both fine-grained suspended sediment and, where directly connected to higher order streams, of bed material sediment. For the most part, the mapped debris flows in the DNR inventory run out onto relatively low-gradient terraces adjacent to Sallal Prairie or the Middle Fork Embankment. Only in Granite Creek and a few localized areas on the face of the Middle Fork Embankment does the DNR mapping show a debris flow hazard that connects directly with the Middle Fork. However, the DNR mapping does not appear to characterize the entire watershed. For instance, recent aerial photography shows several debris flow tracks and large near-channel slumps in the Pratt River basin that obviously supply sediment to the main channel network.

The most comprehensive study of landslide risk covering the entire Middle Fork watershed is the analysis performed by the Mount Baker-Snoqualmie National Forest (1998). This analysis is based on a simple classification system to qualitatively identify zones of decreased slope stability across the entire watershed. Results show the highest risk on the north side of the Middle Fork valley upstream of Tanner, near the position of the Middle Fork Embankment. This region coincides with many of the debris flow channels mapped by DNR, and indeed, some slides are evident in this area on aerial imagery. However, above the Embankment, the channel is not adjacent to the north side of the valley wall for a significant fraction of this reach. The Mount Baker-Snoqualmie National Forest (1998) study also documents a large slump of glacially-derived clay adjacent to the Pratt River approximately 0.5 miles above the confluence with the Middle Fork that causes a noticeable increase in turbidity. The report also discusses a major debris avalanche that occurred on Thunder Creek (near RM 28) between 1942 and 1962. This event introduced a large amount of sediment into a portion of the upper Middle Fork that experienced observable channel widening after the event. However, it is not clear whether the avalanche, floodplain logging, or subsequent large floods were responsible for the observed channel change. In any case, any coarse material that enters the Middle Fork upstream of the Embankment may not be easily conveyed through the low gradient part of the elevation profile of the Middle Fork above the Embankment.

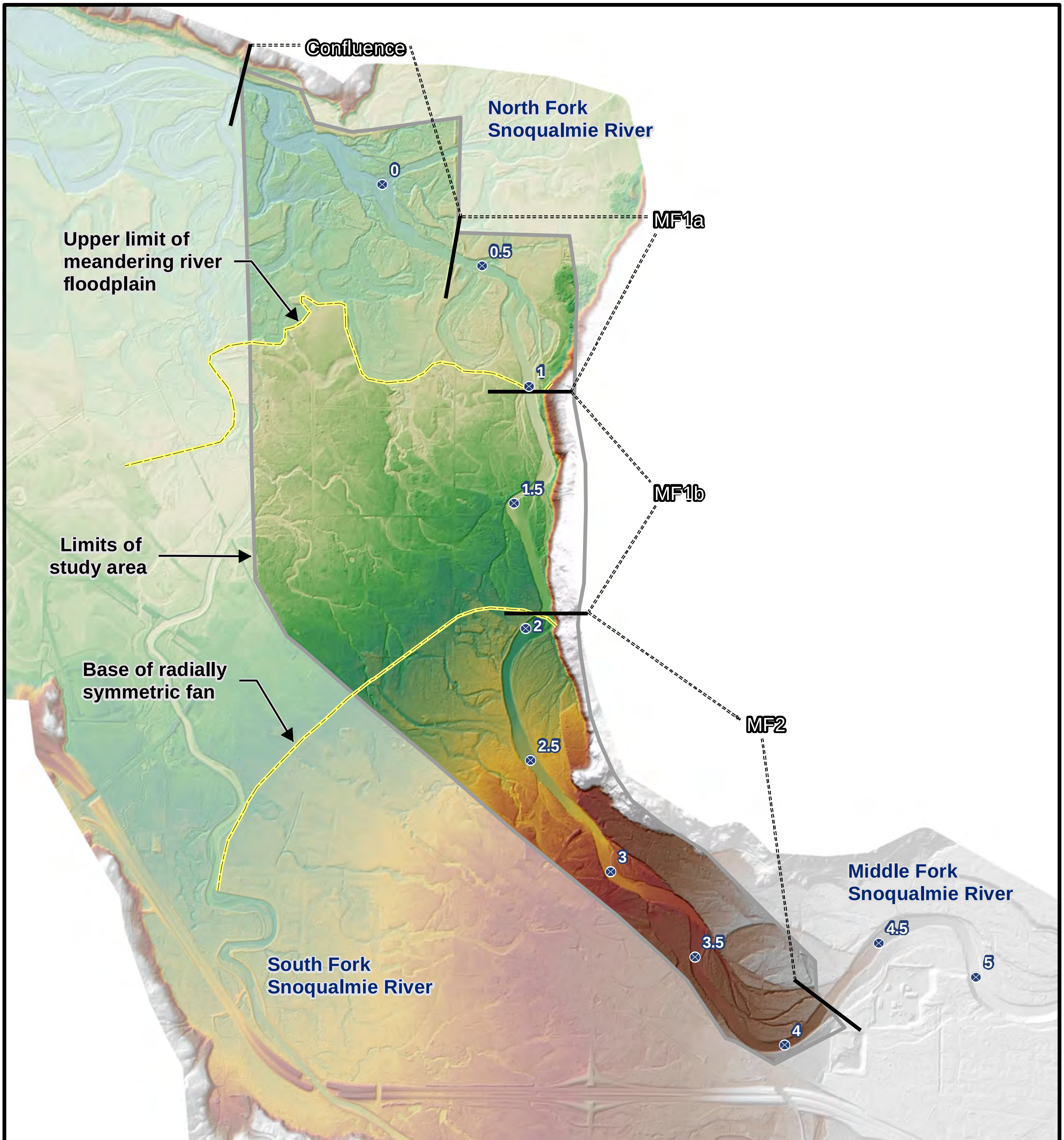
Fewer landslides have been documented from Mount Si adjacent to the study reach. However, rockfall certainly occurs on the Middle Fork side of Mount Si, as reported by local residents on cold winter mornings (J. Bethel, personal communication). Much of this activity is probably focused on a light-colored patch of rock on a west-facing cliff on the mountain. The precise age of this feature is not known. There is evidence for even larger slope failures, probably triggered by large seismic events, on the North Fork side of the mountain. Huge boulders are present at the base of the talus slope near the river in this area. There is at least one such boulder on the Middle Fork side, near the Mason Thorson Ells Extension levee, indicating that the vertical relief necessary for supplying rockfall blocks to the river is present in select places along the Middle Fork below Tanner. For much of the study reach, rockfall and debris flows originating high on the mountain do not have a direct pathway to the Middle Fork. Instead, Little Mount Si would divert any sediment to the north or south, probably resulting in significant storage of material at the base of Little Mount Si (see Figure 3). Several debris flow fans are also present on the floodplain at the base of Mount Si near the confluence with the North Fork, indicating that sediment storage occurs between the base of the mountain and the river channel.

CHANNEL AND FLOODPLAIN MORPHOLOGY WITHIN THE STUDY REACH

The Middle Fork changes markedly through the study reach. The dissected Sallal Prairie marks the upper end of the study area. The channel then passes across a lower gradient alluvial fan before entering a zone of much lower slope near the confluences with the North and South Forks. Perkins (1996) and Tetra Tech (2011) both divided the study reach into three subreaches whose boundaries roughly coincide with these geomorphic features. The subreaches are illustrated in Figure 7. The lowest subreach, termed the Confluence subreach, extends downstream from approximately Middle Fork RM 0.4 (i.e., 0.4 miles upstsream of the confluence with the North Fork). For the most part, the channel maintains a single thread through this subreach, and the adjacent floodplain is characterized by extensive meandering channel topography. The Middle Fork 1 (MF1) subreach extends upstream from this point to what is essentially the base of the radially symmetric part of the alluvial fan at Middle Fork RM 1.9. This subreach is characterized by several active mid-channel bars that are crossed by chutes that historically have resulted in small-scale channel avulsions around the bars. This subreach may have been located several hundred feet further west in the early part of the 20th century (Perkins 1996), but the quality of the historical mapping is not sufficient to conclusively identify channel position. Further upstream, the Middle Fork 2 (MF2) subreach hugs the base of Mount Si and/or high terraces to the north of the channel.

The channel morphology changes through the study reach from a single thread, pool-riffle or plane bed channel in subreach MF2 to a wandering or anabranching planform morphology containing a channel characterized by a pool-riffle sequence in subreach MF1. As sediment size and slope decrease further in the lower portions of subreach MF1 and within the confluence subreach, bed material becomes finer, although gravel is present to the downstream end of the study area.

Floodplain morphology also changes significantly within the study area. A transition occurs at the lower limit of the radially symmetric alluvial fan that characterizes the upper part of the study area. This transition coincides very closely with the boundary between subreaches MF1 and MF2 as defined by Perkins (1996) and Tetra Tech (2011). Upstream of this transition, the channel runs along the base of a large terrace that buffers the channel from potential sediment inputs originating on the lower slopes of Mount Si. The presence of this terrace (the banks of which are shown in Figure 5 panels C, D, E and F) implies that the channel may be somewhat incised into its alluvial fan in this area, as it is in the upstream Sallal Prairie area. Channel migration rates are generally low within the study area upstream of RM 1.9. The alluvial fan in the left (west/south) bank floodplain in both the MF1 and MF2 subreaches is characterized by a series of cross floodplain channels (Perkins 1996) that diverge from the Middle Fork at a high angle. They are generally smaller than the modern channel of the Middle Fork and convey flow toward the South Fork or the Confluence subreach during large floods. Their significance is discussed later in this report, and detailed hydraulic modeling



Legend

River mile

Project area

Elevation (ft)

High : 550

Low : 410

Figure 7. Floodplain DEM and Reach Boundaries.

N

0 0.25 0.5 1

Miles

King County

Prepared for King County by Herrera

K:\Projects\10-04766-015\Project\Geomorph_assessment\reach_dem-report.mxd (2/26/2013) results for these are presented by WSE (2013) in the companion hydraulic modeling study to this report. However, as a general rule, flow leaving the Middle Fork in subreach MF2 eventually enters the South Fork, while most flow leaving the Middle Fork in subreach MF1 returns to the Middle Fork in the Confluence subreach.

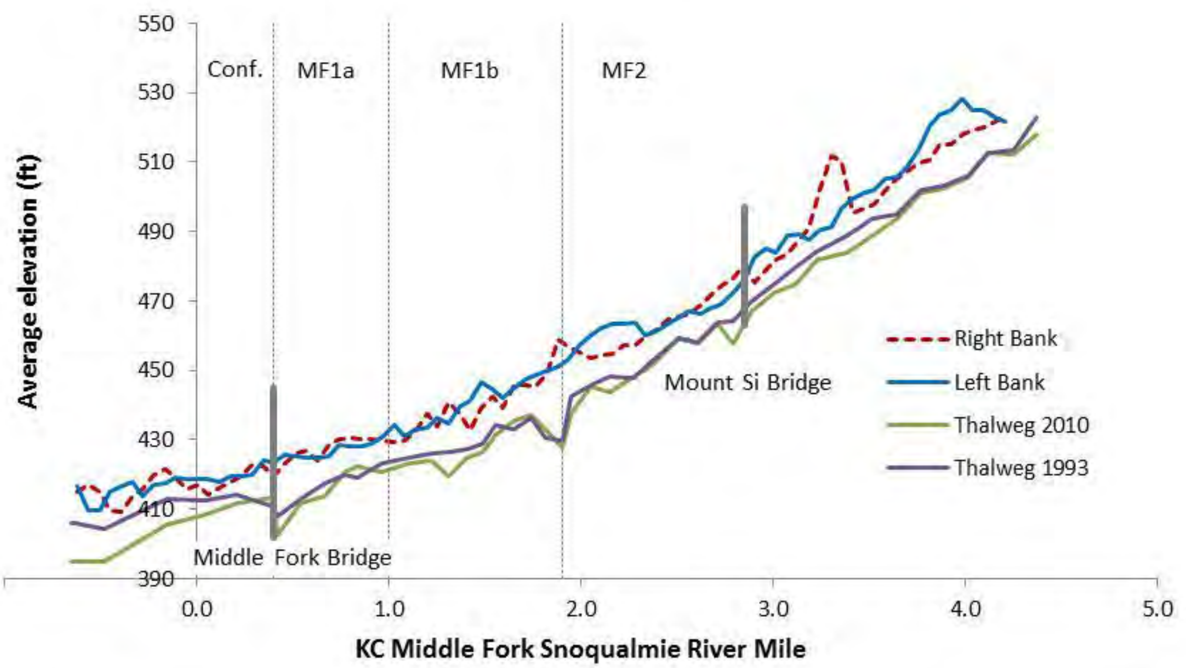
The character of both the channel and floodplain changes significantly below the base of the radially symmetric portion of the alluvial fan at RM 1.9, at the upper end of subreach MF1 described by Perkins (1996) and Tetra Tech (2011). Through most of subreach MF1, the Middle Fork channel remains adjacent to the base of Mount Si and is characterized by an anabranching pattern. Within a distance of one or two channel widths from the main channel, and perhaps further west, floodplain deposits are characteristic of those typically deposited by an anabranching river. The irregular, shifting channel pattern typical of anabranching rivers has led to the use of another, more descriptive term for this type of system: a wandering river. The two terms are used synonymously in this report). Here, point bars typically grow until one or more chutes cut them off, leaving a mid-channel bar or bars that are slowly stabilized by vegetation or large wood deposition. Overbank flow on these vegetated bar surfaces can eventually result in the accumulation of a layer of fine-grained sediment. Despite relatively high rates of lateral erosion along islands, chute channels can be maintained for decades or longer. In subreach MF1, it is not clear from lidar data or aerial imagery how far from the existing channel that anabranching floodplain deposits might extend. However, the floodplain adjacent to most of subreach MF1 certainly contains fewer anomalously high areas than that near subreach MF2, implying less incision into the alluvial fan surface than has occurred upstream. During flood events, most overbank flow that leaves the Middle Fork in subreach MF1 flows in a generally northward direction and re-enters the Middle Fork upstream of the confluence with the North Fork. There is much less cross floodplain slope toward the South Fork than is the case adjacent to subreach MF2 upstream.

A final floodplain transition occurs within subreach MF1 near Middle Fork RM 1.0, about 0.5 river miles upstream from where the channel begins to achieve a single thread meandering planform geometry near the Middle Fork Bridge. Between this point and the lower limit of the study area, the floodplain slope is low and the floodplain contains numerous abandoned meandering channel courses with widths similar to that of the existing Middle Fork channel. Lateral accretion associated with point bar deposition is a dominant process in this type of floodplain, causing meander bends to elongate until neck or chute cutoff creates an oxbow lake and the process begins anew. The numerous floodplain channels with geometries similar to that of the existing Middle Fork channel indicate that the Middle Fork has migrated extensively across the floodplain in this area. Overbank flow in the floodplain tends to follow these abandoned channel courses. The modern channel of the Middle Fork changes form from anabranching to single thread within this meandering river reach. Perkins (1996) and Tetra Tech (2011) use this transition, which occurs near RM 0.5, as the boundary between the MF1 and Confluence subreaches. However, the primary reason that the transition in channel morphology occurs downstream of the obvious break in floodplain processes at RM 1.0 is associated with a channel engineering project that cut off a meander bend in this area in the 1960s. To distinguish between the two sections of subreach MF1 that exhibit different geomorphic character, while also maintaining consistency with previous work, subreach MF1 has been split here into two parts, MF1a (downstream of RM 1.0) and MF1b (upstream of

RM 1.0). Subreach MF1a, which angles away from the base of Mount Si across the low-gradient floodplain was historically characterized by a meandering morphology, while subreach MF1b, which hugs the base of Mount Si for its entire length, was historically characterized by a wandering or anabranching morphology.

Reach Scale Channel Dynamics

Longitudinal profiles of the thalweg and banks of the Middle Fork within the study reach are presented in Figure 8. Thalweg elevations are taken from cross-section surveys performed by the County in 1993 and 2010 (note that in the Confluence subreach, several of the 1993 cross-sections did not capture the entire inundated width of the channel and thus may have missed parts of the thalweg). Bank elevations are taken from topography produced with 2010 lidar after sampling the average elevation within a region 10 feet wide adjacent to the channel banks (as defined by the vegetation line). A break in thalweg slope occurs at RM 1.9, at the transition between subreaches MF1 (MF1b) and MF2. The top-of-bank slope (as sampled from lidar for a 10-foot-wide corridor adjacent to each 2010 bank line) remains relatively high through the entire anabranching or wandering section but then drops near RM 1.0, implying that shear stress and sediment transport capacity also drop where the channel enters the low gradient meandering river floodplain.



Note: Left and right bank elevations are sampled from the 2010 lidar within a 10-foot wide corridor immediately outside the channel bank polygon.

Figure 8. Longitudinal Thalweg and Bank Profiles in the Study Reach.

The recent trend in channel bed elevation is one of slight incision, with the 2010 thalweg elevation on average 0.66 feet lower than the 1993 profile. Thalweg elevation change is most notable within the meandering river reach near the confluence with the North Fork. Some of this change may be due to error in the 1993 cross sections, but the trendis also present in the upper part of the study area. A full description of volumetric change associated with the cross section survey is presented in the Sediment Budget section of this report. However, it is worth noting that the recent trend contrasts with the numerical modeling results of Booth et al. (1991), who simulated (but did not observe) sediment accumulation rates of as much as 1 foot per century in the reach between the Three Forks Natural Area and Snoqualmie Falls which contains the Confluence subreach.

The recent decrease in thalweg elevation is corroborated by changes in the stage-discharge rating curve at the USGS Tanner flow gage. While this gage is located several river miles upstream of the study area, immediately upstream of the Middle Fork Embankment, many of the watershed-wide processes that have influenced the study reach have also affected the site of the Tanner gage. Figure 9 shows the change in the relationship between stage and discharge at a daily discharge of 1,090 cfs, which is a typical discharge just below the mean annual flow of 1,219 cfs. There is a long-term decrease in stage of roughly 0.15 feet over the period of record, with most of the change occurring between 1996 and 2001 and then between 2006 and 2007 (a period that included the flood of record). Results are similar for the analysis of 10 percent, 50 percent, and 90 percent exceedance flows performed by the US Geological Survey (C. Magirl, personal communication). The largest change in stage occurred between January 1998 and October 1999. While there is a remote possibility that adjustments in the position of the gage occurred during the period of record that would explain the shift, it is more likely that incision on the order of 0.1 to 0.2 feet in the reach near the gage is responsible for the observed shift in the rating curve.

Longitudinal channel profile concavity is often associated with a downstream decrease in sediment grain size. Perkins (1996) performed pebble counts on exposed bar surfaces and documented a decrease in the median grain size (D_{50}) from around 70 mm at the upper end of the study area to less than 40 mm near the confluence with the North Fork, a distance of around 5 miles. These were supplemented as part of the present study using Wolman pebble counts performed by County personnel and Herrera staff. In addition, a subsurface sediment sample was collected at the head of a mid-channel bar near RM 0.7. Finally, the geometric mean of river bed surface sediment size was computed from photographs of the bed surface taken at several locations in the study reach using a photosieving technique incorporated into the US Geological Survey's grain size toolbox software (Buscombe et al. 2010). Results of all grain size characterizations are shown in Figure 10. The data show a strong decrease in grain size in the downstream direction through the study reach. Most of the decrease occurs downstream of RM 1. The anomalously high mean grain size (D_{50}) at RM 1.5 could be associated with local-scale hydraulic effects or the supply of coarse material from eroding banks immediately upstream of there. In any case, the decrease in grain size moving downstream implies that over long time scales, the channel and/or floodplain are probably storing gravel downstream of RM 1, probably mainly in bar deposits that are overlain by finer sediment.

Planform Change

Channel migration activity varies significantly throughout the study reach. Perkins (1996) presents historic channel positions and reach-average migration rates for the study reach and

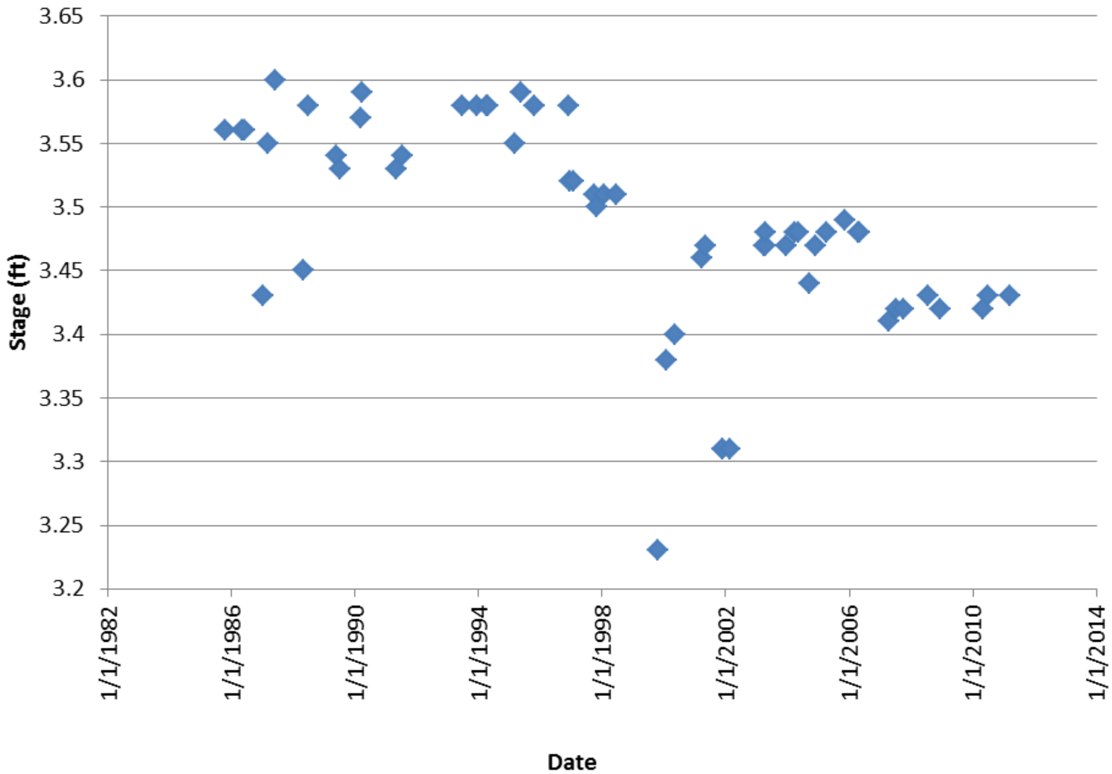
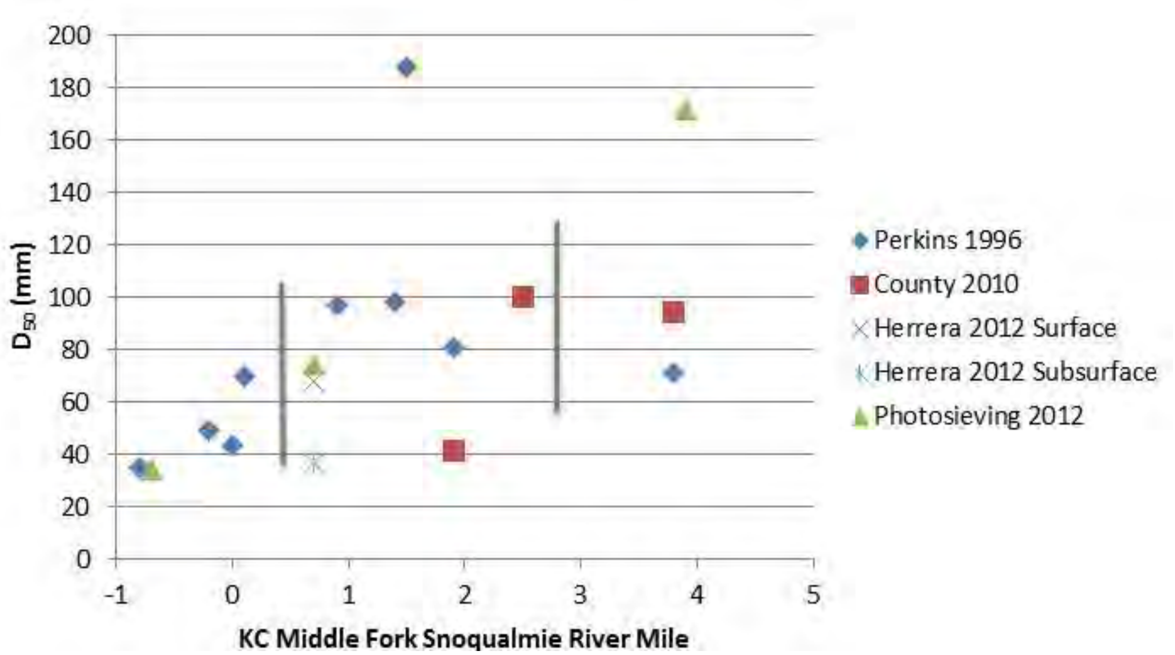


Figure 9. Change in Water Surface Stage at Tanner Flow Gage (Between RM 11 and RM 12) for Discharge of 1,090 cfs Between 1985 and 2012.



Note: Photosieving results present geometric mean size rather than D_{50}.

Figure 10. Median Grain Size (D_{50}) of Sediment Sampled from Bars in the Middle Fork Snoqualmie River.

for the North and South Forks within the Three Forks Natural Area. The study considered maps as old as 1865, but the planimetric accuracy of the data sources is unclear prior to the 1920s. With the exception of the meandering river floodplain near and immediately upstream of the Confluence subreach (see Figure 7), historic maps indicate that the channel has, for the most part, followed its present course during the documented era.

Figure 11 illustrates channel position for four periods during the era when aerial photography allows for relatively accurate delineation of channel banks. The most obvious planform change that occurred during this period began in 1941, with relatively rapid shifting of the channel alignment in the lowest part of the study reach, below the confluence with the North Fork. This channel change may have been associated with the construction of upstream flood protection facilities or with a large flood that occurred in 1959. Another major change that occurred early in the historical record is the slow accumulation of sediment in a large oxbow lake near RM 0.5 that probably formed between 1913 and 1921. The lake is not mapped as part of the channel after 1961. Historic maps indicate that several other oxbow lakes may have formed in this area in the early 20th century. Despite the construction of levees and revetments during the earlier part of the 20th century, the anabranching subreach (MF1) remained relatively active through this period. The details of the evolution of several bars within this subreach are presented by Tetra Tech (2011). Conversely, despite an overall lack of engineered bank stabilization structures, the channel alignment in subreach MF2 remained relatively stable for the entire period of historical record. However, local bank erosion in this subreach caused the destruction of several houses in 1959.

Perkins (1996) presents reach average summaries of bank erosion rates for the Confluence and MF1 subreaches for the periods 1942-1961, 1961-1993, 1942-1958, and 1958-1961. The erosion rates for the 1958-1961 period reflect the effects of the relatively large 1959 flood. Tetra Tech (2011) added reach-average bank erosion rates for the period of 1993-2010, which included the two largest floods on record: 31,700 cfs on November 6, 2006, and 31,200 cfs on January 7, 2009, both approximately 25-year recurrence interval events. However, flows of similar magnitude occurred within the 1942-1961 and 1961-1993 periods, before the Tanner gage was established (Perkins 1996).

Bank erosion rates were estimated by Perkins (1996) by computing the lateral change in position along each bank line at 200-foot intervals along the channel length. The results were summarized both for areas not associated with channel bank protection (unarmored reaches) and for areas where at least one bank was adjacent to some form of bank protection (armored reaches). While many armored banks within the study reach and elsewhere tend to be located at the outside of bends and thus tend to fix the most erosive part of the flow against the armored bank, there are usually some locations where the channel remains free to migrate away from the armor. It is thus expected that installation of bank armor, if effective, would result in reach-average erosion that is oriented away from the armored bank. Averages were computed by subreach for each type of bank condition (armored and unarmored). Tetra Tech (2011) used a similar methodology to update the analysis through year 2010. Because of uncertainty regarding the accuracy of the aerial imagery and relatively minimal change in subreach MF2, lateral migration rates were not presented for that subreach by Perkins (1996). The results of these studies are summarized in Tables 2, 3, 4, and 5. In general, migration rates for all three subreaches decreased during the 1961-1993 period

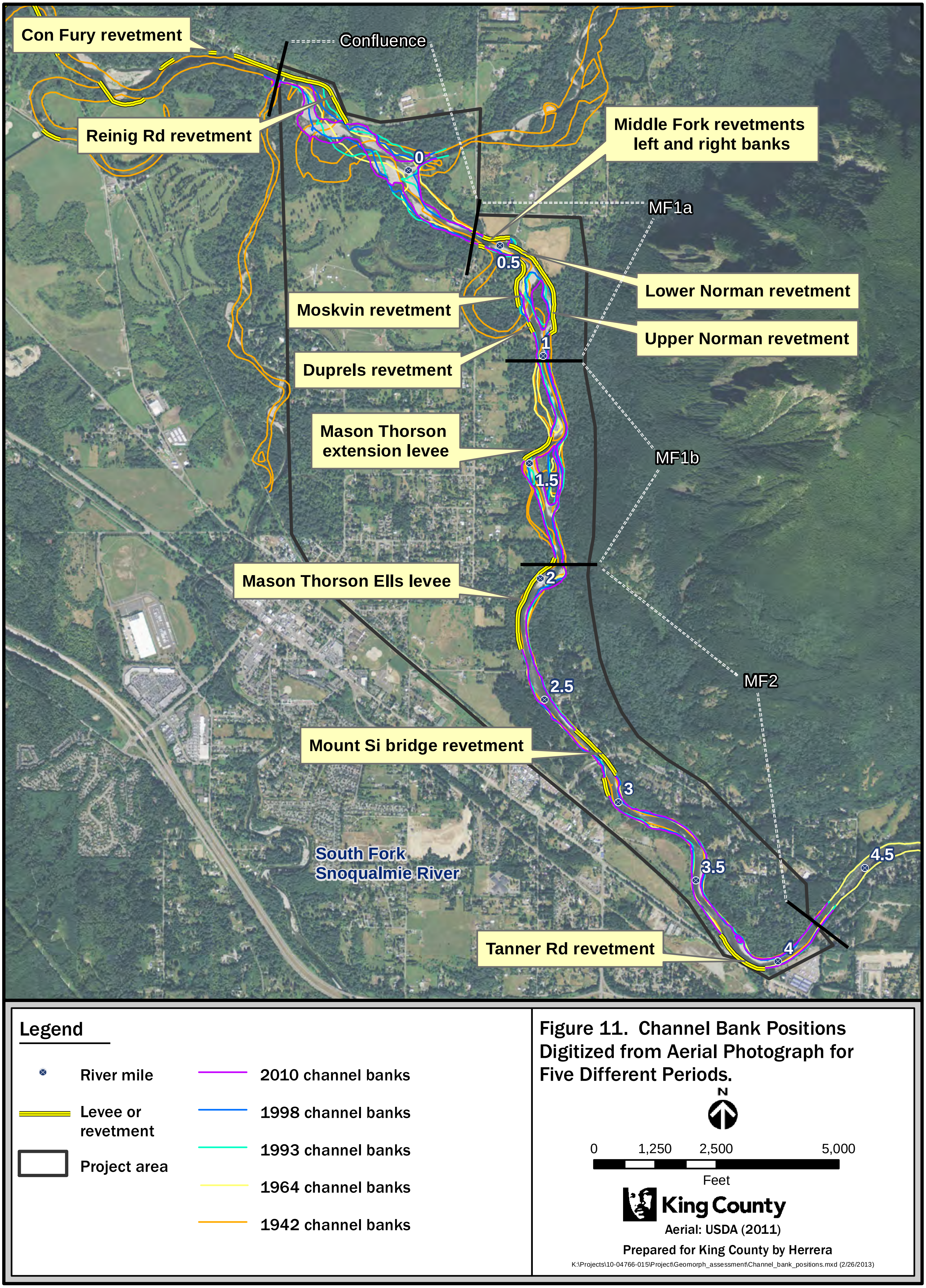


Figure 11. Channel Bank Positions Digitized from Aerial Photograph for Five Different Periods.

