Susitna-Watana Hydroelectric Project
(FERC No. 14241)

Fluvial Geomorphology Modeling below Watana Dam
Study Plan Section 6.6

2014-2015 Study Implementation Report
Attachment 1: Appendix A
1-D Bed Evolution Model of the Middle and Lower Susitna River: Model Development and Calibration

Prepared for

Alaska Energy Authority

SUSITNA-WATANA HYDRO

Clean, reliable energy for the next 100 years.

Prepared by

Tetra Tech, Inc.

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Abbreviation	**Definition**
1-D	One-Dimensional
2-D	Two-Dimensional
ADCP	Acoustic Doppler Current Profiler
AEA	Alaska Energy Authority
BEM	Bed Evolution Model
cfs	cubic feet per second
$D_{\#\#}$	Sediment grain diameter, where ## represents the percent of a sediment sample finer than this diameter
ESS	Alaska Energy Authority Surface Water Station on the Susitna River
FA	Focus Area
FA-IFS	Fish and Aquatics Instream Flow Study (Study 8.5)
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FESWMS-2DH	Finite-element Surface-water Modeling System for Two-Dimensional Horizontal Flow
ft	Feet
FGM	Fluvial Geomorphology Modeling
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
GPS	Global Positioning System
HEC	Hydrologic Engineering Center
HEC-DSS	Hydrologic Engineering Center Data Storage System
HEC-RAS	Hydrologic Engineering Center River Analysis System
HEC-ResSim	Hydrologic Engineering Center Reservoir System Simulation
ISR	Initial Study Report
lbs	pounds
LiDAR	Light Detection and Ranging
LR	Lower River

Abbreviation	Definition
MatSu	Matanuska-Susitna
Max LF OS-1b	Maximum Load Following Operation Scenario 1B
mm	Millimeter
MR	Middle River
MVUE	Minimum Variance Unbiased Estimator
NAVD88	North American Vertical Datum of 1988
OS	Operation Scenario
OWFP	Open-Water Flow Periods
POC	Proof of Concept
PRM	Project River Mile
Q	Flow
Q_s	Sediment discharge
RM	River Mile
RSP	Revised Study Plan
RTK	Real Time Kinematic
s	Second
SPD	Study Plan Determination
sq-ft	square foot
t	tons
UR	Upper River
USGS	U.S. Geological Survey
USACE	U.S. Army Corps of Engineers
WY	Water Year

1. INTRODUCTION

The Alaska Energy Authority (AEA) is preparing a License Application that will be submitted to the Federal Energy Regulatory Commission (FERC) for the Susitna-Watana Hydroelectric Project (Project) using the Integrated Licensing Process. The Project is located on the Susitna River, an approximately 300-mile-long river in the south-central region of Alaska. The Project's dam site will be located at Project River Mile (PRM) 187.1. Ongoing studies will provide information needed to support the FERC's National Environmental Policy Act analysis for the Project license.

On December 14, 2012, AEA filed its Revised Study Plan (RSP), which included 58 individual study plans, with the FERC for the Susitna-Watana Hydroelectric Project (FERC Project No. 14241) (AEA 2012). Included with the RSP is the Fluvial Geomorphology Modeling below Watana Dam (FGM) Study (RSP Study 6.6). As described in the RSP and summarized below in Table 1.0-1, the three components of Study 6.6 focus on the modeling planned for assessing the effects of the proposed Project and its operations on the fluvial geomorphology of the Susitna River downstream of Watana Dam.

When the FERC issued its Study Plan Determination (April 1 SPD), which approved the FGM Study, it recommended that AEA file a technical memorandum providing additional information on the models and methods for addressing several aspects of the RSP Study 6.6. In response, on July 1, 2013 AEA submitted the *Fluvial Geomorphology Modeling Approach Technical Memorandum* (Tetra Tech 2013a). As the modeling approach was refined through informal coordination with various study teams and through meetings of internal teams, Technical Teams, and Technical Workgroups, a Proof of Concept (POC) effort was agreed upon. As described in Section 4.3.2.2 of the Study 6.6 Initial Study Report (ISR) the POC effort is a demonstration of the initial integration of the various modeling efforts being carried out under the Fish and Aquatics Instream Flow Study (FA-IFS) (Study 8.5), the Ice Processes in the Susitna River Study (Study 7.6), the Groundwater Study (Study 7.5), the Water Quality Modeling Study (Study 5.6), the Geomorphology Study (Study 6.5), and the FGM Study (Study 6.6). While results of the 2-D hydraulic modeling for Focus Area (FA) 128 (Slough 8A) were presented and integration of these results with other studies was demonstrated at the POC meeting held April 15-17, 2014, results of the 1-D Bed Evolution Modeling (BEM) were not available at that time. To document the model integration and refinements resulting from the POC meeting, the *Updated Fluvial Geomorphology Modeling Approach Technical Memorandum* (Tetra Tech 2014a) was filed with the FERC in May 2014.

Section 7.2.1 of the Study 6.6 ISR states that a technical memorandum describing 1-D BEM development, simulations of existing and with-Project conditions, and coordination and interpretation of model results will be prepared. This appendix documents further POC specific to development of 1-D modeling components of the FGM Study. This appendix and Appendix B, which describes the 2-D BEM POC for FA 128 (Slough 8a), provide model development information as part of Attachment 1, which is the technical memorandum for overall fluvial geomorphology model development. The model described in this appendix is the initial 1-D BEM that was developed to support the decision whether to extend fluvial geomorphology modeling below PRM 29.9 (Tetra Tech 2014b).

1.1. Background

The purpose of the fluvial geomorphology studies is to assess the potential effects of the Susitna-Watana Hydroelectric Project on the dynamic behavior of the river downstream of the proposed dam, with particular focus on potential changes in instream and riparian habitat. The Project will alter flows and sediment supply downstream of the dam, and the channel form is expected to respond to the changes. Whether the existing channel morphology will remain the same or at least be in dynamic equilibrium under post-Project conditions is a key question that can be addressed through numerical BEM. Tetra Tech (2014a) differentiated reach-scale from local-scale issues that the BEM needs to address. Reach-scale issues involve the overall behavior and general characteristics of the Susitna River over many miles; local-scale issues are limited spatially to a few miles. The reach-scale issues are the focus of the 1-D BEM; the local-scale issues are the focus of the 2-D BEM. The 1-D BEM will inform reach-scale sediment routing conditions, potential changes in bed and water-surface elevations, changes in channel profile, and potential changes in bed material gradation. The results of the 1-D BEM also provide boundary conditions for the local-scale modeling carried out using the 2-D BEM.

1.2. Objectives

The objectives of the POC effort specific to the 1-D BEM include:

1. Develop and calibrate an initial 1-D BEM for the Susitna River from the proposed Watana Dam (PRM 187.1) to Susitna Station (PRM 29.9), including the lower 18.4 miles of the Chulitna River and the lower 4.7 miles of the Talkeetna River.
2. Simulate 50 years of open-water flow periods (OWFP) under existing conditions and the proposed maximum load-following operation scenario (Max LF-OS-1b).
3. Ensure information from the Geomorphology Study (Study 6.5) is properly considered and incorporated into the 1-D BEM.

1.3. Study Area

As shown in Figure 1-1, the Susitna River, located in the south-central region of Alaska, drains an area of approximately 20,010 square miles and flows about 320 miles from its headwaters at the Susitna glacier, West Fork Susitna glacier, and East Fork Susitna glacier to Cook Inlet (Curran 2012). The Susitna River basin is bounded on the west and north by the Alaska Range, on the east by the Talkeetna Mountains and Copper River Lowlands and on the south by Cook Inlet. The highest elevations in the basin are on Mt. McKinley at 20,320 feet, while its lowest elevations are at sea level where the river discharges into Cook Inlet. Major tributaries to the Susitna River between the headwaters and Cook Inlet include the Chulitna, Talkeetna and Yentna Rivers. These tributaries are glacially fed in their respective headwaters.

The overall study area extends from PRM 0 at Cook Inlet to the Maclaren River confluence at PRM 261.3. The Geomorphology Study (Study 6.5) divided the Susitna River into three segments whose general characteristics are governed by the basin geology as described by Wilson et al. (2009). The segments are referred to as the Upper, Middle, and Lower River and they are identified in Figure 1.3-1 with the associated extents:

- Upper River (UR): Maclaren River confluence (PRM 261.3 / RM 260) downstream to the proposed Watana Dam site (PRM 187.1 / RM 184).[1]
- Middle River (MR): Proposed Watana Dam site (PRM 187.1 / RM 184) downstream to the Three Rivers Confluence (PRM 102.4 / RM 98.5).
- Lower River (LR): Three Rivers Confluence (PRM 102.4 / RM 98.5) downstream to Cook Inlet (PRM 3.3 / RM 0).

The 1-D BEM includes the Middle River segment and the Lower River segment upstream of Susitna Station (PRM 29.9). An earlier decision to include the Lower River below PRM 87.9 resulted in the extension of this model to PRM 29.9. This initial model does not include the lower 18.4 miles of the Chulitna River and the lower 4.7 miles of the Talkeetna River, though does include the flow and sediment inputs from these rivers. The Chulitna and Talkeetna River reaches will be added to the next version of the model. Thus, the FGM study area encompasses the contributing drainage area to PRM 187.1 and the contributing drainage areas from PRM 187.1 to PRM 29.9, including the major watersheds of the Chulitna, Talkeetna, and Yentna Rivers. The 1-D BEM focuses on the main channels and floodplains of the Susitna River, Chulitna River, and Talkeetna River within the study area. The upstream extent of the modeling on the Chulitna River is the U.S. Geological Survey (USGS) gaging station (No. 15292400 Chulitna River near Talkeetna) and the upstream extent of modeling on the Talkeetna River is the USGS gaging station (No. 15292700 Talkeetna River near Talkeetna). While the flow and sediment conveyed by the Yentna River into the Susitna River are included in the 1-D BEM, geomorphic changes to the Yentna River channel and floodplain are not simulated in the model.

2. DEVELOPMENT AND CALIBRATION OF FIXED-BED HYDRAULIC MODEL

Tetra Tech (2014a) presents an overview of the approach and methods for developing the 1-D BEM. Details pertinent to the initial model developed for the POC effort are presented in the following sections. The final selection of the U.S. Army Corps of Engineers' (USACE) Hydrologic Engineering Center River Analysis System (HEC-RAS) Version 5.0.0 (beta) software for the 1-D BEM is presented in Tetra Tech (2014a); therefore, the following details of the model development are linked to the required inputs for this software. The following methods describing model development and calibration address the first and third objectives of this POC effort (Section **Error! Reference source not found.**).

The development of the 1-D BEM followed the following series of steps:

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[1] Note: Project River Miles (PRMs) are the stationing system used for the current Susitna-Watana Project. River Miles (RMs) were the stationing system used for the 1980s Project. The PRM delineation starts about 3 miles farther into Cook Inlet than the RMs, and the PRM alignment is slightly different than the RM alignment. Thus, PRM values are generally 3 to 4 miles greater than the RM values.

1. Develop a fixed-bed hydraulic model.
2. Test hydraulics simulated with the fixed-bed model.
3. Calibrate the fixed-bed hydraulics.
4. Validate the fixed-bed hydraulics.
5. Develop a moveable-boundary sediment routing model using the validated fixed-bed model.
6. Test sediment routing simulated with the moveable-boundary model.
7. Calibrate the moveable-boundary sediment routing simulation.

To facilitate the presentation of the model development, the documentation has been separated between Steps 1 through 4 associated with the fixed-bed model and Steps 5 through 7 associated with the moveable-boundary. The development (Step1), testing (Step 2), calibration (Step 3), and validation (Step 4) of the fixed-bed hydraulic model are presented in this section (Section 2); the development (Step 5), testing (Step 6), and calibration (Step 7) of the moveable-boundary sediment routing model is presented in Section 3. This separation of the documentation is logical because the validated fixed-bed hydraulic model was used to develop the mobile-bed sediment routing model.

It is important to note that the 1-D BEM developed, calibrated, and applied for the POC effort is an initial model that was used in the decision whether to extend fluvial geomorphology modeling below PRM 29.9. The initial model will be updated as the Fluvial Geomorphology Modeling Study advances. The model is considered initial because coordination with other studies has been ongoing and data collection efforts continued through the development, calibration, and implementation of the initial 1-D BEM. The additional coordination includes revised tributary hydrologic information provided by FA-IFS (Study 8.5) and more operational scenarios that will be considered. The additional data that were collected in 2014 and need to be incorporated in the final 1-D BEM include channel surveys, discharge and water-surface elevation measurements, LiDAR topographic mapping, bed material sampling, and surveys and sediment sampling in tributaries.

2.1. Existing Information

The POC effort specific to the 1-D BEM was represents the integration of multiple previous and ongoing study efforts. The following subsections summarize pertinent existing information related to the development and calibration of the fixed-bed hydraulic model.

2.1.1. Hydraulic Models

Hydraulic models were previously developed to support (1) the 1980s studies of the Susitna Hydroelectric Project (R&M 1982) and (2) the Flood Insurance Study (FIS) of the Matanuska-Susitna Borough (FEMA 2011).

2.1.1.1. 1980s HEC-2 Models for the Susitna Hydroelectric Project

The USACE HEC-2 software was used to develop a mathematical hydraulic model of the Susitna River to simulate open-water river hydraulics under proposed post-Project flows (R&M 1982). Two reaches were modeled (1) the Susitna River from Deadman Creek (PRM 189.4) to Devil Creek (PRM 164.8) (hereafter referred to as the upper reach), and (2) the Susitna River from the outlet of Devil Canyon (approximately PRM 154.0) to the confluence with the Chulitna River

(PRM 102.5) (hereafter referred to as the lower reach). Topographic and hydrographic surveys were the source of the cross section geometry (Section 3.1.3.1). Qualitative field observations of vegetation and bed material were the basis of initial n values; surveyed water-surface elevations and measurements at crest-stage recorder sites and stream gages were the basis of calibrated and validated Manning's *n*-values. The upper reach HEC-2 model included 23 cross sections; the lower reach HEC-2 model included 103 cross sections. Site-specific hydraulic data consisted of open-water width, surface velocity, water-surface elevation, and rate of rise of the water surface.

Due to the prevalence of split-channel conditions in the lower reach, two flow regimes were analyzed. The low-flow regime was characterized by restriction of flow from certain side channels at their upstream ends by a gravel "berm". The high-flow regime (flow greater than 20,000 cubic feet per second (cfs)) did not include these split-channel restrictions.

The models were calibrated to four flows, and validated to two additional flows. In the upper reach, the flows for calibration and validation ranged from 8,100 cfs to 46,400 cfs; in the lower reach the flows ranged from 9,700 to 52,000 cfs. The upper end of each range, as limited by the scope of the study, was selected to closely match the mean annual peak flow and represent bankfull stage. The computed water-surface elevations were expected to be accurate to within 0.5 feet of the true elevations in most cases and to within 1.0 foot at almost every cross section. Due to the software's assumed uniform water-surface elevation at a cross section, the problem areas for calibration and validation were points widely separated from the observation sites, islands, sloughs, side channels, and bends.

The HEC-2 models were useful references for developing the 1-D BEM and assessing model results.

2.1.1.2. FEMA FIS Models

Following the late-1970s printing of the original FIS report and Flood Insurance Rate Map (FIRM), a map modernization for the Matanuska-Susitna Borough was completed in July 2009 (FEMA 2011). As part of this effort, hydraulic analyses were carried out for the Talkeetna River and the Susitna River using FESWMS and HEC-RAS models. A FESWMS-2DH model was developed and applied along the Talkeetna River for 4.5 miles upstream of the railroad bridge (NHC 2008). A HEC-RAS model was developed and applied along about 2.5 miles of the Susitna River at the confluence with the Talkeetna River. The availability of these hydraulic models was learned of after the completion of the initial 1-D BEM, so the models were not reviewed or used in the development of the 1-D BEM; however, they may be useful during future refinements to the initial 1-D BEM.

2.1.2. 2012/2013 Surveys of Cross Sections and Water-surface Elevations

A specific objective of the Fish and Aquatics Instream Flow Study (FA IFS) (Study 8.5) is to develop a mainstem Open-water Flow Routing Model to simulate water-surface elevations and average velocity along modeled cross sections under alternative operation scenarios (OS). Two models were developed to simulate changes in flows downstream of the proposed dam site under Project conditions (1) a reservoir operations model to simulate the storage and release of water within the Project reservoir, and (2) an Open-water Flow Routing Model to simulate the movement of releases from the proposed dam to downstream locations (R2 2014).

The HEC-RAS software was selected for the Open-water Flow Routing Model, and this model was developed using cross sections surveyed between 2012 and 2013. The ground surface adjacent to the channel and water-surface elevations were surveyed using Real Time Kinematic (RTK) GPS instrumentation; river bathymetry was surveyed using an Acoustic Doppler Current Profiler (ADCP) system. The overbank geometry was derived from the Matanuska-Susitna (MatSu) Light Detection and Ranging (LiDAR) mapping collected in 2011 and indexed in 2013 to the North American Vertical Datum of 1988 (NAVD88). A total of 88 cross sections was surveyed in 2012—16 sections between the proposed dam site and Devils Canyon, 59 sections between Devils Canyon and the Three Rivers Confluence, and 13 downstream from the Three Rivers Confluence. An additional 80 cross sections were surveyed in 2013 between PRM 29.9 and PRM 146.1. The 2012 cross sections were surveyed during three trips to capture high-flow (28,000 cfs), medium-flow (16,000 cfs), and low-flow (8,000 cfs) conditions corresponding to the USGS gaging station at Gold Creek. The topographic and bathymetric surveys were merged, and the points were aligned and projected onto cross section alignments to create station-elevation pairs. Cross sections with multiple channels were altered by changing bed elevations in side channels to maintain the correct cross sectional flow area; of the 167 total cross sections, 108 cross sections required shifting of side channel elevations (R2 et al. 2014).