King County

Aerial: USDA (2011)

Prepared for King County by Herrera

K:\Projects\10-04766-015\Project\Geomorph_assessment\Channel_bank_positions.mxd (2/26/2013) relative to the 1942-1961 period. Between 1993 and 2010, migration rates returned to levels similar to those of the 1942-1961 period in the Confluence subreach, but remained relatively low in subreach MF1. Subreach MF2 was characterized by low rates of shifting during all time periods analyzed.

Table 2. Reach Average Channel Migration Rates (feet/year).

Time Period	Confluence Subreach	Subreach MF1	Subreach MF2
1942-1961	7.4	3.7	n/a
1961-1993	3.3	0.6	n/a
1993-2010	7.3	1.0	0.5

Table 3. Average Channel Migration Rates for Eroding Areas Only (feet/year).

Year	Confluence Subreach	Subreach MF1	Subreach MF2
1942-1961	10.9	4.6	n/a
1961-1993	3.9	2.3	n/a
1993-2010	9.7	1.9	1.5

Table 4. Average Channel Migration Rates for Armored Areas Only (feet/year).

Year	Confluence Subreach	Subreach MF1	Subreach MF2
1942-1961	6.0	6.9	n/a
1961-1993	2.8	0.5	n/a
1993-2010	6.8	0.5	0.2

Table 5. Average Channel Migration Rates for Unarmored Areas Only (feet/year).

Year	Confluence Subreach	Subreach MF1	Subreach MF2
1942-1961	7.6	2.6	n/a
1961-1993	3.9	0.5	n/a
1993-2010	7.4	1.1	0.6

The general decrease in erosion rates during the 1961 to 1993 period may have been associated with a relatively quiescent hydrologic period, particularly with respect to the 1993-2010 period. Bank armoring, which was generally installed in the early 1960s, may also be partly responsible for the decrease in erosion rates after 1961, but it does not explain the increase that occurred within the Confluence subreach after 1993 even in unarmored areas. This increase was most likley caused by the large floods that occurred during the 1993 to 2010 period. However, since a similar increase in erosion did not occur in unarmored sections of subreach MF1 during the same period, another explanation may be that long-term reorganization of channel geometry was occurring during this time period, which is a normal part of meander bend evolution within the Confluence subreach. The analyses of Perkins (1996) and Tetra Tech (2011) provide a reach-averaged description of channel migration. However, migration is a local process, with some banks retreating rapidly while nearby banks remain static. The summary of reach average migration rates is supplemented here by an analysis of historic channel width and erosion rates as a function of location (river mile).

Average channel width was computed by dividing the overall channel bank polygons digitized from aerial photographs by Perkins (1996) or Tetra Tech (2011) into regular segments every 300 feet along the 1993 channel centerline. The planform area of each segment (including any side channels) divided by the centerline spacing represents the average width for the segment. To the extent that the original bank lines developed by Perkins (1996) and/or Tetra Tech (2011) include side channels adjacent to island bars, the width estimate represents the average width of the entire active flow area, whether or not islands were present in the channel. Erosion rates were computed by developing a channel centerline from the Perkins (1996) and Tetra Tech (2011) bank lines. For anabranching areas (e.g., in subreach MF1), the centerline was drawn down the largest channel. Shifting rates were then computed by measuring the lateral offset (positive toward river left) between centerlines at regular intervals. The centerline offsets incorporate channel change on both eroding and depositional banks. Large shifts in centerline position can also occur in conjunction with a chute cutoff. The rates presented from this analysis are thus not directly comparable to the bank line offsets measured by Perkins (1996) and Tetra Tech (2011). However, they provide a much more detailed description of spatial variability in historical erosion activity. Analysis was performed for four periods: 1942 to 1964, 1964 to 1981, 1981 to 1998, and 1998 to 2010. Note that periods of analysis differ slightly from those used by Perkins (1996) because data from years considered in the Perkins analysis did not extend to the upstream end of the study area.

Historical aerial photographic images are typically assigned geographic coordinates by identifying control points visible on both the historical photograph and on a modern georeferenced image and then applying a mathematical algorithm to assign geographic coordinates to each pixel of the historical image. This process is imperfect because human judgment is required to select control points and because distortion of either the historical or recent image due to camera angle or lense properties can be difficult to completely remove. Because it is not possible to perfectly align historical aerial photographs with a base map, and because of the subjective nature of aerial photograph interpretation, some of the bank erosion identified by Perkins (1996) and Tetra Tech (2011) is probably a result of misalignment in channel bank positions. Both studies accounted for this by assuming that channel migration rates were zero in areas where the observed bank shift was below a threshold value. The channel centerline offset measurements developed for this study are also susceptible to photograph alignment error. However, centerline position can be used to develop a description of zones of geomorphic change that is not sensitive to photograph misalignment. This is accomplished by comparing the cumulative up-channel position of a given channel centerline derived from two separate photographic dates. When channel erosion occurs, it is usually associated with a net increase in channel centerline length. In other words, regions that are elongating are doing so because erosion is occurring in the vicinity. Elongation usually continues until a chute or neck cutoff causes instantaneous shortening. Accurate measurement of total channel centerline length on any given photograph (and thus the rate of elongation, which is computed by comparing centerline length derived from two separate photographs) only requires that the photograph is scaled correctly, not that it is aligned perfectly. Plotting the local rate of change of channel centerline length (with length measured up-channel starting at the lower limit of the study area) thus represents a metric for characterizing channel change that is not greatly affected by photograph alignment error.

Figure 12 presents channel widths, measured lateral centerline shifting rates, and measured centerline elongation rates. Each variable is plotted against the 1993 centerline position (which has been adopted as the standard river mile reference for this study). In Figure 12c, which presents elongation rates, areas of the curve with steep upward slopes represent areas where the channel elongated during a given period. Steep downward slopes represent zones of local channel shortening, usually because of a bend cutoff. The figure shows that planform change is focused in three zones. The first extends from the lower end of the study reach, at the confluence with the South Fork (RM -0.65), to a point approximately 0.25 miles upstream of the confluence with the North Fork (i.e., RM 0.25). In this area, which represents all but the upper 0.15 miles of the Confluence subreach, channel width has remained relatively constant, but the channel has shifted either to the left or the right during the historical period of record. This was primarily through classic channel migration that resulted in regular elongation in this subreach except during the 1941-1964 period, when a bend cutoff shortened this section of channel significantly. This is consistent with the channel position adjacent to several large oxbow lakes in the floodplain.

The second relatively active area is in subreach MF1a between RM 0.5 and RM 0.75, near the lower end of a large mid-channel bar close to the Upper Norman levee and the Moskvin revetment, just upstream of a large oxbow lake that formed between 1913 and 1921. This zone is characterized by channel width that is generally greater than anywhere else in the study reach and that is also quite variable temporally. The channel width in this area increased dramatically between 1942 and 1964, generally decreased between 1964 and 1981, remained relatively stable between 1981 and 1998, and then increased significantly between 1998 and 2010. Lateral change in channel centerline position in this zone was from left to right between 1964 and 1981 and from right to left between 1998 and 2010, primarily because the main thread of the channel shifted to either side of a stable mid-channel bar during these periods. Centerline change in this zone depends strongly on the dynamics of vegetation and debris on the mid channel bar and within the side channel that is presently located to the east of the main channel, not simply on progressive channel migration of the main thread of the largest active channel.

The third zone of high channel migration activity is located near RM 1.5 in subreach MF1b, at and just upstream of the site of the Mason Thorson Extension levee. This zone is also characterized by multiple channel threads and a large mid-channel bar. As in the active zone between RM 0.5 and RM 0.75, channel width was locally high in all photograph dates, with the highest width observed in 1964. In general, the direction of channel centerline migration in this zone has been toward river left since the 1980s, primarily because of bank erosion upstream of the Mason Thorson Extension levee. However, except during the 1998 to 2010 period, migration has not consistently been associated with overall channel elongation in this area. This indicates that prior to 1998, change of centerline position in this area was closely associated with evolution of the mid-channel bar and the side channels to the east of it. The widening prior to 1964 was associated with the capture of the majority of the channel's flow in such a side channel. Because adjustment during the 1964 to 1998 period did not produce overall centerline elongation in this area, it is likely that most geomorphic change focused on the evolution of the bar. After 1998, the channel centerline began to elongate and the channel narrowed significantly, perhaps signaling a switch to more typical pattern of meander bend growth. However, the history of the site indicates that there is potential for complete rearrangement of the bar and the associated side channels, so it is not clear whether the post-1998 elongation is indicative of a sustained change in process at this location.

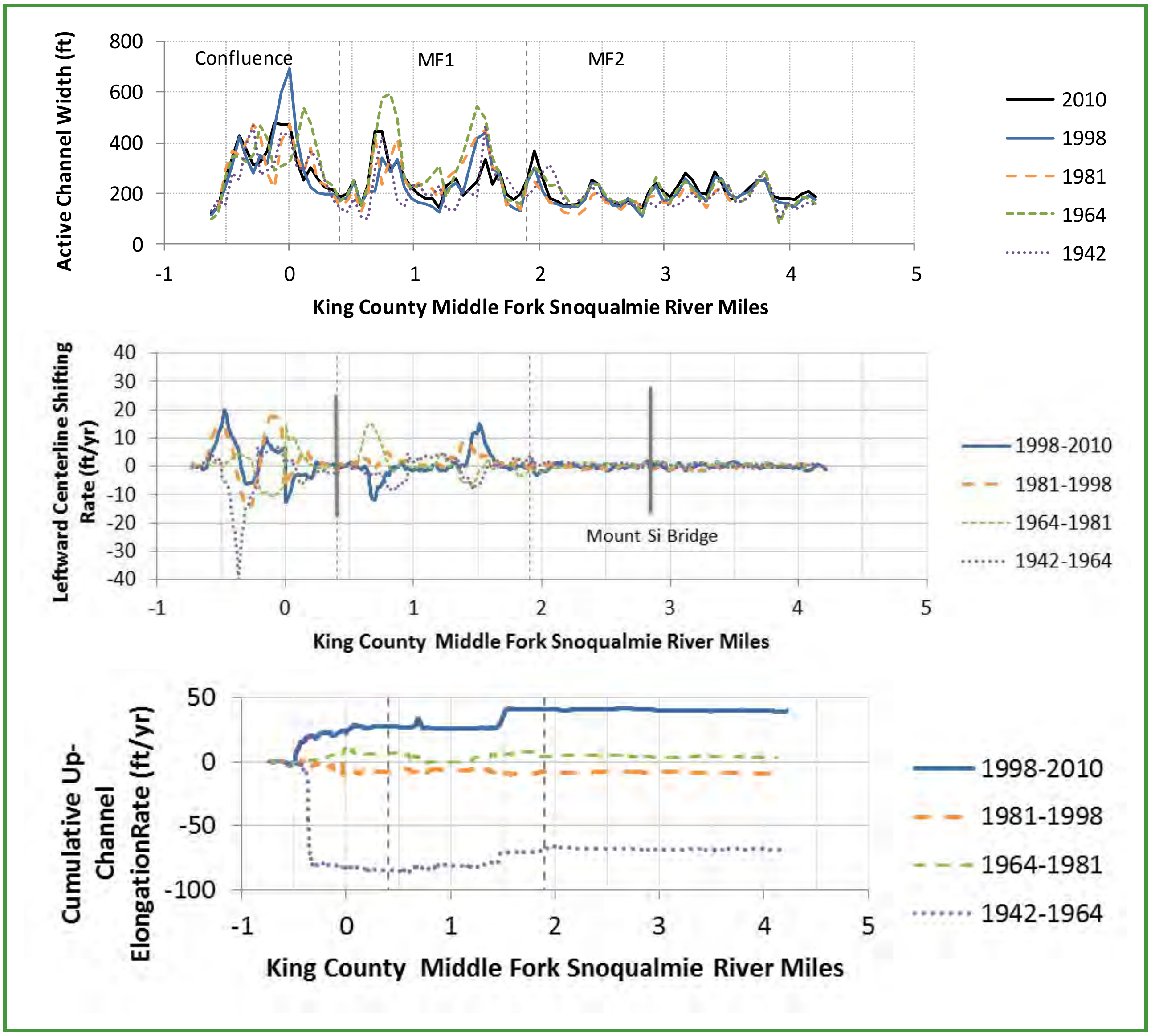


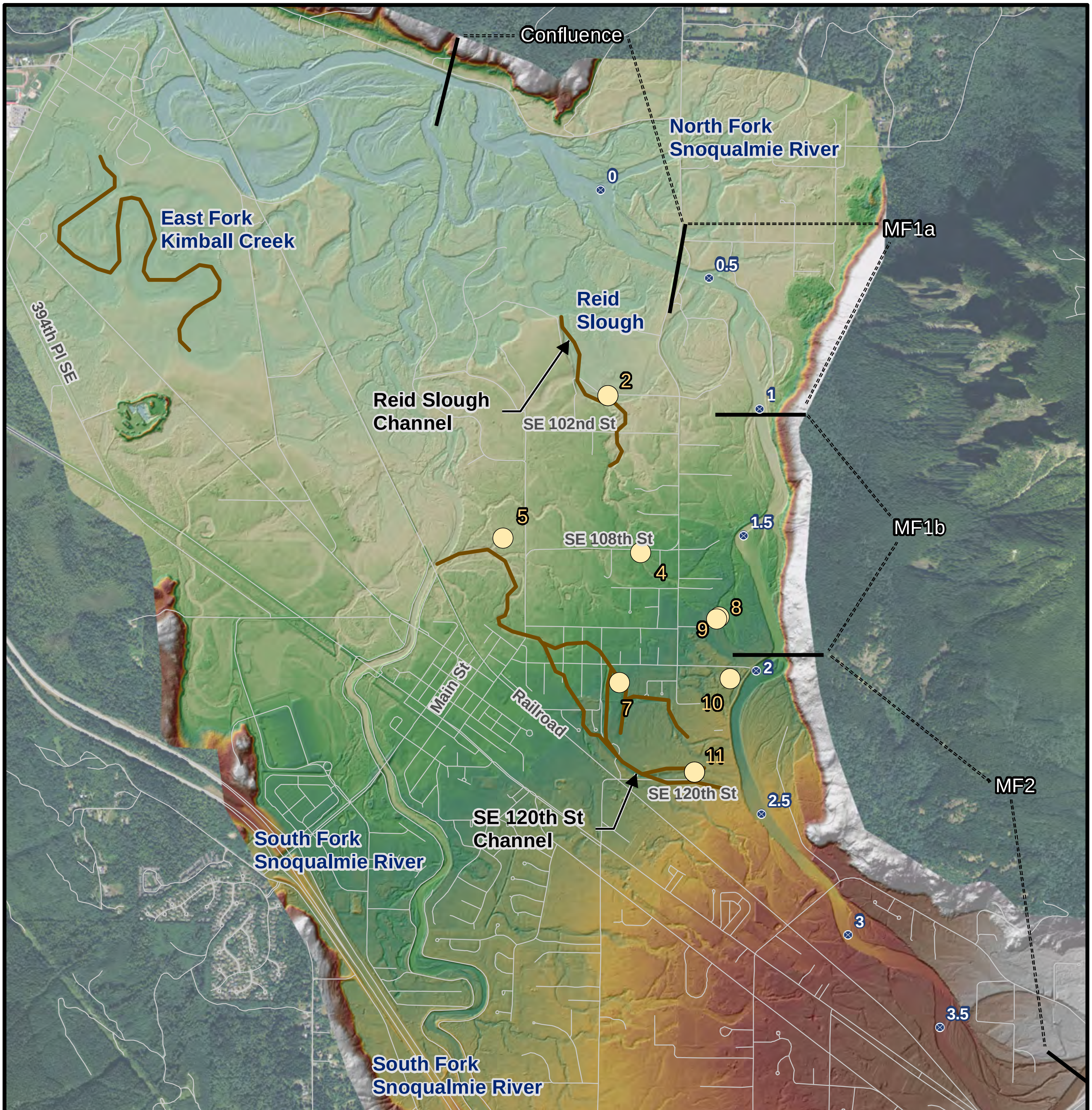
Figure 12. Profiles of Channel Width, Lateral Migration Rates, and Cumulative Up-channel Elongation Rates for the Study Reach.

Outside of the three zones of channel migration activity described above, the data presented in Figure 12 are consistent with relatively minimal planform change in the past 70 years. While some changes in overall channel width are visible in Figure 12, particularly upstream of RM 3 in subreach MF2, the width measurements in those areas are sensitive to the in-channel vegetation and to human error in identifying the bank lines. If width change were occurring primarily through channel migration on the outer cut bank, this should be associated with overall elongation of the channel centerline. Similarly, if width change were occuring primarily through removal of vegetation on the inner point bar bank, overall centerline shortening should occur. The relatively constant slopes of each line in the cumulative up-channel elongation rates shown in Figure 12 upstream of RM 1.5 indicates that neither process is consistently occurring. If channel change is occurring in this area at all, it appears to be associated with slow, progressive widening of both banks and/or shifts in vegetation lines on both banks, and not with traditional meander migration.

Side Channels and Paleo-channel Courses

Two basic types of floodplain channels are present within the study area. The larger of the two, referred to as parallel channels by Perkins (1996) and Tetra Tech (2011), are present mainly on the meandering river floodplain near the confluence with the South and North Forks, below the radially-symmetric part of the alluvial fan. These channels represent historic courses of the Middle and South Forks that have been abandoned by neck cutoff and/or large scale channel avulsions. A second type of floodplain channel is present on the main body of the alluvial fan and on the wandering river floodplain of subreach MF1b. These channels, referred to as cross-floodplain channels by Perkins (1996) and Tetra Tech (2011), are generally significantly smaller than either the Middle or South Fork channels and run primarily across the alluvial fan between the Middle Fork and South Fork. The extent of the connection is the subject of a complimentary hydraulic modeling study (WSE 2013)that indicates that they are hydraulically connected to the main channel at flows greater than approximately a 5-year recurrence interval event. Because the slope toward the South Fork is greater along several of these cross-floodplain channels than the slope along the Middle Fork, Perkins (1996) speculated that under the right conditions, it may be possible for erosion within these channels to allow the Middle Fork to be diverted through one of them. Conditions for such an avulsion could include a very large flood or a debris jam on the Middle Fork that would divert flow into one of the cross channels. Tetra Tech (2011) points out that the cross-floodplain channels convey groundwater discharge before they become connected to river flow across the floodplain.

Perkins (1996) identified several floodplain channels that might be abandoned courses of the Middle Fork. The most prominent of these are shown in Figure 13. An obvious set of historic channels is located downstream of the confluence with the North Fork, in the low gradient meandering reach. These channels form part of the present course of Kimball Creek and are almost certainly old meander loops formed by one of the forks of the Snoqualmie River. Only two major channels were identified on the alluvial fan proper: the SE 120th Street channel near RM 2.4 and a short channel south of Reid Slough (henceforth termed the Reid Slough channel), which connects to the Middle Fork near RM 1.5. Both of these channels are presently significantly smaller than the existing Middle Fork channel.



Legend

- River mile
- Sample site
- Major floodplain channel identified by Perkins (1996)
- Road

Figure 13. Key Potential Floodplain Channels Identified by Perkins (1996) and Sites from which Sediment was Sampled for Radiocarbon Dating Purposes.

0 1,250 2,500 5,000
Feet

King County

N

Aerial: USDA (2009)
Lidar: Snoqualmie (2010)

Prepared for King County by Herrera

K:\Projects\10-04766-015\Project\Geomorph_assessment\Floodplain Channel Map.mxd (6/17/2013)

The mechanism for formation of the cross floodplain channels is not clear. It is possible that the channels on the alluvial fan proper represent prehistoric courses of one or more distributary channels of the Middle Fork. However, another likely formative mechanism is the upstream progression of a headcut that forms at a break in slope near the lower end of one of these channels. An example of such a headcut-controlled channel condition in the Elwha River on the Olympic Peninsula in northwest Washington is provided in Figure 14. A similar process has been illustrated in scale model experiments of channel evolution representing vegetated gravel floodplains (Tal and Paola 2010). In these experiments, upstream headcut growth can eventually lead to full scale channel avulsion. Because the rate at which the headcut can proceed upstream depends on the flow passing across the floodplain, obstructions to flow such as log jams that divert flow out of the channel can in principle increase the rate at which overflow channel headcuts migrate upstream. In addition, any large-scale aggradation of the Middle Fork caused by a major increase in bed material sediment supply, for instance after a large fire or landslide, would increase overbank flow and could eventually activate such channels. Despite the historic logging activity in the watershed, the recent trend near the upstream end of the study reach appears to be toward a small amount of incision. Without a major catastrophic input of sediment into the system, the possibility of large scale aggadation seems rather remote. In any case, the extent to which a large fire or landslide would lead to in-channel aggradation is a challenging research topic that is beyond the scope of this study.

For a headcut in the floodplain to propagate upstream all the way to the main channel, it would need to cut through floodplain material near the banks of the main channel. Much of this material would need to be conveyed downstream, out of the channel for the channel to grow. The presence of cobble in all eroding banks upstream of approximately RM 1 probably limits this possibility. The banks of the Middle Fork exhibit a systematic change in stratigraphy through the study reach, with gravel and cobble present near the surface in subreaches MF1 and MF2. As one moves downstream, an increasingly thick cap of sand/silt that was probably deposited through overbank flooding characterizes the banks, with this fine layer representing more than half of the overall bank thickness within the Confluence subreach. The lidar surface shows that the floodplain channels are much better defined near their lower ends within the study area than they are near their upper ends. This raises the interesting possibility that the floodplain channels are capable of eroding through fine sediment deposits (which are probably thicker along the downstream parts of the channels) but do not convey sufficient flow to mobilize the coarser bed and bar material that characterizes the underlying part of the floodplain deposits. If this is the case, the floodplain channels would also presumably not be able to headcut through the cobble-rich deposits that tend to characterize the banks of the Middle Fork adjacent to subreaches MF1 and MF2. While bank erosion along the Middle Fork could bring the main channel closer to locations where overflow enters the floodplain channels, the existing revetments limit this possibility.

When channel avulsions occur, they often reoccupy previously abandoned channel courses. Accumulations of woody debris can play a role in this process, as discussed below. While full-scale channel avulsion has certainly occurred along the Kimball Creek channel northwest of the study area, and while part of the Reid Slough channel runs through an abandoned oxbow lake in the meandering floodplain section of the valley, it is not clear whether the full flow of the Middle Fork has ever occupied either the SE 120th Street channel or the portion of the

Figure 14. Headcuts in Vegetated Floodplain Areas, Elwha River, Olympic National Park and Lower Elwha Klallam Indian Reservation, Washington.

Reid Slough channel upstream of the oxbow lake. If the main channel of the Middle Fork has not occupied the alluvial fan since the Pleistocene (i.e., if the main shape of the fan was established at the time of deglaciation), the likelihood of a full-scale avulsion is probably much lower than if the fan has been regularly active during the Holocene.

Floodplain Dating

The scientific understanding of the geomorphic history of the study reach can be enhanced by a better understanding of the age of floodplain deposits. As part of this study, radiometric ages were determined for eight sedimentary deposits, based on 11 wood and/or charcoal fragments collected from the floodplain. Sample sites are shown in Figure 13. In general, samples were selected in order to estimate when sediment presently stored within floodplain channels or adjacent floodplain deposits was last reworked by active flow. Samples at sites 2, 4, 5, and 7 were collected in September 2012. Site 2 is located within a meander bend that was cut off prior to the historical mapping of the valley. An age for this deposit helps characterize whether pre-historic channel migration rates in the lower part of the study reach were similar to those documented from the photographic record. Site 4 is located in a floodplain swale that follows a course geometrically similar to that of the existing Middle Fork in the nearby anabranching reach (subreach MF1b), at a point where floodplain flow could enter the Reid Slough overflow channel. A date from this deposit helps to estimate the maximum reworking rate for the floodplain in the anabranching reach and also helps characterize the age of the Reid Slough channel. Site 5 is located in the floodplain near the lower end of one of the larger floodplain swales where it enters the South Fork. A date of deposited material at this location helps characterize the relative geomorphic activity of the South Fork. Site 7 is located within a branch of the SE 120th Street channel, which is the primary Middle Fork flood overflow channel identified by Perkins (1996). Dating of floodplain deposits in this location could help estimate the age of one of the most likely avulsion pathways.

In order to fill data gaps, four additional pits were excavated using a backhoe in February 2013. These sample sites (sites 8 through 11) are also shown in Figure 13. Site 8 (pit MFP1) was located in an abandoned main channel course within the anabranching section of subreach MF1. A date from this location helps estimate the relative frequency of flow occupation of off-channel courses in the anabranching section of the study area. Site 9 (pit MFP2) was located in higher ground in the floodplain immediately adjacent to site 8 (pit MFP1). Dates from this location help estimate the age of the overbank floodplain deposit and also provide additional information regarding when the channel was last active in this location. Site 10 (pit MFP3) was located near the transition between subreaches MF1 and MF2 at RM 2.0. A bone fragment (which subsequently was dated as modern) was found near the surface of this pit. Site 11 (pit MFP4) was located in the northern of two floodplain swales that parallel SE 120th Street, adjacent to subreach MF2.

A total of 11 samples from these eight sites were dated using standard radiocarbon techniques. The samples from sites 2, 5, and 7 were all collected using a hand auger. The sample at site 4 was collected from a shallow hand-dug pit. With the exception of the bone sampled at site 10, which was collected from the spoils pile created by the excavator, samples from sites 8 through 11 were all collected from the wall of the respective pit after the wall had been scraped clean using a hand-shovel and stainless steel spoon. Appendix A presents a full description of each sample.

Table 6 provides summary information describing each sample and overall dating results. As is standard practice in radiocarbon dating studies, uncalibrated radiocarbon ages are presented with respect to the year 1950. However, since ^{14}C concentration in the sampled material cannot be determined with perfect precision, the samples should be interpreted as providing a range of possible ages, not a single age. The range of conventional radiocarbon ages represents 95 percent confidence limits on the measurement. Furthermore, since ^{14}C concentrations in the atmosphere have varied over time, conventional radiocarbon ages do not necessarily correspond with a single calendar date. Calibration to calendar dates was performed using the INTCAL09 database (Reimer et al. 2009). For relatively young samples, multiple calendar dates are possible for a single radiometric age. Where this is the case, the associated dates are provided in the “Intercepts with Calibration Curve” column of the table. Once confidence intervals on the ^{14}C measurement and calibration datasets are accounted for, this results in several possible age ranges. These are reported in the “Calibrated Range” column of the table. The common interpretation is that there is roughly a 95 percent chance that the true age of the sample falls within one of the reported date intervals.

Two wood fragments from site 2 were dated. In general, the samples collected from site 2 were quite young, with estimated radiocarbon ages of 80 and 130 years, respectively. At these ages, the precision of the dating technique does not rule out the possibility that the sample is modern (i.e., from the present day). However, the stratigraphic context of the samples collected at site 2, both of which were located below the water table in a massive sandy deposit immediately above gravel, implies that the samples were deposited near the time the oxbow lake formed. The aerial photograph record rules out the possibility that this occurred within roughly the past 100 years. While there is a small possibility that the dated material fell into the sample pit from above and that both samples represent modern wood, the fact that both samples were collected from soil in the auger bucket that was relatively undisturbed makes this unlikely. There is also a possibility that the samples could be modern root fragments from nearby trees. However, their position roughly 5 feet below the water table is not consistent with conditions that would cause fragmentation of tree roots. The most reasonable explanation is that the oxbow lake from which the samples were taken was formed in the earlier part of the calibrated age range for these samples, sometime between 1670 AD and the beginning of the photograph record. The fact that several other oxbow lake deposits are present between site 2 and the modern course of the river implies that the lake from which the samples were taken probably formed rather early within the possible age range, probably in the 1680 AD to 1730 AD period described by the calibrated age range of the sample from this site. In any case, the samples support the idea that the oxbow lake deposit from which they were collected is not older than several hundred years. This is corroborated by the fact that only a single sand layer was observed at the site, and that this layer was overlain by a single silt-clay layer. If the sample were significantly older than a few hundred years, it is likely that large floods would have been capable of depositing several sequences of fine overbank sediments, each of which would probably contain some fine sand (as at site 5).

The sample from site 4, a charcoal fragment collected from the 1.2-foot deep hand-dug pit in the relict floodplain channel near 12th Avenue, provides a calibrated date of 1650 AD

Table 6. Radiometric Sample Description and Results.

Site	Sample	Material	Approximate Coordinates	Depth of Sample	Depth to Water Table	Conventional Radiocarbon Age (years before 1950)	Intercepts with Calibration Curve (calendar date AD unless indicated otherwise)	Calibrated Range, 2 Standard Deviations (calendar date AD unless indicated otherwise)
2	MFS F2-4.3 we	wood	W 121.77442, N 47.51036	2.2 m (7.1 ft)	0.76 m (2.5 ft)	130 +/- 30	1690, 1730, 1810, 1920, post 1950	1670 to 1780, 1800 to 1900, 1900 to 1940, post 1950
2	MFS F2-3.8 we	wood	W 121.77442, N 47.51036	2.3 m (7.5 ft)	0.76 m (2.5 ft)	80 +/- 30	1890, 1900, post 1950	1680 to 1730, 1810 to 1930, post 1950
4	MF4-C	charred material	W 121.77198, N 47.50292	0.36 m (1.2 ft)	n/a	270 +/- 30	1650	1520 to 1570, 1590, 1630 to 1670, 1780 to 1800, 1950
5	MF5-G	wood	W 121.78161, N 47.50355	2.3 m (7.5 ft)	0.70 m (2.3 ft)	1300 +/- 30	680	660 to 770
7	MF7-A	wood	W 121.77334, N 47.49676	0.55 m (1.8 ft)	n/a	1100 +/- 30	900, 910, 970	890 to 1020
8	MFP1-0.9	wood	W 121.766412, N 47.499917	0.9 m (3.0 ft)	n/a	320 +/- 30	1520, 1560, 1630	1470 to 1650
9	MFP2-0.35	charred material	W 121.766583, N 47.499832	0.35 m (1.1 ft)	n/a	1870 +/- 30	130	70 to 230
10	MFP3-BONE	bone	W 121.765600, N 47.497420	Spoils at surface	n/a	30 +/- 30	1700, 1720, 1820, 1830, 1880, 1920, post 1950	1680 to 1760, 1770 to 1780, 1800 to 1940, post 1950
11	MFP4-0.6	charred material	W 121.767741, N 47.492540	0.6 m (2.0 ft)	n/a	880 +/- 30	1160	1040 to 1100, 1120 to 1140, 1150 to 1220
11	MFP4-1.2	charred material	W 121.767741, N 47.492540	1.2 m (3.9 ft)	n/a	1820 +/- 30	220	130 to 250
11	MFP4-1.4	organic sediment	W 121.767741, N 47.492540	1.4 m (4.6 ft)	n/a	2970 +/- 30	BC 1210	BC 1300 to 1120

with a range that extends from 1520 AD to 1950 AD. While the calibrated age range does not completely rule out the possibility that this sample is modern, this is much less likely than for the sample collected from site 2. The stratigraphic position of this sample, at the transition between a layer of cobble and an overlying layer of fine sand and silt implies that the sample was deposited well after the cobble layer formed. In addition, since the sample was collected at such a shallow depth, bioturbation (e.g., animal burrowing and/or tree fall) could have resulted in placement of the sample even after the silt deposited above the cobble. Either way, the sample should be interpreted as providing a minimum age for the underlying cobble. There is thus a good chance that the relict floodplain swale from which the sample was collected formed long before the 1650 AD radiometric date of the sample.