For safety reasons, no cross sections were surveyed in Devils Canyon (PRM 154.6 to PRM 166.9). Instead, cross section geometry was estimated using the overbank LiDAR and an assumed rectangular channel developed by Study 7.6 Ice Processes in the Susitna River.

Measurements of flow and water-surface elevation at selected cross sections were carried out in June/July 2012, August 2012, September/October 2012, June/July 2013, August 2013, and September/October 2013 (R2 2014). The cross section surveys and measurements of flow and water-surface elevations were used in the development and calibration of the hydraulics simulated by the 1-D BEM.

2.1.3. Hydrology

Two source of information that focus on the hydrology of the Susitna River and its tributaries were helpful in the development and calibration of the fixed-bed hydraulic model.

2.1.3.1. FA-IFS Open-water Flow Routing Model

One-dimensional, unsteady-flow, hydraulic modeling was carried out as a component of the FA-IFS Study 8.5. The following is extracted from Section 4.4.1.2 of the Study 8.5 ISR.

The HEC-RAS software was selected as the Open-water Flow Routing Model for routing stage fluctuations downstream from the proposed Project dam under open-water conditions (i.e. summer, ice free). The Open-water Flow Routing Model was developed to analyze the impacts of alternative Project operational scenarios that include load following, on changes in flow and stage downstream of the proposed Watana Dam site. This model utilized outputs from the Reservoir Operations Model as input to assess the magnitude, timing, and frequency of hourly flow and stage conditions during open-water periods at locations from PRM 187.2 downstream to PRM 29.9.

During the development and calibration of the Open-water Flow Routing Model, the drainage areas of ungaged tributaries were quantified and used to help estimate accretion flows to the Susitna River between locations where flows are measured.

This approach used to estimate time series of accretion flows from ungaged tributary drainages was mirrored to develop the time series corresponding to the calibration period, and the estimated time series were used directly for the validation period. The calibration time period was extended to include higher flows, which are important for sediment-transport simulations.

2.1.3.2. Hydrologic Data Collection

Hydrologic data were collected as a component of the FA-IFS Study 8.5. The information summarized in this paragraph was extracted from Section 4.3.1.1.2 of the Study 8.5 ISR. Continuous stage measurements were recorded at AEA hydrology stations at 15-minute intervals and made available to studies via the real-time reporting data network. The hydrology stations have a naming convention that serves to identify station locations and the primary purpose of the station. The convention is of the form: $EX_1X_2X_3$ where E represents AEA, X_1 indicates the river drainage (S = Susitna, C = Chulitna, and T = Talkeetna), X_2 is the primary station purpose (B = base station, C = camera station, F = pit tag array, G = groundwater station, M = meteorological station, R = repeater station, and S = surface water station), and X_3 is the station sequence number. For example, ESS80 represents Alaska Energy Authority Surface water station number 80 on the Susitna River.

The water-surface elevation hydrographs collected at ESS stations were used to calibrate the hydraulic simulations.

2.2. Development of Fixed-Bed Hydraulic Model

The fixed-bed model development includes geometric inputs, hydraulic inputs, hydrologic inputs, and unsteady-flow simulation options and tolerances.

2.2.1. Geometric Inputs

Geometric inputs to the HEC-RAS 1-D BEM consist of flow paths for the channels and overbank areas, cross section alignments, cross section geometry, and flow splits/junctions. The geometric inputs were largely developed by evaluating geospatial data in a GIS running ESRI ArcMap 10.0 (ESRI 2010) with the HEC-GeoRAS Version 10.0 extension (USACE 2012). HEC-GeoRAS facilitates the preparation and import of geometric data into HEC-RAS.

2.2.1.1. Flow Paths

The 1-D BEM is comprised of four main reaches:

1. The Middle Susitna River from the proposed Watana Dam site to below the Three Rivers Confluence (PRM 187.1 to PRM 96.2),
2. The Lower Susitna River from above the Three Rivers Confluence to Susitna Station (PRM 107.1 to PRM 29.9),
3. The lower extent of the Chulitna River from the USGS gaging station to Three Rivers Confluence (PRM 18.1 to PRM 0.0), and
4. The lower extent of the Talkeetna River from the USGS gaging station to Three Rivers Confluence (PRM 4.7 to PRM 0.0).

The overlap in the Middle River and Lower River models was included to move boundary conditions away from this major transition. The separate models were required to accommodate a change in bed sorting methods and sediment-transport functions at this location. The Middle River model results are used above PRM 102.4 (Chulitna River confluence) and the Lower River model results are used below this location.

Three flow paths are required in HEC-RAS for each reach: (1) main channel, (2) left overbank, and (3) right overbank. Each flow path was delineated along the estimated center of mass of flow. For the main channel the flow path alignment was digitized in a GIS using recent aerial photography and the alignment of the PRMs for reference. Unlike the PRM alignment which follows flow during low-flow conditions, the main channel flow path for the 1-D BEM focused on (1) hydraulics during flood-flows, and (2) properly representing the length of the bed sediment control volume for the mobile boundary simulations (Section 3.2.1.1). Where split flow channels were simulated in the Middle River and Lower River, the split flow channel flow path was delineated as though it was a main channel flow path.

The extents of the overbank areas were defined by the geomorphic top of bank along the main channel and the high ground along the landward edge of the floodplain. Unless the available LiDAR mapping indicated substantial side channels/abandoned channels, the overbank flow paths were typically delineated about mid-way between the top of bank and landward edge of the floodplain.

The delineated flow paths are shown in Figures 2.2-1 through 2.2-8. These flow paths were first presented in Tetra Tech (2014a) and have been used to determine reach lengths between cross sections for the main channel and both overbanks.

2.2.1.2. Cross-section Alignments

The alignments of the cross sections were also established in Tetra Tech (2014a) and are provided on Figures 2.2-1 through 2.2-8. The landward extent of each cross section approximately encompasses the 500-year water-surface extents. The cross sections were located to capture key hydraulic controls. The cross-section alignments were “doglegged” (angled) where needed to ensure a perpendicular alignment to the expected primary direction of flood flow. Although the delineated main channel flow path alignment differs in many locations from the PRM alignment, each cross section was assigned an identification corresponding to the PRM. For the initial model, three secondary flow paths (flow splits) are included in key locations in the Middle River and two are included in the Lower River. The Middle River is defined by 166 cross sections with an average spacing of about 3,000 feet. The Lower River is defined by 93 cross sections with an average spacing of about 4,000 feet. The Chulitna River is defined by 34 cross sections with an average spacing of about 2,800 feet. The Talkeetna River is defined by 14 cross sections with an average spacing of about 1,800 feet.

2.2.1.3. Cross-section Geometry

The cross section geometry was derived by merging LiDAR mapping with channel surveys. Since the LiDAR data are not reliable through water, channel geometry was surveyed. Overbank topography for the Middle River and Lower River was based on the MatSu LiDAR mapping collected in 2011 and indexed to the NAVD88 (feet) in 2013; LiDAR mapping for the modeled extents of the Chulitna River and Talkeetna River was collected in September 2013 (ISR Study

6.6, Part A, Section 5.1.9.5). As described in Section 2.1.2 the ground surface adjacent to the channel was surveyed using RTK GPS instrumentation; river bathymetry was surveyed using an ADCP system (ISR Study 8.5, Part A, Section 5.3.1). Surveys along the Middle River and Lower River occurred between June 2012 and August 2013; the Chulitna and Talkeetna surveys were carried out in August 2013.

Between PRM 165.9 and PRM 154.6 (Devils Canyon), the Middle River cannot be safely accessed for surveying, so a simplified rectangular geometry developed as part of Ice Processes Study (Study 7.6) in the Susitna River was used to estimate the bathymetry. The approach used in Study 7.6 to estimate the trapezoidal geometry of the Devils Canyon cross sections was applied to the Chulitna River because only two of the delineated cross sections were surveyed. The below water geometry was estimated based on the water surface elevation and overall slope from the LiDAR data, and discharge from the Chulitna River near Talkeetna Gage (15292400) to determine a flow area. The flow area was distributed in a realistic shape based on the surveyed cross sections.

The HEC-GeoRAS extension was used to generate a northing, easting, and elevation for points along each cross section alignment using LiDAR mapping. In-house tools were used to merge the surveys into the LiDAR-derived topography. This software projects the surveyed elevations onto the cross section alignment to preserve the stationing along the alignment. Engineering judgment was required to smooth transitions between the LiDAR mapping and the surveys, particularly in areas where appreciable differences existed (e.g., bank erosion or deposition) between the time of the LiDAR mapping and the survey. The merged geometry at each cross section (for example, Figure 2.2-9) was carefully reviewed to ensure (1) all appropriate surveyed points were included, (2) alternate alignments or extraneous points were excluded, (3) transitions between the surveys and LiDAR mapping were reasonable, and (4) projections, particularly near doglegs in the alignments were appropriate.

Following guidance provided by staff at the Hydrologic Engineering Center (HEC) for using the sediment routing capabilities within HEC-RAS, the number of points that define each cross section was filtered. While the number of cross section points in HEC-RAS is limited to 500, a substantially lower number can maintain relationships between (1) depth and cross-sectional area, and (2) depth and wetted perimeter. The advantage of such a reduction in points is increased stability of long-term simulations because of the decreased potential for unintended adjustments to bed elevation (e.g., isolated/stranded nodes). The filtering routines in HEC-RAS were used to reduce the points in each Middle River cross section in a step-wise process down to 300, 200, 100, 90, 80, 70, 60, and ultimately a goal of 50; the Lower River cross sections were filtered to 300, 275, 250, 225, 200, 180, 160, and ultimately a goal of 140. Using a tolerance of 5 percent, the changes in filtered cross-sectional area and wetter perimeter as a function of depth were compared to baseline values from 500-point sections. If filtering caused a change in either area or wetted perimeter exceeding this tolerance, a lesser degree of filtering not causing such large change was selected. The number of points at most sections could be filtered to the ultimate goal without exceeding the tolerance for change in cross sectional area or wetted perimeter, but if more points were required the cross section from an earlier step that did not exceed the 5 percent tolerance was used.

After filtering the cross section points, the bank stations were set to the geomorphic top of banks. At sections spanning islands (except within the extents of a modeled flow split) the bank stations were set to the landward bank of each channel to maintain continuity of channel flow in the downstream direction.

2.2.1.4. Flow Splits/Junctions

For the POC effort, only a few key split flow reaches were included in the 1-D BEM:

1. Middle River PRM 129.3 to PRM 128.0,
2. Middle River PRM 116.4 to PRM 115.5,
3. Middle River PRM 115.4 to PRM 114.0,
4. Middle River PRM 105.9 to PRM 104.6,
5. Lower River PRM 74.2 to PRM 65.7, and
6. Lower River PRM 55.3 to PRM 46.3.

When the next version of the model is developed, approximately 12 split-flow reaches are planned to be included; for the POC effort, it was only necessary to ensure the hydraulic and sediment routing capabilities in HEC-RAS are appropriate so only the above listed split-flow reaches were incorporated. The Energy Balance Method of modeling junction hydraulics was selected. This option calculates an energy balance across a junction to compute water surfaces accounting for distances across the junction.

2.2.2. Hydraulic Inputs

Hydraulic inputs to the HEC-RAS 1-D BEM consist of energy loss parameters (Manning's *n*-values and contraction and expansion coefficients), ineffective flow areas, and levees. These inputs were specified by cross section.

2.2.2.1. Manning's n-values

Manning's *n*-values were initially specified based on field observations and through relations to mapping of geomorphic features (Tetra Tech 2013c). The HEC-GeoRAS extension used the geomorphic features mapping to assign horizontally variable n-values at each cross section across the channel and overbanks. Table 2.2-1 summarizes the channel and floodplain *n*-values associated with the geomorphic features. Since HEC-RAS limits the number of horizontal changes in the *n*-value at a single cross section to 20, engineering judgment was applied to ensure this maximum was not exceeded while retaining the most hydraulically significant changes in flow resistance (i.e. transitions between polygons with the same *n*-value were eliminated first, typically followed by relatively short transitions in the overbanks).

Since Manning's *n* is a parameter that combines several processes related to boundary friction and energy loss, it cannot be directly measured. Manning's *n*-values typically the primary means of hydraulic calibration. In the 1-D BEM, initial values would be refined during the hydraulic calibration and validation.

2.2.2.2. Contraction and Expansion Coefficients

In general, contraction and expansion losses are not used in unsteady flow simulations because forces due to contractions and expansion are handled in the momentum equation through pressure force differences (USACE 2010a). However, in steady-flow simulations, energy losses due to contractions or expansion are computed by multiplying user specified contraction and expansion coefficients by the absolute difference in velocity head between two adjacent cross sections. The coefficients are specified as part of the input at the upstream section. As recommended in USACE (2010b), where changes in adjacent cross sections are relatively small, and the flow is subcritical, coefficients of contraction and expansion are typically on the order of 0.1 and 0.3, respectively. These values were specified for all cross sections in the 1-D BEM so that steady-flow simulations could be carried out during model testing. These coefficients were not used in the unsteady-flow simulations.

2.2.2.3. Ineffective Flow Areas

HEC-RAS allows for specification of areas where water can pond, but the velocity of that water in the downstream direction is nearly zero. Ineffective flow areas were used frequently in the development of the models. The water in an ineffective area is included in the storage calculations and other wetted cross sections parameters, but it is not included as part of the active flow area (USACE 2010a). Ineffective areas do not add wetted perimeter to the flow area. Ineffective flow areas were set to be permanent, if appropriate. The extents and elevations of ineffective flow areas were adjusted during the model testing and calibration.

2.2.2.4. Levees

Levees in HEC-RAS prevent flow from accessing the cross section landward of the levee station, until the levee elevation is overtopped (USACE 2010a). Although levees were not used in the development of the initial model, they may be used in the next version of the model if they are needed and applicable. Only one left and one right levee can be specified per cross section. The stations and elevations of levees were specified depending on conditions within a reach represented by a cross section.

2.2.3. Hydrologic Inputs

To carry out unsteady-flow simulations in HEC-RAS, two types of hydrologic inputs are required (1) boundary conditions, and (2) initial conditions. Boundary conditions are needed at all external boundaries to the model. Initial conditions are required to establish conditions at the beginning of the simulation.

2.2.3.1. Boundary Conditions

Necessary boundary conditions are a function of the flow regime. For the 1-D BEM, calculations of water-surface elevations were constrained to critical depth or greater by specifying a subcritical flow regime. While local sections of the Susitna River may experience supercritical conditions during floods, such as through Devils Canyon, the overall reach hydraulics were reasonably expected to be subcritical. Thus, a single downstream boundary was coupled with flow hydrographs at all upstream boundaries.

2.2.3.1.1. Downstream Boundary

Since a subcritical flow regime was specified, the water-surface profile calculations begin at the downstream most cross section and proceed upstream. A boundary condition was needed to establish the water-surface elevation at the downstream end of the model. The model was extended downstream of PRM 29.9 along a normal depth slope of 0.0003492 feet/foot. Computed water-surface elevations at PRM 29.9 were compared to the rating curve published by the USGS for the Susitna Station gage (Gage No. 15294350). For flows less than about 130,000 cfs, the simulated water-surface elevations were less than the corresponding elevations from the rating curve (Figure

2.2-10). To better align the simulated water-surface elevations with the elevations from the rating curve, the channel n-values were varied as a function of discharge (Figure 2.2-10). This adjustment provided a simulated rating curve that closely matched the published rating curve, so this relationship was used as the downstream boundary condition.

2.2.3.1.2. Upstream Boundaries

Flow hydrographs were used as upstream boundaries for the mainstem Susitna River and all modeled tributaries. Time series of flows were input to the USACE HEC-Data Storage System (DSS) to facilitate the storage, retrieval, and processing of these inputs by HEC-RAS.

The flow series for each hydrograph was developed using average-hourly flows provided by (1) USGS gaging station records, (2) results of the FA-IFS Study 8.5 Reservoir Operations model, or (3) results of the FA-IFS Study 8.5 Open-water Flow Routing Model. Since only the OWFP was of interest for the 1-D BEM simulations, flows were constrained between the dates of ice break-up and freeze-up for each year as provided by Study 7.6 Ice Processes in the Susitna River. The flow series in each year were merged using a linear transition over two days between the end of one OWFP and the beginning of the following OWFP. This transition was necessary to prevent discontinuities that could create instabilities in the simulation. Since the transition was only two days in duration and occurred during the lowest flows of the OWFP when little sediment is transported and minimal bed material is mobilized, it is reasonable to expect the transitions have no detectible bias on the simulation results. HEC-RAS relies on dates associated with the flow series. The open water flow periods are generally 5 to 6 months and must be a continuous series. To avoid discontinuities between open water-flow periods, the flow series were merged. The starting point was set as January 1, 1900 and a key was develop to translate the simulation dates to calendar dates. Setting this early date meant that none of the output could be confused with actual dates in the long-term flow record.

2.2.3.2. Initial Conditions

Initial conditions of the system at the beginning of an unsteady-flow simulation consist of flow and stage at each cross section (USACE 2010a). Initial conditions were established by specifying flows corresponding to the beginning of each simulation and letting HEC-RAS carry out a steady-flow backwater simulation to compute the corresponding stages at each cross section. Due to the split-flow reaches in the model, the option in HEC-RAS was selected to optimize the flows across the splits during the initial steady-flow backwater computations.

2.2.4. Unsteady-Flow Simulation Settings and Options

Simulation settings and options include (1) the simulation time window, (2) computation settings, and (3) tolerances.

HEC-RAS requires the user to specify a simulation time window that defines the start and end of the simulation. These times need to be consistent with the times specified for the hydrologic inputs. For the hydraulic calibration and validation, the time window was set to the calendar dates of interest. For the simulations, the start and end times were set to the simulation dates corresponding to the series of merged OWFP (Section 2.2.3.1.2).

The required computation settings include the computation interval, the hydrograph output interval, and the detailed output interval.

1. The computation interval determines the frequency of hydraulic computations, and is dependent upon multiple factors, such as the time to rise of a flood hydrograph, cross section spacing, and balancing model accuracy against length of time required to complete a simulation. Computation intervals of 5 minutes to 1 hour were specified, with the variability a function of calibration, validation, or simulations.
2. The hydrograph output interval defines the frequency that stage and flow hydrographs are written to results files. This interval was set equal to the selected computation interval.
3. The detailed output interval defines the frequency that detailed hydraulic results are written to results files. In general, the unsteady-flow computations only produce stage and flow at every cross section, so detailed hydraulics such as slope of the energy grade line, hydraulic radius, and velocity are computed only at the frequency of the detailed output interval. The detailed output interval was set to 1 day.

Default calculation options and tolerances were used, except for the following changes.

1. The theta implicit weighting factor, which is used to assign relative importance to the time derivative in an unsteady model, was set to 0.8. The available range for this factor is 0.6 (greater accuracy, less stability) to 1.0 (less accuracy, greater stability).
2. The water-surface calculation tolerance was reduced from the default of 0.02 feet to 0.01 feet. While reducing this tolerance has the potential to increase the number of iterations in a simulation, it reduces potential for errors to cause instabilities that could result in early termination of a simulation.
3. In accord with the decrease in the water-surface calculation tolerance, the maximum number of iterations was increased from the default value of 20 to 40.

2.3. Fixed-bed Hydraulic Testing

Prior to commencing the hydraulic calibration, the hydraulic simulations were tested to identify and resolve issues. Hydraulic testing began with steady-flow simulations for a range of flows. Computed water-surface profiles were reviewed and hydraulic results checked for reasonableness. Examples of issues include Froude numbers being forced to 1.0 (critical flow) and crossing water-surface profiles.

The summary of errors, warnings, and notes generated by HEC-RAS was reviewed. Of particular concern were warnings about excessively high or low conveyance ratios between adjacent cross sections. While these warnings can typically be addressed by interpolating additional cross sections, investigation showed the warning was frequently not primarily caused by changes in geometry as much as by changes in Manning's *n*-values, particularly when values within the channel were composited by HEC-RAS. This issue was resolved by specifying a single *n*-value for the channel and single values for each overbank; where vegetated bars and islands were present in the channel, an ineffective flow area was used rather than an increased *n*-value to account for the reduced conveyance. This approach minimized abrupt changes in conveyance, which decreased potential for instabilities during the simulations.

Once the errors, warnings, and notes were addressed and the steady-flow hydraulics were judged reasonable, hydraulic testing continued with unsteady-flow simulations. Initially the results of the geometric preprocessor were reviewed. The calculated hydraulic properties tables were reviewed, and additional points were added, or vertical increments reduced, to achieve reasonable curves. The number of vertical increments ranged from 20 to 100.

The unsteady-flow testing revealed an issue related to stability when flow changed rapidly, such as during the rising limb of the flood hydrograph. The issue was greater when diurnal fluctuations were imposed on the daily hydrographs developed for the Open-water Flow Routing Modeling (ISR Study 8.5, Part C, Section 5.4.2.2). To avoid decreasing the computation interval and increasing simulation times, the option in HEC-RAS was used to monitor changes in flow, and where changes exceed a user-specified maximum, the software cuts the time step in half until the change in flow rate decreases below the user-specified maximum.

2.4. Fixed-bed Hydraulic Calibration and Validation

The objective of hydraulic calibration was to adjust the parameterization of the model so the model results suitably match the observed data. The final values are kept with acceptable limits. If the model does not calibrate using reasonable input values, then the model needs further review and checking to determine of other data errors are present. Calibration consisted of (1) supplying numerical values for variable inputs and boundary conditions, (2) running the model to simulate results, (3) comparing simulated results to observations, and (4) adjusting variable inputs to achieve a specified degree of agreement between the simulated results and the observations. Hydraulic validation tests whether the calibrated model can simulate within a desired level of accuracy observations during a period different from the calibration period. Validation followed the same steps as calibration.

Since flood flows have the greatest potential to mobilize bed material and transport sediment, it was important to focus the calibration and validation efforts for the 1-D BEM on flood hydrographs.

2.4.1. Calibration

Hydraulic calibration was carried out using measured flow and water-surface elevations during periods of high flow conditions (Table 2.4-1). Calibration periods were selected based on availability of observed measurements and the magnitude of the flood event. Since calibration data in the Middle River and Lower River were available for different periods, these two reaches of the model were calibrated independently. The Chulitna River and Talkeetna River models were not calibrated because data for the calibration period is only available at the USGS gaging stations, which are used as the boundary condition inputs; these models will be calibrated using surveyed water-surface elevations when these models are finalized.

For the hydraulic calibration, the flow hydrograph for the mainstem Susitna River was derived from measurements recorded at the USGS gaging station above Tsusena Creek (Gage No. 15291700). Flow hydrographs for ungaged tributaries were calculated following the method described in ISR Study 8.5, Part C, Appendix K, Section 5.4.1.2.4. USGS gages on the Chulitna River (Gage No. 15292410) and Talkeetna River (Gage No. 15292700) provided flow hydrographs for these two model reaches. The rating curve at the downstream boundary is described in Section 2.2.3.1.1.

Water-surface elevations were the focus of the hydraulic calibration, and for the POC effort the objective was for simulated water-surface elevations to be within one foot of an observation. This objective was not set as an absolute threshold due to unknown discharges associated with many of the point-in-time water surface observations. The available observations for calibration consisted of water-surface elevation hydrographs (Section 2.1.3.2) measured at ESS stations and water-surface elevation and flow hydrographs measured at USGS gaging stations.

Calibration of the simulated hydraulics to the observed flows and water-surface elevations was primarily achieved through adjustments to the Manning's *n*-values. In the Middle River, the n-values were further refined by decreasing the values with increasing discharge, reflecting the reduction in grain resistance due to the greater submergence of the coarse bed material. Overbank *n*-values were simplified to single values (0.13 to 0.15) from the horizontally-varied values. Consistent with the Open-water Flow Routing Model (ISR Study 8.5, Part C, Appendix K, Section 5.4.2) the final calibrated main channel roughness values varied between 0.032 and 0.035 in the Middle River, except through Devils Canyon where greater values (0.035 to 0.050) were needed to maintain model stability and are consistent with the large boulders, bedrock outcrops and rapids present in this steep canyon reach. In the Lower River, the calibrated main channel roughness values varied between 0.025 and 0.032.

Calibration results indicate high levels of consistency between observed and simulated flow and stage hydrographs. Figures 2.4-1 through 2.4-8 illustrate the comparisons to USGS gaging station measurements, progressing from the upstream gage at Tsusena Creek to the downstream gage at Susitna Station. Figures 2.4-9 through 2.4-14 show the comparisons of the simulated water-surface elevation hydrographs to the measurements collected at the ESS stations. In addition to confirming local consistency in water-surface elevation, all of these figures illustrate the model is appropriately simulating the translation and attenuation of the flood wave. Figure 2.4-15 illustrates the results of the comparisons between the surveyed point-in-time water-surface elevations along the Middle River to simulated elevations. Simulated water-surface elevations were within one foot of the observed values at 33 of the 36 locations (92 percent). The average difference for all 36 observations was -0.13 feet with a root-mean-square of 0.65 feet. The differences could be due to simulation errors, survey errors, variation in water-surface elevation at either bank and across multiple channels, and uncertainties in discharge at the time of survey. These excursions were judged acceptable for the POC effort. Figure 2.4-16 illustrates the results of the comparisons between the surveyed point-in-time water-surface elevations along the Lower River to simulation elevations. Simulated water-surface elevations were within one foot of observed elevations at 91 of the 119 locations (76 percent). The average difference for all 119 observations was -0.08 feet with a root-mean-square of 0.95 feet. In the Lower River a larger percentage of points are outside of the 1-foot objective relative to the Middle River, but the Lower River is a multi-channel system with greater potential for differences in water-surface elevation across channels that cannot be represented accurately with a 1-D model. While the simulated water-surface elevations have an average bias of about 0.1 feet lower than observations, this difference was judged acceptable and no further adjustments were made.

2.4.2. Validation

The hydraulic calibration was validated using data collected at the USGS stations during the spring freshet in 1981 (the end of May through August). These observations were selected because they correspond to the representative wet year. The Chulitna River and Talkeetna River models were not validated since they were not calibrated.

For hydraulic validation, flow hydrographs developed by Study 8.5 were input to the model and simulated flows were compared to flows measured at USGS gaging stations. The validation approach is consistent with the validation approach used for the validation of the FA-IFA Open-Water Flow Routing Model (ISR Study 8.5, Part C, Appendix K, Section 5.4.3). Study 8.5 provided flow hydrographs for the dam site, ungaged tributaries, the Chulitna River, the Talkeetna River, and the Yentna River. Measured average daily flows were available at the USGS gaging stations at Gold Creek, Sunshine, and Susitna Station (the Tsusena Creek gage was not operational at this time); observations more frequent than daily average were unavailable. Stage hydrographs were not available, so validation focused only on comparison of simulated and observed flows.

Results of the hydraulic validation are presented in Figure 2.4-17 (Gold Creek), Figure 2.4-18 (Sunshine), and Figure 2.4-19 (Susitna Station). The simulated discharge at Gold Creek and Sunshine closely follow the daily average flows. At Susitna Station, the simulated flows appear to exceed the daily average observations, with greater differences during higher flows. Due to the similarity in the simulated and observed flows at the two upstream gaging locations, the issue at Susitna Station was most likely a function of an influence located downstream of Sunshine. The average daily flows recorded at the Yentna River gaging station were added to the average daily flows recorded at the Sunshine gaging station (lagged one day to account for travel time between the Sunshine gaging station and the confluence with the Yentna River) to compare to the measured flows at Susitna Station. The combined flows exceed the observed flows at the Susitna Station gage, and the combined flows do not account for the ungaged tributary inflows over the intervening reach. The combined flows tend to be less than the observed and simulated flows, which agree well with each other for flows less than 150,000 cfs. This indicates that the differences are primarily attributable to the ungaged tributary inflows. For flows greater than 150,000 cfs, the greatest differences between the observed and simulated values occur between 7/10/81 and 7/16/81, a period when the observed flows at Susitna Station are less than the combined flows of the Sunshine and Yentna River gages. This is very unlikely. Consequently, the simulated flows at the Susitna Station gage indicate the observed flows during portions of the validation period are biased. Probable sources of this bias are (1) the rating curve used by the USGS was relatively new (about 5 years old) and didn’t yet include measurements during flows as high as experienced in 1981, (2) a depositional bar just downstream of the Susitna Station gage may be mobile at higher flows, allowing greater flows to pass at lower stages than would occur if the bar was a permanent feature, or (3) there are potential inaccuracies at the Yentna River gage. Therefore, the simulated flows appear to be more realistic than the observed flows at the Susitna Station gage for this short time period, and the differences between the simulated and observed flows at Susitna Station didn’t warrant any adjustments to model parameterization. The validation was judged to have confirmed the calibrated parameterization of the hydraulic model. The validated hydraulic model provided the foundation for the development of the sediment-routing model.

3. DEVELOPMENT AND CALIBRATION OF MOVEABLE-BOUNDARY SEDIMENT ROUTING MODEL

The moveable-boundary sediment routing model was developed by adding sediment routing functionality to the validated fixed-bed hydraulic model. Existing information was reviewed to facilitate development, testing, and calibration of the model. The existing information included sediment-transport measurements and historic cross sections. No geometric data (change in cross section) were available for the calibration and validation periods of the sediment routing model.

3.1. Existing Information

The POC effort specific to the 1-D BEM was related to incorporating information from previous and ongoing study efforts. The following subsections summarize pertinent existing information related to the development and calibration of the moveable-boundary sediment-routing model.

3.1.1. Dam Effects on Downstream Channel and Floodplain Geomorphology

R2 Resource Consultants and Tetra Tech (2014) synthesized studies of hydroelectric project impacts. The goal of this synthesis was to inform potential responses of the Susitna River channel, floodplain, and riparian ecosystem to flow modifications associated with Susitna-Watana Hydroelectric Project OS. The authors note that downstream dam effects are dependent upon (1) the type of operations, (2) river network dam location, and (3) influence of downstream tributary flow and sediment contributions. Due to multiple influences on potential dam effects, and the variability in physical and hydrologic conditions across drainage areas, substantial uncertainty was noted in the geomorphic responses of channels and floodplains downstream of dams. The 1-D BEM provides a means to address this uncertainty and more clearly define expectations for the geomorphic responses of the Middle and Lower River segments.

3.1.2. Geomorphic Reaches

2014cSIR Attachment 1 of the Geomorphology Study (Study 6.5) presents the technical memorandum Geomorphic Reach Delineation and Characterization, Upper, Middle and Lower Susitna River Segments—2015 Update (Tetra Tech 2015), which (1) developed a geomorphic classification system for the Susitna River that considered both form and process, (2) applied the classification system to delineate large-scale geomorphic reaches in the Middle and Lower River segments, and (3) characterized geomorphic parameters for each of the identified geomorphic reaches. The authors note that the geomorphic characteristics of the study area of the Susitna River are predominantly the result of (1) geologic setting and the relative erodibility of the channel bounding materials, (2) the balance between the sediment supply and the potential for sediment storage within a reach and (3) the third factor is the relative importance of fluvial and ice processes.

Regarding the first factor, the Middle River is dominated by the presence of relatively erosion-resistant meta-sedimentary, gneissic and granitic rocks and the distribution of Pleistocene age glacially-derived materials. In contrast, the Lower River is primarily an alluvial system with a wide valley that is laterally constrained by Pleistocene-age, glacially-derived materials that have variable resistance to erosion. Eight geomorphic reaches were delineated for the Middle River and six geomorphic reaches were delineated for the Lower River.

Regarding the second factor, extensive braid-plains downstream of the active glaciers at the headwaters of the Susitna River buffer sediment supply to the project reach, and this is reflected in the general absence of sedimentary deposits, both in-channel (bars and islands) and channel margin (floodplain). The available sediment record at the Gold Creek gage confirms a relatively low annual bed-material load, which is reflected in the somewhat limited sediment storage potential within the Middle River. In contrast, the annual bed-material loads delivered to the Lower River by the Chulitna, Talkeetna, and Yentna Rivers are relatively high, which is reflected in the extensive sediment storage potential in the Lower River. For Lower River geomorphic reaches where the coarse sediment supply is likely higher than the transport capacity, the channel form is primarily braided, and where the coarse sediment-transport capacity and supply are likely more balanced, the channel form is dominantly anastomosed.

Regarding the third factor, in the Middle River Segment the form and dynamics of the various order channels, bars and islands as well as floodplains and terraces are the result of the combined effects of both ice and fluvial processes. In the Lower River Segment, while ice processes occur, the widths of the valley bottoms tends to mitigate their effects, and hence the segment is fluvially dominated.

These geomorphic reaches provide meaningful framework for interpreting the response of the channel and floodplains to changes in hydrology and sediment supply. Therefore, the results of the 1-D BEM were primarily considered in the context of reach-scale trends within these geomorphic reaches.

3.1.3. Comparison of Cross-section Geometry

Cross sections surveyed during the 1980s studies of the Susitna Hydroelectric Project provided a basis for characterizing geomorphic change by comparison to recent cross section surveys.

3.1.3.1. 1980/1981 Cross-section Surveys

R&M (1981) surveyed cross sections of the Susitna River to define the river gradient and configuration of the channel and active floodplain. Key features measured or described during the surveys of each section included major breaks in slope of the land surface, geometry of all river channels, limits of vegetation, and average bed-material size along the exposed riverbed. Surveys at 23 cross sections in the upper reach were collected in March 1981 by drilling holes through the ice cover; surveys of 68 cross sections in the lower reach were collected prior to and during freeze-up in the fall of 1980. All of the cross-section data, including bed-material analysis, were used in calibrating the HEC-2 hydraulic models. The channel geometry, river gradient, and bed-material size distributions were used in sediment yield and river morphology studies.

The 1980s survey data provided a basis for comparing simulated changes in channel morphology under existing conditions as a component of assessing the reasonableness of the sediment-routing component of the 1-D BEM.

3.1.3.2. Cross-section Geometry Comparison

Tetra Tech (2014d) compared the cross section geometry from the 1980/1981 surveys (R&M 1981) to the 2012/2013 surveys (Study 8.5) to identify geomorphic changes over the intervening three decades. Channel profiles were also compared to assess longitudinal bed elevation differences. Most of the profile changes are less than about 2 feet with many portions of the profile showing only minor changes of less than 1 foot. Spatially consistent patterns of degradation or aggradation are not apparent, indicating that the thalweg profile has generally been dynamically stable over the past three decades.

These comparisons were used to support the calibration of the simulated sediment-routing capability of the 1-D BEM.

3.1.4. Hydrology

There are four sources of information that focus on the hydrology of the Susitna River and its tributaries that informed the development and calibration of the moveable-boundary sediment-routing model.

3.1.4.1. Streamflow Record Extension Report

Between water years 1950 and 2010 the daily flow records at the 14 USGS gaging stations within the Susitna River Basin range in length from 4 to 57 years. Evaluating potential impacts of the proposed Susitna-Watana Project requires streamflow information beyond the observed records available at these USGS gages (Curran 2012). Correlations between daily discharges sufficed for extending daily flow records to the full 61-year period at 11 of the 14 gaging stations on the basis of relatively long-term records for one or more of the gages within the basin, or one outside the basin.

The extended flow records were used to develop existing conditions (pre-Project) hydrologic inputs for the 1-D BEM.

3.1.4.2. FA-IFS Reservoir Operations Model

Reservoir operations modeling was carried out as a component of the FA-IFS Study 8.5. The following is extracted from Section 4.4.1.1 of the Study 8.5 ISR.