The sample dated from site 5, a wood fragment collected near Silver Creek, provides a radiometric date of 680 AD with a range that varies from 660 AD to 770 AD. The stratigraphic position of this sample below several upward fining sequences of sand-silt-clay is consistent with this result. Its position approximately 7 feet below the existing low-flow water surface of Silver Creek and the fact that the sample was collected near the base of a relatively thick (2.1 feet) sand layer indicates that it was probably deposited as channel fill, most likely in a long abandoned course of the South Fork but possibly in an ancient floodplain swale. Either way, it implies that the majority of the floodplain near site 5 formed over 1,000 years ago.

The sample dated from site 7, a wood fragment collected from a sand layer in the eastern of the two floodplain swales in E.J. Rogers Park, provides calibrated dates ranging from 890 AD to 1020 AD. Because this sample was obtained at a shallow depth of 1.8 feet, it is virtually impossible to determine whether it was placed at the time the sediment was deposited or whether it represents the root of a long-dead tree. However, the relatively consistent texture of the sand and lack of fine organic material within the sand from which the wood fragment was collected implies that the sample was not placed by a burrowing animal. The sand-over-gravel stratigraphy of the area surrounding this sample site is also consistent with the sample having been deposited with the sand during a flood. Either way, the dates should only be considered limiting. The underlying floodplain swale is probably at least 1,000 years old.

The two samples dated from sites 8 and 9 were collected in pits characterized by a layer of overbank fines (sand and silt) several feet thick above a layer of much coarser gravel and cobbles. The gravel and cobbles probably represent bed material deposited by the river channel. The fines were probably deposited over the course of many years after the channel was abandoned. The relatively young age for the sample from site 8 (calibrated dates from 1470 AD to 1650 AD), which was collected near the base of the fine sediment within a few centimeters of the underlying stream cobble, provides some evidence that this channel may have been active during the relatively recent past (i.e., within a few hundred years). However, significant uncertainty remains due to the nature of the sample, which was simply a detrital wood fragment collected from the pit wall. As with any detrital radiocarbon sample, it is possible that the material may have formed in-situ after deposition (for example, as part of a tree root) and is thus younger than the surrounding deposit or, alternatively, that the material formed long before the time of the material deposited around it (for example, in the center of a long-lived tree that took years to decompose) and is thus older than the channel. However, because the sample was small and discontinuous, the simplest interpretation is that it is of similar age to the surrounding fine-grained sediment and therefore provides a minimum time since abandonment of the channel.

The context of the sample collected at site 9 differs considerably from that at site 8. This sample, which consisted of small (on the order of 1 mm diameter) particle(s) of charred material, was collected within the upper part of the soil column within 1.1 feet of the surface. It probably represents charcoal deposited in the natural levee of the channel during or immediately after a fire. Its age (calibrated dates from 70 AD to 230 AD) provides some indication of when the channel at site 9 may have been active, but its presence near the surface of the soil profile implies that the active phase of levee building may have occurred significantly earlier. Furthermore, the possibility that the charred material represents aged wood that burned during a more recent fire cannot be ruled out completely. Additional dates from lower in the soil profile near this location could help confirm overall age of the floodplain fines. In any case, taken together, the dates from sample sites 8 and 9 imply that the timescale for evolution of the wandering river floodplain adjacent to subreach MF1b is longer than that of the meandering river of subreach MF1a further downstream (i.e., at sample site 2).

The bone sample at site 10 provides very little information regarding the geomorphic history of the system. This sample was collected from the surface of the pit excavated at site 10, in spoils created by the excavator. The radiocarbon dates imply that the bone is most likely modern in age and therefore does not provide age control for the underlying deposit.

The pit excavated at site 11 and the samples that were dated from this pit provide a compelling history for the north branch of the SE 120th Street floodplain channel. Like the pits at sites 8 and 9, this pit was characterized by a layer of sand and silt, probably placed through overbank sedimentation, above a layer of cobble. The abrupt transition between silt and cobble in this pit implies that the channel was abandoned relatively rapidly, and the relative stratigraphic homogeneity of the overlying overbank fines implies that these sediments were deposited in a series of relatively fine layers over many years (although a lens of sand at the base of the pit may have been deposited during a single event). Dates from the sample of overbank sediments are consistent with this interpretation. The lowest sample, organic material collected from the pit wall at a depth of 4.6 feet below the ground surface, provides a calibrated date range of 1300 BC to 1120 BC. The mid-depth sample, collected at a depth of 3.9 feet below ground surface, provides a calibrated date range of 120 AD to 250 AD. The upper sample, collected at a depth of 2.0 feet below ground surface, provides a calibrated date range of 1040 AD to 1220 AD. The trend of increasing age with depth is consistent with relatively constant and low-intensity overbank deposition at the site for the past several thousand years.

Implications of Floodplain Dating Results

Unfortunately, the presence of gravel and cobble prevented collection of floodplain samples from channel or bar deposits using hand equipment techniques, and no datable material was found within gravel or cobble layers exposed in the pits excavated by the backhoe. It is consequently not possible to say from the sample dating results described above when or if the main channel of the Middle Fork reworked a given section of floodplain. However, the

>1,000-year-old sample collected from the floodplain channel in E.J. Rogers Park and the >2,000-year-old samples collected from the north branch of the SE 120th Street channel indicate that any reworking along the pathway of the SE 120th Street floodplain channel may have been very long ago. Similarly, the sample at site 4, which probably represents the distal boundary (i.e., edge) of recent floodplain reworking in this area, indicates that the channel that potentially contributes flow to the Reid Slough channel may have been characterized by low energy for several hundred years.

The sample at site 2 indicates that rapid reworking of the floodplain occurred in pre-historic times within the Confluence and MF1a subreaches. The relatively young age of this oxbow lake, which is at the terminus of the Reid Slough channel, also implies that any headcutting at the downstream end of the Reid Slough channel may have occurred within the past several hundred years. However, the relatively steep slopes of the channel upstream from Reid Slough as well as the cobble present near the surface at site 4 imply that any headcutting did not progress rapidly upstream.

SEDIMENT BUDGET

The position of the study reach at the transition between a glacially-derived sedimentary deposit and an alluvial valley fill results in significant changes in sediment transport characteristics through the study reach. Both median sediment grain size and channel slope drop significantly through the reach, implying that at least the lower portions of the study reach are likely accumulating sediment under modern conditions. Farther upstream, long-term decreases in thalweg elevation and river stage (see Figures 8 and 9) imply that the channel bed has experienced a small net loss of sediment to the downstream reach over the past several decades. Additionally, streambank erosion represents a sediment source along much of the reach, particularly in the relatively low gradient Confluence subreach. There is probably a complex feedback between these processes along much of the study reach, with deposition in one location (e.g., on an in-channel bar) altering the flow field and leading to erosion at another location (e.g., at an eroding streambank).

This section presents a reach-scale accounting of sediment transport and storage. It provides estimates for the overall supply of sediment to the study reach and quantitatively accounts for the erosion and deposition of sediment in each of the three subreaches (MF2, MF1, and Confluence). Because it is not possible to measure every term in the sediment budget with great precision, the budget was developed iteratively using a range of sources, with the goal of developing realistic limits on the transport of sediment in the coarser size fraction (i.e., gravel and cobbles).

Types of Sediment Evaluated

When discussing sediment movement, distinguishing between relatively coarse sediment that moves as bed load (generally cobble, gravel, and some sand in the Middle Fork) and the much finer material that moves primarily in suspension (fine sand, silt, and clay) is traditional. It is also helpful to distinguish between sediment based on where it tends to be stored — for example, on the channel bed (bed material), on in-channel bars (bar material), or on the floodplain (floodplain material). The grain size distributions of sediment stored in each of these areas can vary significantly from location to location. However, for the purposes of this analysis, it is assumed that bed material and bar material consist primary of cobble, gravel and some sand, and that these size fractions move primarily as bedload. Floodplain material is assumed to consist of a mixture of old bar deposits (i.e., bar material) and suspendable sediment (typically fine-grained) deposited in overbank areas or within abandoned oxbow lakes during floods.

Sediment Supply and Transport

Overall sediment supply (yield) to the study reach was estimated using two separate, independent methods. The first involved application of the suspended sediment yield equation developed by Syvitski (2003), which provides a long-term yield over centuries or millenia. The second involved the use of published sediment yield estimates that were generally developed from data collected over periods of a few years to decades. These results were both compared to sediment transport capacity calculations performed using the Bedload Assessment in Gravel-bedded Streams (BAGS) model (Pitlick et al. 2009) at a representative location within the study reach. The sediment transport capacity computation provides an estimate of the bed material transport rate that could be achieved should sufficient sediment be supplied from upstream. Because it is driven by a period-of-record flow duration curve, it represents a decadal to century-scale average.

In gravel-bed rivers that are free to migrate laterally, sediment transport is often associated with geomorphic change, with bed material particles often not being transported more than a meander bend or two before being captured in a bar or stored on the bed (Friedkin 1945; Pyrce and Ashmore 2003). To the extent that particles do not bypass geomorphic features such as bars, sediment transport in such reaches should be relatively closely related to rates of geomorphic change. Where this is the case, sediment budgets can be produced from measurements of geomorphic change, an approach that is relatively common in wandering gravel bed rivers (Lane 1997; McLean and Church 1999; Ham and Church 2012). While subreach MF2 does not appear to experience rapid geomorphic change and is probably best considered to be a transport reach, both the MF1 and Confluence subreaches are set at a natural zone of sediment accumulation and are thus appropriate for a morphometric sediment budget. A subreach scale sediment budget was developed for the study reach by computing the difference between 2002 and 2010 lidar-based DEMs of the reach, supplemented where possible using County cross-section surveys performed in 1993 and 2010. The sediment budget provides estimates of the net storage of bed/bar material sediment (sand, gravel, and cobble) and of overbank fines (fine sand, silt, and clay) in the MF2, MF1, and Confluence subreaches.

Syvitski Model of Sediment Yield

The Syvitski model was originally developed for determining the supply of sediment to the global ocean over geological time scales (i.e., thousands to millions of years). Because the governing equation includes variables known to influence sediment production such as topographic relief, precipitation rates, and latitude, it provides a first-order estimate of what might be expected (based on global averages) from a basin the size of the Middle Fork Snoqualmie River watershed. Because the Syvitski model was developed using a global dataset, it does not directly account for local-scale processes such as glacial history, though those effects are indirectly accounted for since the empirical parameters are latitude dependent. The large glacial Middle Fork Embankment and relatively low slope of the channel upstream of the Embankment probably limit sediment movement from the watershed as a whole into the study reach. For this reason, the Syvitski model may overstate sediment supply to the study reach. However, it provides a first order estimate of possible yield. The governing equation of the model is the following:

$$Q_s = 6.15 \times 10^{-5} A^{0.55} R^{1.12} e^{0.07T} \qquad (1)$$

Where: Q_s is the long-term average sediment input (kilograms per second)
A is the basin area (square kilometers, km^2)
R is the maximum relief in the basin (meters)

e is the base of the natural logarithm, approximately equal to 2.718
T is the calculated average annual temperature throughout each subbasin (degrees Celsius)

The average annual temperature (T) is frequently not known and therefore must be estimated from an elevation-based equation:

$$T = T_0 - LH \quad (2)$$

Where: L is the lapse rate of the atmosphere (i.e., the decrease in temperature with elevation above sea level [calculated to be 7.43°C/km for the Middle Fork Snoqualmie River basin])
T_0 is the measured average annual temperature
H is the average basin elevation (kilometers).

For the purposes of this analysis, the average annual temperature at NOAA's National Weather Service (NWS) Cooperative weather station (station #457773) near Snoqualmie Falls, 10.2°C, was used to define the average annual temperature.

Geographic information system (GIS) spatial analyst tools were used to delineate the Middle Fork Snoqualmie River watershed boundary from a US Geological Survey 10-meter DEM (USGS 2001) of the basin. The size of the drainage basin and its maximum, minimum, and average elevations were used in the Syvitski model calculations.

GIS spatial analyst results yielded a basin area of 171 square miles (mi^2) (443 km^2), with maximum and minimum elevations ranging from 410 to 7,600 feet (125 to 2,317 meters). The area-averaged elevation is 3,560 feet (1,086 meters). These parameters result in an estimated sediment yield entering the study reach of 2,062 tons/mi^2/year (876 Mg/km^2/year).

Regional Sediment Yield Estimates

Nelson (1971) presents a long-term suspended sediment yield estimate for the Middle Fork Snoqualmie River of 638 tons/mi^2/year (105 Mg/km^2/year) based on suspended sediment concentration measurements made near the Tanner gage between October 1967 and June 1969 and on a 7-year discharge record. Assuming suspended load is 85 percent of total load, as assumed by Syvitski et al (2005), this corresponds with a total yield estimate of 750 tons/mi^2/year (263 Mg/km^2/yr). Because the time period of that study was relatively short, additional sediment yield data for other Puget Sound river basins were compiled based on studies by Downing (1983), Wise et al. (2007), and Czuba et al. (2011). Table 7 summarizes the results. Data are presented from rivers ranging in basin area from 16 mi^2 (130 km^2) for the Wallace River to 84,970 mi^2 (220,065 km^2) for the Fraser River.

Reported yield values from Downing (1983) and Wise et al. (2007) are based on short-term measurements of suspended sediment transport. Nelson (1971) and Czuba et al. (2011) report total sediment yield, again based on relatively short-term measurements. Because short-term measurements likely miss the largest events that transport most sediment, they will necessarily be less than the long-term averages estimated by the Syvitski model (Mastin et al. 2008). For the purposes of comparison with Syvitski model results, the sediment yield results reported by Downing (1983) and Wise et al. (2007) were revised upward to represent total yield rather than suspended sediment yield, based on the assumption that suspended sediment is 85 percent of total sediment yield, consistent with assumptions made by Syvitski et al. (2005). While estimates of bedload to total load ratios are rather uncertain and range from 2 percent for the gravel component of the Fraser River near Hope, British Columbia, (Ham and Church 2012) to as high as 35 percent for a steep Himalayan river (Pratt-Sitaula et al. 2007), uncertainty in the ratio of bedload to total load does not greatly affect the conversion between suspended load and total sediment yield. Some basin areas in the Downing (1983) study were unreported (the Hamma Hamma, Duckabush, Dosewallips, and Quilcene river basins). For those areas, basin area was measured using GIS, and sediment yield was then computed by dividing reported sediment load by basin area. The overall average yield for all rivers in the dataset is 567 tons/mi^2/year (219 Mg/km^2/year).

Many of the rivers listed in Table 7 drain watersheds that are either much larger or much smaller than the Middle Fork Snoqualmie River watershed. In addition, the headwater areas of several of the rivers listed in the table are located amid geologically active slopes of Cascade Range volcanoes and are thus likely to have much greater sediment supply than the Middle Fork. In order to develop a yield estimate that is most likely to represent long-term sediment supply to the study reach, an average yield was computed for all basins in the dataset with drainage areas between 50 and 500 mi^2 (130 and 1,300 km^2). While somewhat arbitrary, this selected subset results in the exclusion of all rivers draining Cascade volcanoes and also excludes most of the small Olympic Peninsula basins that have a significantly different glacial history and lithology than the Cascades. The average sediment yield computed using this approach is 413 ton/mi^2/year (159 Mg/km^2/year).

Sediment Transport Capacity Estimates

The sediment yield estimates described above were compared to sediment transport capacity as computed using the BAGS computer model, which performs sediment transport computations using a range of published transport equations. Computations depend on sediment grain size distribution, channel slope, long-term average flow duration curve, channel roughness, and channel cross-sectional geometry. With the possible exception of the flow duration curve, none of these variables are uniform throughout the study reach. Consequently, a representative location was selected mid-way through the reach, at RM 1.0, where channel slope drops from 0.424 percent (average top-of-bank slope between RM 1.9 and RM 1.0) to 0.285 percent (average top-of-bank slope between RM 1.0 and RM 0). Upstream of this location, the greater slope and large boulders present on the bed indicate that the river is only partly alluvial, meaning that the geomorphic configuration of the bed is not strongly coupled with sediment load except when a large pulse of sediment moves through. Actual transport rates in the study reach are probably limited primarily by upstream sediment supply. With the exception of gravel bars near the Mason Thorson Extension and Mason Thorson Ells levees, there are minimal long-term bed material storage opportunities upstream of RM 1.0. Downstream of RM 1.0, below the slope break at the transition to the historic meandering river floodplain, large gravel bars indicate the potential for large amounts of bed material storage, implying that the downstream part of the study reach is depositional. For the purposes of the computation, sediment grain size was characterized in

Table 7. Sediment Yield from Puget Sound River Basins.

River Basin	Basin Area (mi^2)	Total Sediment Yield ($tons/mi^2/year$)
Deschutes[b]	170	227
Deschutes[c]	96	314
Dosewallips[f]	77	418
Duckabush[c]	66	125
Duckabush[d]	66	248
Duwamish River[c]	459	250
Duwamish[b]	500	462
Fraser[b]	84,967	259
Hamma Hamma[d]	58	218
Middle Fork Snoqualmie River near Tanner[a]	154	750
Nisqually[b]	770	171
Nooksack[c]	737	1,337
Nooksack[d]	786	785
North Fork Skykomish River near Index[a]	146	148
North Fork Snoqualmie River near North Bend[a]	96	502
North Fork Snoqualmie River near Snoqualmie Falls[a]	64	353
Puyallup[c]	919	1,763
Puyallup[d]	366	1,688
Quilcene[d]	50	129
Raging River near Fall City[a]	31	265
Skagit River[c]	2,324	687
Skagit[b]	3,199	963
Skagit[d]	3,093	473
Skokomish[c]	131	1,480
Skokomish[d]	88	1,927
Skykomish River at Gold Bar[a]	535	517
Skykomish River at Monroe[a]	834	510
Snohomish[c]	1,714	225
Snoqualmie River near Carnation[a]	600	602
Snoqualmie River near Snoqualmie[a]	375	702
South Fork Skykomish River near Index[a]	355	408
South Fork Snoqualmie River above Alice Creek near Garcia[a]	42	90
South Fork Snoqualmie River at North Bend[a]	82	828
Stillaguamish[d]	684	27
Sultan River at Sultan[a]	106	475
Tolt River at Carnation[a]	101	713
Wallace River at Gold Bar[a]	19	145
Woods Creek near Monroe[a]	56	346

[a] Source: Nelson (1971), digitized from Figure 16 therein.
[b] Source: Czuba et al. (2011).
[c] Source: Wise et al. (2007).
[d] Source: Downing (1984).
Notes: Annual Sediment Yield totals have been manipulated for comparison purposes.
Where basin areas were not reported, Herrera calculated the basin area.
Suspended sediment loads reported were assumed to be 85 percent of total sediment load.

this depositional reach, near the head of the mid-channel bar at RM 0.7. The surface grain size distribution was measured using a surface pebble count performed at the head of the bar in September 2012. The pebble count characterizes the surface armor on the upstream face of a gravel bar within an approximately 50 foot square zone roughly mid-way between the bar crest and the low-flow water surface elevation. A subsurface grain size distribution was also measured in this area by removing a single layer of surface cobble and excavating approximately 100 pounds of sediment from the underlying deposit. This material was sieved by King County (see Appendix B). Results are presented in Figure 10. Because sediment deposited near the head of the bar is probably similar to bed material sediment that was in transit in the upstream reach during periods of bar growth, the bar represents a reasonable proxy for bed material in the reach immediately upstream.

The BAGS model presents bedload sediment transport capacity based on four equations: Parker (1990), Parker et al. (1982), Parker and Klingeman (1982), and Wilcock and Crowe (2003). Each of these equations represents transport differently and includes slightly different input parameters. However, because their sensitivity to input parameters varies, in total they provide a range of the possible rates of transport that might be expected given the sediment observed at the site and the hydraulic and geomorphic characteristics of the reach represented by the computation.

Table 8 presents the results of the BAGS computations using either the higher slope of 0.424 percent (RM 1.9 to RM 1.0) or the lower slope of 0.285 percent (RM 1.0 to RM 0). The results of the regional yield computations presented above are shown in Table 8 for comparison. For this comparison, the regional sediment yield computations were partitioned into suspended load and bedload components by assuming that bedload is 15 percent of the overall yield. In general, the yield-based bedload estimates are somewhat higher than the transport capacity computations. However, given the somewhat arbitrary nature of the 15 percent conversion between overall yield and bedload yield, and given the expectation that the Syvitski method overpredicts typical sediment discharge because it includes extreme events that the other methods do not, the agreement in the results is quite good.

Averaging the BAGS transport calculations performed for the lower slope reach (RM 1.0 to RM 0) provides a bedload transport capacity estimate on the order of 800 tons/year. There is significant variability in this estimate from equation to equation within the BAGS model. Because sediment transport equations can give wide-ranging results when shear stresses are just above the threshold of motion, this indicates that hydraulic conditions are probably barely capable of mobilizing bed material downstream of RM 1.0, particularly larger cobbles. This is consistent with the observed downstream fining present in the channel substrate in the MF1 and Confluence subreaches. On the other hand, because sediment size decreases rapidly downstream of RM 1.0, the capacity to transport the material that is present on the bed near the confluence with the North Fork may be higher than the average of roughly 800 tons/year indicated by the BAGS computations.

The average transport rate calculated using the higher channel slope (between RM 1.0 and RM 1.9) is on the order of 8,700 tons/year. However, because the grain size distribution on the bed at RM 1.0 is probably somewhat coarser than on the bar at RM 0.7, the actual capacity for transporting sediment through the reach immediately upstream of the cross section used for the computation is probably somewhat less than indicated by the 8,700 tons/year average estimate. In addition, the relatively steep slope in the channel upstream of RM 1.0 may be controlled primarily by the presence of the large boulders that are exposed on the bed, particularly upstream of RM 2.0. To the extent that these boulders were supplied by processes that have no modern analog (e.g., if the erosion of relatively coarse near-channel deposits placed during deglaciation represents a local source of very large material), the channel may be sediment supply limited. If so, it would not ordinarily be expected to achieve its full transport capacity. In any case, the BAGS computations indicate that the bedload flux at RM 1.0 is most likely in the range between 800 and 8,700 tons/year. It is also worth noting that the Parker (1990) and Wilcock and Crowe (2003) equations are sensitive to the sand fraction in the bed material size distribution used as input. In these calculations, no sand was specified in this area because sand was not included in the surface pebble count. If sand were included, the results would be somewhat higher.

Table 8. Bedload Transport Estimates at RM 1.0 Computed Using BAGS Computer Program and Estimated Using Regional Yield Data.

Source	Annual Sediment Yield (tons/mi^2/year)	Suspended Load (tons/year)	Bedload (tons/year)
Nelson (1971) for Middle Fork Snoqualmie River @ Tanner, 154 mi^2 basin	750	98,200	17,300
Average from literature, 50 mi^2 < basin area < 500 mi^2, 171 mi^2 basin	567	82,300	14,500
Syvitski, entire Middle Fork Snoqualmie River basin (171 mi^2)	2,270	330,000	58,200
BAGS computation, S = 0.00285 (average RM 0-RM 1)			
Parker (1990)	–	–	1,000
Parker-Klingeman-McLean equation (Parker et al. 1982)	–	–	800
Parker and Klingeman (1982)	–	–	900
Wilcock and Crowe (2003)	–	–	400
Average	–	–	800
BAGS computation, S = 0.00424 (average RM 1-RM 1.9)			
Parker (1990)	–	–	8,500
Parker-Klingeman-McLean equation (Parker et al. 1982)	–	–	12,600
Parker and Klingeman (1982)	–	–	10,900
Wilcock and Crowe (2003)	–	–	2,800
Average	–	–	8,700

As an independent check on the BAGS computer model, the recently published sediment transport equation of Recking (2013) was used to estimate bedload transport. To simplify the computation, a simplified rectangular cross section was used to estimate flow depth at each bin of the flow duration curve used to drive the BAGS model. The Recking (2013) equation is developed for total load estimates from a large dataset of transport rates observed in the field (rather than flume data) and is not as sensitive to the sand fraction in the bed as the equations used in BAGS. It also includes an empirically derived friction coefficient that depends on the surface size distribution, thereby removing the sensitivity of BAGS sediment transport estimates to the estimate of Manning's roughness. When the Recking (2013) equation is used, the results are 13,900 and 4,600 tons/year for the upper and lower reaches, respectively, broadly consistent with the BAGS results.

Subreach Scale Sediment Budget Based on Cross-sections and DEMs

In gravel-bedded rivers, high rates of sediment transport are typically associated with high rates of geomorphic change (Ham and Church 2012). Bars can be very efficient at capturing and storing bed material, which is only remobilized once the surface armor in the bar breaks up or when the channel thalweg changes position in response to large-scale reorganization of the flow caused by regular bar growth and bank erosion (Van De Weil and Coulthard 2010; Ham and Church 2012). Because the lower part of the study reach is characterized by numerous potential sediment storage zones that include both mid-channel bars and point bars, measurements of geomorphic change can be used to independently verify whether the sediment yield calculations presented above are reasonable.

This section presents a sediment budget that quantifies the volumetric change rates in each of the three subreaches in the study area: MF2, MF1, and Confluence. The budget is primarily developed for the period between 2002 and 2010, although cross-section surveys collected in 1993 and 2010 supplement the analysis. Estimates are made of how much of the overall volumetric change observed in this time period is associated with bed/bar material (i.e., cobble, gravel, and sand) and how much is associated with erosion of floodplain fines (i.e., fine sand, silt, and clay). Data were of insufficient quality to estimate the storage of floodplain fines on vegetated surfaces near the river.

In principle, overall in-channel geomorphic change in a given time period can be quantified by calculating the difference between two high-resolution DEMs and/or by looking at topographic change along a series of closely-spaced channel/floodplain cross sections. However, while a simple cut/fill analysis (based either on DEMs or cross sections) produces results that characterize overall mass movement, it cannot distinguish, at least in isolation, between relatively coarse bed/bar material and the much finer sediment usually stored on the floodplain and in channel banks. Furthermore, when change is measured using lidar-based DEMs, there are usually questions regarding the accuracy of the topography and bathymetry. The bathymetry in particular is questionable in lidar-based DEMs because the data collection method cannot accurately detect the channel bed below the water surface. Lidar vendors usually address this by masking the water surface visible in an image taken near the time of the flight and disregarding all returns from this area or by filtering out the poor returns that occur from inundated areas. Either way, a lidar-based DEM does not represent the bed in inundated areas. Cross-sections surveyed in the field usually capture adequate bathymetry, but it is difficult to ensure that cross-sections are spaced closely enough to adequately describe the full range of geomorphic change. Where planform changes are large, cross-section surveys are particularly problematic because it becomes difficult to reoccupy old cross-sections.

The approach taken for this analysis involves the use of two lidar-based DEMs, one from 2002 and the other from 2010, supplemented by cross-section surveys performed by the County in 1993 and 2010. Sediment grain size and potential inaccuracies in the DEMs were accounted for by classifying the study reach into several categories based on estimates of whether a given surface was vegetated, dry, or inundated at the time of each respective lidar survey. In places that were characterized by bare ground in both surveys, the cut/fill computed from DEM differencing procedures was assumed to represent bed/bar sediment material. In places that were likely inundated during both lidar surveys, reach-average change computed from the cross-section surveys was used to estimate volumes of eroded and/or deposited sediment. Where water was present during one lidar survey and bare ground was present in the same area in the other lidar survey, volumetric change was computed by DEM differencing and then adjusted to account for the likely error in the DEM in inundated areas.

Eroding streambanks within the lower parts of the study reach where bank erosion is most active generally consist of a layer of floodplain fines above a gravel/cobble layer, as shown in Figure 15. While the relative thickness of the two layers varies from bank to bank, the overall average fines content is probably at least 50 percent and could be significantly higher. Much of the volumetric change in sediment storage in the study reach results from the erosion of banks similar to that shown in Figure 15. Consequently, it is necessary to partition the total volume of material eroded from vegetated surfaces into two classes: floodplain fines (i.e., silt, sand, and clay) and coarse bed/bar material. In order to test the sensitivity of the sediment budget to this parameter, computations were performed using reach average fines contents of 50, 65, and 80 percent, representing what were judged to be low, mid-range, and high values for possible fines content in the banks.

DEM Representing Difference Between 2002 and 2010/2011 Topographic Datasets

The first step in the subreach scale sediment budget analysis involved developing a DEM "of difference" for the channel corridor. This DEM was produced by subtracting the 2002 lidar surface from the 2010/2011 bathymetric surface that serves as input to the hydraulic model for the reach. Because the hydraulic model (WSE 2013) did not extend all the way downstream to the South Fork, there is a short region in the Confluence subreach where 2010/2011 bathymetry is not available. In this area, topography generated from the 2010 lidar was used even in inundated areas. The DEM of difference produced by this procedure is presented in Figure 16. The most significant volumetric changes in the study reach evident in this analysis were the erosion of cut banks in the Confluence and MF1 subreaches.

The quality of the DEM of difference depends on whether a given area was inundated during the 2002 and/or 2010 lidar surveys. To identify inundated areas, polygons representing the water surface were developed for both 2002 and 2010. Because aerial imagery is not available for 2002 close to the time the lidar survey was performed, the water surface was delineated by hand using GIS based on the apparent point density of the survey in the 2002 lidar-based DEM. Areas with low point density (and thus low surface resolution) were assumed to represent water. The 2010 water surface was drafted based on aerial imagery collected concurrently with lidar, during the period between March 18 and March 20, 2010. The average daily discharge at the Tanner gage during this period was 482 cfs. For floodplain areas, the quality of the lidar also depends on whether vegetation was present on the date of the survey. The channel bank delineations provided by King County were assumed to represent the boundary between vegetation and water/bare sediment. Together, these datasets were used to classify the near-channel corridor into three categories: water, bare sediment, or vegetated areas. For simplicity, these areas are referred to as water, bar, or floodplain in the following discussion. The results of this classification process are superimposed on the DEM of difference in Figure 16.

Figure 15. Typical Cut Bank in Confluence Subreach Showing Relatively High Content of Fine-grained Sand/Silt/Clay at the Top of Bank.

Cross-Section Analysis

King County surveyed a total of 45 cross-sections within the study reach in 1993. These cross-sections are shown in Figure 16 and have been given six-digit identification codes, with the last digit being zero (e.g., section MS-1020). Bed and bank elevations were surveyed at all 1993 cross-sections except at sections MS-1010, MS-1060, and MS-1450, where much of the in-channel data is missing. Sections with missing in-channel data were excluded from all subsequent analysis.