The HEC-ResSim software was adapted and used to forecast a range of reservoir outflows associated with different operational scenarios to be evaluated as part of the IFS. The software incorporates a reservoir water balance that is governed by a set of operating rules such that inflow minus all outflows, including turbines, valves, and spillway, equals the change in reservoir storage for a given time period. For the proposed Watana Dam, the required long-term reservoir inflow time series data were provided by the continuous 61-year record of daily flows for Water Years 1950 through 2010 (Curran 2012).

Two of the extended-record gages spatially bracketed the proposed Watana Dam site, so inflows to the Watana Reservoir were based on proportioning the extended flows based on drainage area (R2 2014). In addition to HEC-ResSim, AEA applied a reservoir operation model developed by MWH for making preliminary operational runs; the MWH model can perform an automated iteration to maximize firm energy to specified reliability criteria, which then form the input generation requirements for the HEC-ResSim model (R2 2014).

The reservoir outflows from the HEC-ResSim model were used to develop post-Project hydrologic inputs for the 1-D BEM.

3.1.4.3. Streamflow Assessment

The *Streamflow Assessment* (Tetra Tech 2013b) involved analysis of pre-Project and post-Project flows in the Susitna River below Watana Dam. The pre-Project condition was based on the extended flow record developed by Curran (2012); the post-Project condition was based on the reservoir outflows simulated using the HEC-ResSim model (developed within Study 8.5) for a hypothetical operational scenario referred to as Maximum Load Following OS-1. The purpose of the streamflow assessment was to identify the potential Project related changes in Susitna River flows and stage in the Lower River. Of primary interest was whether the results of the assessment indicated the need to extend portions of the Fluvial Geomorphology Modeling Study and other studies further downstream in the Lower River. The most significant finding of the streamflow assessment came from the results of the annual peak flow-frequency analysis. Relationships between channel size and discharge were applied to suggest that the level of post-Project peak flow reduction could result in narrowing of the Lower River channel width by about 10 percent. This result served as part of the decision criteria to extend the Fluvial Geomorphology Modeling Study 50 miles further downstream in the Lower River to the Susitna Station USGS gage (No.15294350) at PRM 29.9

The downstream extent of the 1-D BEM was defined as the Susitna Station USGS gage based, in part, on the results presented in the *Streamflow Assessment*.

3.1.4.4. FA-IFS Open-water Flow-routing Model

One-dimensional, unsteady-flow, hydraulic modeling was carried out as a component of the FA-IFS Study 8.5. The following is extracted from Section 4.4.1.2 of the Study 8.5 ISR.

The HEC-RAS software was selected as the Open-water Flow Routing Model for routing stage fluctuations downstream from the proposed Project dam under open-water conditions (i.e. summer, ice free). The Open-water Flow Routing Model was developed to analyze the impacts of alternative Project operational scenarios that include load following, on changes in flow and stage downstream of the proposed Watana Dam site. This model utilized outputs from the Reservoir Operations Model as input to assess the magnitude, timing, and frequency of hourly flow and stage conditions during open-water periods at locations from PRM 187.2 downstream to PRM 29.9.

During the development and calibration of the Open-water Flow Routing Model, the drainage areas of ungaged tributaries were quantified and used to help estimate accretion flows to the Susitna River between locations where flows are measured.

The estimated time series of accretion flows from ungaged tributary drainages were used as input to the 1-D BEM simulations.

3.1.5. Sediment Transport

Preliminary estimates of the overall sediment balance in the Middle River and Lower River under existing conditions, along with the potential magnitude of the changes that could occur under Maximum Load Following OS-1 hydrologic conditions, are presented in *Development of Sediment-Transport Relationships and an Initial Sediment Balance for the Middle and Lower Susitna River Segments* (Tetra Tech 2013d). The sediment load rating curves and preliminary estimates of the overall sediment balance under existing conditions were updated in *2014 Update of Sediment-Transport Relationship and a Revised Sediment balance for the Middle and Lower*

Susitna River Sediments Technical Memorandum (Tetra Tech 2014e). The updated sediment load rating curves reflect additional measurements collected by the USGS in 2012 and 2013; while the USGS collected additional measurements in 2014 that will be reviewed, AEA does not anticipate further revision of the sediment rating curves.

Linear regressions of sediment transport and discharge were calculated at five USGS gaging stations along the mainstem Susitna River (1) Denali, (2) Cantwell (Vee Canyon), (3) Gold Creek, (4) Sunshine, and (5) Susitna Station, and on the three USGS gage locations on the largest tributaries (1) Chulitna River, (2) Talkeetna River, and (3) Yentna River. The minimum variance unbiased estimator (MVUE) technique was used to convert the sediment load regression lines into unbiased sediment load rating curves. The sediment rating curves were applied to develop the sediment balance along the Susitna River mainstem. Unlike the 2013 analyses, operational conditions were not considered as part of the 2014 updated analyses because the effect of the operational conditions will be based on results of simulations carried out using the 1-D BEM.

The sediment rating curves were used to quantify sediment inflows to the 1-D BEM, and the sediment balance was used to support the calibration of the simulated sediment routing.

As noted in Winter Sampling of Main Channel Bed Material Technical Memorandum, Fluvial Geomorphology Modeling Below Watana Dam Technical Memorandum (Tetra Tech 2014f), quantification of the gradation of the main channel bed material is key for the 1-D BEM to accurately simulate geomorphic response of the bed, but such quantification for the main channel of the Susitna River has not previously been carried out. Tetra Tech (2014f) analyzed whether gradations determined from sediment samples on bar heads (i.e. the shallower areas of the main channel) were representative of the bed material in the deepest areas of the channel. Underwater cameras lowered through holes in the river ice were used to measure sediment sizes and quantify main channel bed material gradations. The results showed that the bed material in the deepest portions of the main channel of the Middle River segment of the Susitna is appreciably coarser than sediment sampled on the bar heads.

The results of the winter bed-material sampling were used to prescribe gradations of main channel bed material input to the 1-D BEM.

3.2. Development of Moveable-Boundary Sediment-routing Model

The development of the moveable-boundary sediment-routing model was based on adding capabilities for the routing of bed-material sediment to the validated fixed-bed HEC-RAS model. HEC-RAS simulates the mobilization, transport, and deposition of bed-material sediment by grain-size fraction, thereby allowing representation of hydraulic sorting and bed armoring (USACE 2010a). This capability is important for the Middle River reach because of the wide size range of bed material and the evidence of armoring.

The following description of the sediment-transport procedure implemented by HEC-RAS during unsteady-flow simulations is summarized from USACE (2010a). Channel hydraulics must be simulated as input to computations of sediment transport and associated geometry change. The channel flow at a cross section is held constant for the duration of the user-specified computation interval. During a computation interval, based on a user-specified mixing increment, the sediment-transport potential is constant but the sediment transport capacity can change in response to changes in the composition of the bed mixing layers. [Note: HEC-RAS defines *sediment-transport* *potential* as the measure of how much of a particular grain class can be transported by a hydrodynamic condition, independent of the prevalence of that grain class in the bed material. The *sediment-transport capacity* is a fraction of the sediment-transport potential that reflects the prevalence of a grain class in the bed; this is based on Einstein's (1950) classic assumption that the sediment discharge of a grain class is proportional to the fractional abundance of that grain class in the bed (Vanoni 1975).] HEC-RAS solves the sediment- continuity equation, also known as the Exner equation, to relate the downstream change in transport sediment load to the change in bed sediment volume and cross-section geometry. Between computation intervals, the geometry can be updated, and if needed, new hydraulic rating tables calculated.

Based on this procedure, it is necessary for sediment-routing simulations with HEC-RAS to specify sediment inputs and prescribe sediment simulation settings and options.

3.2.1. Sediment Inputs

The sediment continuity equation is solved in HEC-RAS by (1) computing the sediment-transport capacity by grain class at a cross section, and (2) comparing this capacity to the supply entering from upstream. If capacity exceeds the available supply, there is a sediment deficit that can be satisfied by erosion of the bed; however, if supply exceeds capacity, excess sediment is deposited on the bed. A sediment deficit may not be fully satisfied by erosion of the bed if a coarse surface layer shields the deeper supply of finer grain classes. The following sediment data are required to carry out these computations:

1. The dimensions of the bed sediment control volume,
2. A method for sorting bed material and controlling the exchange of sediment between the bed and the water column,
3. Bed material gradations,
4. A function to calculate transport potential,
5. A fall velocity method, and
6. Inflowing sediment loads at model boundaries.

3.2.1.1. Bed Sediment Control Volume

HEC-RAS uses the concept of a control volume to quantify the amount of sediment in the bed. In the direction of flow, each cross section represents half the distance upstream to the next adjacent section and half the distance downstream to the next adjacent section. The width of the control volume at each section is defined by the moveable boundary limits. These limits were specified by station and were initially set equal to the bank stations. Erosion of the bed was confined within these limits; deposition was allowed along the entire wetted perimeter including ineffective flow areas. Thickness is the final dimension required to calculate a sediment-control volume. The bed thickness was set to 10 feet. The bed sediment control volume for each cross section is its length multiplied by the lateral extent between moveable boundary limits multiplied by the thickness.

3.2.1.2. Bed Sorting Method

HEC-RAS provides three bed sorting methods: (1) Active Layer, (2) Exner 5, and (3) Exner 7. The active layer method is a simplified two-layer approach appropriate for gravel beds and intended for use with the Wilcock Crowe (2003) transport function. Exner 5 is a three layer approach that provides two active layers (the cover layer and the subsurface layer) over an inactive layer. Exner 7 is a refinement of Exner 5. Details regarding the formulation of Exner 7 are presented in Copeland (1993), including the basis for the layer thicknesses, the incorporation of cover layer shielding of the subsurface layer, the check of cover layer stability based on Gessler (1965), and accounting by grain class by layer over time.

Based on modeling experience, Exner 5 is better suited to gravel bed systems with static armor, so it was selected as the most suitable starting point for the bed sorting method in the Middle River. Exner 7 is more suitable for systems without a static armor, so it was selected as the best starting point for the bed-sorting method in the Lower River.

3.2.1.3. Bed Material Gradations

Surface and subsurface bed material samples were collected from the Susitna River in 2013 as described in ISR Study 6.6, Section 5.1.9.1. These samples were the basis of the inputs to the HEC-RAS model for the gradations of the bed material. Additional samples analyzed in the winter of 2014 (Tetra Tech 2014f) were used to establish the bed material gradation in the Middle River. Because the Exner 5 and Exner 7 bed sorting methods were selected for the Middle River and Lower River, respectively, separate gradations were required for the cover layer and the inactive layer (the software does not allow for direct specification of the subsurface layer gradation; the gradation is established from the inactive layer at the start of a simulation).

The representative cover layer and inactive layer gradations for the Middle River and Lower River, as well as quantiles associated with each representative sample, are provided in Table 3.2-1. In the Middle River, the representative cover layer gradation was based on the arithmetic average of 10 of the 12 surface gradations analyzed during the winter of 2014 between PRM 104.1 and PRM 185.4 (Tetra Tech 2014f). The two samples that were excluded (PRM 129.0 and PRM 184.3) were excessively coarse for inclusion in the representative gradation for the entire Middle River. The thickness of the representative cover layer was set to 1.15 feet, corresponding to 3*D_{90} (which is the maximum thickness allowed for the Exner 5 bed sorting method), where D_{90} is derived from the inactive layer gradation. The representative inactive layer gradation was based on the arithmetic average of 29 subsurface samples collected from bar heads between PRM 103.9 and PRM 145.5 (ISR Study 6.6, Section 5.1.9.1). Since the maximum grain size in the representative inactive layer gradation (512 mm) was less than the maximum size of the representative cover layer gradation (1,024 mm), the upper end of the inactive layer gradation curve was extended to 1,024 mm by slightly adjusting the percentages of material in the coarsest two size classes. This adjustment was made to ensure the coarsest bed material in the cover layer had an available supply in the bed sediment reservoir.

In the Lower River, the representative cover layer gradation was based on the arithmetic average of 23 bar head samples collected between PRM 29.9 and PRM 101.8 (ISR Study 6.6, Section 5.1.9.1). The thickness of the representative cover layer was set to 0.63 feet, corresponding to 3*D_{90}. The representative inactive layer gradation was based on the arithmetic average of 22 subsurface samples collected from bar heads between PRM 29.1 and PRM 101.8 (ISR Study 6.6, Section 5.1.9.1).

The surface and subsurface bed material samples illustrate variability in gradations within both the Middle River and Lower River. Therefore, the HEC-RAS model was developed with these representative gradations, but refined gradations and layer thicknesses were expected to be better established during “warm-up” simulations carried out during testing (Section 3.3.3).

3.2.1.4. Sediment-transport Function

HEC-RAS offers eight transport functions to calculate sediment-transport potential.

1. Ackers and White (1973, and Ackers 1993),
2. Engelund and Hansen (1967),
3. Copeland and Thomas (1989),
4. Meyer-Peter and Müller (MPM) (1948),
5. Toffaleti (1968),
6. A coupling of MPM and Toffaleti,
7. Yang (1973 and 1984), and
8. Wilcock and Crowe (2003).

Two important distinctions are evident in the available transport functions: (1) representation of total load versus bed load, and (2) development using sand-dominated sediment versus sand gravel mixtures. Considering the gradations of the representative bed material samples, it is reasonable to expect that sand and fine gravels are transported as bed load and in suspension, and it is apparent there is abundant coarse gravel. The bed-load functions of MPM and Wilcock and Crowe exclude a potentially important component of the transported sediment (i.e. the suspended bed-material load), so the total load function were preferred. Of the six available total load functions, the Engelund and Hansen, Toffaleti, and Yang functions were developed using sand dominated sediment, so these were considered less suitable for application to the Susitna River and were not prioritized for testing. The Ackers and White, Copeland and Thomas, and coupled MPM and Toffaleti functions were considered most appropriate, and were thus prioritized for testing.

3.2.1.5. Fall Velocity Method

The fall velocity is important in computing the transport of suspended bed material. The suspension of a grain of sediment is initiated once the bed-level shear velocity approaches the same magnitude as the fall velocity for that grain; the grain will remain in suspension as long as the vertical component of the bed-level turbulence exceeds that of the fall velocity (USACE 2010b).

The *Report No. 12* (IACWR 1968) method for computing fall velocity was selected from the options available in HEC-RAS. This method relates fall velocity to sieve diameter of sediment, water temperature, and shape factor. The sieve diameter is the geometric mean of the upper and lower bound for each grain class. The shape factor is a parameter used to classify the shape of a sediment grain as a function of three mutually perpendicular axes of the grain (IACWR 1968). The default in HEC-RAS of 0.6 was used.

3.2.1.6. Sediment Rating Curves

A means for prescribing the magnitude and gradation of the inflowing sediment load is required at all locations where sediment enters the model. Sediment rating curves were selected to define the bed-material loads entering at upstream boundaries. It is currently anticipated that the final 1-D BEM will have sediment loads quantified at each tributary represented in the model; for the POC effort sediment rating curves were specified only at (1) the Susitna River at the proposed Watana Dam site, (2) the Chulitna River, (3) the Talkeetna River, and (4) the Yentna River. This simplification is appropriate for the POC effort because field observations and limited historical sediment sampling data collected at Indian River and Gold Creek indicate ungaged tributaries to the Middle River and Lower River supply virtually no wash load and little sand to the Susitna River (Tetra Tech 2014e). Further, gravel transported by the ungaged tributaries to the Middle River may either be stored in fans at the tributary mouths or stored along the Middle River channel. Gravel transported by ungaged tributaries to the Lower River is either stored in fans or on the terraces the tributaries cross before entering the Lower River (Tetra Tech 2014e). Thus, for the POC effort, the exclusion of the bed-material loads from the ungaged tributaries was not expected to prevent moveable-boundary calibration or unduly bias simulated sediment-transport results.

The basis for the sediment rating curves was the bias-corrected, linear regression analyses of measured sediment loads and discharge. Tetra Tech (2014e) completed these analyses using measurements collected by the USGS, and then applied the minimum variance unbiased estimator (MVUE) bias correction. Since the bias correction varies across the relationship between sediment load and discharge, the bias-corrected relationship is not a line-of-best-fit. Tabular values of discharge and bias-corrected sediment load are provided in Appendix C of Tetra Tech (2014e), and these tables were the basis of the inputs to HEC-RAS. The rating curves represent only bed material, in all cases assumed to be material coarser than the lower bound for very fine sand (0.0625 mm).

The rating curve specified for the upstream boundary of the Middle River (PRM 187.1) was based on the regression relationships developed from measurements mostly collected on the Susitna River near Talkeetna (USGS Gage No. 15292100), which approximately located at PRM 107. It was assumed that the Middle River between the proposed dam site and the location of the measurements is supply limited, so that the sediment loads measured near Talkeetna were similar to the loads transported past the proposed dam site. Since the flow duration relationships differ appreciably between these two locations, the sediment rating curve developed from the measurements collected near Talkeetna was adjusted. The adjustment consisted of identifying the annual exceedance of a flow near Talkeetna and reducing the magnitude of that flow in the rating curve to correspond to the same annual exceedance at the proposed Watana Dam site. The gradation of the loads in the rating curve were varied as a function of flow magnitude to account for differences in the mobilization of coarser grains. The gradations were developed using the gradations of the measured sediment loads.

The rating curves specified for the Chulitna River, Talkeetna River, and Yentna River were developed following the same approach used for the rating curve for the upstream boundary of the Middle River, except, no flow adjustments were made to account for the USGS gaging station locations being upstream of the confluences with the Susitna River. In the final 1-D BEM, the Chulitna River and Talkeetna River 1-D BEMs will be included in the moveable-boundary simulations to better represent the sediment loads delivered into the Susitna River.

3.2.2. Sediment Simulation Settings and Options

Unsteady-flow sediment routing simulations settings and options that were changed from defaults were setting sediment pass-through nodes and specifying computation options.

Setting sediment pass through nodes entails identifying cross sections where all sediment that enters the control volume represented by a cross section is transported out of the control volume, resulting in no change in geometry. Initially, only the cross sections in Devils Canyon were set as pass through nodes since this canyon is bedrock controlled and changes in channel geometry through the canyon are not of primary interest.