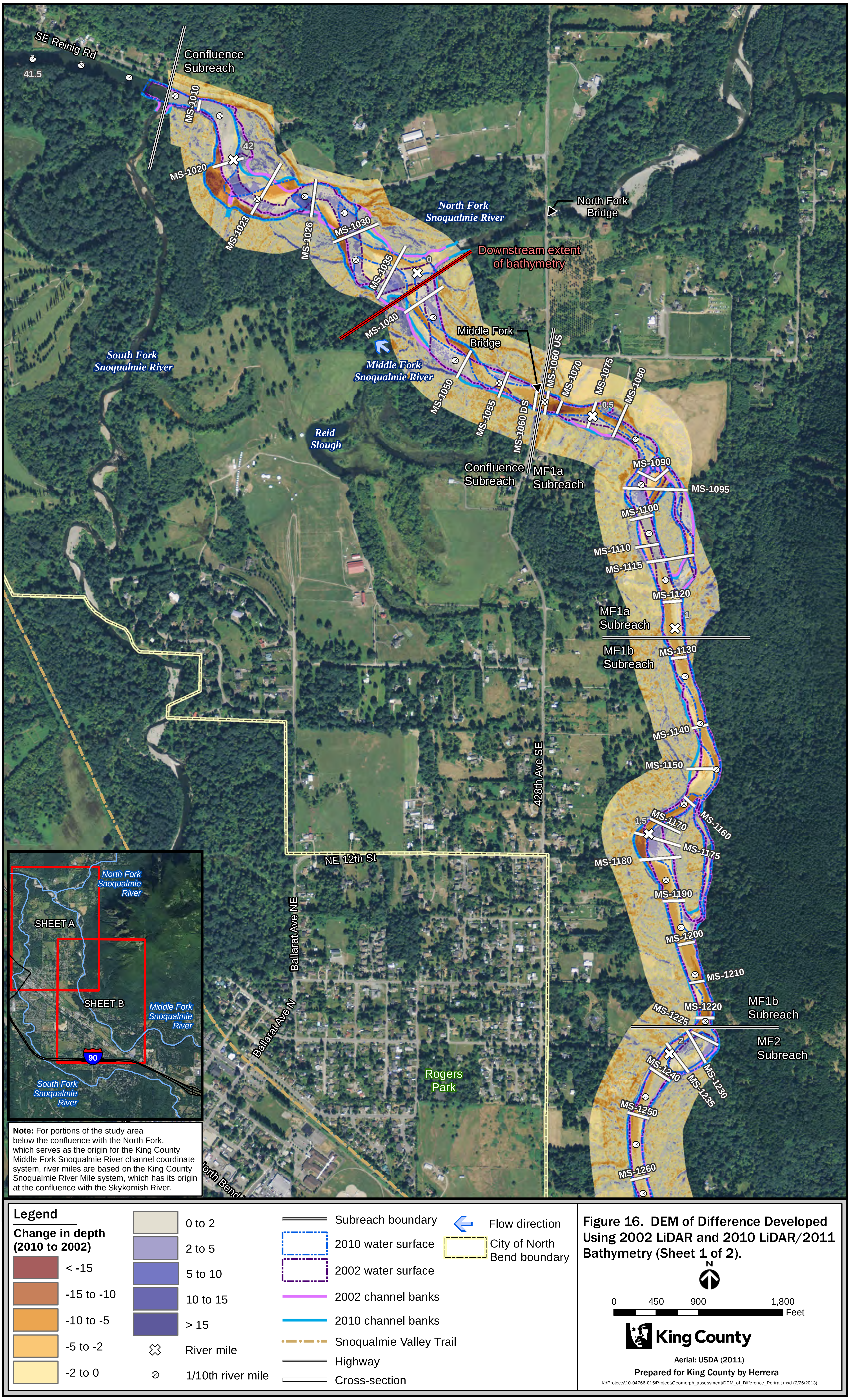
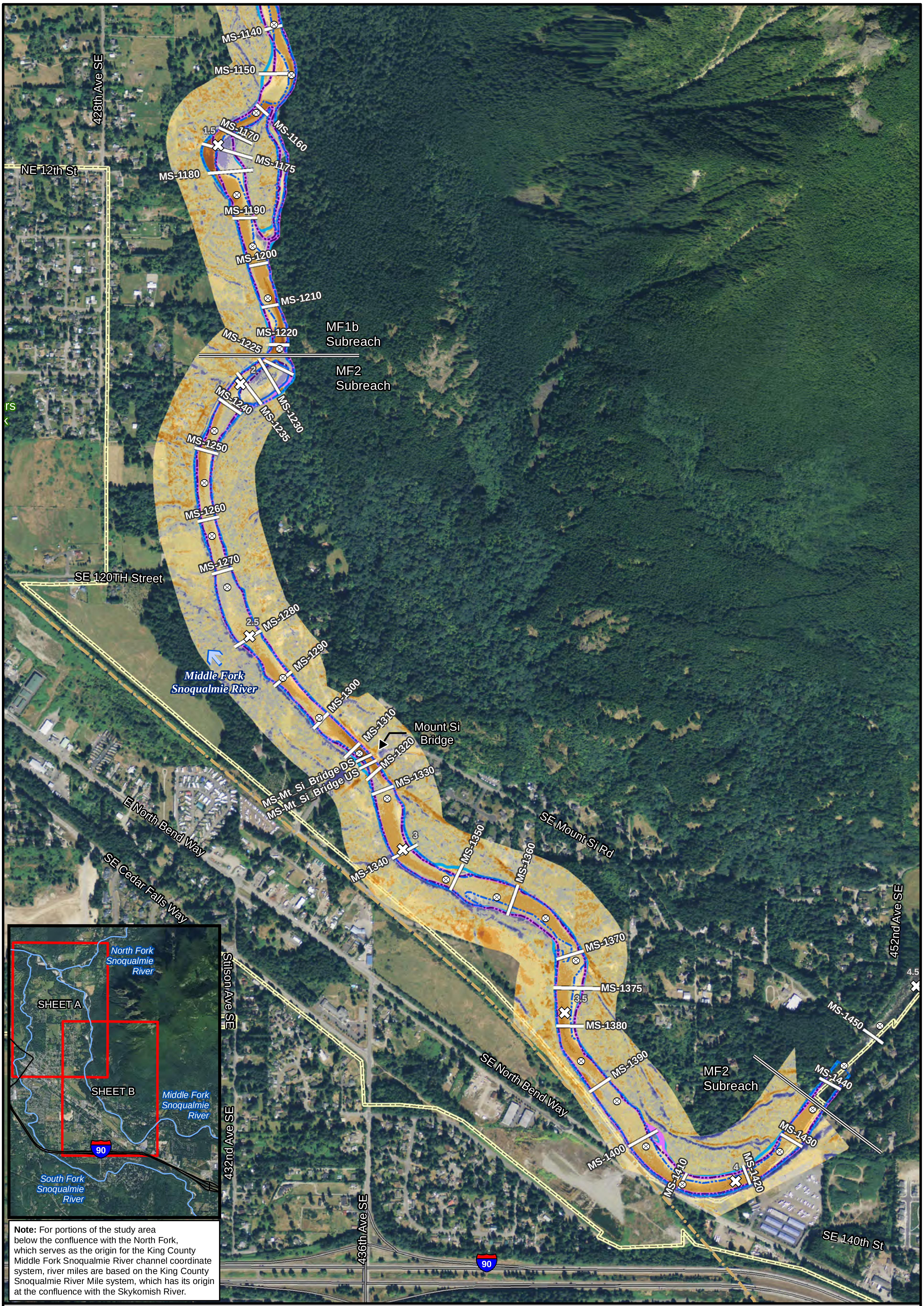


Figure 16. DEM of Difference Developed Using 2002 LiDAR and 2010 LiDAR/2011 Bathymetry (Sheet 1 of 2).



Note: For portions of the study area below the confluence with the North Fork, which serves as the origin for the King County Middle Fork Snoqualmie River channel coordinate system, river miles are based on the King County Snoqualmie River Mile system, which has its origin at the confluence with the Skykomish River.

Legend

Change in depth (2010 to 2002)

- < -15
- -15 to -10
- -10 to -5
- -5 to -2
- -2 to 0
- 0 to 2
- 2 to 5
- 5 to 10
- 10 to 15
- > 15
- River mile
- 1/10th river mile
- Subreach boundary
- 2010 water surface
- 2002 water surface
- 2002 channel banks
- 2010 channel banks
- Snoqualmie Valley Trail
- Highway
- Cross-section
- Flow direction
- City of North Bend boundary

Figure 16. DEM of Difference Developed Using 2002 LiDAR and 2010 LiDAR/2011 Bathymetry (Sheet 2 of 2).

N

0 450 900 1,800 Feet

King County

Aerial: USDA (2011)

Prepared for King County by Herrera

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The County resurveyed the 1993 cross-sections in 2010. While monuments marking the end points of the sections were not found except in special cases, the differential GPS technology used for the survey ensures that the horizontal accuracy of the repeated sections is within a few meters of the original section position (M. Ruebel, personal communication). Additional sections (with identification codes ending in a non-zero digit) were added for the 2010 survey.

Change in cross-sectional area during the 1993 to 2010 time period was calculated at each cross-section. Results of these calculations are presented in Figure 17. Average bed elevation change rates were also calculated based on the total area of cross-sectional change divided by the width over which change was judged to have occurred, which generally corresponds with the banktop width of the channel. Average rates of bed elevation change resulting from these calculations are shown in Figure 18. In general, the analysis shows net evacuation of sediment within the Confluence subreach, variable results in sub-reachsubreach MF1, and moderate incision in subreach MF2. In subreach MF2, the rates of incision (average of 0.051 feet per year) are similar to the long-term trend in stage at the Tanner gage presented in Figure 9. Consequently, the cross-sections appear to characterize change reasonably well in laterally stable parts of the system. However, in the laterally active lower part of the Confluence subreach below the confluence with the North Fork, only two repeat cross-section surveys are available (MS-1020 and MS-1030). It is unlikely that this is a sufficient number to adequately characterize geomorphic change in the Confluence subreach. In addition, as in the DEM of difference analysis, it is unclear from the cross-sections alone how to partition the topographic change between bed/bar material and floodplain fines. No attempt at partitioning between coarse and fine material was made.

Table 9 presents the number of repeat cross-sections in each subreach, the subreach boundaries, subreach-averaged rates of bed elevation change, total 1993 to 2010 change in sediment storage volume computed using the average end area method, and the calculated 17-year average sediment accumulation rate. Volumetric results are not presented for the Confluence subreach because of the small number of cross-sections and extensive channel and floodplain planform change in that area. While these calculations indicate that average bed elevation decreased in all subreaches, the volumetric calculation shows net storage of sediment in subreach MF1 due to focused deposition in several large bar complexes.

Table 9. Subreach Average Results from Surveyed Cross-section Analysis, 1993-2010.

Subreach	Subreach Boundaries	Number of Repeat Cross-sections Surveyed	Average Rate of Bed Elevation Change (ft/yr)	Total Change in Sediment Storage Volume, 1993 to 2010 (yd^3)
Confluence	< RM 0.4	4	-0.090	N/A
MF1	RM 0.4 to RM 1.9	16	-0.023	28,100
MF2	> RM 1.9	23	-0.032	-54,500

Hybrid Sediment Budget Derivation

Because it is difficult to interpret either the DEM of difference or the cross-section surveys in isolation, a hybrid sediment budget was developed using data from both sources. Volumetric change for areas submerged during both the 2002 and 2010 lidar surveys was estimated using reach-average rates of bed elevation change computed from the 1993 and 2010 cross-sections. Volumetric change for other areas was estimated using the lidar-based DEM of difference and several assumptions regarding water depth in inundated areas at the time of the lidar surveys. In general, lidar best characterizes geomorphic change in areas where large amounts of lateral erosion occurred. This is the case for both the Confluence and MF1 subreaches. In these subreaches, the hybrid sediment budget results are probably most representative of average rates of change for the 2002 to 2010 time period. Where lateral channel change was and is not occurring rapidly, such as in subreach MF2, the lidar-based DEM of difference does not show large rates of volumetric change relative to those derived from the cross-section surveys. For this reach, the hybrid analysis is probably most representative of the 1993 to 2010 time period.

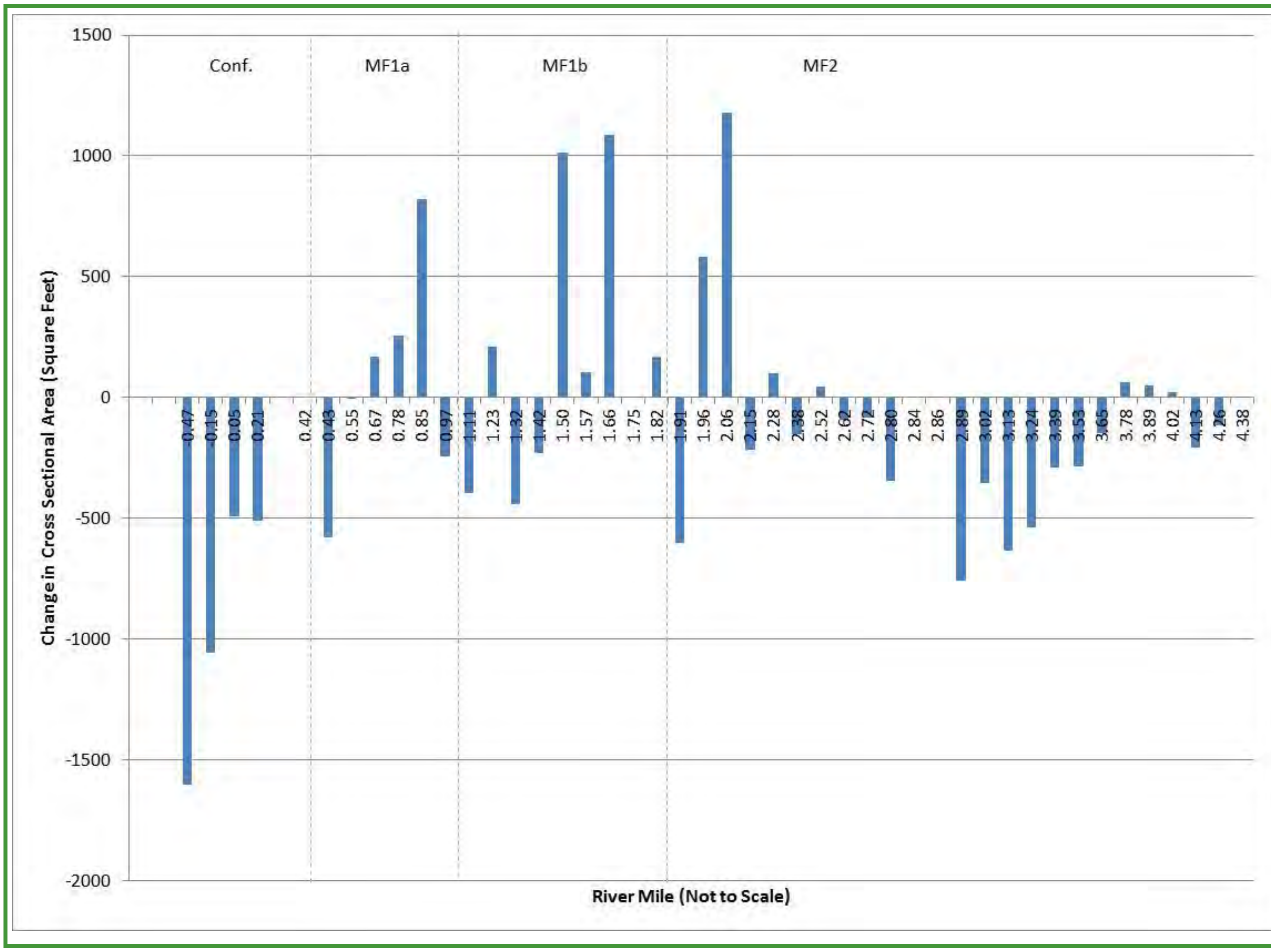

Figure 17. Total Change in Cross-sectional Area at Surveyed Cross-sections Between 1993 and 2010.

The details of the computation depend on the type of change experienced in a given area of the study reach. Based on the classification of near-channel area into three types (Water, Bar, or Floodplain) for each lidar survey, there are a total of six possible classes of change and three possible classes of stasis (i.e., no change). The nine possibilities are: Water→Bar, Water→Floodplain, Floodplain→Bar, Floodplain→Water, Bar→Floodplain, Bar→Water,

Water→Water, Bar→Bar, and Floodplain→Floodplain. Because neither DEM is of sufficient accuracy to identify changes that occurred entirely within vegetated areas of the floodplain, the Floodplain→Floodplain class was dropped from further analysis, leaving eight classes. Overall topographic change and net storage or evacuation of bed/bar material and of floodplain fines was estimated for each of these eight classes in each subreach, as described in Appendix C.

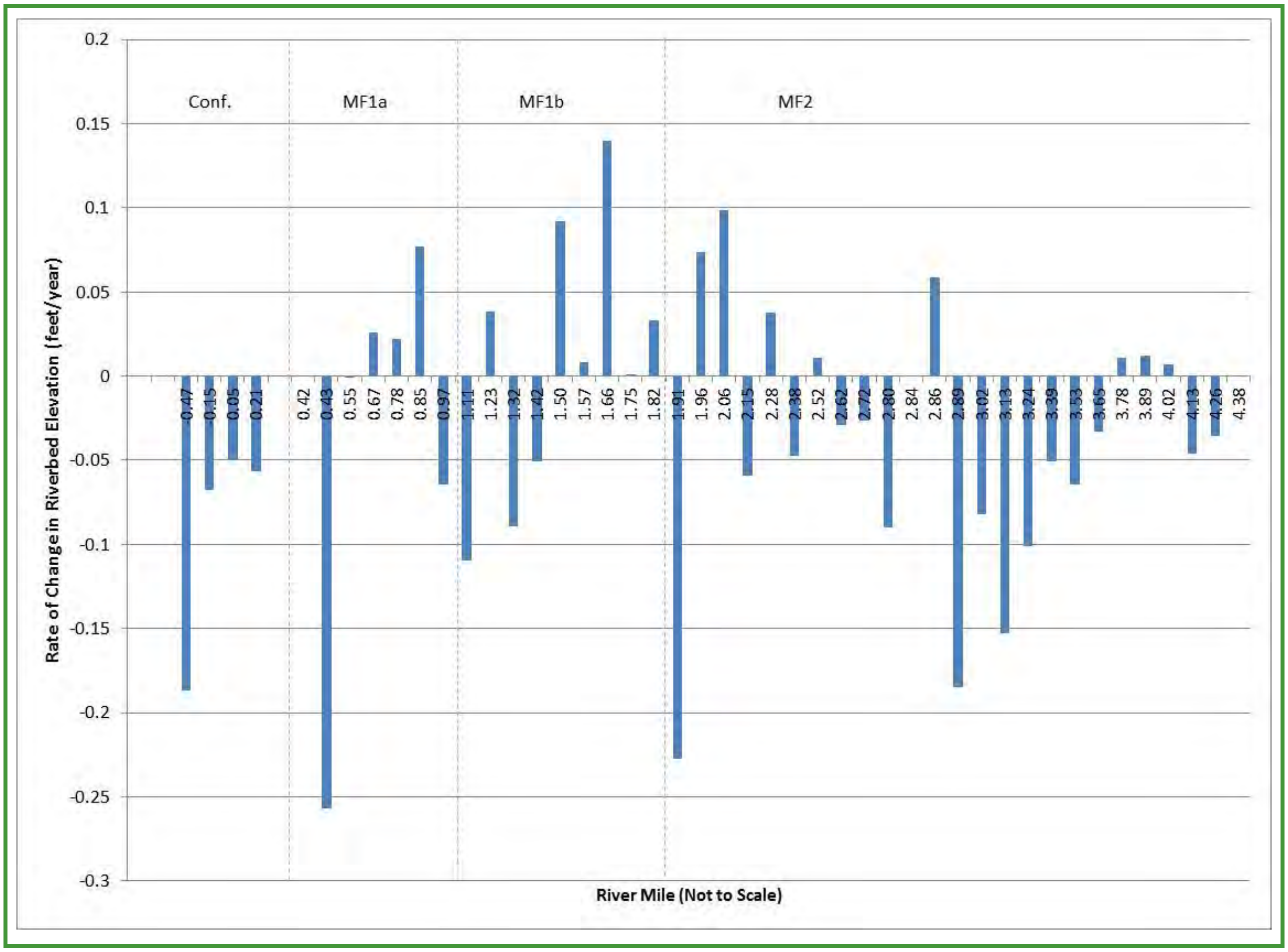

Figure 18. Average Rate of Change of Bed Elevation at Surveyed Cross-sections Between 1993 and 2010.

Results of Hybrid Subreach Scale Sediment Budget

Because the sediment budget calculations are sensitive to the fines content of eroding floodplain material, computations were performed three times, one each for fines contents of 50, 65, and 80 percent. Tabular summaries of cut/fill results for each class of channel change in each subreach are presented in Appendix C. In general, volumetric change was greatest for 1) the Floodplain→Water class in the Confluence subreach, and 2) the Water→Bar class in the Confluence and MF1 subreaches.

Table 10 presents the subreach average volumetric sediment accumulation rates for either bed/bar material or floodplain fines computed for each of the three assumed fines fractions. Table 11 presents estimated subreach specific rates of mass change, assuming gravel has a bulk density of 2.1 grams per cubic centimeter (g/cm^3) and floodplain fines have a bulk density of 1.3 g/cm^3 (Bunt and Abt 2001). Negative numbers in the table represent net sediment export. Positive numbers represent net sediment accumulation. In all cases, the results show export of both floodplain fines and bed material from the Confluence subreach, storage of bed/bar material and export of fines from subreach MF1, and export of both bed/bar material and fines from subreach MF2. However, because the analysis does not account for deposition of fines on vegetated floodplain surfaces, it is not possible to rule out net storage of fines in any subreach. With respect to bed/bar material, there is a rough correspondence between net erosion in subreaches MF2 and Confluence and net deposition in subreach MF1, particularly for the higher floodplain fines fractions of 65 and 80 percent.

Table 10. Volumetric Summary of DEM-based Sediment Budget Computations, by Subreach.

	Fines Fraction = 50%		Fines Fraction = 65%		Fines Fraction = 80%	
Reach	**Bed/Bar Material Storage Rate (yd^3/yr)**	**Floodplain Fines Storage Rate [a] (yd^3/yr)**	**Bed/Bar Material Storage Rate (yd^3/yr)**	**Floodplain Fines Storage Rate [a] (yd^3/yr)**	**Bed/Bar Material Storage Rate (yd^3/yr)**	**Floodplain Fines Storage Rate [a] (yd^3/yr)**
Confluence	-5,400	-6,400	-3,400	-8,300	-1,500	-10,300
MF1	1,200	-1,400	1,700	-1,800	2,100	-2,200
MF2	-1,000	-700	-800	-900	-600	-1,200
Total for Study Area	-5,200	-8,500	-2,600	-11,100	-100	-13,700

[a] Neglects overbank deposition.

Table 11. Mass Summary of DEM-based Sediment Budget Computations, by Subreach.

	Fines Fraction = 50%		Fines Fraction = 65%		Fines Fraction = 80%	
Reach	**Bed/Bar Material Storage Rate (tons/yr)**	**Floodplain Fines Storage Rate [s] (tons/yr)**	**Bed/Bar Material Storage Rate (tons/yr)**	**Floodplain Fines Storage Rate [a] (tons/yr)**	**Bed/Bar Material Storage Rate (tons/yr)**	**Floodplain Fines Storage Rate [a] (tons/yr)**
Confluence	-9,500	-7,000	-6,100	-9,100	-2,700	-11,200
MF1	2,200	-1,500	2,900	-2,000	3,700	-2,400
MF2	-1,800	-800	-1,500	-1,000	-1,100	-1,300
Total for Study Area	-9,100	-8,500	-4,600	-12,200	-100	-15,000

[a] Neglects overbank deposition.

For any of the assumed floodplain fines fractions, the results presented in Tables 10 and 11 indicate that geomorphic change within the Confluence subreach should have resulted primarily in the export of fine-grained material. However, there is a large amount of uncertainty regarding the interpretation of the sediment budget in the Confluence subreach, particularly with respect to bed/bar material. Depending on the fraction of floodplain fines, the calculations indicate a bed/bar material export rate of between 2,700 and

9,500 tons/year (2,500 and 8,600 Mg/yr) from the subreach. This is somewhat at odds with the idea that the Three Forks area is depositional for bed material (Booth et al.1991) and with observations of numerous sediment storage locations in the subreach. However, the sediment budget computation is sensitive to several parameters that are difficult to accurately define and whose impact is not represented in the results of Tables 10 and 11. These include 1) the average bed elevation change rate, which is based on the four available cross-section surveys in the subreach, and 2) the assumption of the flow depth at the time of the 2002 lidar survey, which might reasonably be expected to be deeper in the relatively low slope Confluence subreach than at the Tanner gage where the 1.2 foot depth estimate was made. To address the sensitivity of the budget to these parameters, both were iteratively adjusted until the sediment budget calculations showed no net removal of bed material in the Confluence subreach for the mid-range floodplain fines estimate (65 percent). In the case of average bed elevation change, an average bed aggradation rate of 0.08 feet per year in the Confluence subreach, rather than the incision rate of 0.09 feet per year as computed from the four available cross-sections (see Table 9), is sufficient to result in calculated net storage of bed/bar material in the Confluence subreach. If the average depth of water is assumed to be 3.0 feet in conjunction with the 2002 lidar survey, the calculation results for the Confluence subreach change to a net storage of bed/bar material.

Given the uncertainty in the above parameters, it is not possible at this time to close the bed/bar material budget for the Confluence subreach. Additional field measurements of floodplain fines fraction and higher resolution bathymetric data are both required for increasing the confidence in this part of the sediment budget. Consequently, despite the results shown in Tables 10 and 11, it is possible that the Confluence subreach has been storing bed and bar sediment material for the past several decades. However, another possible explanation for the calculated net export of bed/bar material from the Confluence subreach is the overall change in channel planform area that occurred during the 2002-2010 period. Total channel area in this subreach (i.e., total of Water and Bar classes) increased from 1.55 to 1.68 million square feet (144,000 to 156,000 m^2) between 2002 and 2010, an increase of nearly 10 percent. This is probably associated both with widening that occurred during the 2006 and 2008/2009 high flow years and also potentially with the recent overall increase in sinuosity in the subreach illustrated in Figure 12c. Together, the sinuosity change and hybrid sediment budget results imply that the channel may simply be adjusting to the large channel cutoff that occurred in this subreach downstream of the confluence with the North Fork sometime between 1942 and 1964 (see Figure 11).

The sediment budget computations are much less sensitive to uncertainty resulting from inadequate cross-sectional surveys or estimated water depth in subreaches MF1 and MF2. It is clear that bed/bar material sediment has accumulated within subreach MF1, and it is very likely that a net export of bed/bar sediment material occurred in subreach MF2 in the 8-year period represented by the sediment budget calculations. These are perhaps the most significant findings of the sediment budget analysis.

Because the hybrid sediment budget only represents net change in sediment storage and does not estimate overall sediment load, the sediment accumulation numbers presented in Tables 10 and 11 are not directly comparable to the sediment transport numbers presented in Table 8. Particularly in subreach MF2, which is primarily a sediment transport reach, the morphological budget almost certainly underrepresents net flux through the reach since it does not account for bed/bar material that enters the study area from upstream. However, the net deposition of bed material within subreach MF1 computed by the hybrid sediment budget, which ranges from 2,200 to 3,700 tons/year (2,000 to 3,400 Mg/yr) depending on the assumed fraction of floodplain fines, is within the range of the bounding sediment transport capacity estimates computed using the BAGS model. Since the transport capacity computations are intended simply to place upper and lower limits on sediment transport capacity for this study, it is likely that the actual transport rate is somewhere between the average BAGS results of roughly 800 to 8,700 tons/year (700 and 8,000 Mg/yr). It is thus possible that a large fraction of the channel's bed material load is deposited in bars within subreach MF1 (as indicated in the DEM-based results presented in Tables 10 and 11). If correct, the implication is that geomorphic changes leading to overall reductions in channel hydraulic capacity are most prevalent in subreach MF1. The Confluence subreach may be less sensitive to the supply of bed/bar material, despite its lower overall slope (although note that the Confluence subreach is also affected by sediment supply from the North Fork, a variable that has not been addressed by this study). This implies that any monitoring of the hydraulic impact of geomorphic change should be focused on subreach MF1, particularly immediately upstream from the large gravel bars in this subreach.

Role and Presence of Wood in the Study Reach

In the Pacific Northwest and elsewhere, wood plays an important role in stream and river channel geomorphic processes. Accumulations of wood can significantly affect the hydrodynamics of flow near log jams, often diverting flow across the floodplain and through chute channels. Cross-floodplain flow associated with wood, along with the local stabilizing effect of individual jams, tends to contribute to the multiple-thread flow pattern typical of anastomosing or anabranching rivers (Abbe and Montgomery 1996; Sear et al. 2010; Collins et al. 2012). On the other hand, roots of banktop vegetation can stabilize streambanks, and individual pieces of wood and fallen trees can buttress the bank toe, both of which can reduce long-term channel migration rates in the local area. Wood that comes to rest on the channel bed can alter the flow field near the bed, resulting in greater variability in substrate size distribution and in local bed topography. In relatively undisturbed Pacific Northwest rivers, the majority of pools are associated with accumulations of wood (Abbe and Montgomery 1996; Collins et al. 2002). Large pieces of wood and logjams provide significant local resistance to flow, transferring force that would otherwise be conveyed by the sediment on the stream bed or by stream banks. The partitioning of shear stress between large pieces of wood and the bed can result in greater geomorphic stability and/or smaller bed material sediment size than would otherwise be the case. By creating and maintaining pools, providing cover and shade, increasing the size range and patchiness of bed sediment material, and controlling channel planform morphology and floodplain flow patterns in some places, wood can play a critical role in the creation and maintenance of in-stream riparian habitat. Living and down wood in and near the channel also plays an integral role in the evolution of floodplain forests (Naiman et al. 2010).

Log jams result in local changes in flow patterns that can sometimes lead to additional overbank flooding and localized erosion, particularly when the jam spans an entire channel (Brummer et al. 2006). Increased floodplain flow is sometimes associated with the formation of headcuts that eventually bypass the jam (Tal and Paola 2010), sometimes leading to a partial or full channel avulsion. The unpredictable nature of flow near log jams and the associated loss of hydraulic capacity historically led to the wholesale removal of wood from river channels, especially in Washington (Collins et al. 2002). While there are no published data on wood removal activities in the study area, wood was certainly removed from the lower Snoqualmie River, starting around 1887 (Collins and Sheikh 2002). Given the pervasive wood removal from rivers throughout the lowland areas of Puget Sound in the historical record, wood removal activities within the study area likely occurred until recent decades. As listed in Table 1, burning of wood pulled from the Middle Fork occurred as recently as 1991. This led to significantly reduced amounts of in-channel wood in the Middle Fork. Trees in the riparian area continue to be cut as part of regular levee maintenance activities and by residential landowners to improve views, to reduce perceived tree-fall hazards, and for firewood. The resulting loss of in-channel wood has most likely contributed to a simpler and more stable channel planform, fewer pools, fewer avulsions, and less capacity in the system for buffering upstream pulses of sediment relative to what would probably have been the case prior to human modification. The stability of wood debris jams depends significantly on whether there are large diameter logs ("key pieces") within the jam (Abbe and Montgomery 1996). The size required for a large piece of wood to be stable depends on log length to width ratio, the ratio of channel bankfull depth to log diameter, and also on whether the wood includes attached root balls (Collins et al. 2002; Brauderik and Grant 2000). Consequently, it is not always possible to determine how large a log must be in order to serve as a key piece. In a relatively undisturbed reach of the lower Nisqually River, which has a channel width similar to the Middle Fork Snoqualmie River, key pieces in log jams had average length and diameter of 80 feet (24 m) and 3.2 feet (0.98 m), respectively, and generally included attached root balls (Collins et al. 2002).