Two types of computation options were specified differently than the defaults: (1) cross section weighting factors and (2) bed exchange iterations. Since sediment-transport calculations can be highly sensitive to local changes in channel hydraulics, such changes can generate instabilities (USACE 2010a). To dampen the effect of such local changes, HEC-RAS allows the user to average the hydraulic inputs to the sediment-transport calculations across one or more cross section upstream and one or more cross sections downstream; the tradeoff of such averaging may be a decrease in accuracy. Even moderate averaging can cause oscillations in the bed profile, so current recommendations are that very small or no weight be placed on the upstream and downstream cross sections. As a starting point, no averaging was applied at internal cross sections. At the upstream boundaries, one cross section downstream of the boundary was averaged with equal weight applied to each section. At the downstream boundaries, one cross section upstream of the boundary was averaged with equal width applied to each section.

The bed exchange iterations allows the user to specify the number of iterations the sorting and armoring algorithms per computation increment to account for changes in bed material availability (USACE 2010a). This parameter can be set to an integer between 1 and 50, inclusive, and the default is 10. Following guidance provided by HEC, the parameter was initially set to 50 since it does not appreciably increase computation burden and the greater value minimizes potential for unrealistically leaching of finer grains from the bed sediment reservoir.

3.3. Moveable-Boundary Sediment Routing Testing

Prior to commencing the moveable-boundary sediment routing calibration, the sediment-transport calculations were tested to identify and resolve issues. Testing began by focusing on the candidate sediment-transport functions. Additional elements that were tested included bed sorting methods, generating and reading gradational hotstart files, investigating sediment routing through flow splits, adjusting cross section hydraulic weighting factors, and adjusting the bed exchange iterations.

3.3.1. Sediment-transport Function

The challenge for the Middle River was to appropriately simulate the routing of supply-limited sand loads and capacity-limited gravel loads using a sediment-transport relationship coupled with a bed sorting method. The bed sorting method accounts for armor layer formation that limits access to the finer grains in the subsurface. Of the total load functions that were prioritized for testing (Section 3.2.1.4), a version of Ackers and White was calibrated for the Middle River to provide the best match of simulated sediment transport to the sediment-transport measurements collected at the USGS gaging station Susitna River near Talkeetna. Specifically, the exponent in the transport function was increased from 1.78 to 3.2, so the calibrated transport function was no longer the Ackers and White function, but a function based largely on the Ackers and White function.

The Lower River transports much greater load than the Middle River, with a greater gravel fraction, but the Lower River bed material is finer than the Middle River. As with the Middle River, several transport functions were tested and the Ackers White function (Ackers White 1973; Ackers 1993), without need for calibration, provided the best match of simulated sediment transport to measurements collected by the USGS at the Sunshine and Susitna Stations gaging stations.

3.3.2. Bed Sorting Method

The testing of bed sorting methods confirmed that the Exner 5 method was reasonably simulating the static armor layer in the Middle River and that the Exner 7 method was producing reasonable layers and gradations in the Lower River. Both of these tests were based on coupling the bed sorting method with the selected transport functions. It is important to note that it was at this point in the testing that the decision was confirmed that the Middle River sediment routing simulations would have to be separated from the Lower River sediment routing simulations. The HEC-RAS software does not allow for either the transport function or the bed sorting method to be varied spatially within a single model.

3.3.3. Bed Material Gradations and Hotstart Files

Based on the selection of the transport functions and bed sorting methods, it became clear that the representative gradations and layer thickness assigned to each cross section were not exactly aligned with the channel hydraulics. Simulations were carried out to allow the simulated hydraulics to adjust the gradations and layers on a cross section specific basis. These initial adjustments would occur in any simulation, but the adjustments reflect variability and uncertainty in the initial conditions, which should be separated from actual geomorphic responses. HEC-RAS can write a gradational hotstart file at the completion of a simulation that records the gradation and thickness of each of the three bed layers (i.e. cover, subsurface, and inactive layers). This hotstart file can then serve to set initial conditions for future simulations. In the Middle River, the 50 years of OWFP were used to establish the gradational hotstart file; in the Lower River, only 15 years of OWFP were needed for the hotstart gradations to stabilize.

3.3.4. Flow Splits

Further testing focused on the ability of HEC-RAS to route sediment through flow splits. After considerable testing and consultation with staff at HEC, it was decided that the software is not yet able to reasonably simulate sediment routing through split flows. The problem is that the only option currently available in the software is to route sediment in proportion to the flow conveyed in each channel. In the Susitna River, many of the side channels branch off from the main channel at an elevation greater than the bed of the main channel. In reality, it is expected that most of the bedload would remain in the main channel and only suspended bed material would be routed into the side channel. Since this is not how the software routes the sediment, the bedload routed into the side channel causes rapid aggradation of the side channel, ultimately leading to a dry side channel and model instability. HEC is working on a solution to this problem, but for the POC effort, in the Middle River the flow splits, flow junctions, and main channel and side channel cross sections through a split flow reach were set as pass through nodes. In the Lower River, only the cross sections bounding the splits and junctions had to set as pass through nodes. It is anticipated that when the 1-D BEM is finalized, the updates to the software will enable successful routing of sediment through splits and junctions.

3.3.5. Sediment Simulation Options

Two changes were made to sediment simulation options in the Lower River during the testing process. The first change was the weights of the factors applied for averaging calculated channel hydraulics for input to sediment computations. For internal sections to the model, hydraulic averaging was changed to assign a weight of 0.05 to the upstream and to the downstream section, and 0.90 to the main cross section. At upstream sections, the weight at the boundary was set to 0.9 and the weight at the next downstream section was set to 0.1. Similarly, at downstream boundaries, the weight at the boundary was set to 0.9 and the weight at the next upstream section was set to 0.1. These changes were made to improve model stability. The second change was made to the bed exchange iterations. The iterations were reduced from 50 to 25 because similar results were produced and the computation burden was decreased.

3.4. Moveable-Boundary Sediment Routing Calibration

After completing the testing of the moveable-boundary sediment routing, the moveable-boundary sediment routing simulation was calibrated to various observations of sediment transport and geomorphic change. Different data were available within the Middle River and Lower River, so the models were calibrated separately.

3.4.1. Observations Available for Calibration

Observed data used for calibration of the Middle River model include (1) USGS measurements of sediment transport (rates and gradation) at the Susitna River near Talkeetna gage, and (2) changes in channel geometry and bed profile based on cross section surveys collected in the early 1980s and 2012/2013.

Observed data used for the calibration of the Lower River model include (1) USGS measurements of sediment transport (rates and gradation) at the Sunshine and Susitna Station gages, and (2) changes in channel geometry based on surveys of a single cross section collected in the early 1980s and 2012/2013. Additionally, results presented in Tetra Tech (2014e) indicate (1) aggradation of gravel between Sunshine and Susitna Station, and (2) sand may be in balance along the Lower River based on the rating curve analyses, but the channel form indicates potential for aggradation. The braided form of certain geomorphic reaches of the Lower River indicates sediment supply exceeds the transport capacity (Tetra Tech 2014c).

The observations of transported loads and gradations and geomorphic change are based on measurements collected primarily in the 1980s and the current licensing studies. Ideally the calibration period would correspond to a similar timeframe (e.g., 1981 through 2014), but sufficient geometric data are not available to develop a model of 1980s conditions. The 1980s cross sections that are available show minimal change compared to current conditions. Therefore, the model was run for the full series of open water flow periods as a comparison with the available data. While this didn’t provide a consistent timeframe for comparison, it provided a reasonable basis for evaluating the parameterization of the moveable-boundary sediment routing models. The calibration of the POC 1-D BEM therefore provided a preliminary tool for assessing the potential effects of the Susitna-Watana Hydroelectric Project on the sediment balance and geomorphology of the channel and floodplain downstream of the proposed dam.

3.4.2. Calibration of Middle River Model

No additional adjustments beyond those made during model testing were required to simulate loads and gradations of bed material transport, along with corresponding geomorphic changes, that closely matched observations. Consequently, the sediment routing model was successfully calibrated and judged suitable for POC effort simulations of changes in the sediment balance and bed evolution of the Middle River.

3.4.2.1. Transported Sediment Loads and Gradations

The measurements of transported sediment loads and gradations were considered as total bed-material load and as gravel load.

3.4.2.1.1. Total Bed-Material Load

The total bed-material sediment rating curve simulated at PRM 107.1 (Susitna River near Talkeetna gaging station) was compared to measured bed-material transport presented in Tetra Tech (2014e); the gradation of the simulated bed-material load was also compared to the USGS-measured gradations.

For the selected 50 years of OWFPs (existing conditions hydrology) in the Middle River, the bed-material loads simulated at the Susitna River near Talkeetna location closely match measured transport rates (Figure 3.4-1). This figure includes all sand (0.0625 mm to 2 mm) and coarser sizes, but the load is dominated (approximately 99 percent) by sand. The scatter in the simulated loads is nearly as great as the measured scatter even though the sediment supply is based on a rating curve that assigns a single supply rate to each discharge (i.e. the rating curve doesn’t account for variability in sediment supply as a function of discharge). This an indication that a number of complex interactions are being simulated by the model, which include exchange of sediment between the water column and channel boundary, and differences in energy slope and flow velocity on the rising versus falling limbs of flow hydrographs.

The total transported gradation over the entire 50 years of OWFPs is also similar to measured gradations over a range of flows (Figure 3.4-2). The model transported gradation is 97.3 percent finer than coarse sand (1 mm) compared to the measured average of 98.9 percent. The measurements include virtually no very coarse sand (1 to 2 mm) and the model includes 2.4 percent of this material. Gravel sizes (>2 mm) appear to be slightly underrepresented in the model as discussed in the next section.

3.4.2.1.2. Gravel Load

Although sand is the predominant bed material in transport, gravel and coarser sizes are important for the development and maintenance of channel features and aquatic habitats. Whereas, the sand is primarily transported in suspension from the glaciated headwater through the Middle River, gravel is primarily transported as bed load.

Figure 3.4-3 shows the transported loads at the Susitna River near Talkeetna gaging station with sand and gravel sizes separated. At this gaging station, the measured sand loads are generally two orders of magnitude greater than the gravel loads (i.e. gravel makes up approximately 1 percent of the total bed-material load) and the measured gravel loads generally scatter over nearly two orders of magnitude. The simulated gravel loads are also widely scattered at about one order of magnitude or less for flows greater than 20,000 cfs; for flows less than 20,000 cfs the scatter increases substantially but the loads are minimal.

In general, the measured gravel loads show greater scatter and uncertainty than the sand loads. The model results generally plot within the scatter indicating that the initial 1-D BEM reasonably represents the bedload transport.

Figure 3.4-4 provides a detailed comparison of the gradations of the gravel transport. These are the same data as shown in Figure 3.4-2, but only the coarsest 20 percent of the gradation is shown.

For the Middle River, the average measured gravel load is 1 percent of the total bed-material load and the model simulates 0.3 percent. Although the model transports gravel up to 64 mm in size during high flows, the amounts of simulated transport over the full open water flow period for sizes greater than 8 mm are very small relative to sand transport. The difference between the model results and the measurements, therefore, is in the gravel sizes greater than 8 mm. The measured results surprisingly have virtually no transport of sizes between 2 mm and 16 mm and comparatively large rates of transport for each increasing size class above the 16 mm size (i.e. more transport of coarse gravel than medium gravel). Adding to this discrepancy is that in the measured data, larger sizes (32 to 64 mm) appear to be transported by low to medium flows whereas high flows have little or no transport of these sizes. This is discussed further in section 4.6 and will be evaluated further in relation to the final modeling.

3.4.2.2. Geomorphic Change

The observed changes in cross sections and the bed profile along the Middle River between the early 1980s surveys and the current surveys are described in Tetra Tech (2014e). The comparisons were made at 37 Middle River cross sections between PRM 186.2 and PRM 104.1. Most of the profile changes are less than about 2 feet with many portions of the profile showing only minor changes of less than one foot. Spatially consistent patterns of degradation or aggradation are not apparent, indicating that the thalweg profile has generally been dynamically stable over the past three decades.

The simulated changes in bed elevation for the Middle River over the selected 50 years of OWFP average close to zero feet and ranged from +1.8 to -2.0 feet, with 90 percent of the cross sections exhibiting changes between +0.9 and -1.1 feet; these changes compare favorably with the results presented in Tetra Tech (2014e) comparing the 1980s surveys to current surveys. The simulated changes also did not exhibit any longitudinal trends of aggradation or degradation.

3.4.3. Calibration of Lower River Model

The Lower River moveable-boundary sediment routing model was calibrated by adjusting model parameters to closely simulate (1) measurements of transported sediment loads and gradations, and (2) observed geomorphic change. No adjustments beyond those made during model testing were required to simulate loads and gradations of bed material transport, along with corresponding geomorphic changes, that closely matched observations. Consequently, the sediment routing model was successfully calibrated and judged suitable for POC effort simulations of changes in the sediment balance and bed evolution of the Lower River.

3.4.3.1. Transported Sediment Loads and Gradations

The measurements of transported sediment loads and gradations were considered as total bed-material load and as gravel load.

3.4.3.1.1. Total Bed-material Load

The simulated total bed-material rating curve and transported gradations at the USGS gaging stations at Sunshine and Susitna Station were compared to measured sediment-transport rates and gradations presented in Tetra Tech (2014e). The daily average bed material loads simulated at Sunshine closely match measured transport rates (Figure 3.4-5). This location shows greater scatter for measurements and model results than the Susitna River near Talkeetna gage. The scatter for the measurements and simulation results is likely caused by highly variable inputs of water and sediment from the Middle River, the Chulitna River in particular, and the Talkeetna River. The average transported gradation over the entire simulation is similar to the measured gradations over a range of flows (Figure 3.4-6). As would be expected for this location, the measured gradations are much more variable due to the multiple sediment inputs. The average gradation of the simulated bed-material transport over the selected 50 years of OWFPs and the average of the measured gradations are both 95 percent finer than coarse sand (1 mm). As with the Middle River, the measurements include almost no very coarse sand (only 0.5 percent) compared to 2 percent in the simulation. Again, the model slightly underrepresents gravel loads as discussed in the next section.

The same patterns are evident at Susitna Station (Figure 3.4-7 and Figure 3.4-8). The transport of 1 mm and finer sand is again similar between the total model (97.5 percent of the total bed material load) and average of the measurements (97.9 percent). For very coarse sand the measurements indicate 0.6 percent and the simulation produces 1.2 percent. The gravel contribution is very similar at this location.

3.4.3.1.2. Gravel Load

Although sand is the predominant bed material in transport, gravels and coarser sizes are important for the development and maintenance of channel features and aquatic habitats. Whereas the sand is primarily transported in suspension from the glaciated headwaters of the mainstem and major tributaries through the Lower River, gravel is primarily transported as bed load.

Figure 3.4-3 shows the transported loads at the Sunshine and Susitna Station gaging stations with sand and gravel sizes separated. For the Sunshine gage the measured gravel loads are more than one but less than two orders of magnitude lower than the sand loads (i.e. gravel makes up more than 1 percent but less than 10 percent of the total bed-material load). The measured gravel loads are scattered over approximately two orders of magnitude. The simulated gravel transport is very similar to the measurements, but the scatter is generally less than one order of magnitude.

At Susitna Station there are relatively few gravel load measurements and they are all for flows greater than 50,000 cfs. The measured gravel loads are approximately two orders of magnitude less than the sand loads (i.e. gravel makes up approximately 1 percent of the total bed-material load). For flows greater than 50,000 cfs, the simulated gravel loads appear to be slightly low; for flows less than 50,000 cfs the model transports too much gravel. This may be due to assigning too large a percentage of gravel to the Yentna River rating curve for lower flows. This will be investigated in the next version of the model.

In general, the measured gravel loads show greater scatter and uncertainty than the sand loads. The model results generally plot within the scatter indicating that the initial model reasonably represents the bed-load transport. Compared to the measured data, the Susitna Station results suggest slightly low gravel transport at the highest flows and likely high gravel transport at flows less than 50,000 cfs.

Figure 3.4-9 and Figure 3.4-10 provide a detailed comparison of the gradations of the gravel transport. These are the same data as shown in Figure 3.4-6 (Susitna River at Sunshine) and Figure 3.4-8 (Susitna River at Susitna Station), but only the coarsest 20 to 30 percent of the gradation is shown.

For the Lower River at Sunshine, the model indicates that 3 percent of the material in transport is gravel and the measurements average 4.5 percent. Given the scatter in the measured gradations, however, the difference is not a concern. This difference is almost entirely in the very coarse gravel (32 to 64 mm) size class and each of the other gravel size classes compare well between the model and measurements.

For the Lower River at Susitna Station, the average gravel load measurement of 1.7 percent compares well with the 1.5 percent calculated from model results, though the measured gravels again tend to be slightly coarser than the model.

Figures 3.4-4, 3.4-9 and 3.4-10 have common features, including:

- Percentage finer than 1 mm (coarse sand and finer is close to the measured amounts)
- The model consistently simulates more very coarse sand (between 1 and 2 mm) than is measured and the measured is close to zero for this size class.
- In the gravel range the largest differences occur for largest sizes (>32 mm for the Middle River and at Sunshine and >16 mm for Susitna Station)
- For the Susitna River near Talkeetna and Sunshine locations, a few measurements (out of approximately 40 total at each gage) have a major influence on the averages for sizes greater than 16 mm. For example, in Figure 3.4-4 the measurements at 20,000 and 24,200 have large representations of material greater than 16 mm. Also, in Figure 3.4-9 the measurements at 64,600 and 75,500 cfs have very large rates of transport for the larger gravel sizes compared to smaller gravel.