In the study reach, the primary source of large wood is probably the floodplain forest immediately adjacent to the river. Wood is entrained as banks erode and individual trees collapse into the channel. Another source of wood in the study reach is material transported from upstream in high flows, associated with either mass wasting on hillslopes or bank erosion processes. The most important upstream bank source is probably in the highly sinuous, low gradient reach upstream of the Middle Fork Embankment. However, much of the riparian forest along the Middle Fork was logged historically, significantly reducing the lengths and diameters of trees that fall into the channel when banks erode. Riparian forest clearing in the study reach and upstream of it occurred through the 1980s (Mount Baker Snoqualmie National Forest 1998). It is therefore unlikely that significant numbers of large "key piece" logs enter the study reach from upstream or fall into the channel within the study reach.

Trees that are sufficiently large to serve as key pieces in log jams are present within the study area. Figure 19 presents a map of tree canopy height in the corridor adjacent to the Middle Fork. The map was created by computing the difference between a lidar-based grid of canopy height (produced from the earliest return of the lidar signal) and the bare-earth lidar-based DEM (generally produced using a filtering algorithm to identify the last return for a given region). The analysis shows three primary areas of high canopy (greater than 120 feet) correlating to large trees. The first is present on the southwest bank at RM 2.5. However, the channel migration analysis described previously shows that the channel has not eroded appreciably in this area in the past 70 years, so it is unlikely that large pieces of wood are recruited via bank erosion in this stand. A second area of high tree canopy is on the slopes of Mount Si and on the terraces at its base. Trees in this area are generally not accessible for recruitment to the channel because channel migration is generally to the west (away from the hillslope and terraces at the toe) in this area. A third area of high tree canopy is located on the southwest bank of the Middle Fork, downstream of the confluence with the North Fork, where the channel is laterally active. This is an important recruitment area for large wood, at least for the Confluence subreach and further downstream.

Despite the relative paucity of wood recruitment sites upstream of the Confluence subreach, accumulations of wood are present in the channel and on bars at several locations in the study reach. Figure 20 shows photographs of several typical wood accumulations. Wood is present in subreach MF2 at the entrance to several side channels, as shown in Figure 20A. It

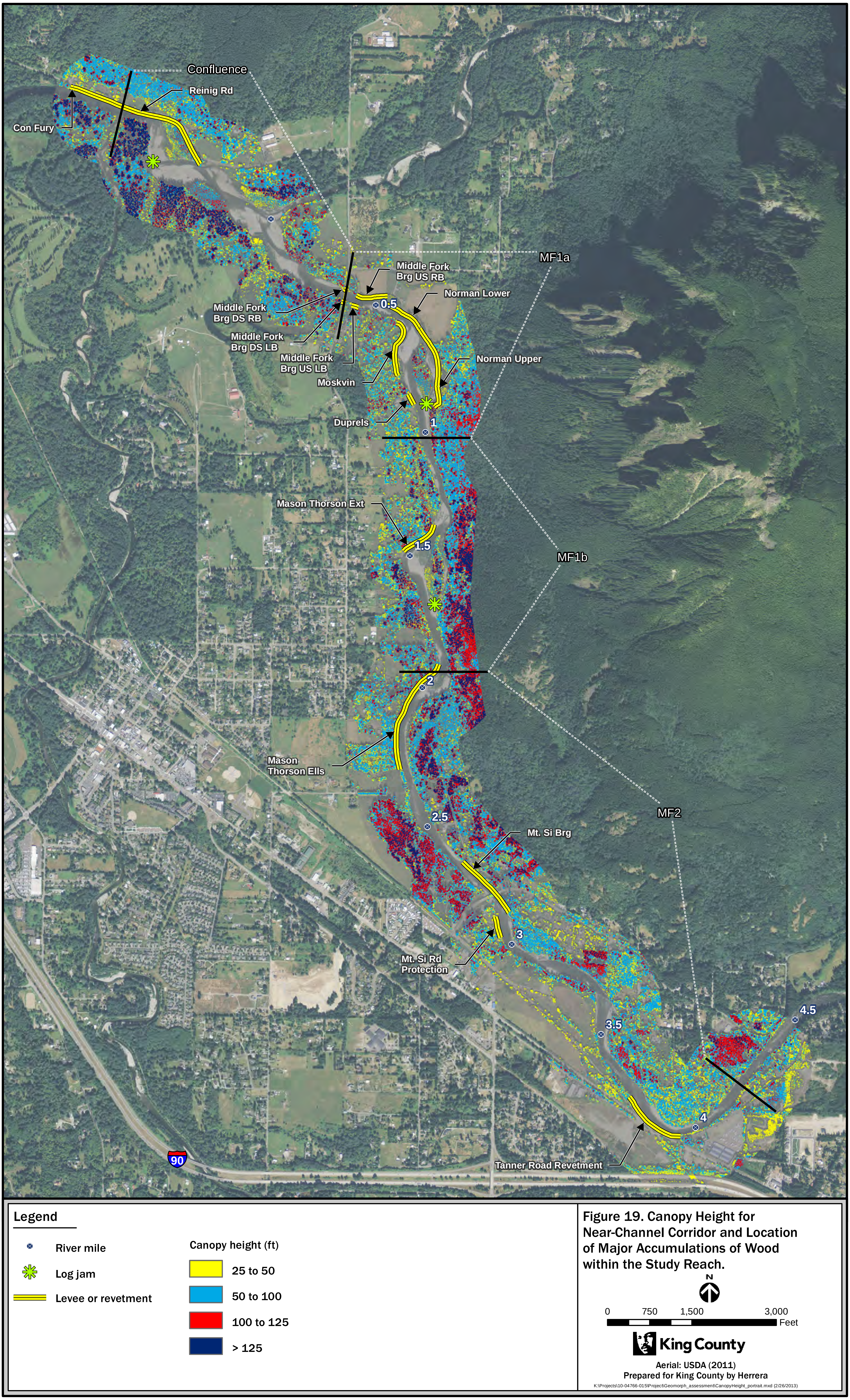

Figure 19. Canopy Height for Near-Channel Corridor and Location of Major Accumulations of Wood within the Study Reach.

King County

Aerial: USDA (2011)
Prepared for King County by Herrera

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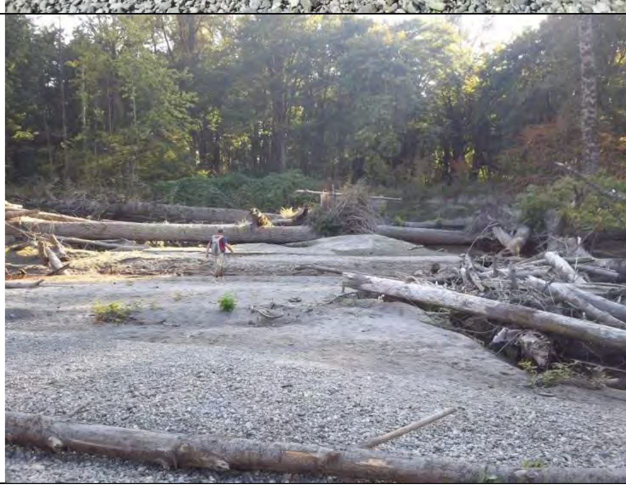
A

Logjam in subreach MF2 at the entrance to a side channel

B

Logjam in subreach MF1 at RM 0.9



C

Large logs on a bar in the Confluence subreach

Figure 20. Log Jams in the Study Reach.

probably plays a significant role in modulating the discharge in these side channels. Large log jams are present on both of the major mid-channel bars in the channel within subreach MF1, at RM 0.9 and RM 1.7. Figure 20B shows the log jam at RM 0.9. Based on review of aerial photography, wood has been present at these sites since at least 1993, when this log jam measured approximately 160 feet parallel to the flow direction. Additional wood accumulated in this jam between August 2006 and May 2009. There is another large log jam in the Confluence subreach, immediately upstream of the lower limit of the study area. Most of the logs in this area were recruited into the channel where channel migration caused bank failure amid a mature Cottonwood forest. Some of these logs are very large, as shown in Figure 20C, and are almost certainly capable of serving as key pieces in future log jams, although their presence at the downstream end of the study reach means that these logs are not available for recruitment on most of the existing jams in the study area. Because cottonwood logs decay relatively rapidly, even large diameter cottonwood logs may not serve as key pieces for more than a few decades. Individual (usually much smaller) logs are present elsewhere in the reach. While potentially important from an in-stream habitat perspective, the geomorphic importance of these scattered individual logs is probably primarily associated with the potential for them to become mobile during a large flood. Once mobilized, it is likely that they would accumulate on one of the existing log/debris jams downstream.

IMPLICATIONS OF HYDRAULIC MODELING RESULTS ON UNDERSTANDING GEOMORPHIC PROCESSES

A two-dimensional, depth-averaged RiverFLO-2D hydraulic model was developed for the majority of the study reach (from the upper boundary downstream to the confluence with the North Fork) by WSE (2013) and was used to simulate a set of flow events ranging from a typical flood through a 500-year recurrence event. A full description of the model and modeling results is provided by WSE (2013). The model was based on topography from the 2010 lidar survey and bathymetry developed from cross sections surveyed in 2012. It was calibrated using a set of observed high water marks and water level measurements collected near several flood protection facilities and near the Mount Si Bridge. In general, the model shows that overbank flooding is most likely to occur in the downstream sections of the study area. Floodplain swales that originate in subreaches MF1b and MF2 begin to convey some overbank flow at events with 5- to 10-year return periods. Site-specific model results are discussed later in this report.

Because boundary shear stress is proportional to the square of flow velocity, the highest velocity zones in a 2-D numerical flow model can provide some indication of where geomorphic change is most likely. In general, the highest velocities simulated in the WSE (2013) model occur near the center of the channel upstream of RM 1.8. However, even areas further downstream, in subreaches MF1a and MF1b, the model results show some high velocity zones. It is possible that these areas may be prone to scour during large floods. The hydraulic model also shows relatively low flow velocities where flow crosses gravel bars near RM 2.0, RM 1.5, and RM 0.7. These are areas shown by the aerial photograph analysis presented earlier in this report as historically being prone to changes in channel position.

However, there are several reasons why 2-D depth-averaged hydraulic models are not capable of describing geomorphic change in detail. First and most importantly, 2-D hydraulic models are quite sensitive to the representation of the bathymetric surface (Bates 2012). For logistical reasons, this surface is invariably surveyed at low flow, and thus any geomorphic adjustment that occurs as stage rises is not captured in the model, unless the model allows for simulation of deforming bed and bank characteristics. Deformable bed models are inherently difficult to calibrate, and that type of modeling was not attempted for this study. As a result, hydraulic models applied to mobile-bed systems with fixed bed representation in the model will over-represent flood flow velocities in some areas and underrepresent them in others. Furthermore, because of depth averaging, 2-D hydraulic models cannot fully characterize the details of a fluid velocity field. Importantly, they generally do not represent the complex secondary flow patterns that develop where flow is curved and thus often fail to accurately represent the impingement of a high velocity core on eroding stream banks at meander bends. In addition, the lateral redistribution of velocity and shear stress is usually controlled by an eddy viscosity parameter that can be difficult to accurately define. Finally, in gravel bedded rivers, geomorphic change is strongly influenced by the size distribution of sediments on the bed and by locally transient features such as log jams. These cannot be fully represented in any existing hydraulic model.

Calibration is the procedure normally used to address the limitations discussed above. In the case of the present study, the friction parameter (Manning's roughness) was calibrated across a range of flow events and at several near-channel locations to ensure that the model represented flood flow elevations as accurately as possible (WSE 2013). High water marks were available for several recent flood events between the Mount Si Bridge (RM 2.8) and the Mason Thorson Extension Levee (RM 1.5). Because of the relatively complete high flow calibration dataset, confidence in the quality of the simulated water surface elevations is relatively high, at least for the zone between RM 2.8 and RM 1.5. The slope of the modeled water surface was used as input for the sediment transport capacity calculations performed as part of the sediment budget described earlier in this report.

The WSE (2013) hydraulic analysis presents several cross-sections where the model output exhibits very high flow velocities (locally over 20 feet/second) and high Froude numbers. (Froude number describes the ratio between inertial and gravity forces in the flow. Flow characterized by Froude numbers greater than 1 is generally referred to as "supercritical" or "rapid" flow and tends to be highly erosive.) While the confidence in simulated high flow velocity results is not as high as the confidence in simulated water surface elevations, it is plausible that supercritical flow could occur locally in the study reach. In alluvial channels, flow near critical depth often causes the formation of bedforms known as anti-dunes that tend to be associated with relatively high rates of sediment transport. These features can significantly increase energy dissipation and usually prevent flow velocities from increasing much higher than those associated with flow at critical depth. After calibration, the WSE model retained a few localized instances of supercritical flow, but in general, these are located in the center of the channel away from channel boundaries. While these areas are probably subject to significant change during large floods, it is unlikely that this change alone would cause large scale differences in the flood inundation patterns indicated in the model results (WSE 2013) and discussed below.

Anthropogenic Constraints on Geomorphic Activity

King County maintains six bank protection revetments and four training levees within the study reach. In addition, two major bridges cross the river in the study reach, the Mount Si Bridge at RM 2.85 and the Middle Fork Bridge at RM 0.4. Residential development on the alluvial fan and floodplain surface between the Middle and South Forks has also influenced the potential for geomorphic change in the reach. The locations of the major flood and erosion protection facilities are shown in Figure 11. Dates of construction are presented in Table 1. In most cases, these flood and erosion protection facilities were constructed in the 1960s or 1970s. Historic (1942) and recent aerial photographs of the study area overlain with the present location of the flood and erosion protection facilities are provided in Figures 21 and 22, respectively. Figure 23 presents an overlay of these facilities on the 2010 lidar surface. Hydraulic modeling results for a range of discharges are presented on identical graphic panels in WSE (2013).The complimentary report documenting ecological resources in the study area (Herrera 2013) presents an interpretation of habitat characteristics on nearby geomorphic surfaces using this same graphic base. Many of the County-maintained flood and erosion protection facilities were apparently intended to reduce lateral movement of the main channel of the Middle Fork. Others provide flood protection for residential development in the floodplain. Particularly near the downstream end of the study reach, several flood and erosion protection facilities appear to be associated with engineered realignment of a meander bend just upstream of the confluence with the North Fork.

Because of the relative paucity of aerial photographs prior to the 1940s, it is difficult to state with precision how each of these facilities has influenced geomorphic evolution of the reach. It is not possible to state with certainty what would have occurred had a given facility not been constructed. However, it is possible to make general statements regarding the type of geomorphic change that might have occurred were it not for the flood and erosion protection facilities. Much of the discussion that follows is based on changes in morphology and channel position observed between 1942 and 1961 using aerial photographs, relative to rates and styles of change observed in more recent aerial imagery taken after the facilities were constructed. Because the original purpose and present function of these facilities varies widely, and because the overall geomorphic trends in the system vary spatially by subreach, the roles of flood and erosion protection facilities and other infrastructure are described on a subreach specific basis. A brief discussion of the role of infrastructure in limiting geomorphic change on the floodplain between the Middle Fork and South Fork is also provided.

Subreach MF2

Three major facilities are present in subreach MF2. These include the Tanner Road Revetment, the Mount Si Bridge Revetments, and the Mason Thorson Ells Levee. Much of the potentially flood-prone area adjacent to the channel in subreach MF2 is at relatively high elevation and is crossed by relict channels that are much smaller than the existing Middle Fork channel. Despite its relatively low slope, this area is mapped as alluvial fan in the complimentary ecological resources assessment report (Herrera 2013). This differentiates it from lower and more frequently flooded wandering river floodplain area closer to the channel along subreach MF1 that was probably reworked by the river in the recent geologic past (i.e., within the past several hundred years). It also differentiates this area from lower gradient surfaces at the downstream end of the alluvial fan that are mapped as distal fan/floodplain.

The historic aerial photograph presented in Figure 21 shows that in-channel change since 1942 has been relatively modest, despite the fact that flood and erosion protection facilities stabilize only a few bends within this subreach. Nevertheless, there has been some lateral channel change, so it is likely that the facilities have reduced lateral channel movement. The most significant geomorphic impact of a constructed facility in this subreach is probably related to the hydraulic effects of the Mason Thorson Ells Levee. Because hydraulic model results (WSE 2013) show only moderate flow on the upland side of this facility, it probably reduces overbank flooding and increases flow velocities in the main channel near RM 2.0, thereby changing local sedimentation and erosion patterns. Model results show that much of the overbank flow that reaches the relict channels that cross the alluvial fan originates near the Mason Thorson Ells Levee.

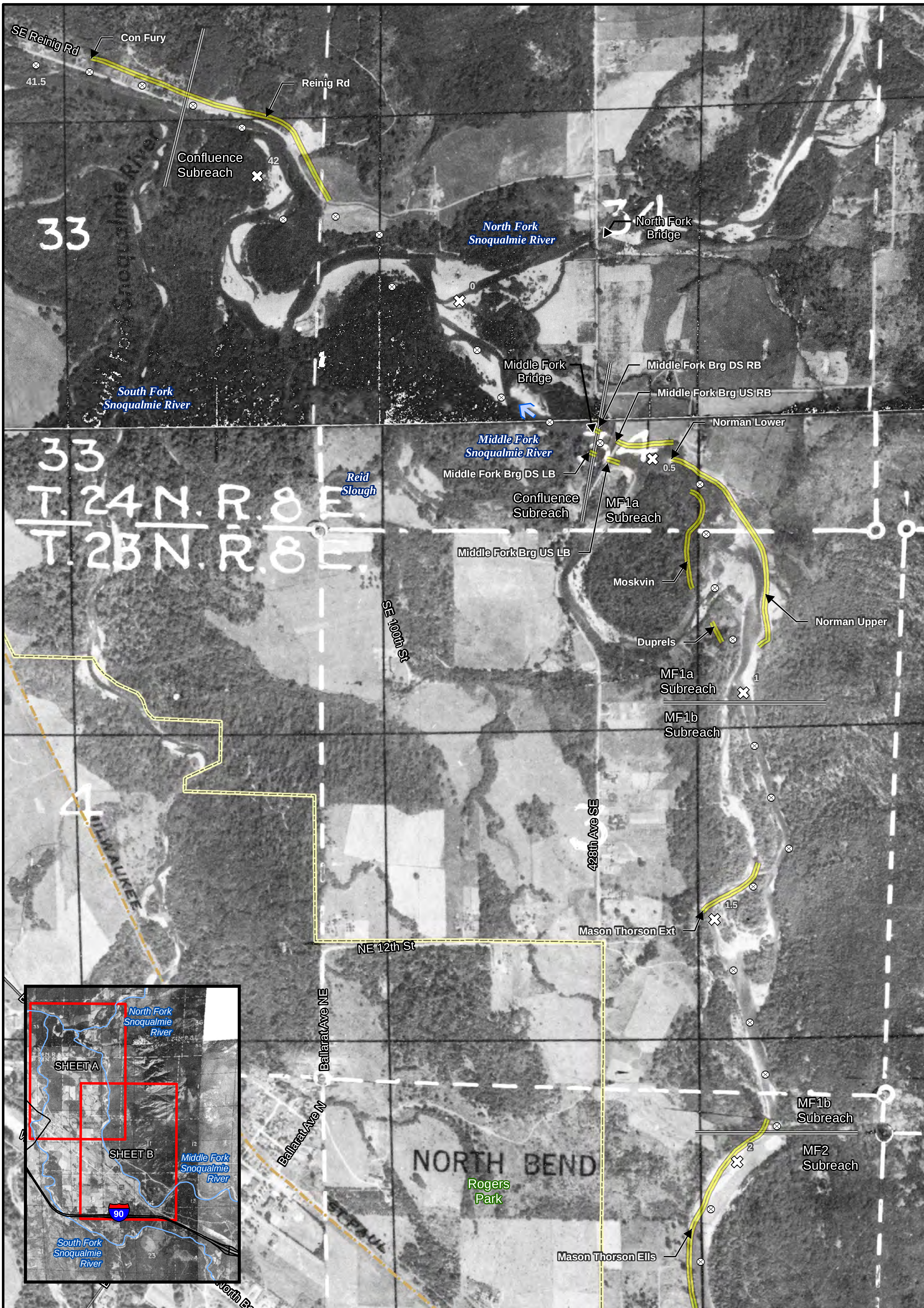
The potential geomorphic effects of each constructed facility in this subreach are described in detail below.

Tanner Road Revetment

This revetment is located on river left between RM 3.7 and RM 3.9. It protects the left bank of a large rightward-curving bend. SE Tanner Road and SE North Bend Way are immediately adjacent to the top of bank at this location. Because the channel has been relatively stable at this location through the entire period of photographic record, it is difficult to conclusively determine the role of the revetment in preventing local bank erosion. However, the movement of nearby streambanks has been documented (e.g., at RM 3.4), so it is possible that the revetment plays an important role in preventing westward migration of the channel. This facility was repaired in 1988 and 1998 (Tetra Tech 2011).

Mount Si Bridge Revetment

This revetment is located on river right between RM 2.5 and RM 3.0. The revetment was installed in 1961/62 in response to dramatic erosion at the site resulting from the flood of 1959. Additionally, the Mount Si Bridge was replaced in 2008 with a significant increase in the bridge hydraulic opening resulting from a left bank pier setback. Aerial photograph analysis shows that lateral channel movement has not been extensive anywhere within subreach MF2 during the historical period. However, several structures were damaged at this site during the 1959 flood event. The existing revetment likely prevents local bank erosion along the east side of the channel both upstream and downstream of the Mount Si Bridge.



Legend

- River mile
- 1/10th river mile
- Subreach boundary
- Snoqualmie Valley Trail
- Highway
- City of North Bend boundary
- Levee or revetment (Note: These facilities were constructed later than the date of the aerial photo)
- Flow direction

Note: For portions of the study area below the confluence with the North Fork, which serves as the origin for the King County Middle Fork Snoqualmie River channel coordinate system, river miles are based on the King County Snoqualmie River Mile system, which has its origin at the confluence with the Skykomish River.

Figure 21. 1942 Aerial Photography (Sheet 1 of 2).

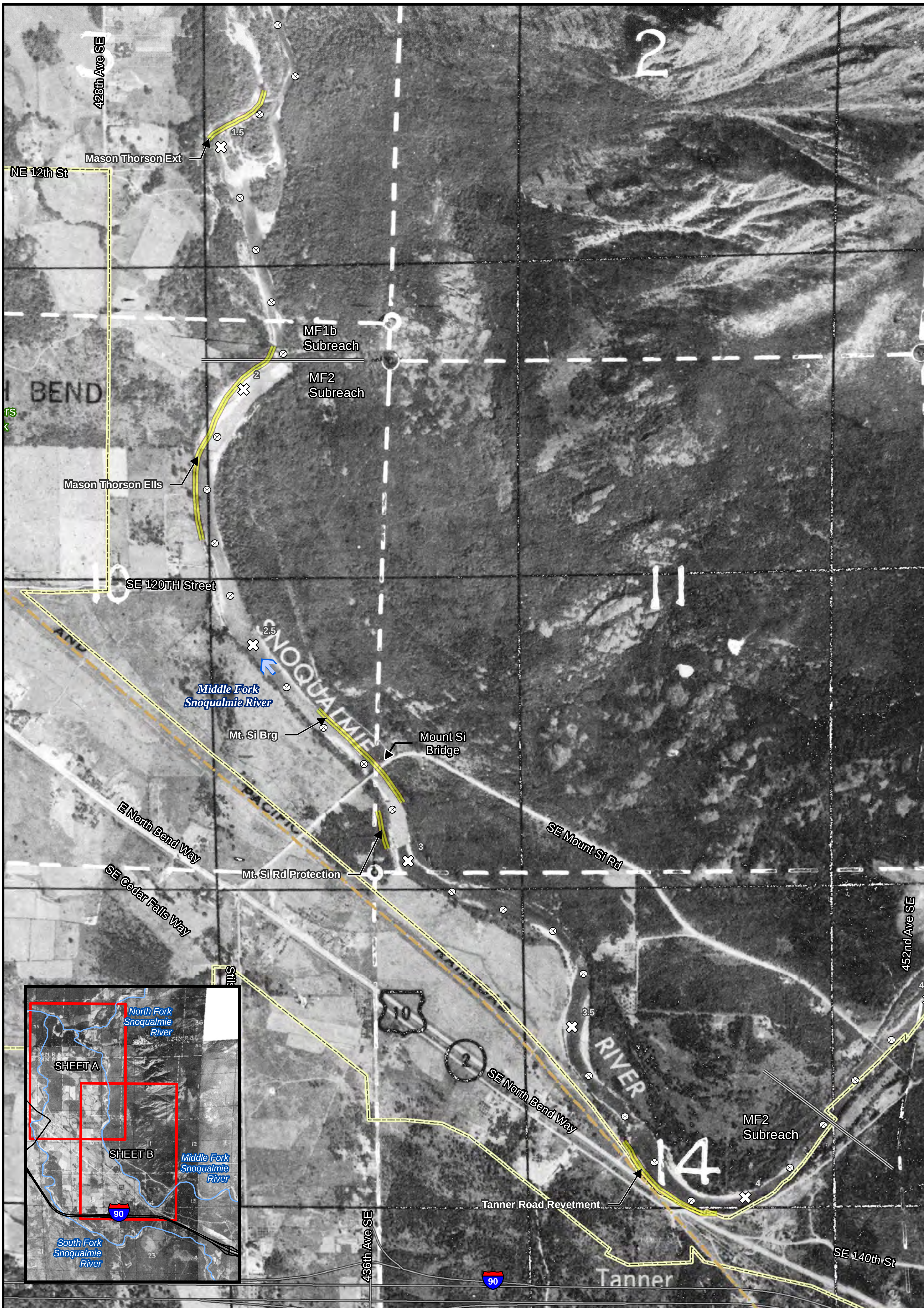
N

0 450 900 1,800 Feet

King County

Prepared for King County by Herrera

K:\Projects\10-04766-015\Project\Geomorph_assessment\1942_Aerial_Photography_Portrait.mxd (6/17/2013)



Legend

- River mile
- 1/10th river mile
- Subreach boundary
- Snoqualmie Valley Trail
- Highway
- City of North Bend boundary
- Levee or revetment (Note: These facilities were constructed later than the date of the aerial photo)
- Flow direction

Note: For portions of the study area below the confluence with the North Fork, which serves as the origin for the King County Middle Fork Snoqualmie River channel coordinate system, river miles are based on the King County Snoqualmie River Mile system, which has its origin at the confluence with the Skykomish River.

Figure 21. 1942 Aerial Photography (Sheet 2 of 2).

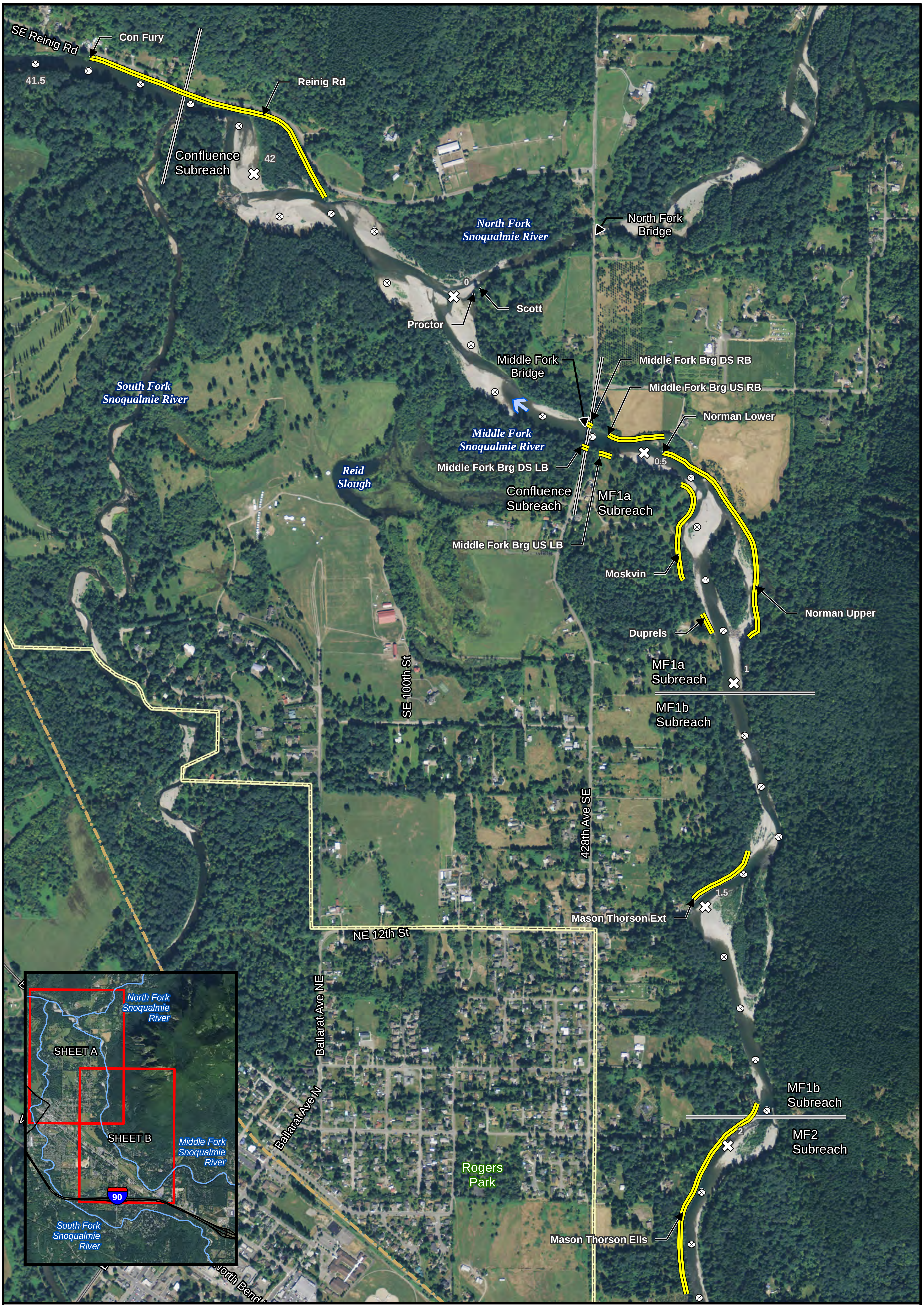
N

0 450 900 1,800 Feet

King County

Prepared for King County by Herrera

K:\Projects\10-04766-015\Project\Geomorph_assessment\1942_Aerial_Photography_Portrait.mxd (6/17/2013)



Legend

⊗ (cross)	River mile	(dashed box)	City of North Bend boundary
⊗	1/10th river mile	(yellow line)	Levee or revetment
(double line)	Subreach boundary	(arrow)	Flow direction
(dash-dot line)	Snoqualmie Valley Trail		
(line)	Highway		

Note: For portions of the study area below the confluence with the North Fork, which serves as the origin for the King County Middle Fork Snoqualmie River channel coordinate system, river miles are based on the King County Snoqualmie River Mile system, which has its origin at the confluence with the Skykomish River.

Figure 22. 2011 Aerial Photography (Sheet 1 of 2).