3.4.3.2. Geomorphic Change

PRM 98.4 is the only cross section in the Lower River that was available for comparison of 1980s and current geometry. Although the thalweg lowered by 3.6 feet, the overall cross section changed dramatically over the 30 years and the net accumulation of sediment at this location is equivalent to 2.9 feet of aggradation (Tetra Tech 2014e). The accumulation of sediment in the Lower River is expected because of the braided planform, indicating sediment supply exceeds transport capacity (Tetra Tech 2014c). The Lower River model shows zero to 2 feet of aggradation in the LR-1 geomorphic reach (PRM 102.4 to PRM 87.9) with an average of 1.2 feet over 50 years of OWFPs. The simulated geomorphic change through LR-1 is similar to the single measurement of change at PRM 98.4, and since only a single observation was available, no further refinements were pursued. The specific gage analysis (Tetra Tech 2013b) shows much less than 1 foot of variability over the entire flow range at Susitna Station (PRM 29.9) and no trends. A specific gage analysis was not performed for Sunshine (PRM 87.9) due to the short gage record. The Susitna Station results add little information since this is a very laterally confined location where vertical change is less likely to occur.

4. FUTURE DEVELOPMENT AND IMPROVEMENTS FOR FINAL 1-D BEM

While the moveable-boundary sediment routing model (i.e. 1-D BEM) was successfully calibrated for the POC effort, the initial model will be revised and the calibration will be revisited in future phases of the FGM study. The following sections describe continued model development and potential improvement of the calibration to finalize the 1-D BEM.

4.1. Channel and Floodplain Geometry

As described in Section 7.2.1.1.9.5 of Part C of the Study 6.6 ISR, LiDAR mapping was collected for the entire floodplain in the Middle River from approximately PRM 107 to PRM 187.1. The 2013 and 2014 LiDAR mapping will be used to update the overbank geometry currently represented by the MatSu LiDAR mapping collected in 2011 and indexed to the NAVD88 in 2013.

As described in Section 7.3.1 of Part C of the Study 8.5 ISR, bathymetric surveys at approximately 60 cross sections were either collected in 2014 or planned for later (above Devils Canyon). Where needed to improve the 1-D BEM, such as around flow splits and flow junctions, these surveys will be merged with the 2013 and 2014 LiDAR mapping and input to the 1-D BEM.

The Chulitna and Talkeetna River tributaries will be added to the final 1-D BEM. This will allow for sediment and flow routing from the measurement locations (USGS gage sites) rather than having these inputs directly in the model.

A more complete set of split flow reaches will be included in the Middle Susitna River model.

4.2. Hydrologic Inputs

As described in Section 7.4 of Part C of the Study 8.5 ISR, lateral inflows will be updated with synthesized tributary flows that were updated based on relationships developed from data collected in 2013 and 2014. The updated flow series will replace the current flow series.

Incorporating ice jam breakup flows will also be considered. This may provide additional information on the potential for bed mobilization during breakup.

4.3. Hydraulic Calibration Criteria

The hydraulic calibration for the POC effort was based on simulating water-surface elevations within approximately one foot of observations. This criterion could be reduced to better simulate hydraulic conditions. Additionally, the water-surface elevation hydrographs measured at ESS stations and point-in-time water-surface elevation surveys can be reviewed to ensure the observations are robust. For example, surveys of water-surface elevations along the Lower River include multiple channels and the arithmetic average of these elevations was used for the POC effort; it may make more sense to use elevations along the main channel only or to use the variability across channels to better set thresholds for the expected calibration.

4.4. Sediment-routing Calibration Period

Since observations of sediment-transport and geomorphic change that were used for the calibration of the moveable-boundary sediment routing model were primarily collected between the early 1980s and 2014 (Section 3.1.3), the calibration of the final model can focus on this period. The POC effort used the OWFP of the selected 50 years for comparison to the observation, so decreasing this period to 35 years that better overlap with the measured data could improve the calibration.

4.5. Bed-material Gradations

Section 3.3.3 describes the approach used to establish the initial bed material gradations for the moveable-boundary sediment routing simulations. While this approach provided reasonable inputs to the model, the inputs could be refined during the development of the final 1-D BEM. For example, coarser cover layer gradations could be prescribed in reaches of the Middle River were lag deposits have been observed, and surface layer gradations in the Lower River could be varied by geomorphic reach. The measured bed material gradations will be reviewed to determine if trends should be applied when developing surface and subsurface gradations for model input.

4.5.1. Middle River Lag Deposits

Field observations, as confirmed through the main channel sediment sampling (Tetra Tech 2014f), indicate the main channel of the Middle River is dominated by boulders and coarse cobbles in locations that appear to be lag deposits. These locations are evident between (1) the proposed dam site (PRM 187.1) and the upstream end of Devils Canyon (PRM 166), (2) PRM 146 to PRM 132, and (3) PRM 116 to PRM 107. Specifying coarser cover layer gradations and thicker cover layers in these reaches may reduce channel degradation that was simulated during the POC effort modeling. Such changes will be investigated during the development and testing of the final 1-D BEM.

4.5.2. Lower River Surface Gradations

Figure 4.5-1 compares D_{84}, D_{50}, and D_{16} values calculated from surface sediment samples to geomorphic reach-averaged values calculated from results at the end of the calibration period. This figure shows a notable difference between the comparison in the Middle River and the Lower River. In the Middle River, the simulated reach-averaged values closely align with the values derived from the winter sampling (Tetra Tech 2014f). Both the simulated and observed values show slight decreases in magnitude with decreasing PRM. The similarity in magnitudes and spatial trends was expected given the dynamically-stable morphology of this reach and the simulation of recent historical conditions (i.e. existing conditions). However, the same similarity does not persist through the Lower River.

Downstream of the Three Rivers Confluence, surface sediment sizes abruptly decrease by about a factor of two relative to Middle River surface sediment. A noticeable fining of the surface sediment is simulated from geomorphic reaches LR-1 through LR-3; whereas, the winter samples and bar-head surface samples show a more consistent surface gradation from geomorphic reaches LR-2 through LR-5. The cause of this discrepancy will be investigated in the development and testing of the final 1-D BEM. It is expected that the discrepancy is attributed to the simplifying assumption of a consistent cover layer gradation through the Lower River; using the sampled data to generate gradations that vary by geomorphic reach may better align the simulated gradations with the observations. For instance, Figure 4.5-2 shows a progressive decline in the cobble (>64 mm) fraction of the bar-head subsurface samples (which are representative of transported gradations) between the Three Rivers Confluence and about PRM 55. This indicates that cobbles delivered to the Lower River by the Middle River, Chulitna River, and Talkeetna River may not be appreciably transported downstream of about PRM 55. However, Figure 4.5-2 shows the presence of cobbles between about PRM 47 and PRM 39. It is believed these cobbles are sourced from erosion of the terraces that confine the main channel through this reach rather than from upstream. The surface samples through this reach that target the coarser bar-heads may represent less mobile concentrations of coarse gravel and cobble sourced locally; perhaps the subsurface gradations better represent the majority of the bed surface. It is not expected that these adjustments to the initial cover layer gradations will appreciably influence the simulated sediment balance and associated geomorphic change, but are worth investigating to confirm this expectation.

4.6. Estimates of Sediment Supplies

During the testing of the moveable-boundary sediment routing simulations, a concern arose because of differences between the simulated gradation of transported loads and USGS measurements of bedload transport of coarse gravel (16 to 32 mm), very coarse gravel (32 to 64 mm), and small cobble (measured up to 75 mm). Investigations of these differences led to several conclusions:

- None of the sediment-transport measurements collected by the USGS occurred during fully mobile bed conditions.
- Sediment moving through the Middle River is likely supply-limited and is conveyed as either wash load (fine material—including fine sand—transported in suspension) or throughput load (coarser material including coarse sand and finer gravels transported over the armored channel bed).
- Because of potential sampling bias, USGS bedload measurements of gravel sizes, especially coarse and very coarse gravels, may not be indicative of actual transport rates.
- If significant bed disturbance of the Middle River occurs, it may only occur for brief periods during breakup when potentially more extreme hydraulic conditions exist.

These conclusions require some context related to sediment transport in coarse systems with armor layers. For the Susitna River, initial measurements of the bed material sizes were conducted by Tetra Tech at bar- and island-heads. The bar-head location is often used to efficiently estimate material size of the main channel bed material where sampling of the main channel is difficult or impossible. For the Middle River, bar-head surface D_{50} is nearly 60 mm and the subsurface D_{50} is approximately 30 mm. The winter bed sampling (Tetra Tech 2014f) was conducted to more accurately determine the gradation of the main channel bed surface. The average D_{50} of the Middle River bed surface from winter sampling was determined to be 83 to 88 mm depending on which of the samples are included in the averaging. For the bed to mobilize, the surface D_{50} needs to mobilize. For lower flows, particles may move along the bed, but this movement does not indicate a mobile bed. In general, smaller particles are shielded in the wakes of larger particles and may occasionally move to another shielded location. Larger particles may also occasionally move if they project well into the flow, but they come to rest again without continued movement. Thus, the bedload measurements of the grains both similar in size and coarser to the bed surface D_{50} are questionable when the hydraulic conditions do not indicate the bed surface was fully mobile.

One approach for evaluating bed mobilization is using the Shields (1936) relationship to compute the dimensionless shear stress, τ^*, related to surface D_{50}. For the surface D_{50}, an incipient motion condition is often related to τ^* of 0.03 (Neill 1968) and for low but measureable transport (bed mobilization) τ^* values are greater (0.045 to 0.06). Andrews (1983) equation (based on Middle Susitna River surface and subsurface D_{50} values of 83 and 30mm) indicates an initiation of motion at τ^* of 0.036. Neill indicated that consistent movement and bed deformation is observed at values of 0.06, which is consistent with Vanoni (1967) attributing small but measureable transport to a value of 0.06. Buffington and Montgomery (1997) conclude that for gravel bed rivers, visually based incipient motion values range from 0.03 to 0.073 with 0.045 as a typical value. They concluded that reference based (extrapolating to zero transport) values are higher, ranging from 0.052 to 0.086. Although values of 0.03 may indicate incipient motion of some particles, higher values, such as 0.045, are more indicative of bed mobilization when materials under the then disturbed armor are more available for transport. To initiate motion of the bed with D_{50} of 83 mm a shear stress of 0.84 lbs/sq-ft is required, and bed mobilization occurs at a shear stress of 1.26 lbs/sq-ft.

Another important finding comes from comparing simulated to measured bed load transport rates. Figure 4.6-1 shows the average gradation of USGS total load (suspended bed material plus bedload) measured at the Susitna River near Talkeetna gaging station compared to the gradation calculated from the cumulative total load simulated at this same location over the selected 50 years of OWFP under existing conditions. For comparison, the bar surface and subsurface samples, as well as the winter sampling gradations are also shown in the figure. Nearly all of the transport occurs for sizes less than 0.5 mm. For larger sizes, the HEC-RAS model shows 5.2 percent in the 0.5 to 1 mm range compared to 3.1 percent in the measured values and 2.3 percent in the 1 to 2 mm range compared to 0.1 percent in the measurements. For total gravel load (>2mm), more clearly shown in Figure 4.6-2, the 1-D BEM computes 0.3 percent and the measurements are 1.0 percent. The measurements include material up to 75mm (opening of the Helley-Smith sampler used by the USGS). Although HEC-RAS computed transport up to 64mm, the rates for any size greater than 8 mm were much less than 0.1 percent of the total.

Although the bar-head surface samples and the winter bed samples show little or no material less than 8 mm, the material is probably present in small quantities but the sampling methods are not well suited to include them. However, if they aren't present in appreciable amounts, then the absence of 8 mm and finer material from the USGS load measurements isn't surprising. However, these sizes are appreciably represented in the subsurface material. Therefore, if the bed were mobilized, then these sizes should be well represented in the measurements.

Figure 4.6-2 is a detailed view of the upper 20 percent of Figure 4.6-1, and Table 4.6-1 shows the incremental percentages of the loads from the USGS measurements and the HEC-RAS results. The largest percent of the gravel load in the USGS measurements are for the two coarsest fractions, which is why the gradation curve is steeper for the larger sizes. The 32 to 75 mm range has 0.6 percent of the total load (60 percent of the gravel load).

Table 4.6-2 shows the bed load measurements in the 1980s, 2012 and 2013 conducted for open water conditions when suspended loads were also measured. The table includes total and incremental bedload as well as hydraulic conditions included with the 1980s measurements (Knott and Lipscomb 1983; Knott and Lipscomb 1985; Knott et al. 1986; Knott et al. 1987). Because channel hydraulic depth and water surface slope were included as part of the measurements, the total shear stress was estimated and dimensionless shear was computed (far right columns of the table). All the values are less than 0.03 (initiation) though some approach this value. Therefore, none of the 1980s flow conditions would appear to mobilize the 83 mm D_{50}. These results are shown in Figure 4.6-3, which indicates that flows in excess of 80,000 cfs would be needed to mobilize the bed of the Middle River.

These results bring into question the reliability, or at least the interpretation of some of the USGS measurements. The first three measurements (6/3/1982 to 6/22/1982) in Table 4.6-2 are the only samples that include 64- to 75-mm material. This single size class of these three samples actually comprises 26 percent of the gravel load measured in the total record, which includes 38 measurements. Similarly, nearly 40 percent of the 32- to 64-mm material sampled was in these first three samples. Another concern is that lower flows often include the larger size classes while high flows exclude the larger sizes. The 5/23/2012 measurement at a flow of only 20,000 cfs shows half the gravel load in the 32- to 64-mm size class and none in the 2- to 8-mm range. The three highest discharges measured (each greater than 40,000 cfs) show a very different picture of bed-load transport in the Middle River. These three measurements (8/26/1984, 5/29/1985, and 9/25/2012) have no material in the 32- to 75-mm range and actually relatively little load in the 2- to 32-mm range. These measurements would be expected to have some of the highest measured loads especially if the bed were mobilized.

The most likely reasons that could explain the discrepancies noted in the bedload measurements are (1) disturbing the bed as the Helley Smith sampler makes contact with the bed surface such that dislodged particles enter the sample, or (2) scooping the bed with the Helley-Smith sampler. Both of these conditions are especially likely when using a cable system from a boat in high velocity, shallow water. The Helley-Smith sampler is initially pulled downstream under the boat and may scoop bed material as the sampler moves upstream into final position. The purpose of noting these considerations is to recognize the difficulty of making these measurements for the field conditions and to acknowledge potential sources of uncertainty in the measurements.

The sampling method used in the 1980s involved approximately 20 verticals with the sampler on the bed for 30 seconds at each vertical. The 3-inch-wide sampler therefore covered 5 feet of the approximately 600-foot-wide channel. From this sampling procedure the contribution a single particle makes to the total load measurement was calculated and is shown in the column headings in Table 4.6-2. For example, collecting a single 64-mm particle accounts for approximately 140 tons/day of the measured load. In the 64- to 75-mm size class, the first three measurements were apparently heavily influenced by including one to five particles. Similarly the 32- to 64-mm size class appear to include one to ten particles. When the bed is disturbed, smaller shielded particles would also be dislodged and the measurements also likely exaggerate the loads for smaller size classes.

Why then do the highest flow measurements exclude material greater than 32 mm and flows as lows less than 20,000 cfs include 32-mm material? For example, the measurement on 5/23/2012 at 20,000 cfs includes the second largest measurement of the 32- to 64-mm size class, which represents approximately six particles. One possible explanation is that lowering the Helley-Smith sampler in deeper, higher-flow conditions is less likely to result in dredging because the deeper water allows sampler and cable to swing into a more vertical position and the sampler is less likely to disturb the bed or scoop bed material.

One other comparison was made using the Wilcock-Crowe (2003) bed-load transport function to compute transport capacity for the 1980s hydraulic conditions. The average Middle River winter bed surface gradation (Tetra Tech 2014f) was used in these calculations. This function does not include a critical dimensionless shear stress but computes vanishingly small bedload transport rates for all flow conditions. As shown in Figure 4.6-3, the highest load is only 3.1 tons/day. The measured gravel load for this measurement (6/1/1983 at a flow of 39,100 cfs) is 179 tons/day, of which 160 tons/day is in the 32- to 64-mm size class, likely from only a few particles. The large discrepancies between measured and computed bed-load transport rates indicates that the measurements may not be representative, especially when very few particles can dominate the measured load. If, however, bed load is calculated using the subsurface gradation, which would be correct with full bed mobilization, several thousand tons/day load is expected for each of the individual gravel size classes. Clearly the flow does not have access to the subsurface materials during open-water flow conditions.

As shown in the bottom row of Table 4.6-2, if the first three measurements are excluded, the loads from the three highest measurements (>40,000 cfs) comprise none of the 32- to 75-mm material and between 9 and 22 percent of the smaller size gravel loads. Considering that these three highest-flow measurements make up 9 percent of all measurements, they are expected to represent at least 9 percent of the load. Therefore, it appears that all of the measured load greater than 32 mm could be excluded from the measured rates. If this is done then the measured USGS load would be adjusted as shown in Figure 4.6-2. These results also indicate that the prior estimate that gravel comprises one percent of the open-water total load of the Middle River should be reduced to less than 0.4 percent. This adjustment is also shown in Table 4.6-1. Comparing the adjusted USGS measurements to the HEC-RAS results indicates slight differences in the transport rates for sizes less than 0.5 mm, and that the coarse sand (0.5 to 1 mm) and very coarse sand (1 to 2 mm) differ by about 2 percent.

Based on the comparison of the simulated and measured gradations of sediment transport in the Middle River, the sediment rating curve used to quantify the sediment supply to the Middle River under existing conditions should be reevaluated as the 1-D BEM is finalized. Similar reevaluation will be considered for the other sediment rating curves, such as at the upstream ends of the modeled reaches of the Chulitna River and Talkeetna River, and as the point source inflow for the Yentna River.

The EFDC modeling in Study 5.6 will be used to provide total sediment loading through the Susitna River below Watana Dam.

4.7. Enhancements in HEC-RAS Software

As noted in Section 3.3.4, HEC-RAS was not properly simulating the routing of bed material through flow splits. The HEC-RAS development team has been working to enhance the capabilities of the software related to this issue. It is expected that these enhancements will be available for the final 1-D BEM.

If available, another enhancement that should be tested is the incorporation of a hiding function applicable to the Ackers-White transport function. A hiding function would simultaneously (1) reduce the mobilization of finer size fractions nested in the bed surface among larger size fractions, and (2) enhance the mobilization of larger size fractions that protrude from the bed surface into the flow. The HEC-RAS development team is considering enhancing the software with hiding functions, and such an enhancement is expected to refine simulations of bed mobilization and transport.

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6. TABLES

Table 1-1. Components of FGM Study (Study 6.6).

Study Component	**Goal**
Bed Evolution Model Development, Coordination, and Calibration	Develop a numerical model to simulate channel formation processes in the Susitna River downstream of Watana Dam
Simulate Existing and with-Project Conditions	Provide a baseline and series of with-Project scenarios of future channel conditions for assessing geomorphic changes to the Susitna River downstream of Watana Dam
Coordination and Interpretation of Model Results	Ensure the information from the Geomorphology Study (Study 6.5) is properly considered and incorporated into the FGM Study; ensure the results of the FGM Study are used to update and refine the understanding of key processes identified in the Geomorphology Study; provide the necessary results to the other resources studies that will require knowledge, and where possible and appropriate, quantification of potential natural and Project-induced geomorphic changes to the Susitna River downstream of Watana Dam

Table 2.2-1. Manning's n-values related to Geomorphic Features Mapping.

Geomorphic Feature		Manning's n-value	Applicable Modeling Reaches
Description	**Abbreviation**		
Additional Open Water (Wetland)	AOW	0.10	L. Susitna, Chulitna, Talkeetna
Additional Open Water (Wetland)	AOW	0.12	M. Susitna
Bar / Attached Bar	BAB	0.09	Talkeetna
Background (Densely Vegetated Floodplain)	BG Dense	0.15	M. Susitna, L. Susitna, Chulitna, Talkeetna
Background (Sparsely Vegetated Floodplain)	BG Sparse	0.10	L. Susitna, Chulitna, Talkeetna
Bar Island Complex	BIC	0.05	L. Susitna, Chulitna, Talkeetna
Exposed Substrate – Main Channel	EXP MC	0.05	M. Susitna
Exposed Substrate – Side Channel	EXP SC	0.052	M. Susitna
Main Channel	MC	0.03	M. Susitna, L. Susitna, Chulitna, Talkeetna
Side Channel	SC	0.04	M. Susitna, L. Susitna, Chulitna, Talkeetna
Side Channel Complex	SCC	0.042	L. Susitna, Chulitna, Talkeetna
Side Slough	SS	0.045	M. Susitna, L. Susitna, Chulitna, Talkeetna
Tributary Delta	TD	0.09	L. Susitna
Vegetated Island	VI	0.13	M. Susitna
Vegetated Island in Bar Complex	VI BIC	0.13	L. Susitna, Chulitna, Talkeetna
Vegetated Island in Main Channel	VI MC	0.13	L. Susitna, Talkeetna
Vegetated Island in Side Channel	VI SC	0.13	L. Susitna, Chulitna, Talkeetna
Vegetated Island in Side Channel Complex	VI SCC	0.13	L. Susitna, Chulitna, Talkeetna
Vegetated Island in Side Slough	VI SS	0.13	L. Susitna, Chulitna, Talkeetna

Table 2.4-1. Calibration and validation data for the 1-D Bed Evolution Model

Reach	Period	Available Data
Middle River	Calibration: 9/12/2012 – 10/15/2012	1. Water-surface elevation hydrographs from 7 ESS locations and 2 USGS gages 2. Flow hydrographs from 2 USGS gages 3. Point-in-time water-surface elevations
Middle River	Validation: 7/5/1981 – 9/4/1981	Flow hydrographs from 2 USGS gages
Lower River	Calibration: 5/24/2013 – 8/31/2013	1. Water-surface elevation and flow hydrographs from 2 USGS gages 2. Point-in-time water-surface elevations
Lower River	Validation: 7/5/1981 – 9/4/1981	Flow hydrographs from 2 USGS gages

Table 3.2-1. Middle River and Lower River representative cover layer and inactive layer bed-material gradations and quantiles.

Grain Size (mm)	Cumulative Percent Finer			
	Middle River Cover Layer	Middle River Inactive Layer	Lower River Cover Layer	Lower River Inactive Layer
1,024	100	100	--	--
512	98.8	99.5(100)	--	--
256	88.3	99.0(99.8)	100	100
128	65.6	92.6	99.1	99.1
64	36.7	71.8	85.9	90.3
32	9.82	52.1	48.7	70.7
16	0.78	36.7	15.4	51.0
8	0	28.3	2.1	38.6
4	--	21.9	0.1	28.9
2	--	17.3	0	23.0
1	--	14.5	--	19.4
0.5	--	11.7	--	15.3
0.25	--	4.1	--	4.1
0.125	--	1.5	--	1.4
0.0625	--	0.7	--	0.6
D_{90}	277	117	73.9	63.3
D_{84}	223	94.7	61.7	49.4
D_{50}	85.6	29.3	32.8	15.1
D_{16}	38.1	1.44	16.2	0.56

Table 4.6-1. USGS measured and HEC-RAS computed sediment loads for the Middle Susitna River.

Size Class (mm)	Percent in size class		
	USGS Measurements	USGS excluding >32mm	HEC-RAS
0.0625 - 0.125	25.2	25.4	28.1
0.125 - 0.25	41.2	41.4	34.9
0.25 - 0.5	29.4	29.6	29.2
0.5 - 1	3.1	3.1	5.2
1 - 2	0.1	0.1	2.3
2 - 4	0.1	0.1	0.2
4 - 8	0.0	0.0	0.1
8 - 16	0.1	0.1	0.0
16 - 32	0.2	0.2	0.0
32 - 64	0.4	0.0	0.0
64 - 75	0.2	0.0	0.0

Table 4.6-2. USGS Bedload measurement at station Sutitna River near Talkeetna (#15292100) data and evaluation.

Sample Summary			Bed Load mass (tons/day) by size range (mm) and Bedload contributed by a single particle [tons/day]										Measured Hydraulic Parameters and Bed Mobilization					
Begin date	**Q (cfs)**	**Q_s (tons/day)**	**< 0.25**	**0.25 - 0.5**	**0.5 - 1**	**1 - 2**	**2 - 4**	**4 - 8**	**8 - 16**	**16 - 32**	**32 - 64**	**64 - 75**	**Velocity (ft/s)**	**Mean depth (ft)**	**Width (ft)**	**W.S. slope**	**Shear Stress (lbs/ft^2)**	**τ^* for 83 mm D_{50}**
6/3/1982	35,800	2,840	85	966	284	28	28	85	57	114	454	738	7.4	7.8	625	0.0014	0.68	0.024
6/15/1982	24,200	831	0	199	66	0	8	17	25	50	266	199	7.4	5.3	619	0.0014	0.46	0.017
6/22/1982	37,000	992	20	446	109	20	0	10	0	10	20	357	7.8	7.4	645	0.0015	0.69	0.025
6/30/1982	30,200	442	4	141	27	4	4	9	13	168	71	0	7.4	6.5	623	0.0018	0.73	0.026
7/8/1982	20,800	324	0	211	94	6	3	6	0	3	0	0	6.8	5.2	596	0.0013	0.42	0.015
7/14/1982	30,800	906	9	453	181	27	9	18	36	82	91	0	7.4	6.7	622	0.0014	0.59	0.021
7/21/1982	25,000	360	4	230	90	7	4	4	7	14	0	0	7.1	5.9	603	0.0015	0.55	0.020
7/28/1982	30,800	600	6	414	90	6	12	18	12	42	0	0	6.8	7.3	618	0.0016	0.73	0.026
8/4/1982	22,800	215	4	163	43	2	0	0	2	0	0	0	6.8	5.5	604	0.0014	0.48	0.017
8/10/1982	20,200	282	3	183	79	6	0	0	3	8	0	0	6.7	5.1	596	0.0013	0.41	0.015
8/18/1982	17,800	106	1	72	30	2	1	0	0	0	0	0	6.5	5	557	0.0014	0.44	0.016
8/25/1982	16,900	110	1	75	31	2	1	0	0	0	0	0	6.7	4.5	557	0.0013	0.37	0.013
8/31/1982	19,400	188	0	135	41	4	0	2	0	4	0	0	7	4.7	585	0.0013	0.38	0.014
9/19/1982	28,900	372	7	227	56	7	0	7	7	26	33	0	7.8	6.1	616	0.0014	0.53	0.019
5/25/1983	19,300	298	3	188	69	3	3	0	3	6	24	0	5.8	5.5	601	0.0012	0.41	0.015
6/1/1983	39,100	225	2	41	5	0	0	5	9	5	160	0	8.0	7.4	662	0.0016	0.74	0.026
6/23/1983	27,000	840	8	496	168	17	0	8	17	8	118	0	7.2	6	615	0.0014	0.53	0.019
7/21/1983	19,200	302	3	260	21	3	0	0	3	12	0	0	6.2	5.2	598	0.0013	0.42	0.015
8/2/1983	24,000	668	7	414	100	13	7	13	13	27	73	0	6.9	5.9	600	0.0014	0.52	0.018
8/11/1983	32,900	854	111	265	444	17	0	0	9	9	0	0	8.6	6.2	611	0.0015	0.58	0.021
9/14/1983	11,300	70	0	53	8	3	1	0	0	5	0	0	5.0	4	565	0.0014	0.35	0.012
6/13/1984	24,700	391	0	246	125	4	4	0	8	4	0	0	7.1	5.7	613	0.0014	0.50	0.018
7/9/1984	22,300	238	2	157	50	2	2	0	2	7	14	0	6.7	5.5	604	0.0014	0.48	0.017

7/30/1984	30,900	564	6	338	107	6	11	17	17	6	56	0	7.1	6.9	627	0.0014	0.60	0.022
8/16/1984	15,200	242	2	172	58	2	2	0	0	5	0	0	5.5	4.9	559	0.0012	0.37	0.013
8/26/1984	40,900	894	18	644	179	9	9	18	9	9	0	0	8.4	7.7	636	0.0014	0.67	0.024
5/29/1985	46,000	590	12	372	100	12	12	12	18	53	0	0	9	7.8	658	0.0014	0.68	0.024
6/26/1985	30,600	348	3	247	77	3	3	7	7	0	0	0	7.8	5.8	621	0.0014	0.51	0.018
8/13/1985	29,400	560	6	375	112	6	6	0	6	0	50	0	7.5	6.3	622	0.0014	0.55	0.020
9/19/1985	18,900	212	2	157	40	2	2	0	8	0	0	0	6.1	5.2	594	0.0014	0.46	0.016
5/23/2012	20,000	694	0	49	7	7	0	0	35	285	312	0	Note: shaded values not recorded so average value used					
6/5/2012	30,100	852	0	443	153	26	17	9	17	60	119	0						
7/10/2012	27,800	301	3	217	60	8	2	6	6	0	0	0						
8/14/2012	17,700	28.5	0	20	5	0	0	1	2	0	0	0						
9/25/2012	43,700	199.5	19	116	17	4	2	8	15	16	0	0						
7/10/2013	22,400	12	0	9	2	0	0	0	0	0	0	0						
8/13/2013	17,700	42	0	33	7	1	0	0	0	0	0	0						
9/5/2013	32,200	215.5	14	103	36	9	4	5	8	3	33	0						
Bed Load contributed by a single particle (t/d)							.004-.034	.034-0.27	0.27 - 2.2	2.2 -17	17 - 140	140 - 220						
Total sum of column (t/d)		18,209	367	9,330	3,171	279	159	285	373	1039	1,896	1,295						
Sum of first 3 measurements (t/d)		4,663	105	1,611	460	48	37	112	82	173	740	1,295						
Percent of total in first 3 measurements		26	29	17	14	17	23	39	22	17	39	100						
Sum of 3 measurements >40,000 cfs (t/d)		1,684	49	1,131	296	25	23	38	42	78	0	0						
Pct. of total in measurements >40,000 cfs		9	13	12	9	9	14	13	11	8	0	0						
Subtotal excluding first 3 measurements (t/d)		13,546	262	7,719	2,712	231	122	173	292	865	1,156	0						
Pct. of subtotal in measurements >40,000 cfs		12	19	15	11	11	19	22	14	9	0	0						

7. FIGURES

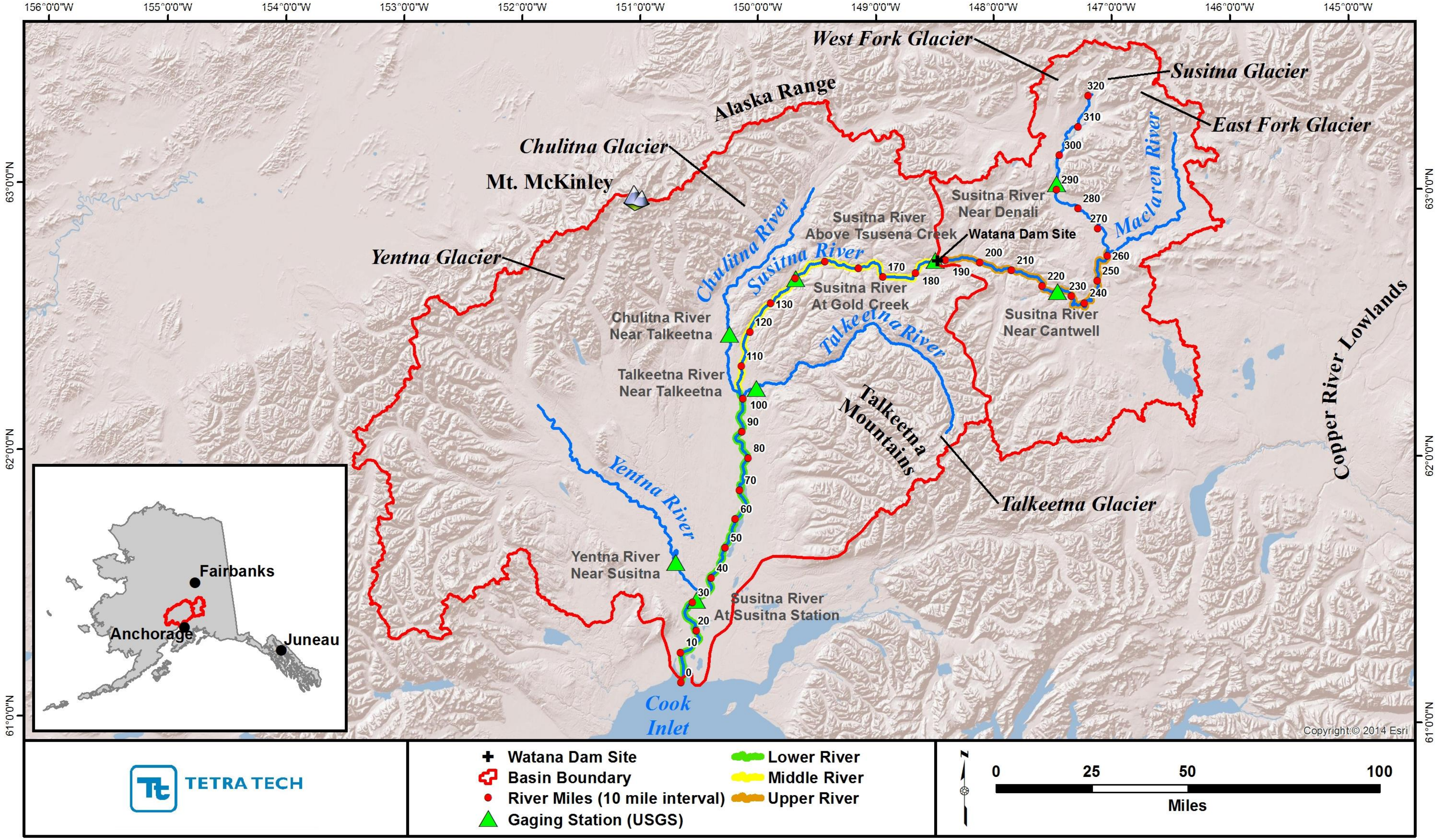

Figure 1-1. Susitna River study area and large-scale river segments.