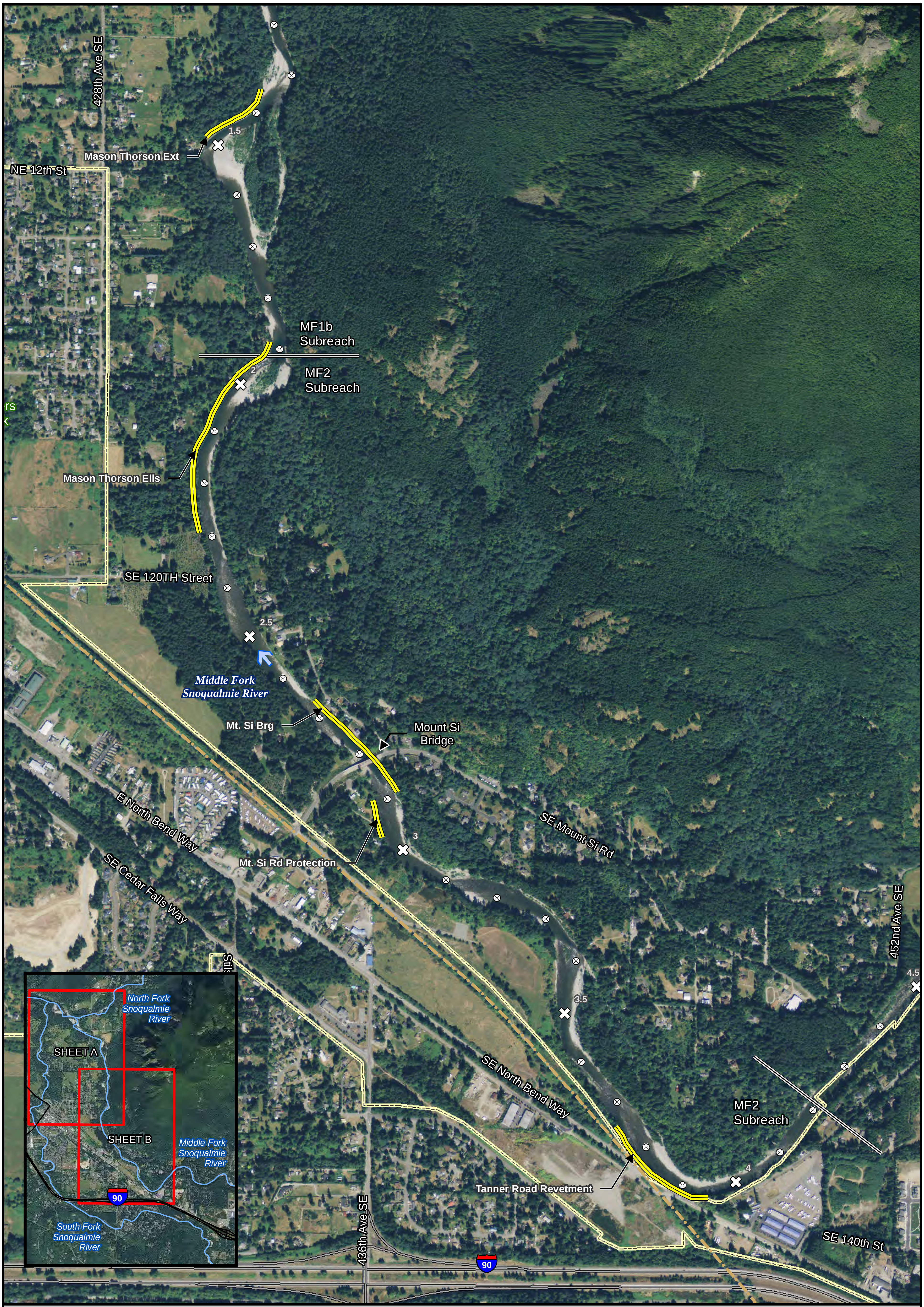
N

0 450 900 1,800 Feet

King County

Prepared for King County by Herrera

K:\Projects\10-04766-015\Project\Geomorph_assessment\2011_Aerial_Photography_Portrait.mxd (6/17/2013)



Legend

River mile	City of North Bend boundary
1/10th river mile	Levee or revetment
Subreach boundary	Flow direction
Snoqualmie Valley Trail	
Highway	

Note: For portions of the study area below the confluence with the North Fork, which serves as the origin for the King County Middle Fork Snoqualmie River channel coordinate system, river miles are based on the King County Snoqualmie River Mile system, which has its origin at the confluence with the Skykomish River.

Figure 22. 2011 Aerial Photography for the Middle Fork Snoqualmie River Geomorphic Assessment (Sheet 2 of 2).

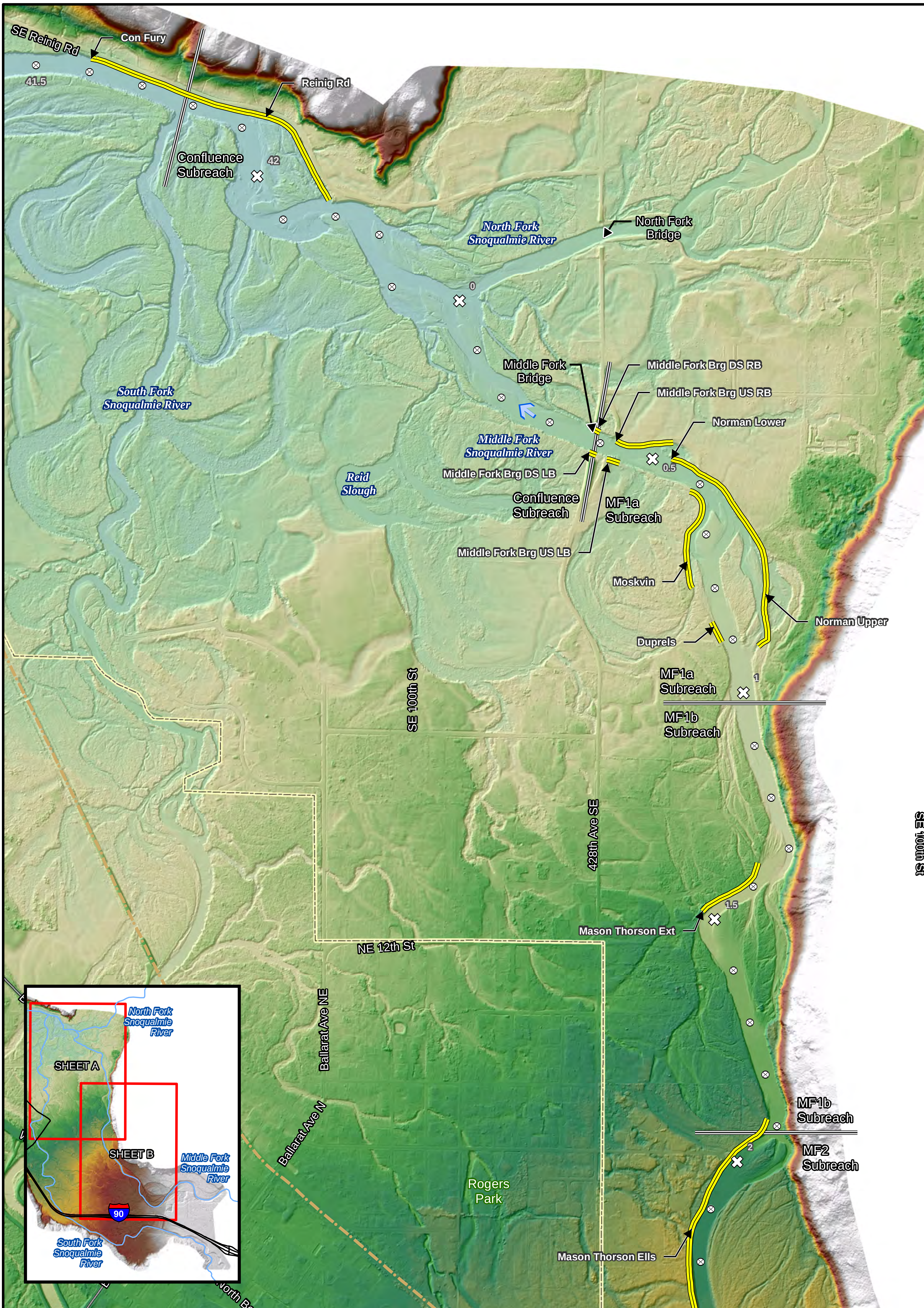
N

0 450 900 1,800 Feet

King County

Prepared for King County by Herrera

K:\Projects\10-04766-015\Project\New_King_County_Template\2011_Aerial_Photography_Portrait.mxd (2/22/2013)



Legend

- River mile
- 1/10th river mile
- Levee or revetment
- Subreach boundary
- Snoqualmie Valley Trail
- Highway
- City of North Bend boundary
- Flow direction

Note: For portions of the study area below the confluence with the North Fork, which serves as the origin for the King County Middle Fork Snoqualmie River channel coordinate system, river miles are based on the King County Snoqualmie River Mile system, which has its origin at the confluence with the Skykomish River.

Figure 23. 2010 LiDAR (Sheet 1 of 2).

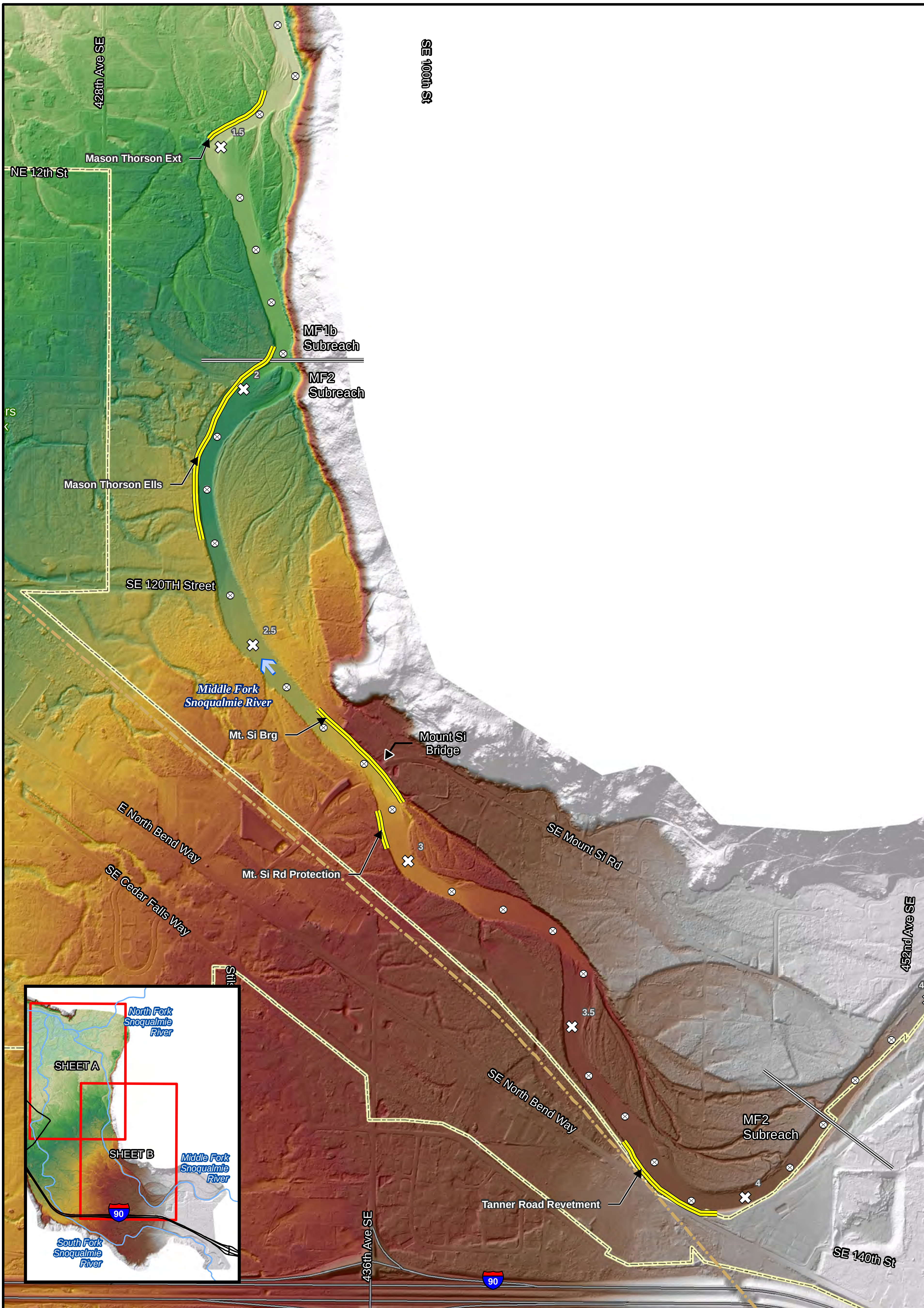
N

0 450 900 1,800 Feet

King County

Prepared for King County by Herrera

K:\Projects\10-04766-015\Project\Geomorph_assessment\2010_LiDAR_Portrait.mxd (6/17/2013)



Legend

- River mile
- 1/10th river mile
- Levee or revetment
- Subreach boundary
- Snoqualmie Valley Trail
- Highway
- City of North Bend boundary
- Flow direction

Note: For portions of the study area below the confluence with the North Fork, which serves as the origin for the King County Middle Fork Snoqualmie River channel coordinate system, river miles are based on the King County Snoqualmie River Mile system, which has its origin at the confluence with the Skykomish River.

Figure 23. 2010 LiDAR (Sheet 2 of 2).

N

0 450 900 1,800 Feet

King County

Prepared for King County by Herrera

K:\Projects\10-04766-015\Project\Geomorph_assessment\2010_LiDAR_Portrait.mxd (6/17/2013)

Mason Thorson Ells Levee

This facility provides flood protection and channel bank stabilization along the left bank between RM 1.9 and RM 2.3. The levee's primary role is to prevent flow from entering several relict channels that cross the alluvial fan/floodplain to the west. The levee does not extend upstream all the way to the head of the SE 120th Street relict floodplain channel, it blocks several swales that would supply flow to the SE 120th Street channel if the levee was not present. It also limits flow to the set of relict channels that ultimately empty to Reid Slough.

Based on changes in channel width adjacent to the levee between 1942 and 1962, it appears that the levee initially resulted in channel narrowing, possibly as a result of fill placed during its construction (see Figure 21 – sheet 2). After the 1960s, a large mid-channel bar formed at the downstream end of the levee, at RM 2.0. WSE (2013) points out that backwater caused by levees may be partly responsible for upstream bar growth. It is also possible that by limiting movement of the long, low-angle, rightward-curving bank that it protects, the levee has reduced the ability of the channel to store bed material in the large point bar upstream of this site (located on the east bank between RM 2.3 and RM 1.9). The side channel to the east of the mid-channel bar has recently led to additional erosion on the right bank.

Channel banks upstream of the levee are relatively stable, with channel change occurring at rates that are not discernible from the aerial photograph record. Sediment in these banks is poorly sorted, and large rounded boulders are present at the bank toe. While it is not clear whether these boulders were imported to the site by human action or whether they were eroded from in-situ deposits in the bank, they are sufficiently large to play an important stabilizing role. In addition, a somewhat cohesive, matrix-supported sedimentary deposit is present in the banks upstream of the upper end of the Mason Thorson Ells Levee (see Figure 5). While the origin of this deposit is in question, if it was placed during deglaciation and has not been reworked since the Pleistocene, this would imply that the channel upstream of the Mason Thorson Ells Levee has remained in roughly its present planform configuration for thousands of years. It was not possible to determine whether this surface extends downstream beyond the upper end of the Mason Thorson Ells Levee. However, several curvilinear breaks in elevation are visible in the lidar surface representing the floodplain starting approximately at RM 1.9 (see Figure 23 – sheet 2). It is likely that the floodplain downstream of this point has been reworked relatively recently and thus the banks protected by the Mason Thorson Ells Levee may be more erodible than the banks upstream of the facility.

The Mason Thorson Ells Levee was repaired in 1997, and since then has been repaired about once every 2 years (Tetra Tech 2011).

Subreach MF1

There are six major flood and erosion protection facilities in subreach MF1. These include the Mason Thorson Extension Levee, the Upper and Lower Norman levees, the Moskvin Revetment, the Duprels Revetment, and the Middle Fork Bridge Upstream Revetment.

In general, this subreach is more geomorphically active than subreach MF2 and continues to exhibit some bank erosion, particularly near the Mason Thorson Extension Levee. Historically, a transition occurred in this subreach between a multiple-threaded anabranching channel dominated by mid-channel bars and a single-thread meandering channel. The transition was located approximately at RM 1.0, near where the 1942 imagery in Figure 21 (sheet 1) shows the relatively recent cutoff of a large meander bend on the west side of the modern channel. Rapid downstream fining of bed material within this subreach indicates that it is probably depositional and is thus characterized by long-term storage of bed and bar material. The levees and revetments in this subreach have reduced lateral movement of the channel. Since channel movement typically results in the storage of sediment in the position of the old channel, the reduction of such movement probably reduced the rate at which coarse sediment was stored within the channel and floodplain, potentially meaning that large gravel and cobble particles that would have been sequestered in a bar deposit now remain within the channel and move further downstream than was historically the case. This additional transport may be partly responsible for the growth of mid-channel bars near the Norman levees. This is consistent with the observations of Reid et al. (2007) that by preventing the transfer of bed sediment material into floodplain storage, channel bank stabilization in areas already prone to sediment deposition can lead to rapid sediment accumulation in the channel. Much of the floodplain downstream of RM 1.0 appears to have been reworked rapidly prior to human modification based on floodplain morphology, radiometric dating of floodplain channel deposits, and on change documented to have occurred between 1942 and 1961. The revetments and levees in this area limit the growth of a point bar that would induce migration of the channel across this part of the floodplain. The Middle Fork Bridge also limits large-scale growth of meander bends in the subreach, but since its influence is probably even more significant on the downstream system, its role is discussed in the section describing the effects of flood and erosion protection facilities in the Confluence subreach.

The potential geomorphic effects of each facility in subreach MF1 are described in detail below.

Mason Thorson Extension Levee

This levee is located on river left between RM 1.3 and RM 1.5. The levee blocks several relict floodplain channels that, in most cases, re-enter the Middle Fork within a mile downstream. Bank armoring at the base of the levee prevents lateral shifting of the channel. However, since about the year 2000, over 130 feet of bank has eroded upstream of the levee.

The channel at the site of the Mason Thorson Extension Levee has maintained an anabranching planform consisting of multiple channel threads since at least the 1940s. The levee is located in a transitional zone where both channel slope and bed material grain size begin to decrease rapidly in the downstream direction. The anabranching planform is probably associated with long-term sediment accumulation in the subreach. Gravel and cobble exposed in the eroding banks upstream of the levee have a similar size distribution as the material presently exposed on nearby mid-channel bars, indicating that the channel may have migrated across this part of its floodplain in the recent geological past. This migration would have been associated both with the storage and resupply of sediment and with a net supply of large wood to the channel. The growth of the mid-channel bar and the relatively small size of some of the side channels that bisected it (as shown in the 1942 aerial photograph in Figure 21 – sheet 1) probably resulted in regular accumulation of large wood. The dynamics of these log jams would probably have influenced discharge across the floodplain to the west of the levee.

Extensive bank erosion occurred upstream of the Mason Thorson Extension Levee during the 2006 and 2008/2009 flood events. This process is described in detail by Northwest Hydraulic Consultants (2011). During these events, an estimated 8,000 cubic yards of gravel and cobble deposited on the point bar upstream of the levee. Additional material has accumulated at the head of a side channel located on river left immediately downstream of the levee, at RM 1.3. The point bar deposition upstream of the levee has redirected high flow velocities toward the left bank immediately upstream of the levee, particularly during the falling limb of a flood hydrograph. The site is less prone to erosion during the largest flood events because backwater forms during high flow at the downstream end of the levee, where the levee approaches bedrock exposed in the east bank, on river right. The backwater reduces near-bank flow velocities upstream of the levee and possibly influences deposition of material on the adjacent point bar. The progressive growth of this bar is probably the primary cause for the recent erosion.

A total of 38,000 square feet of bank area eroded during the 2006 and 2008/2009 flood events at the levee site. Assuming the top of this eroded bank was roughly 10 feet higher than the channel thalweg, Northwest Hydraulic Consultants (2011) computed a total volume of sediment erosion of 14,000 cubic yards (yd^3) during these two events. No explanation for the large discrepancy between sediment erosion and sediment deposition was documented (8,000 yd^3 of deposition versus 14,000 yd^3 of erosion), and there is a possibility that the erosion resulted in a net supply of gravel and cobble to the downstream channel. However, because the eroding bank contains layers of silt and sand above gravel and cobble toe material, it is unclear whether the erosion of this bank resulted in a net supply of bed material to the downstream channel. In any case, there has certainly been deposition of sediment downstream of the levee. It is possible that erosion upstream of it is responsible for the movement of coarse sediment into the side channel located near RM 1.3, as shown in Figure 24A. Sediment grain sizes in this side channel presently decrease rapidly in the downstream direction, with cobbles present only for the first several hundred feet of the channel. However, it is also possible that coarse material was present in this location prior to the recent erosion.

During large floods, flow that bypasses the Mason Thorson Extension Levee could potentially enter a set of relict floodplain channels. The extent of the hydraulic connection is detailed by WSE (2013). Additional erosion of the bank upstream of the levee could provide an additional hydraulic connection to these channels, increasing discharge and associated flood hazards to developed properties in the floodplain. Most of these floodplain channels re-enter the Middle Fork within a mile of the Mason Thorson Extension Levee. However, at least one has the potential to provide flow to the relict channel that connects to Reid Slough. This relict channel was one of the two channels on the floodplain identified by Perkins (1996) as being at risk of enlarging to the point where it could eventually capture the main flow of the Middle Fork in a large-scale channel avulsion.

Figure 24. Side Channels Near RM 1.3 and Relict Floodplain Channels at Various Locations in Floodplain.

In their 2011 report, Northwest Hydraulic Consultants extended the analysis of Perkins (1996) and Tetra Tech (2010) to address the possibility of a large-scale avulsion into this channel due to bank failure at the upper end of the Mason Thorson Extension Levee. They concluded that this is not likely for the following reasons:

1. In the original Perkins (1996) analysis, which was intended primarily for planning purposes, the hydraulic roughness of vegetation in the relict floodplain channels was not considered. Even during large events, vegetation would reduce flow velocities below those required to cause scour.

2. Avulsions usually require significant aggradation of the bed of the main river channel. While some aggradation is occurring at the point bar adjacent to the Mason Thorson Extension Levee, the rest of the main channel in this area appears relatively stable. (Note that this is consistent with County cross-section surveys described previously). There is minimal evidence of large-scale aggradation of the thalweg. Large channel-spanning log jams can also cause large-scale channel avulsions (Brummer et al. 2006), but formation of such a blockage at the Mason Thorson Extension Levee site is unlikely, particularly at the most constricted area at the downstream end of the site where high flow velocities would tend to prevent wood accumulation.

3. The presence of culverts and roadways in the residentially-developed floodplain west of the Mason Thorson Extension Levee would have the effect of grade control during a large event. This would help to prevent large-scale incision of the floodplain ground surface during a single flood event. Since it is expected that any significant damage to roadways would be repaired after a large event, the grade control represented by these features can be considered as relatively permanent.

Northwest Hydraulic Consultants' (2011) conclusions are supported by the fact that large flood events between 2005 and 2010 overtopped portions of the levee. A photograph of the floodplain vegetation in the area of overtopping is shown in Figure 24D. During a site inspection on October 1, 2012, very little evidence of any floodplain erosion was found, even in the area immediately adjacent to the levee where flow velocities would have been the greatest. In addition, even if a log jam formed along the existing thalweg at the Mason Thorson Extension Levee site, it would tend to divert flow into one of the side channels to the east of the large bar that was active in 1942. This would tend to divert the main flow path away from the floodplain west of the site.

The Mason Thorson Extension Levee was repaired in 1986, 1990, 1997, 2009, and 2010 (Tetra Tech 2011).

Upper and Lower Norman Levees and Moskvin and Duprels Revetments

The Upper and Lower Norman Levees line the right bank between RM 0.5 and RM 0.9. The Moskvin and Duprels revetments stabilize the left bank in the same area. These facilities are located at the point where the river probably historically transitioned from an anabranching, multiple thread channel characterized by several mid-channel bars to a single-thread, meandering river. The transition occurs at the point where the channel flows away from the base of Mount Si. Each of these facilities is probably associated with a channel realignment project that cut off two historic meander bends, leaving behind a large oxbow lake to the west and a smaller depression/swale to the east. Although the cutoff probably occurred prior to the 1940s, the older channel alignment can be seen in the 1942 aerial photograph (Figure 21 – sheet 1) and in the 2010 lidar imagery (Figure 23 – sheet 1).

The change in planform morphology was probably associated with a change in channel bed slope. This slope break is still present near RM 1.0 and probably results in a decrease in sediment transport capacity in the vicinity of these facilities. A large mid-channel bar/forested island complex is present near the two levees. While portions of this island may contain floodplain that existed prior to facility construction, erosion of the island mobilizes long-stored sediment into the channel. This eroded material probably does not move far downstream since the channel in the vicinity of the Norman levees is depositional, as described in the Sediment Budget section of this report.

If the levees had not been constructed, it is likely that the channel would have maintained a single-thread meandering planform in this vicinity and downstream through the Confluence subreach. However, if the levees were removed, it is not clear that the channel could quickly re-achieve this planform geometry, since the angle at which flow presently impinges on the banks is far different than it was historically. If the bank armoring associated with the Norman levees were not present, long-term migration could conceivably lead to the channel crossing the floodplain to the north, possibly all the way to the North Fork. However, migration would probably be limited by the debris flow fan present on the floodplain to the northeast, at the base of Mount Si, and also possibly by the position of the Middle Fork Bridge, which for practical purposes is likely to represent a long-term control on channel position.

The sediment budget described in this report indicates significant sediment accumulation in the mid-channel bar at this location. The total amount of accumulation in this bar is limited by the relatively small planform area between the revetments on one bank and the levees on the opposite bank. Historically, migration across the entire alluvial floodplain would have represented a much larger area for storage of cobble-size sediment that the lower-slope channel downstream from this site probably could not, and still cannot, convey. The fact that the levees and revetments prevent lateral movement of the channel limits the lateral storage of this relatively large material, meaning that it will probably continue to accumulate within the channel near these facilities. It is also possible that the lack of lateral storage has increased the supply of relatively large gravel and small cobble material to the Confluence subreach relative to what occurred prior to bank armoring.

Confluence Subreach

Two major erosion protection facilities, both of which are intended to protect top-of-bank roadways, are present in the Confluence subreach. These are the Middle Fork Bridge Downstream Revetment (left and right banks) and the Reinig Road/Con Fury Revetment, which is a single bank stabilization feature located on the north bank at the lower end of the subreach. The Middle Fork Bridge itself also probably plays a significant role in the geomorphic evolution of this reach.

This subreach is the most laterally active of any of the three subreaches in the study area. Banks tend to consist of a basal layer of gravel and cobble material above which a fine-grained sand/silt layer is usually present (see Figure 15). Much of the floodplain adjacent to the channel has been reworked in the past several hundred years. Consequently, the revetments probably play a significant local role in preventing bank erosion and protecting roadways near the channel. However, the overall impact of the revetments on channel planform change may be relatively small because of the relatively small floodplain area that is protected from erosion by the revetments.

The channel alignment through the Middle Fork Bridge, which is maintained by the revetments extending upstream and downstream from the structure, probably influences the magnitude and direction of channel migration downstream of the bridge. By disrupting secondary flow and reducing the likelihood of point bar growth, bridges can have important and long-lasting ramifications for the trajectory of channel migration downstream of the structure (Motta et al. 2011; van Dijk et al. 2012). It is possible that the relative inactivity of the Middle Fork between RM 0.1 and RM 0.3 is related to this bridge constriction. The probable large-scale historic channel realignment near the Upper and Lower Norman levees , as well as other bridges that have historically been located at the site (see Table 1), most likely also disrupted secondary currents in the channel and may have influenced the direction of channel migration downstream of the Middle Fork Bridge.

Downstream of the confluence with the North Fork, the Confluence subreach has been very active geomorphically over the entire period for which aerial photography is available. A large cutoff occurred in this area between 1942 and 1964. This cutoff shortened the channel and probably created a large amount of space for storing sediment in the associated oxbow lake downstream of the confluence with the North Fork. The subreach is probably still responding to this event (see Figure 12 and the Sediment Budget section of this report). Progressive increases in channel sinuosity are likely to occur in this subreach for the foreseeable future. Continued erosion along the left bank immediately upstream of the confluence with the South Fork is likely to eventually allow the Middle Fork to join the South Fork south of the present confluence. If this occurs, it is possible that the Reinig Road/Con Fury Revetment would be left far from the channel for a period that could last many years.

The potential geomorphic effects of each erosion protection facility in the subreach are described in detail below.

Middle Fork Bridge and Middle Fork Bridge Revetments

Four revetments are present at the Middle Fork Bridge—one on each bank both upstream and downstream of the bridge. The upper end of the revetment on the north bank upstream of the bridge terminates immediately downstream of the Lower Norman Levee, resulting in a small backwater eddy on the right bank. The discontinuity is due to an abandoned and dismantled bridge that the upstream revetments were originally constructed to protect. The spacing between the upstream left and right bank bridge revetments then narrows again at the site of a second abandoned and dismantled bridge immediately upstream of the existing bridge. Because flow patterns through the bridge are probably controlled primarily by the Lower Norman Levee, it is not clear whether the constriction results in a disruption to secondary currents in the channel. However, regardless of whether the Lower Norman Levee or the Middle Fork Bridge revetments are responsible, the relatively uniform nature of the bed at the bridge site implies that there is no major tendency for bar growth.

The hydraulic impact of the bridge and its revetments is at least plausibly responsible for the relative lack of channel migration between the bridge and the confluence with the North Fork (see Figure 12) roughly 0.4 miles downstream. Particularly if the old oxbow lake deposit at SE 100th Street is only a few hundred years old as indicated by the radiometric dating presented earlier in this report, recent channel migration rates immediately downstream of the bridge are probably lower than was historically common. The bridge and associated revetments may thus represent features that limit the ability of the Middle Fork channel to migrate across the southern parts of the floodplain in the Three Forks area, between SE 100th Street and the existing channel. Additional study would be required to determine whether the bridge and associated revetments or the Norman levees are primarily responsible.

Reinig Road / Con Fury Revetment

This revetment protects SE Reinig Road in the downstream-most 0.3 miles of the study reach. The portion upstream of the confluence with the South Fork is referred to as the Reinig Road Revetment, while the part that extends downstream of the confluence is known as the Con Fury Revetment. Recent channel change near the confluence has resulted in significant erosion of the left bank, opposite and upstream of this revetment. Some erosion has also occurred on the right bank at the upstream end of the revetment. Continued erosion of the banks in this area is probably not associated with the presence of the revetment and is instead likely associated with natural channel migration in the confluence area. If change progresses as it has for the past several years, erosion of the west bank just upstream of the South Fork confluence could result in a cutoff between the Middle and South Fork channels. This would move the confluence upstream and would possibly allow floodplain vegetation to colonize the area at the toe of the existing revetment. In any case, the revetment is likely to continue to prevent the channel from migrating across its historic floodplain north of SE Reinig Road, although the total floodplain area that was historically accessible to migration in that area is relatively small.

EROSION RISK ON FLOODPLAIN

While not specifically designed for flood control purposes, roadways and other infrastructure play a role in limiting the types of geomorphic change that could occur in the floodplain between the Middle and South Forks. While headcut migration probably occurred across this part of the study area in pre-historic times, the presence of infrastructure such as roadways and culverts probably limits the future upstream migration of such features. The assessment of risk of potential floodplain channel erosion and associated effects on infrastructure presented here is based on the information presented throughout this report in combination with interpretation of hydraulic modeling results for the 25-year recurrence interval flood event. The 25-year event was used for this analysis because it is sufficiently large to cause significant flooding and because it is similar in magnitude to several recent high flow events, some of which were used for model calibration. While the extent of flooding would be somewhat greater in a 100-year recurrence event, simulated flow and shear stress patterns on the floodplain are qualitatively similar for both the 25- and 100-year events. Full hydraulic model results for both events are presented by WSE (2013).

Figure 25 shows modeled 25-year recurrence interval peak flood water surface elevations in the portion of the floodplain for which hydraulic modeling results are available (WSE 2013). The figure shows that overbank flow in the floodplain is expected to concentrate in the two primary floodplain channels identified by Perkins (1996), although the hydraulic connection to the Reid Slough channel is perhaps more extensive than the connection to the SE 120th Street channel, probably because of the hydraulic impact of the Mason Thorson Ells Levee. Very little floodplain flow is simulated to the west of this facility (see Figure 25), indicating that it probably reduces flow to both the Reid Slough and SE 120th Street relict channels.

Figure 26 shows boundary shear stress associated with the hydraulic modeling results for the 25-year recurrence interval flood event. Boundary shear stress is not a perfect indicator of erosion potential because a significant fraction of total boundary shear can be caused by vegetation or other roughness elements (Nepf 2012; WSE 2013). Particularly on river floodplains, only a very small amount of total boundary shear is applied to sediment particles. In general, boundary shear is highest where high velocity flow impinges on dense vegetation. However, boundary shear can be used to characterize in general where a geomorphic surface is most susceptible to change (either through erosion, if the stress is applied to sediment, or through deposition, if flow conveying sediment suddenly impinges upon roughness that reduces the portion of the totally boundary shear that available to move sediment). Hydraulic modeling results indicate that total boundary shear stress is likely to be much greater in the main channel of the Middle Fork and along several active side channels than along either the SE 120th Street or Reid Slough relict floodplain channels. Further, many areas that are shown as inundated in Figure 25 show virtually no shear stress in Figure 26, indicating very low flow velocities across broad swaths of the floodplain. This is probably due to local backwater that would occur where relict channels cross roadways. While the hydraulic model did not specifically include culverts that are present under these roadways, and thus may overestimate the associated backwater effect, the hydraulic capacity of the culverts is probably low relative to the amount of flood flow moving through the culvert crossing areas. The relatively low shear stress simulated across much of the floodplain is thus not unreasonable. This is consistent with observations reported by a longtime resident who has lived in North Bend since the 1950s and who owns the property where radiometric sampling site 4 was located (see Figure A4 in Appendix A). This resident claims that culverts at road crossings in the floodplain cause noticeable backwater (M. Ruppert, personal communication).

Even in areas far from culverts, Figure 26 indicates that shear stresses in the overflow channels should be much lower than shear stresses near the existing Middle Fork channel. The highest shear stress on the floodplain is evident in the 25-year flood model results near the point where the Reid Slough channel drops from the floodplain into the old oxbow deposit immediately upstream of the location of radiometric sampling site 2 (see Figure A2 in Appendix A). However, even here, shear stress is predicted to be much lower than in the side channel at RM 1.3, immediately downstream of the Mason Thorson Extension Levee. Field evidence within this side channel indicates deposition of sediment, rather than erosion, with rapid loss of cobble near the head of the channel (Figure 24A) and deposition of fine-grained sand and silt near its downstream end (Figure 24B). While some of the deposition is probably caused by relatively high sediment supply in the Middle Fork, the fact that the side channel experiences deposition of fines despite relatively high shear stress during floods implies that the shear stress even in the steepest part of the Reid Slough channel is not excessively high. Figure 24C shows a photograph of a relict floodplain channel located a few hundred feet east of the channel shown in Figures 24A and 24B. This photograph was taken at a location roughly 1,000 feet downstream from where flow overtopped the Mason Thorson Extension Levee in 2009, in the zone where the hydraulic model shows relatively high shear stress approximately 500 feet due west from RM 1.2 (WSE 2012). The fine sand and silt on the bed in the relict floodplain channel shown in Figure 24C indicates that this channel did not experience significant erosion during the 2009 flood event. Even closer to the levee, in the highly turbulent zone immediately downstream of where the bank overtopped in the 2009 flood event, floodplain vegetation appears sufficient to protect against erosion. No scour was evident at this location in October 2012, as shown in Figure 24D.

While hydraulic modeling results do not extend across the entire floodplain between the Middle Fork and South Fork, relict floodplain channels downstream of the western extent of the model do not appear to have experienced erosion recently. Figure 24E shows one of the floodplain swales in E.J. Roberts Park, at radiometric sampling site 7. As described previously, radiometric sampling results imply that sediment in this swale has remained immobile for at least 1,000 years, and perhaps longer.

Figure 24F shows the channel of Silver Creek near radiometric sampling site 5. The obvious backwater in this channel and the fine sediment on the bed and in the hand auger samples collected at this site imply that even during floods, shear stress is not sufficient to mobilize coarse material in the channel. While flow velocities and shear stresses in the cross-floodplain channels that supply flow to this area are certainly higher than in Silver Creek, the presence of multiple road crossings and relatively dense vegetation probably mitigates the risk of rapid enlargement of these channels during a single large flood event.

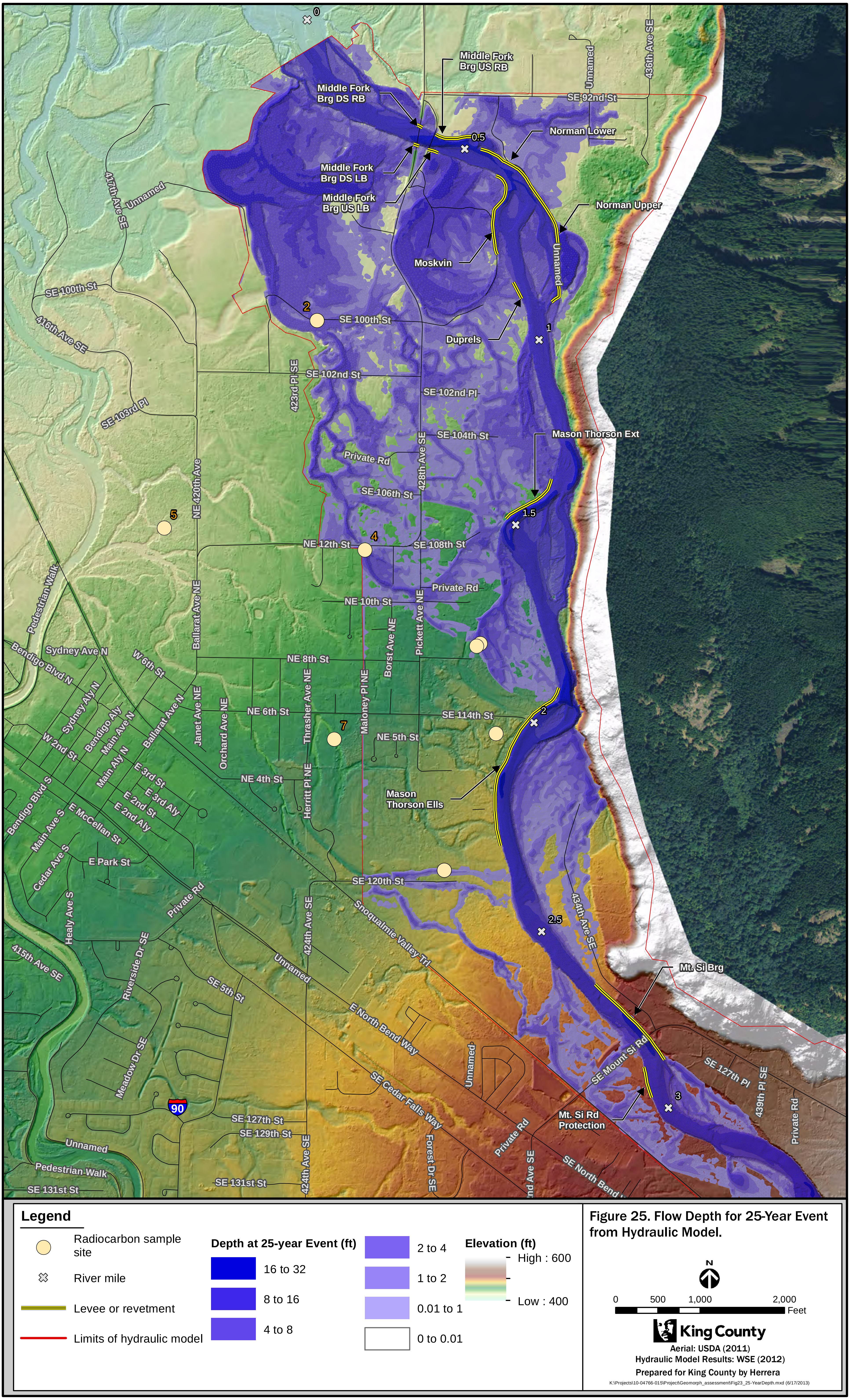


Figure 25. Flow Depth for 25-Year Event from Hydraulic Model.

King County

Aerial: USDA (2011)
Hydraulic Model Results: WSE (2012)
Prepared for King County by Herrera

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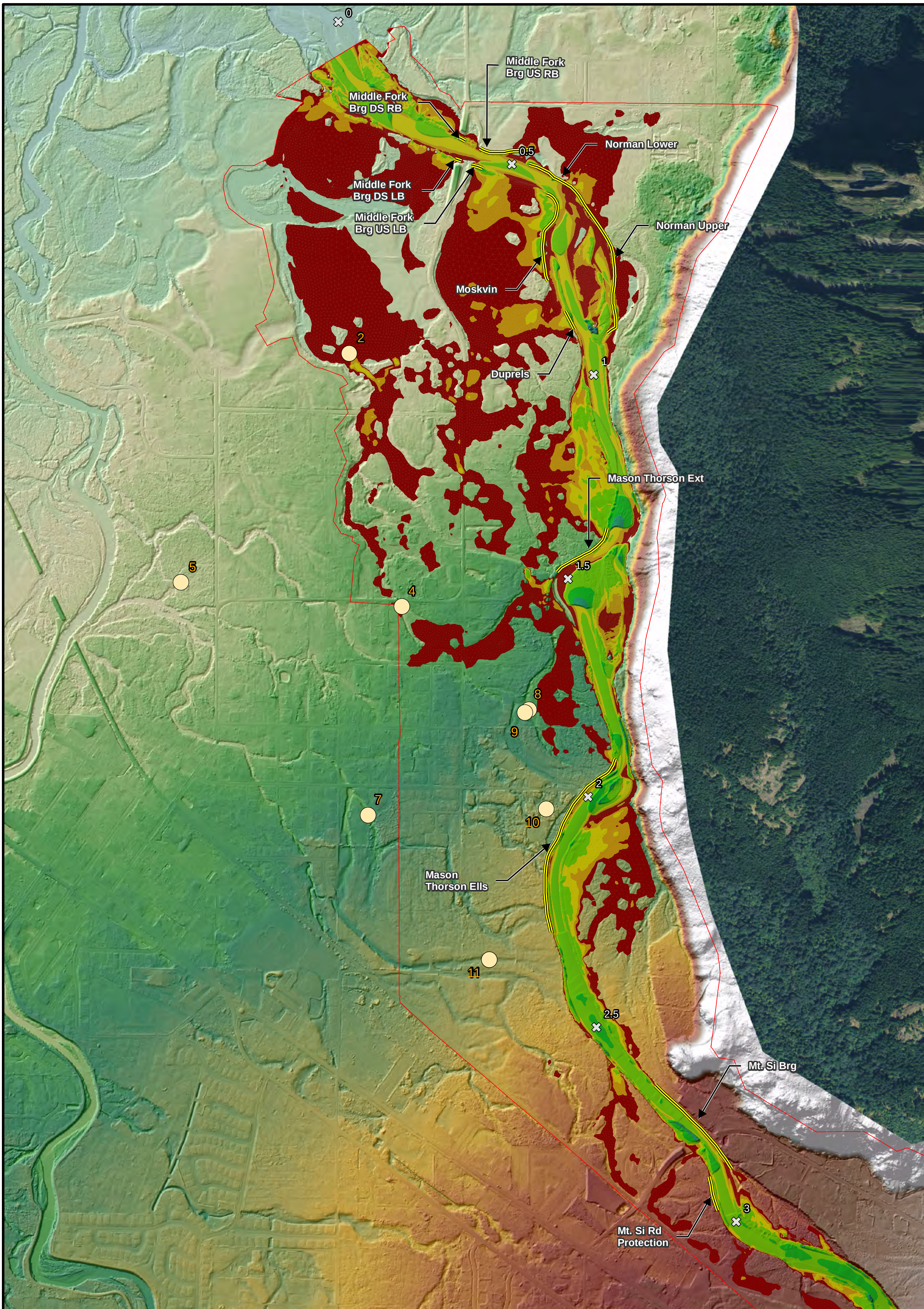

Legend

- Radiocarbon sample site
- River mile
- Levee or revetment
- Roads
- Limits of hydraulic model

Shear Stress (lb/ft2)

- 32
- 16 - 32
- 8 - 16
- 4 - 8
- 1 - 4
- 0.5 - 1
- 0.25 - 0.5
- 0.01 - 0.25
- 0 - 0.01

Elevation (feet)

High : 550

Low : 410

Figure 26. Bed Shear Stress for 25-Year Event from Hydraulic Model.

N

0 500 1,000 2,000 Feet

King County

Aerial: USDA (2011)
Hydraulic Model Results: WSE (2012)
Prepared for King County by Herrera

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Overall, the risk of enlargement or headcutting of relict floodplain channels, including Silver Creek, during major flood events is considered to be very low. Similarly, the risk of failure of roadway cross culverts is quite low, since the channels upstream and downstream of the culverts are likely to remain stable.

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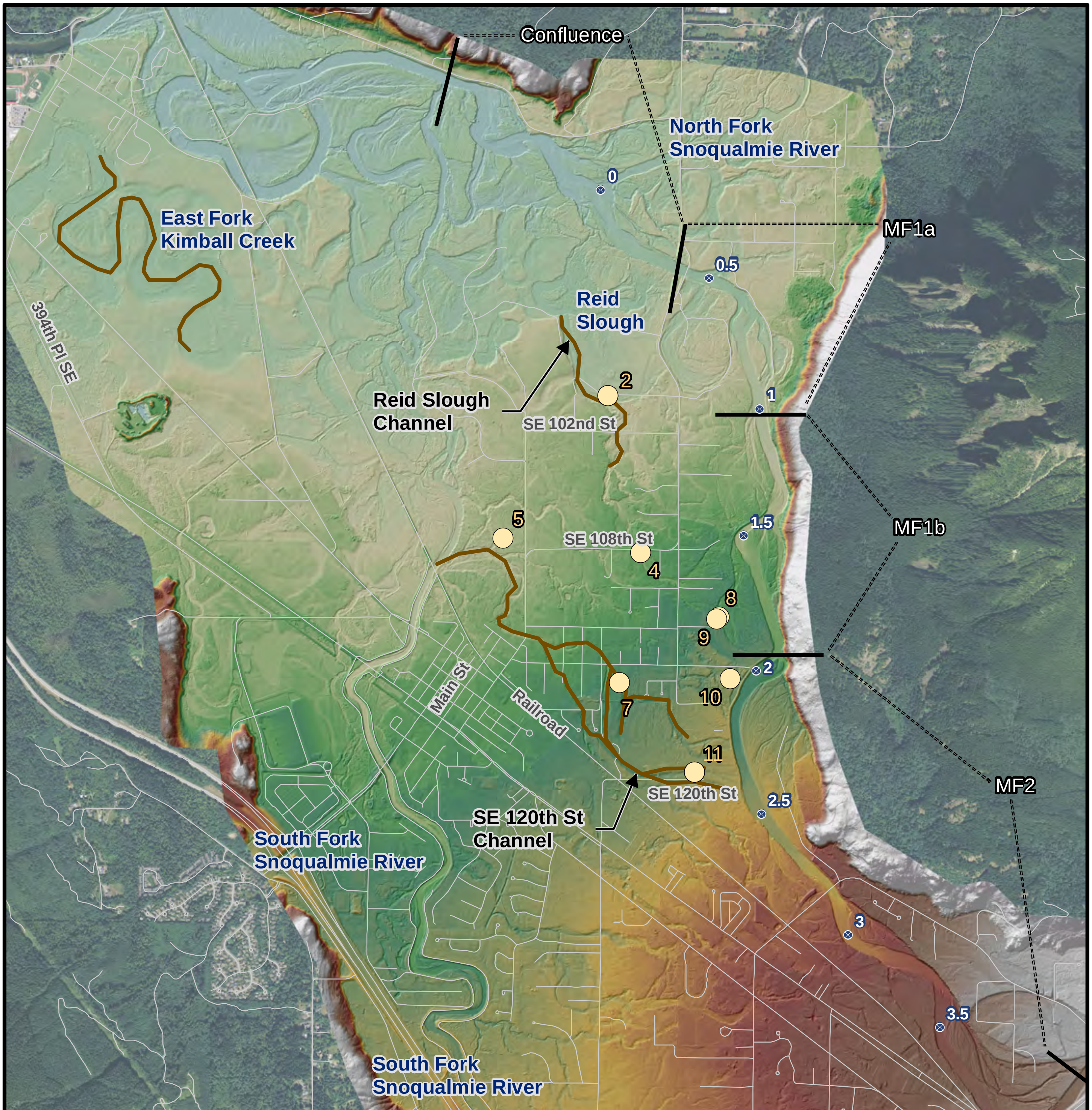
APPENDIX A

Radiocarbon Sampling and Analysis

Eleven samples from a total of eight sampling sites were dated using radiocarbon techniques. Many of the original samples were labeled in the field and submitted to the laboratory using a designation MF#-X, where # represents the site number and X represents a character identifying the sample when multiple samples were taken at a given site. For instance, MF3-B represents the second sample collected at sample site 3. In addition, two of the first samples collected used a different labeling protocol. Since the original codes as designated in the field are used in the laboratory report, they are also presented in this appendix when referring to a specific sample. Samples at sites 2, 4, 5, and 7 were collected using a hand auger while the samples at sites 8, 9, 10, and 11 were collected via excavating a pit with a backhoe. One sample (sample MF4-C) was obtained from the wall of a shallow hand-dug pit. To prevent confusion with subreaches MF1 and MF2 and to provide clarity regarding sample methods, samples are referred to by site number whenever possible. While a total of 11 sites were investigated, only eight sites produced material suitable for radiocarbon dating purposes. Figure A1 shows the sites from which datable samples were collected. An additional exploration site adjacent to the South Fork Snoqualmie River, near site 5, and two additional sites in E.J. Rogers Park, near site 7, are not shown in the figure.

For auger samples, material was collected from the lower half of the auger bucket from soil that showed no evidence of mixing with overlying sediment. The samples were transferred from the auger bucket or, in the case of site 4 (sample MF4-G), from the undisturbed soil in the sample pit, to a plastic Ziploc bag using a stainless steel spoon that had been wiped clean with a cloth rag. Samples from sites 8 through 11 were all collected from the wall of the respective pit after the wall had been scraped clean using a hand-shovel and stainless steel spoon. For samples from sites 4, 5, and 7 (samples MF4-C, MF5-G, and MF7-A), the sample was wrapped in aluminum foil in the field prior to being placed in the plastic bag. Wood fragments from site 2 (samples MFS F2-3.8 we and MFS F2-4.2) were placed directly in a plastic bag and then transferred to clean aluminum foil and placed in new plastic bags prior to shipment to the laboratory. The samples from sites 8, 9, 10, and 11 were wrapped in aluminum foil and labeled in the field, then stored for several weeks prior to shipment to Beta Analytic, where final sample isolation and preparation was performed. Samples were dated by Beta Analytic Corporation using standard Accelerator Mass Spectrometer (AMS) ^{14}C measurement techniques. The samples from the various sites consisted of fragments of wood, charcoal, or bone or organic sediment material.

A full description of each sample is provided below.



Legend

- River mile
- Sample site
- Major floodplain channel identified by Perkins (1996)
- Road

Figure A1. Floodplain Sample Sites.

N

0 1,250 2,500 5,000

Feet

King County

Aerial: USDA (2009)
Lidar: Snoqualmie (2010)

Prepared for King County by Herrera

K:\Projects\10-04766-015\Project\Geomorph_assessment\Floodplain Channel Map_appendix.mxd (6/17/2013)

Site 2 (Samples MFS F2-3.8 we and MFS F2-4.2 we)

These samples were collected by hand auger from an oxbow lake deposit on the south side of SE 100th Street, approximately 100 feet east of a closed gate, near the bottom of the road prism. A photograph of the site is provided in Figure A2.

Figure A2. Sample Site for MFS F2-3.8 we and MFS F2-4.2 we. The Coring Site Was Located Near the White Bucket Shown in the Image. Photo Is Taken Facing West.

Samples were collected at depths of 7.1 and 7.5 feet below the ground surface, respectively. A photograph of the soil from which sample MFS F2-3.8 was collected is shown in Figure A3. Both samples at this site were collected from near the base of a massive, 5.9 foot (1.8 m) thick sand layer, approximately 0.5 feet (0.2 m) above gravel that could not be penetrated by the hand auger. The sand deposit exhibited noticeable upward fining. Minimal oxidation was present. The water table on the day the sample was taken was within 2.5 feet of the ground surface. Since the sample was taken after an extended dry period, it is likely that the sampling depth is permanently below the water table.

Figure A3. Gray Sand From Which Sample MFS F2-3.8 we Was Sampled.

Site 4 (Sample MF4-C)

This charred wood sample was collected from a 1.2-foot-deep pit dug using a shovel in the bed of a relict floodplain channel that crosses NE 12th Street. A photograph of the sample site is shown in Figure A4. Cobbles were encountered in the pit at a depth of 1.2 feet below ground surface, preventing additional excavation. The charcoal fragment was collected from undisturbed sandy-silt soil approximately 0.2 feet below the elevation of the top of the highest cobble and 1.2 feet below the top of the pit. A photograph of the sample prior to its collection is shown in Figure A5. The sample is located to the left of the end of the measuring tape. Figure A5 also illustrates some of the live root fragments that were found near the charcoal fragment.

Broken glass was found in the soil that was excavated from the pit. Consequently, there is a small chance that the soil from which the sample was taken has been reworked during the modern era. However, the close proximity of the sample to the underlying cobbles makes this unlikely. It is more likely that the glass was present at the surface and was moved during excavation of the pit. The sample is shown in Figure A6.

Figure A4. Site 4. The Sample Was Taken at the Location of the Hand Auger.

Figure A5. Photograph of Sample MF4-C Prior to Collection.

Figure A6. Sample MF4-C.

Site 5 (Sample MF5-G)

This wood fragment sample was collected using a hand auger in the forested floodplain of the South Fork Snoqualmie River, adjacent to an inundated backwater channel called Silver Creek. The sample site was approximately 20 feet east of the water's edge. The ground surface elevation was approximately 1 foot above the water level in the creek on the day the sample was taken. The sample was collected near the base of a 2.1-foot-thick upward-fining sand layer. Gravel that could not be penetrated by the hand auger was located at the base of this layer, at a depth of 8.4 feet (2.6 m) below ground surface. Three individual layers of clay separated by silt and/or sand were present above the sand layer from which the sample was taken.

The sample site is shown in Figure A7. The sample is shown in Figure A8.

Figure A7. Site 5. Ponded Water in Silver Creek Is Visible in the Background.

Figure A8. Sample MF5-G.

Site 7 (Sample MF7-A)

This sample was collected from a hand auger core taken in the eastern of two relict floodplain channels in E.J. Rogers Park, in a mowed area approximately 60 feet upstream of a pedestrian footbridge. The sample was located at a depth of 1.8 feet below ground surface, within a 2.0-foot-thick layer of medium sand. A 0.3-foot-thick organic-rich loamy topsoil layer was present above the sand. Gravel that could not be penetrated by the hand auger was encountered at a depth of 2.3 feet. No groundwater was encountered at the site.

A photograph of the sample is shown in Figure A9.

Figure A9. Auger Sample from Which Wood Fragment MF7-A Was Collected.

Site 8 (Sample MFP1-0.9)

This sample was collected from a pit excavated in an abandoned channel within the wandering river floodplain adjacent to subreach MF1b. Cobble was encountered at a depth of about 3.3 feet below ground surface. Wood was dated from a sample (sample MFP1-0.9) collected from near the silt/cobble interface, at a depth of 3 feet (0.9 m). A photograph of the sample site is shown in Figure A10. A photograph of the pit wall showing the location of the sample is provided in Figure A11. The sample was wrapped in aluminum foil and labeled in the field and then stored for several weeks prior to shipment to Beta Analytic, where final sample preparation was performed.

Figure A10. Sample Site 8.

Figure A11. Pit at Sample Site 8. The Arrow Points to Sample MFP1-0.9.

Site 9 (Sample MFP2-0.35)

This sample was collected from a pit excavated in a pasture at the main floodplain level, immediately to the west of site 8. Figure A12 shows site 9 as viewed from site 8. The pit was characterized by a 3.6-foot (1.1-m) thick sequence of fine sand, silt, and clay above a gravel/cobble substrate (Figure A13). The gravel and cobble was noticeably finer than the cobble encountered at site 8. Many fine fibrous roots were encountered in the surface layers (see Figures A13 and A14). These were most likely roots from the grass in the pasture but could also possibly have been associated with nearby fir trees. Two samples were collected from the wall of this pit with a stainless steel spoon after the wall had been scraped clean with a shovel. One sample was a charcoal fragment collected at a depth of 1.1 feet (0.35 m) below ground surface (sample MFP2-0.35, see Figure A14) and another sample was collected at a depth of 3.6 feet (1.1 m) below ground surface, near the silt/clay gravel interface (sample MFP2-1.1, not dated). Samples were wrapped in aluminum foil and labeled in the field and then stored for several weeks prior to shipment to Beta Analytic, where final sample preparation was performed.

Figure A12. Sample Site 9 (at the Excavator). The Photograph Was Taken Standing at Site 8.

Figure A13. Pit at Site 9.

Figure A14. Charred Material Sampled as MFP2-0.35 From Pit Wall at Site 9. Material Similar to That Sampled Is Visible at the 28 cm Level. Measurement Indicates Depth Below Ground Surface.

Site 10 (Sample MFP3-BONE)

Site 10 is located on a County-owned parcel just south of SE 114th Street, in a forested area that is elevated approximately 1.5 feet above the roadway surface. A bone was found at the surface in spoils created by the excavator as it began to dig pit MFP2. No datable material was found in the pit itself.

The stratigraphy of pit MFP2 is shown in Figure A15. The surface at the site to a depth of approximately one foot consisted of silt and fine sand. The soil in the uppermost 0.3 feet of the excavation was noticeably darker and finer than the underlying material. Gravel and sand was encountered below a depth of approximately 1 foot. This material included several coarse sand lenses. In places, gravel clasts were possibly supported by the sandy matrix, but in most places the deposit was clast supported. Silt/clay was present in the soil matrix in places. The deposit revealed in this excavation was unconsolidated. Below a depth of 4 feet, the walls of the pit consisted of loose gravel that collapsed easily.

Figure A15. Pit at Site 10. No Datable Material Was Found In the Pit, But a Bone (Subsequently Dated as Modern) Was Found In The Excavated Spoils.

Site 11 (Samples MFP4-0.6, MFP4-1.2, and MFP4-1.4)

This site is located in a pasture within the northern of two relatively wide floodplain swales that parallel 120th Street. Pit MFP4 was excavated into the northern edge of the channel and included the lower part of the channel bank (Figure A16). The pit was excavated to a depth of approximately 5 feet below ground surface. The stratigraphy of the soil in the pit consisted of a 4.6-foot-thick sequence of sand and silt/clay overlying a cobble substrate (Figure A17). Three samples were collected from the pit: charcoal at depth of 2.0 feet (0.6 m) (sample MFP4-0.6), charcoal at depth of 4.0 feet (1.2 m) (sample MFP4-1.2), and wood fragments/soil collected at the interface between clay and sand immediately above the cobble substrate (reported by Beta Analytic as soil carbon) at depth of 4.6 feet (1.4 m) (sample MFP4-1.4). Photographs of the pit wall where each sample was collected are shown in Figures A18 to A20.

Figure A16. Location of Pit at Site 11. Samples Were Collected on North Side of Pit (Farthest Left from Excavator).

Figure A17. Northern Wall of Pit at Site 11. Cobbles (Not Shown) Were Present At Bottom of the Pit. The Dark Portions of the Image Resulted From Grit Preventing the Camera Lense Cover From Fully Opening. The Scale on the Surveying Rod Is In Tenths of a Foot.

Figure A18. Charred Material in Pit Wall at Site 11 Collected as Sample MFP4-0.6.

Figure A19. Charred Material In Pit Wall at Site 11 Collected as Sample MFP4-1.2.

Figure A20. Organic Material In Pit Wall at Site 11 Collected as Sample MFP4-1.4. A Cobble at the Base of the Pit Is Visible In the Lower Part of the Image.

Description: Site 2
100th Ave, ~100 feet north of gate on west side of road, near bottom of road prism.

Depth (ft)	Description
0 to 0.7	gravel (road fill)
0.7 to 1.6	gray mottled clay
1.6 to 2.1	fine silty sand, gray, not mottled
2.1 to 2.9	fine sand, gray
2.9 to 4.5	fine sand grading to medium sand, gray. Root or twig encountered at 4.5 feet.
4.5 to 4.6	medium sand, gray, large twig.
4.6 to 5.0	medium sand, gray
5.0 to 6.0	medium sand, gray, with some reddish decomposed wood fragments or peat
6.0 to 6.5	medium sand, gray, with reddish decomposed wood fragments
6.5 to 7.0	medium sand, gray, with reddish decomposed wood fragments. Sample MFS F2-4.3WE taken at depth 7.0 ft.
7.0 to 7.5	medium to coarse sand with some pea gravel. Refusal at 7.5 feet. Sample MFS F2-3.8WE taken at depth 7.5 ft.
7.5	pea gravel. Refusal.

Depth to water = 2.5 feet.

Description: Site 4.
In channel on ruppert property on 12th Avenue, ~20 m upstream from culvert.

Depth (ft)	Description
0 to 0.9	mottled brown silt/fine sand
0.9	gravel/cobble. Refusal.
	Sample MF4-C consists of three charcoal fragments sampled from a hand-dug pit at 1.2 foot depth in mottled sandy silt. Living root fragments were present near the sampled charcoal. The top of thie highest cobble in the pit was at approximately 1.0 foot depth.

No groundwater

Description: Site 5

Near Silver Creek (east side), on natural levee, floodplain of South Fork. Some gravel near surface. 6 m from water's edge.

Depth (ft)	Description
0	silt and pea gravel on surface
0 to 0.7	silt with some coarse sand and pea gravel, brown
0.7 to 1.7	silty clay, brown
1.7 to 2.0	dense silty clay, brown, no roots
2.0 to 2.8	fine sand
2.8 to 3.4	silty clay, mottled brown
3.4 to 4.2	silty clay, mottled gray
4.2 to 4.7	fine sand, some clay
4.7 to 5.6	gray clay with vegetation fragments
5.6 to 6.3	medium sand
6.3 to 7.0	medium sand
7.0 to 7.5	coarse sand and pea gravel. Wood fragment (Sample MF5-G at depth 7.5)
7.5 to 7.7	pea gravel and wood
7.7 to 8.4	gravel-refusal.

Depth to water = 2.3 feet.

Description: Site 7
In Rogers Park, east channel 18 m upstream from footbridge.

Depth (ft)	Description
0	topsoil-root mat and grass
0 to 0.5	sand
0.5 to 2.0	sand, gray, wood fragment (sample MF7-A)
2.0 to 2.5	medium sand, gray
2.5	refusal

No groundwater

APPENDIX B

Sediment Grain Size Data

Pebble Count, Lower Norman Levee Site
Near bar top, at upper end of willows, mid way between willow line and low flow channel.
Grains are not noticably imbricated

			For non-sand fraction				
D (mm)	count n	D less than (mm)	fraction in bin	% finer	psi	psi for bin	psi * fraction
<2	3	2	n/a	n/a	1	n/a	
2-2.8		2.8	0	0	1.5	1.25	0
2.8-4		4	0	0	2	1.75	0
4-5.6		5.6	0	0	2.5	2.25	0
5.6-8		8	0	0	3	2.75	0
8 to 11		11	0	0	3.5	3.25	0
11 to 16	3	16	0.0303	0.030	4	3.75	0.11
16 to 23	4	23	0.0404	0.071	4.5	4.25	0.17
23 to 32	7	32	0.0707	0.141	5	4.75	0.34
32 to 45	16	45	0.1616	0.303	5.5	5.25	0.85
45 to 64	16	64	0.1616	0.465	6	5.75	0.93
64 to 90	22	90	0.2222	0.687	6.5	6.25	1.39
90 to 128	5	128	0.0505	0.737	7	6.75	0.34
128 to 180	13	180	0.1313	0.869	7.5	7.25	0.95
180 to 256	11	256	0.1111	0.980	8	7.75	0.86
256 to 362	2	362	0.0202	1	8.5	8.25	0.17

Analysis is only for non-sand fraction

psi 50	6.08	
psi 84	7.39	
psi 16	5.06	
D50	67.6	mm
D84	167.8	mm
D16	33.3	mm

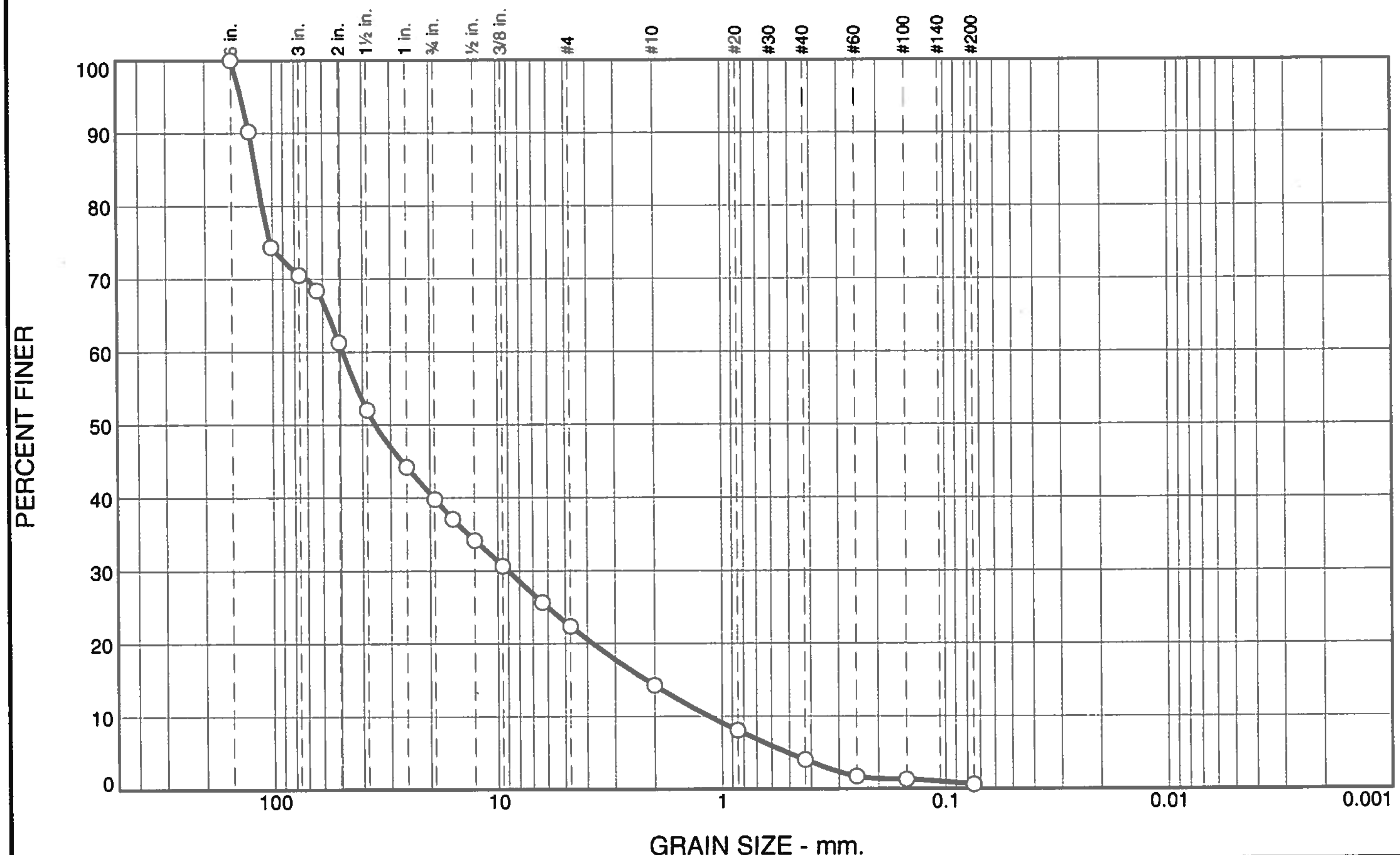
Total = mean psi	6.11	
D mean	69.0	Geometric mean grain size (mm)

Photosieving Results
Software provides only geometric mean diameters

RiverMile	D_mean (mm)	psi_mean	Description	Note
3.9	101	6.65	Boulder Bar	Subset of photo from RM 3.9
3.9	231	7.85	Boulder Bar	Subset of photo from Rm 3.9
3.9	218	7.77	Boulder Bar	Subset of photo from RM 3.9
3.9	172	7.42	Geometric Mean of three subsets	
0.7	75	6.22	Lower Norman Bar, at pebble count location	
-1	34	5.10	Bar above South Fork confluence	
0.8	29	4.86	Bar above log jam, lower Norman site	Subset of photo from RM 0.8
0.8	43	5.42	Bar above log jam, lower Norman site	Subset of photo from RM 0.8
0.8	35	5.14	Geometric mean of two subsets	

At RM 3.9 and 0.8, the photographs were split into sections and mean grain size was computed for each section.
The results from each subset were averaged geometrically to develop an overall geometric mean at each of these sites.

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
29.5	30.7	17.4	8.2	10.2	3.4	0.6	

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
6	100.0		
5	90.2		
4	74.3		
3	70.5		
2.5	68.4		
2	61.3		
1.5	52.0		
1	44.2		
.75	39.8		
.625	37.1		
.5	34.2		
.375	30.6		
.25	25.6		
#4	22.4		
#10	14.2		
#20	8.0		
#40	4.0		
#60	1.7		
#100	1.3		
#200	0.6		

* (no specification provided)

Material Description

MFS-S1

Atterberg Limits

PL= LL= PI=

Coefficients

D_{90}= 126.6042 D_{85}= 118.4291 D_{60}= 48.9965
D_{50}= 35.0785 D_{30}= 9.0429 D_{15}= 2.1919
D_{10}= 1.1429 C_u= 42.87 C_c= 1.46

Classification

USCS= GW AASHTO=

Remarks

Subsurface A and Subsurface B samples combined.

Sample Number: KC-12-1971

Date: 9/19/12

KING COUNTY MATERIALS LABORATORY

Client: Water & Land Resources
Project: Middle Fork Snoqualmie River
Project No: 1044469 **Figure** 1

Tested By: vw

Grain size distribution for subsurface sample collected at RM 0.7.

APPENDIX C

Detailed Sediment Budget Computations

Computational Details for Sediment Budget

Water→Bar Class

Because lidar generally does not penetrate water, areas of the DEM that were inundated during the 2002 lidar survey probably record elevations that are too high. Simply summing the topographic change across the DEM of difference in these areas would underrepresent total geomorphic change since the computation would likely neglect fill that occurred below the 2002 water surface. To address this, an average depth of 1.2 feet, based on the average stage at the Tanner gage during October 2002 (the month when the lidar was flown), was assumed to characterize flow depth through the study reach during the 2002 survey. (The sensitivity of the results to this assumption were assessed by adjusting the average flow depth upward to the point required for the overall sediment budget for the study area to show no net change in bed material, as described below.) This average depth was multiplied by the planform area of the Water→Bar class in each subreach to produce an estimate of the total volume below the water surface. This volume was added to the net fill results from the DEM of difference for this class in order to estimate the overall change in sediment storage volume. All volumetric change in this class was assumed to consist of bed/bar material.

Water→Floodplain

As in the Water→Bar class, the primary uncertainty in calculating volumetric change in this class is related to the depth of flow at the time of the 2002 lidar survey. This issue was handled in the same way as for the Water→Bar class, by computing a total volume of sediment from the DEM of difference and then adding an additional amount of sediment accumulation equal to the planform area of this class multiplied by the assumed flow depth at the time of the 2002 lidar survey. (Note that the planform area associated with this class is generally small, accounting for only 1.3 percent of the total area evaluated in the sediment budget).

Floodplain→Bar

For this class, the DEM of difference was assumed to adequately represent total volumetric change. An assumed fines fraction was multiplied by the overall volumetric change to estimate the volumetric change for floodplain material. The remainder of the eroded material was assumed to consist of bed/bar material. Because it is difficult to estimate representative reach-averaged fines fractions, computations were performed for fines fractions ranging from 50 to 80 percent. Results are presented later in this section for each assumed fraction.

Floodplain→Water

For this class, the DEM of difference probably represents the total volumetric change for the MF1 and MF2 subreaches adequately since the 2010 lidar-based DEM was adjusted to include bathymetry represented by the 2010 cross-sections in these subreaches (WSE 2013). However, since the downstream limit of the adjusted 2010 DEM corresponds with the downstream limit of the hydraulic modeling performed for this project (WSE 2013), at the confluence with the North Fork, it is necessary to adjust the total volumetric change derived by DEM differencing upward within the Confluence subreach. The adjustment accounts for the fact that in the subreach downstream from the North Fork, the 2010 DEM surface is entirely based on lidar and thus probably represents the elevation of the water surface rather than the channel bed. To perform the correction, an average depth of 2.3 feet (the average stage at the Tanner gage during the March 18-20, 2010, lidar survey period) was multiplied by the planform area of this class within the Confluence subreach and then added to the net evacuation of sediment computed from the DEM of difference. The total volume of eroded sediment thus estimated was then multiplied by the assumed fines fraction to estimate the volume of eroded floodplain material. The remainder was assumed to consist of bed/bar material.

Bar→Floodplain

For this class, the DEM of difference was assumed to adequately represent the total volumetric change. All volumetric change was assumed to consist of bed/bar material. In reality, the size distribution of this sediment includes both bar material and overbank fines that accumulated above the abandoned bar, most likely after vegetation became established. Overbank fines were neglected because some of these surfaces were relatively low in the earlier DEM, implying that bar growth accounts for much of the geomorphic change. Field verification could be performed to determine the thickness of overbank fines at these locations. However, the relatively small spatial extent of the class means that this would probably not change the overall budget significantly.

Bar→Water

For this class, the amount of erosion estimated through the DEM of difference was assumed to be accurate in subreaches MF1 and MF2, where 2010 bathymetry is available. In the Confluence subreach, the total volume of eroded material was revised upward by multiplying the average depth of flow at the time of the 2010 lidar survey by the planform area of the class, as described above for the Floodplain→Water class. All sediment eroded in this class was assumed to consist of bed/bar material.

Water→Water

In this class, neither the 2002 nor the 2010 DEMs were adequate for estimating a change in elevation. Consequently, neither DEM was used. Instead, the average rate of change in cross-sectional elevation was computed for each subreach using the 1993 and 2010 cross-section surveys. The change was computed for active areas of the cross-sections only and thus may or may not represent the actual change below the water surface. The change rate was then multiplied by 8 years, providing an estimate of average bed elevation change between 2002 and 2010. An estimate of depth change was developed for each of the three subreaches and then multiplied by the corresponding Water→Water planform area to develop a total volumetric change estimate in each subreach. All of this change was assumed to consist of bed/bar material.

Bar→Bar

For this class, the DEM of difference was assumed to adequately represent the total volumetric change. All material eroded and/or stored was assumed to consist of bed/bar material.

Floodplain→Floodplain

Because the 2002 lidar survey data is of questionable accuracy in vegetated areas and because it is not clear how far from the channel to extend the volumetric change analysis, this class was excluded from the analysis. Note that by neglecting this class, the overall sediment budget shows more net export of floodplain fines than likely occurred during the 8-year analysis period. Also note that there are locations where the DEM of difference shows net aggradation of floodplain surfaces (presumably through overbank deposition of floodplain fines). For example, the north bank immediately downstream of the confluence with the North Fork appears to have aggraded between 2002 and 2010. Unfortunately, the lack of ground-truthed data in other areas of the floodplain and known problems with the 2002 lidar survey prevent inclusion of this data in the analysis.

Middle Fork Snoqualmie River Geomorphic Analysis: DEM-difference based Sediment Budget Results for Fines Fraction = 0.8

Assumptions

Fraction Floodplain Fines in Floodplain Erosion

0.8

Bulk Specific Gravity of sediment deposits

2.100 Bar material

1.300 Floodplain fines

Assumed depth of bed below water on day of 2002 survey

1.2 CON   1.2 Other Reaches

Assumed depth of bed below water on day of 2010 survey

2.3 CON   0 Other Reaches

Average Annual Change for bed, ft/yr (averaged across all sections in a reach from County x-section surveys, 1993-2010)

-0.090 CON   -0.023 MF1   -0.032 MF2

Spreadsheet assumes all deposition on bar area that becomes floodplain is bar material

Spreadsheet ignores capture of fines by floodplain, so overstates loss of material

Reach	Category (2002)	Category (2010)	Area (ft2)	Cut Volume (ft3)	Fill Volume (ft3)	Total Change in Volume (ft3)	Average Elevation Change (ft)	Average Elevation Change After Adjustments (ft)	ESTIMATED Change in Volume Bed/Bar Material (ft3)	ESTIMATED Change in Volume Floodplain fines (ft3)	Note
CON	Water	Bar	357,369	13,830	916,073	902,243	2.52	3.72	1,344,915	0	Assumes water depth in 2002 = average stage for October 2002.
CON	Water	Floodplain	51,136	12,072	68,787	56,715	1.11	2.31	118,078	0	Assumes water depth in 2002 = average stage for October 2002.
CON	Water	Water	536,881	ignore	ignore	ignore	ignore	-0.72	-387,606	0	Depends strongly on incision rate at a few surveyed sections. Could be zero.
CON	Floodplain	Water	260,949	2,166,634	37,961	-2,128,672	-8.16	-10.46	-545,771	-2,183,084	Assumes water depth in 2010 = average stage on days of survey
CON	Floodplain	Bar	29,082	59,932	19,022	-40,910	-1.41	-1.41	-8,182	-32,728	
CON	Bar	Floodplain	103,059	14,799	170,288	155,489	1.51	1.51	155,489	0	
CON	Bar	Water	231,186	642,649	7,643	-635,005	-2.75	-5.05	-1,166,733	0	Assumes water depth in 2010 = average stage on days of LiDAR survey
CON	Bar	Bar	268,498	64,206	226,391	162,185	0.60	0.60	162,185	0	
							TOTAL		-327,624	-2,215,812	cubic feet
									-12,134	-82,067	cubic yards
									-21,466	-89,873	tons
									-2,683	-11,234	tons/year

Reach	Category (2002)	Category (2010)	Area (ft2)	Cut Volume (ft3)	Fill Volume (ft3)	Total Change in Volume (ft3)	Average Elevation Change (ft)	Average Elevation Change After Adjustments (ft)	ESTIMATED Change in Volume Bed/Bar Material (ft3)	ESTIMATED Change in Volume Floodplain fines (ft3)	Note
MF1	Water	Bar	485,307	316,330	554,735	238,405	0.49	1.69	1,137,104	0	Assumes water depth in 2002 = average stage for October 2002.
MF1	Water	Floodplain	18,949	9,898	4,166	-5,732	-0.30	0.90	17,007	0	Assumes water depth in 2002 = average stage for October 2002.
MF1	Water	Water	1,246,911	ignore	ignore	ignore	ignore	-0.18	-225,890	0	
MF1	Floodplain	Water	110,133	522,800	23,360	-499,440	-4.53	-4.53	-99,888	-399,552	Assumes 2010 bathymetry is correct so no adjustment for 2010 water level
MF1	Floodplain	Bar	99,536	156,050	51,684	-104,366	-1.05	-1.05	-20,873	-83,493	
MF1	Bar	Floodplain	4,397	865	617	-248	-0.06	-0.06	-248	0	
MF1	Bar	Water	172,501	333,287	55,331	-277,956	-1.61	-1.61	-277,956	0	Assumes 2010 bathymetry is correct so no adjustment for 2010 water level
MF1	Bar	Bar	704,650	439,956	357,853	-82,103	-0.12	-0.12	-82,103	0	
								TOTAL	447,153	-483,045	cubic feet
									16,561	-17,891	cubic yards
									29,297	-19,592	tons
									3,662	-2,449	tons/year

Reach	Category (2002)	Category (2010)	Area (ft2)	Cut Volume (ft3)	Fill Volume (ft3)	Total Change in Volume (ft3)	Average Elevation Change (ft)	Average Elevation Change After Adjustments (ft)	ESTIMATED Change in Volume Bed/Bar Material (ft3)	ESTIMATED Change in Volume Floodplain fines (ft3)	Note
MF2	Water	Bar	191,888	122,680	46,960	-75,720	-0.39	0.81	277,226	0	Assumes water depth in 2002 = average stage for October 2002.
MF2	Water	Floodplain	21,186	3,820	7,919	4,099	0.19	1.39	29,522	0	Assumes water depth in 2002 = average stage for October 2002.
MF2	Water	Water	1,946,452	ignore	ignore	ignore	ignore	-0.25	-491,481	0	
MF2	Floodplain	Water	164,057	269,020	61,606	-207,414	-1.26	-1.26	-41,483	-165,931	Assumes water depth in 2010 = average stage on days of survey
MF2	Floodplain	Bar	62,093	118,078	10,281	-107,797	-1.74	-1.74	-21,559	-86,238	
MF2	Bar	Floodplain	1,625	307	124	-184	-0.11	-0.11	-184	0	
MF2	Bar	Water	108,652	42,869	88,485	45,616	0.42	0.42	45,616	0	Assumes water depth in 2010 = average stage on days of survey
MF2	Bar	Bar	106,334	27,488	99,305	71,817	0.68	0.68	71,817	0	
								TOTAL	-130,527	-252,169	cubic feet
									-4,834	-9,340	cubic yards
									-8,552	-10,228	tons
									-1,069	-1,278	tons/year

Totals for entire study area:

Bed/Bar Material	Floodplain Fines	
-10,998	-2,951,026	cubic feet
-407	-109,297	cubic yards
-721	-193,351	tons
-90	-24,169	tons/year

Middle Fork Snoqualmie River Geomorphic Analysis: DEM-difference based Sediment Budget Results for Fines Fraction = 0.65

Assumptions

Fraction Floodplain Fines in Floodplain Erosion			Bulk Specific Gravity of sediment deposits	
0.65			2.100	Bar material
			1.300	Floodplain fines

Assumed depth of bed below water on day of 2002 survey

1.2	CON	1.2	Other Reaches

Assumed depth of bed below water on day of 2010 survey

2.3	CON	0	Other Reaches

Average Annual Change for bed, ft/yr (averaged across all sections in a reach from County x-section surveys, 1993-2010)

-0.090	CON	-0.023	MF1	-0.032	MF2

Spreadsheet assumes all deposition on bar area that becomes floodplain is bar material

Spreadsheet ignores capture of fines by floodplain, so overstates loss of material

Reach	Category (2002)	Category (2010)	Area (ft2)	Cut Volume (ft3)	Fill Volume (ft3)	Total Change in Volume (ft3)	Average Elevation Change (ft)	Average Elevation Change After Adjustments (ft)	ESTIMATED Change in Volume Bed/Bar Material (ft3)	ESTIMATED Change in Volume Floodplain fines (ft3)	Note
CON	Water	Bar	357,369	13,830	916,073	902,243	2.52	3.72	1,344,915	0	Assumes water depth in 2002 = average stage for October 2002.
CON	Water	Floodplain	51,136	12,072	68,787	56,715	1.11	2.31	118,078	0	Assumes water depth in 2002 = average stage for October 2002.
CON	Water	Water	536,881	ignore	ignore	ignore	ignore	-0.72	-387,606	0	Depends strongly on incision rate at a few surveyed sections. Could be zero.
CON	Floodplain	Water	260,949	2,166,634	37,961	-2,128,672	-8.16	-10.46	-955,099	-1,773,756	Assumes water depth in 2010 = average stage on days of survey
CON	Floodplain	Bar	29,082	59,932	19,022	-40,910	-1.41	-1.41	-14,319	-26,592	
CON	Bar	Floodplain	103,059	14,799	170,288	155,489	1.51	1.51	155,489	0	
CON	Bar	Water	231,186	642,649	7,643	-635,005	-2.75	-5.05	-1,166,733	0	Assumes water depth in 2010 = average stage on days of LiDAR survey
CON	Bar	Bar	268,498	64,206	226,391	162,185	0.60	0.60	162,185	0	
							TOTAL		-743,089	-1,800,347	cubic feet
									-27,522	-66,680	cubic yards
									-48,687	-73,022	tons
									-6,086	-9,128	tons/year

Reach	Category (2002)	Category (2010)	Area (ft2)	Cut Volume (ft3)	Fill Volume (ft3)	Total Change in Volume (ft3)	Average Elevation Change (ft)	Average Elevation Change After Adjustments (ft)	ESTIMATED Change in Volume Bed/Bar Material (ft3)	ESTIMATED Change in Volume Floodplain fines (ft3)	Note
MF1	Water	Bar	485,307	316,330	554,735	238,405	0.49	1.69	1,137,104	0	Assumes water depth in 2002 = average stage for October 2002.
MF1	Water	Floodplain	18,949	9,898	4,166	-5,732	-0.30	0.90	17,007	0	Assumes water depth in 2002 = average stage for October 2002.
MF1	Water	Water	1,246,911	ignore	ignore	ignore	ignore	-0.18	-225,890	0	
MF1	Floodplain	Water	110,133	522,800	23,360	-499,440	-4.53	-4.53	-174,804	-324,636	Assumes 2010 bathymetry is correct so no adjustment for 2010 water level
MF1	Floodplain	Bar	99,536	156,050	51,684	-104,366	-1.05	-1.05	-36,528	-67,838	
MF1	Bar	Floodplain	4,397	865	617	-248	-0.06	-0.06	-248	0	
MF1	Bar	Water	172,501	333,287	55,331	-277,956	-1.61	-1.61	-277,956	0	Assumes 2010 bathymetry is correct so no adjustment for 2010 water level
MF1	Bar	Bar	704,650	439,956	357,853	-82,103	-0.12	-0.12	-82,103	0	
								TOTAL	356,582	-392,474	cubic feet
									13,207	-14,536	cubic yards
									23,363	-15,919	tons
									2,920	-1,990	tons/year

Reach	Category (2002)	Category (2010)	Area (ft2)	Cut Volume (ft3)	Fill Volume (ft3)	Total Change in Volume (ft3)	Average Elevation Change (ft)	Average Elevation Change After Adjustments (ft)	ESTIMATED Change in Volume Bed/Bar Material (ft3)	ESTIMATED Change in Volume Floodplain fines (ft3)	Note
MF2	Water	Bar	191,888	122,680	46,960	-75,720	-0.39	0.81	277,226	0	Assumes water depth in 2002 = average stage for October 2002.
MF2	Water	Floodplain	21,186	3,820	7,919	4,099	0.19	1.39	29,522	0	Assumes water depth in 2002 = average stage for October 2002.
MF2	Water	Water	1,946,452	ignore	ignore	ignore	ignore	-0.25	-491,481	0	
MF2	Floodplain	Water	164,057	269,020	61,606	-207,414	-1.26	-1.26	-72,595	-134,819	Assumes water depth in 2010 = average stage on days of survey
MF2	Floodplain	Bar	62,093	118,078	10,281	-107,797	-1.74	-1.74	-37,729	-70,068	
MF2	Bar	Floodplain	1,625	307	124	-184	-0.11	-0.11	-184	0	
MF2	Bar	Water	108,652	42,869	88,485	45,616	0.42	0.42	45,616	0	Assumes water depth in 2010 = average stage on days of survey
MF2	Bar	Bar	106,334	27,488	99,305	71,817	0.68	0.68	71,817	0	
								TOTAL	-177,809	-204,887	cubic feet
									-6,586	-7,588	cubic yards
									-11,650	-8,310	tons
									-1,456	-1,039	tons/year

Totals for entire study area:

Bed/Bar Material	Floodplain Fines	
-564,316	-2,397,708	cubic feet
-20,901	-88,804	cubic yards
-36,974	-157,098	tons
-4,622	-19,637	tons/year

Middle Fork Snoqualmie River Geomorphic Analysis: DEM-difference based Sediment Budget Results for Fines Fraction = 0.5

Assumptions

Fraction Floodplain Fines in Floodplain Erosion: 0.5

Bulk Specific Gravity of sediment deposits:
- 2.100 Bar material
- 1.300 Floodplain fines

Assumed depth of bed below water on day of 2002 survey: 1.2 CON; 1.2 Other Reaches

Assumed depth of bed below water on day of 2010 survey: 2.3 CON; 0 Other Reaches

Average Annual Change for bed, ft/yr (averaged across all sections in a reach from County x-section surveys, 1993-2010): -0.090 CON; -0.023 MF1; -0.032 MF2

Spreadsheet assumes all deposition on bar area that becomes floodplain is bar material
Spreadsheet ignores capture of fines by floodplain, so overstates loss of material

Reach	Category (2002)	Category (2010)	Area (ft2)	Cut Volume (ft3)	Fill Volume (ft3)	Total Change in Volume (ft3)	Average Elevation Change (ft)	Average Elevation Change After Adjustments (ft)	ESTIMATED Change in Volume Bed/Bar Material (ft3)	ESTIMATED Change in Volume Floodplain fines (ft3)	Note
CON	Water	Bar	357,369	13,830	916,073	902,243	2.52	3.72	1,344,915	0	Assumes water depth in 2002 = average stage for October 2002.
CON	Water	Floodplain	51,136	12,072	68,787	56,715	1.11	2.31	118,078	0	Assumes water depth in 2002 = average stage for October 2002.
CON	Water	Water	536,881	ignore	ignore	ignore	ignore	-0.72	-387,606	0	Depends strongly on incision rate at a few surveyed sections. Could be zero.
CON	Floodplain	Water	260,949	2,166,634	37,961	-2,128,672	-8.16	-10.46	-1,364,428	-1,364,428	Assumes water depth in 2010 = average stage on days of survey
CON	Floodplain	Bar	29,082	59,932	19,022	-40,910	-1.41	-1.41	-20,455	-20,455	
CON	Bar	Floodplain	103,059	14,799	170,288	155,489	1.51	1.51	155,489	0	
CON	Bar	Water	231,186	642,649	7,643	-635,005	-2.75	-5.05	-1,166,733	0	Assumes water depth in 2010 = average stage on days of LiDAR survey
CON	Bar	Bar	268,498	64,206	226,391	162,185	0.60	0.60	162,185	0	
							TOTAL		-1,158,554	-1,384,883	cubic feet
									-42,909	-51,292	cubic yards
									-75,908	-56,171	tons
									-9,489	-7,021	tons/year

Reach	Category (2002)	Category (2010)	Area (ft2)	Cut Volume (ft3)	Fill Volume (ft3)	Total Change in Volume (ft3)	Average Elevation Change (ft)	Average Elevation Change After Adjustments (ft)	ESTIMATED Change in Volume Bed/Bar Material (ft3)	ESTIMATED Change in Volume Floodplain fines (ft3)	Note
MF1	Water	Bar	485,307	316,330	554,735	238,405	0.49	1.69	1,137,104	0	Assumes water depth in 2002 = average stage for October 2002.
MF1	Water	Floodplain	18,949	9,898	4,166	-5,732	-0.30	0.90	17,007	0	Assumes water depth in 2002 = average stage for October 2002.
MF1	Water	Water	1,246,911	ignore	ignore	ignore	ignore	-0.18	-225,890	0	
MF1	Floodplain	Water	110,133	522,800	23,360	-499,440	-4.53	-4.53	-249,720	-249,720	Assumes 2010 bathymetry is correct so no adjustment for 2010 water level
MF1	Floodplain	Bar	99,536	156,050	51,684	-104,366	-1.05	-1.05	-52,183	-52,183	
MF1	Bar	Floodplain	4,397	865	617	-248	-0.06	-0.06	-248	0	
MF1	Bar	Water	172,501	333,287	55,331	-277,956	-1.61	-1.61	-277,956	0	Assumes 2010 bathymetry is correct so no adjustment for 2010 water level
MF1	Bar	Bar	704,650	439,956	357,853	-82,103	-0.12	-0.12	-82,103	0	
								TOTAL	266,011	-301,903	cubic feet
									9,852	-11,182	cubic yards
									17,429	-12,245	tons
									2,179	-1,531	tons/year

Reach	Category (2002)	Category (2010)	Area (ft2)	Cut Volume (ft3)	Fill Volume (ft3)	Total Change in Volume (ft3)	Average Elevation Change (ft)	Average Elevation Change After Adjustments (ft)	ESTIMATED Change in Volume Bed/Bar Material (ft3)	ESTIMATED Change in Volume Floodplain fines (ft3)	Note
MF2	Water	Bar	191,888	122,680	46,960	-75,720	-0.39	0.81	277,226	0	Assumes water depth in 2002 = average stage for October 2002.
MF2	Water	Floodplain	21,186	3,820	7,919	4,099	0.19	1.39	29,522	0	Assumes water depth in 2002 = average stage for October 2002.
MF2	Water	Water	1,946,452	ignore	ignore	ignore	ignore	-0.25	-491,481	0	
MF2	Floodplain	Water	164,057	269,020	61,606	-207,414	-1.26	-1.26	-103,707	-103,707	Assumes water depth in 2010 = average stage on days of survey
MF2	Floodplain	Bar	62,093	118,078	10,281	-107,797	-1.74	-1.74	-53,899	-53,899	
MF2	Bar	Floodplain	1,625	307	124	-184	-0.11	-0.11	-184	0	
MF2	Bar	Water	108,652	42,869	88,485	45,616	0.42	0.42	45,616	0	Assumes water depth in 2010 = average stage on days of survey
MF2	Bar	Bar	106,334	27,488	99,305	71,817	0.68	0.68	71,817	0	
								TOTAL	-225,090	-157,605	cubic feet
									-8,337	-5,837	cubic yards
									-14,748	-6,392	tons
									-1,843	-799	tons/year

Totals for entire study area:

Bed/Bar Material	Floodplain Fines	
-1,117,633	-1,844,391	cubic feet
-41,394	-68,311	cubic yards
-73,227	-120,845	tons
-9,153	-15,106	tons/year