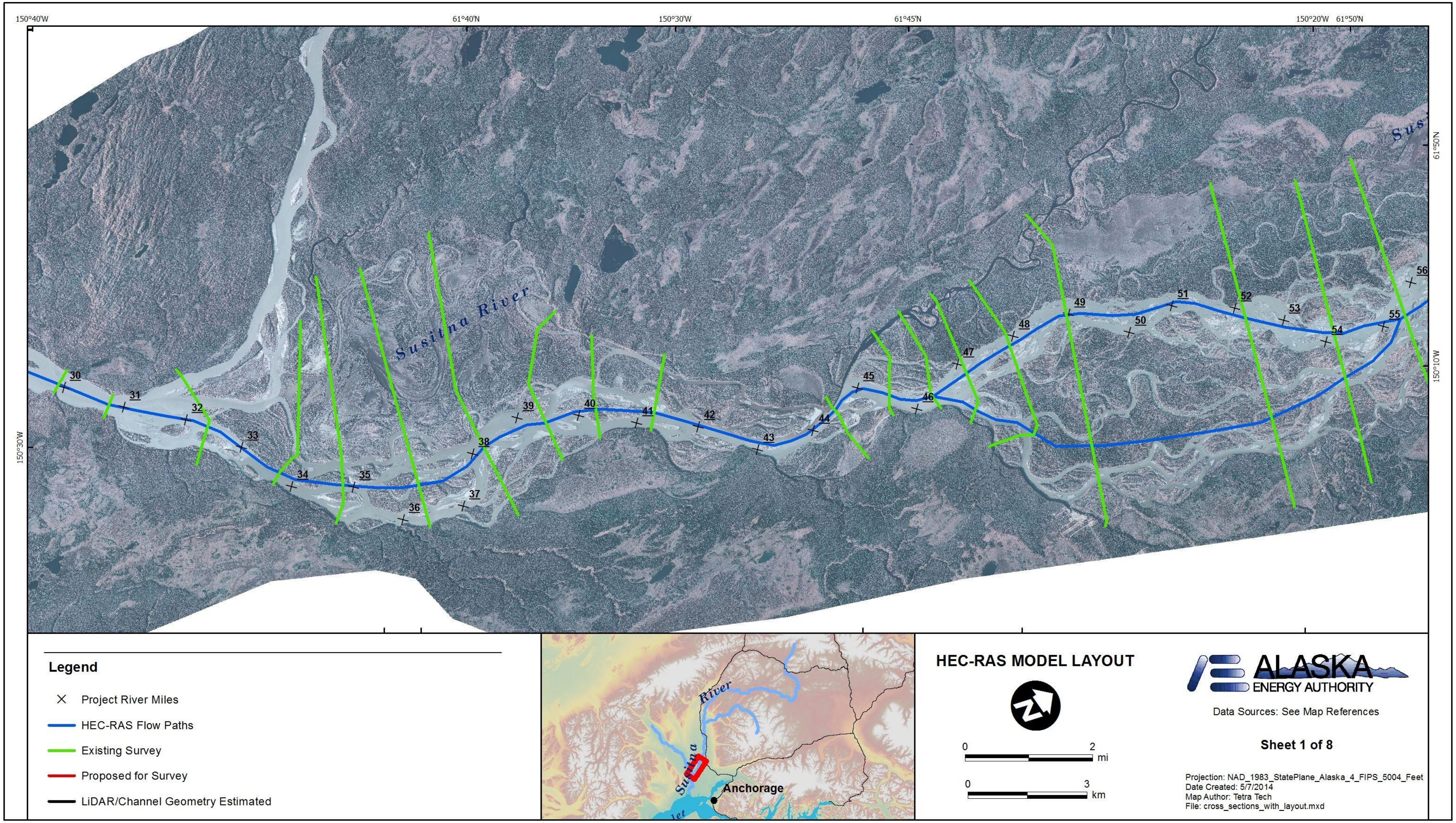

Figure 2.2-1. Survey and Model Cross Sections from PRM 30 to PRM 56.

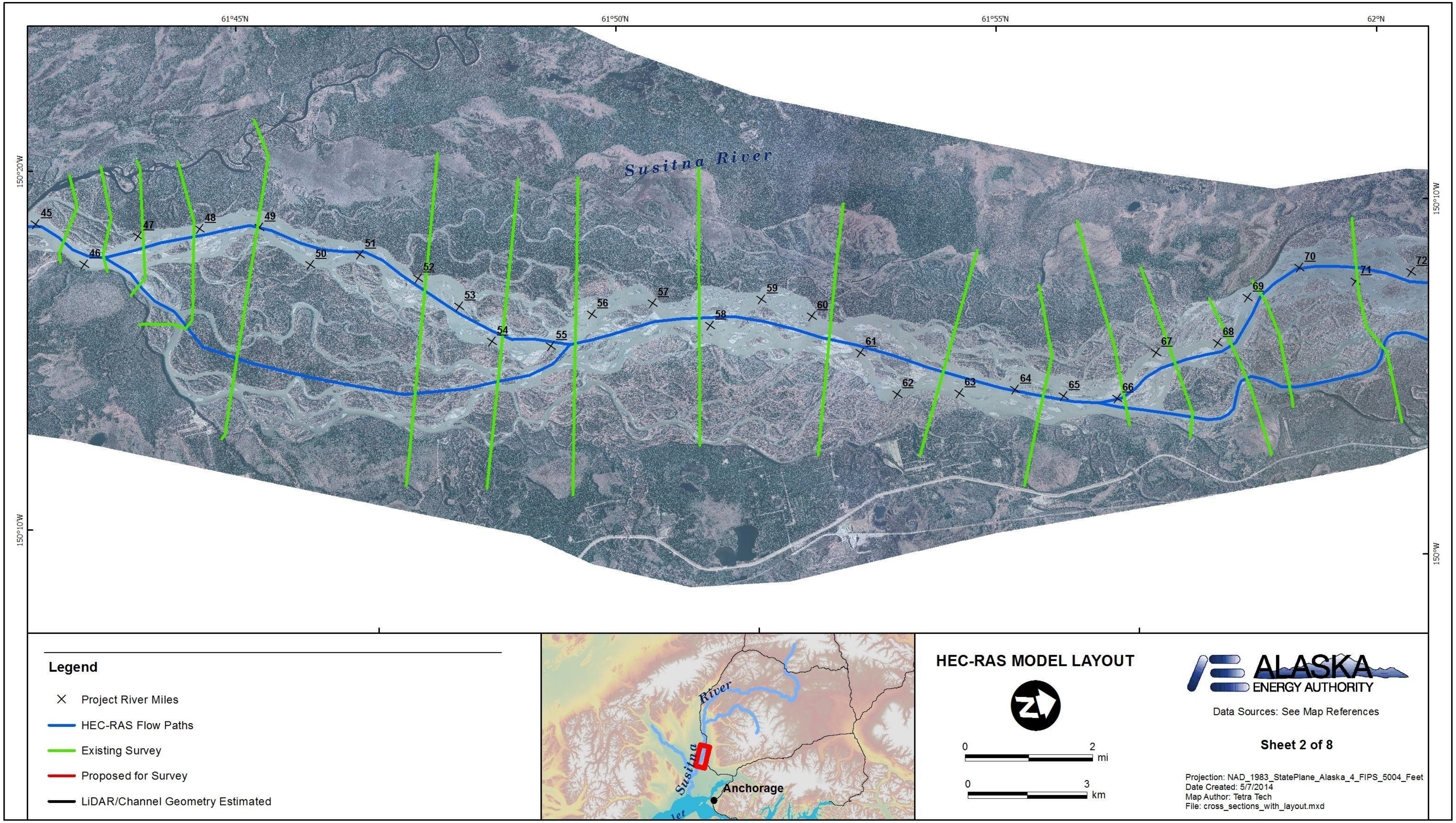

Figure 2.2-2. Survey and Model Cross Sections from PRM 45 to PRM 72.

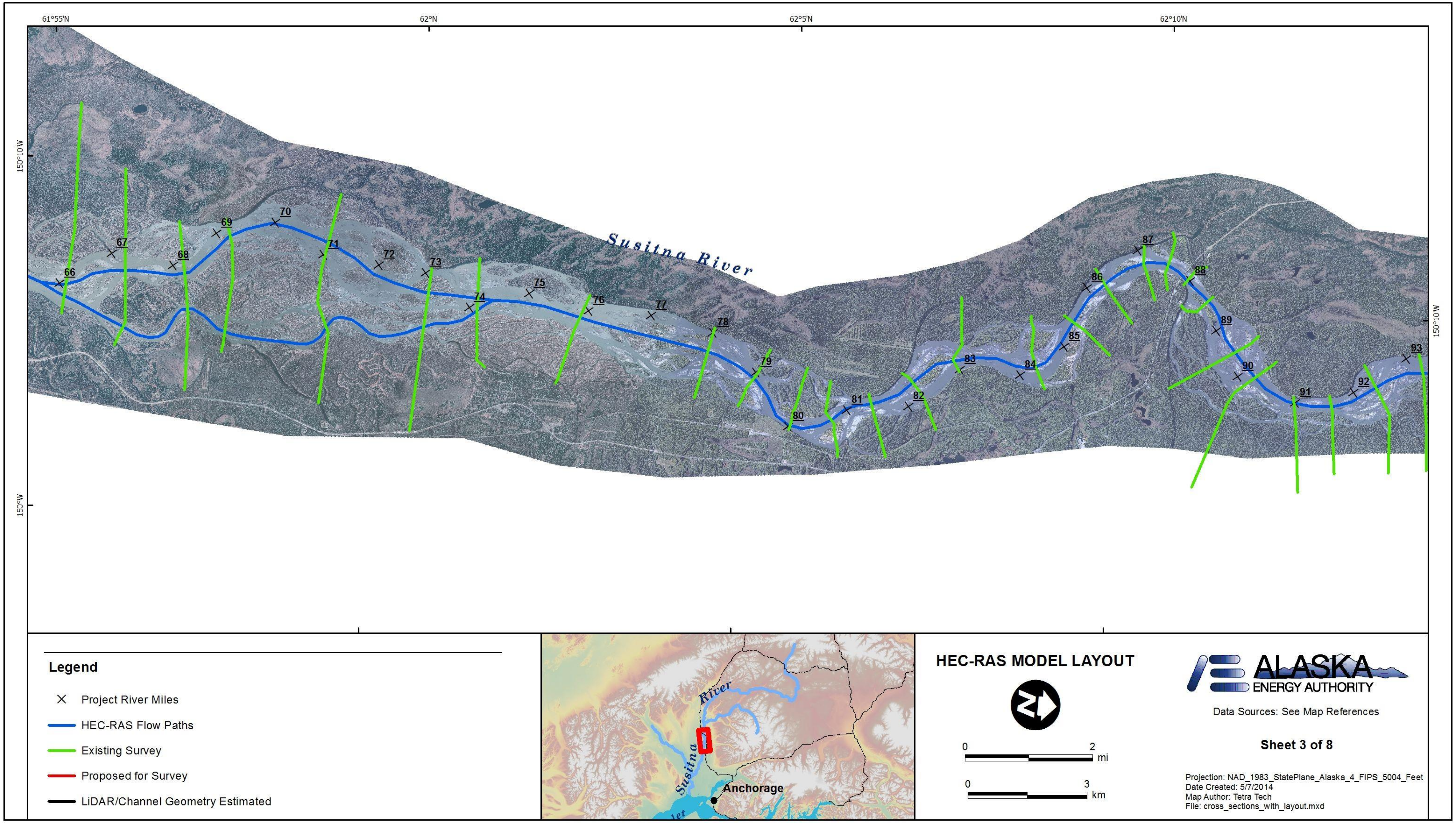

Figure 2.2-3. Survey and Model Cross Sections from PRM 66 to PRM 93.

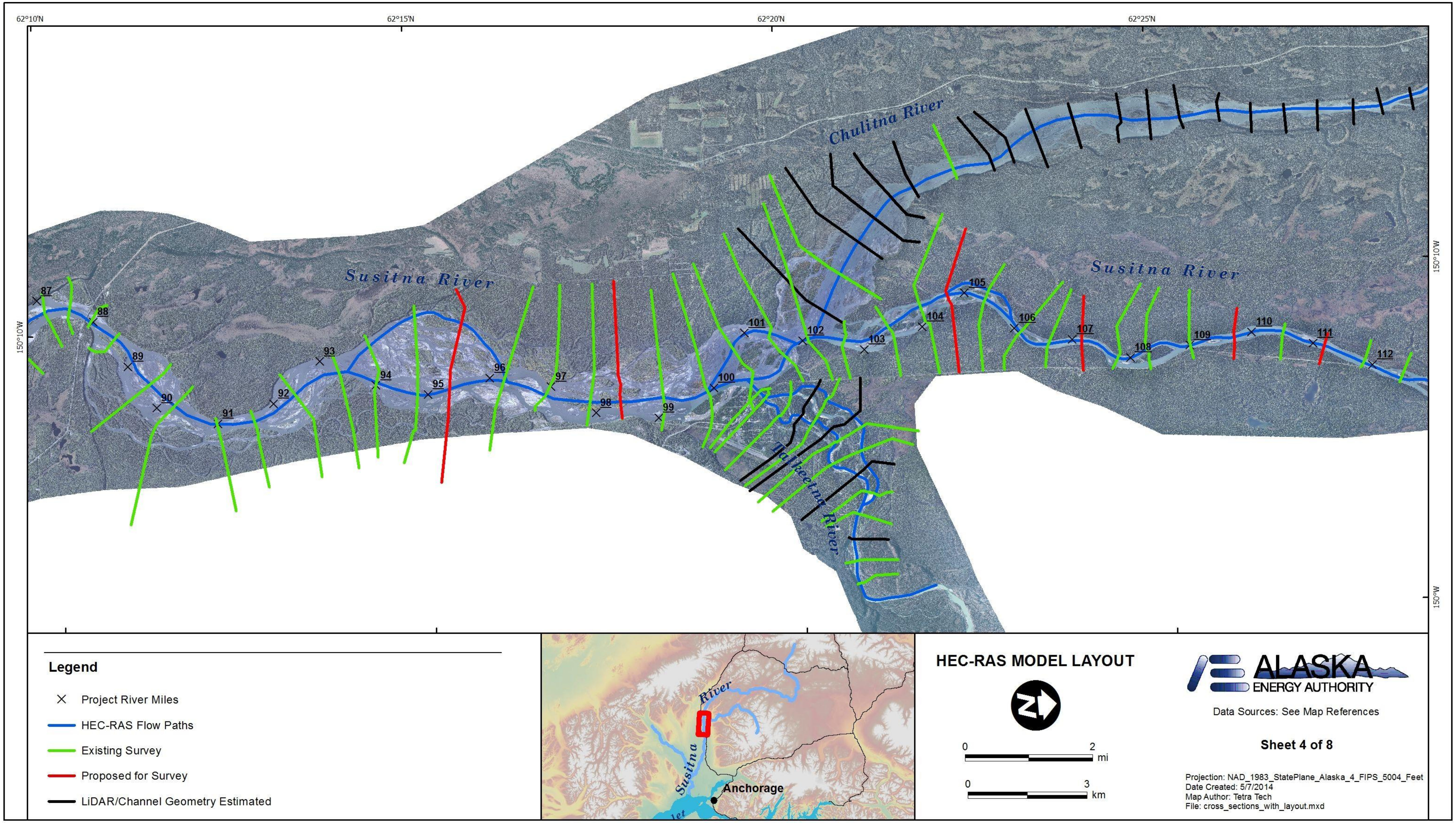

Figure 2.2-4. Survey and Model Cross Sections from PRM 87 to PRM 112.

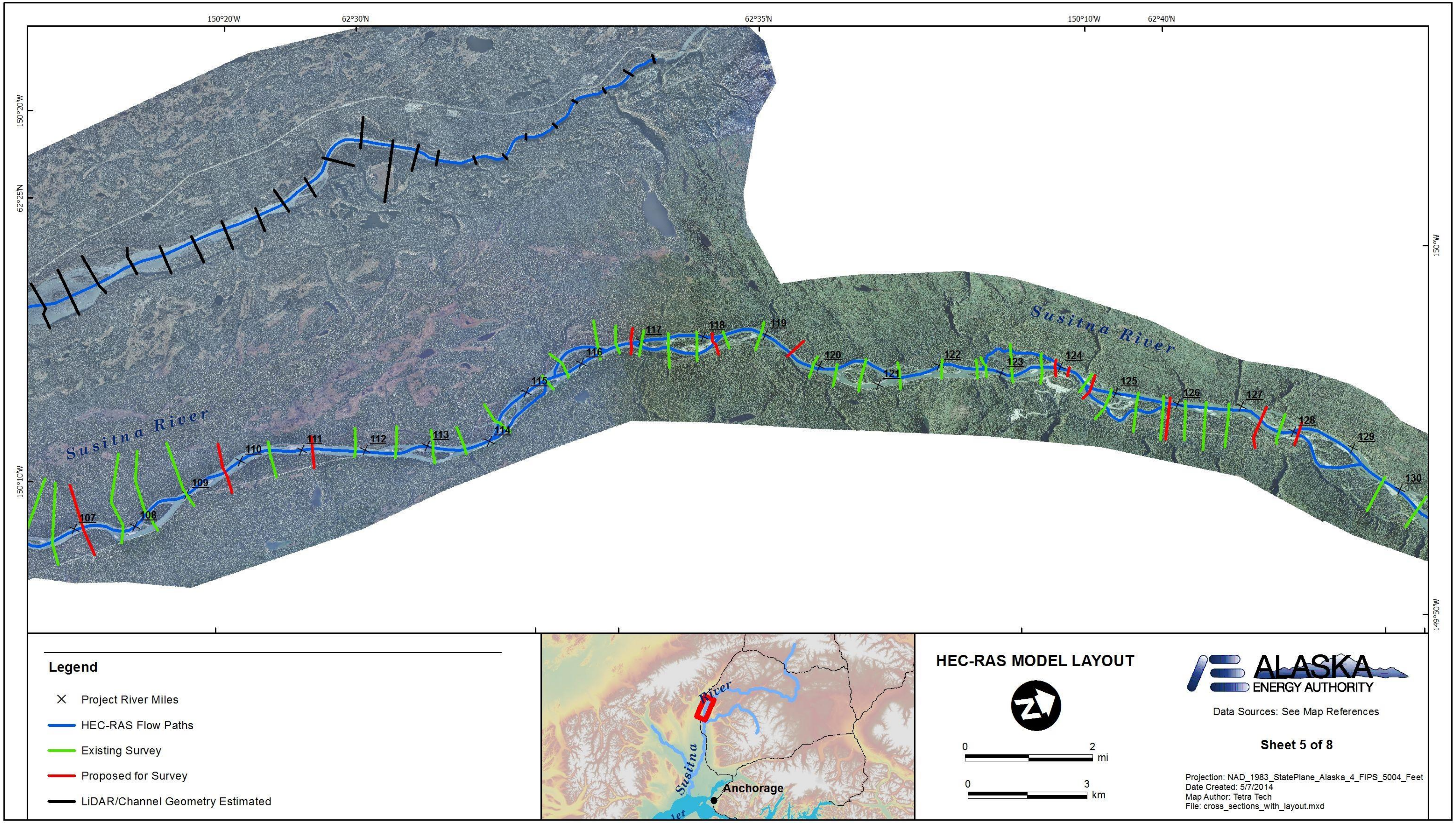

Figure 2.2-5. Survey and Model Cross Sections from PRM 107 to PRM 130.

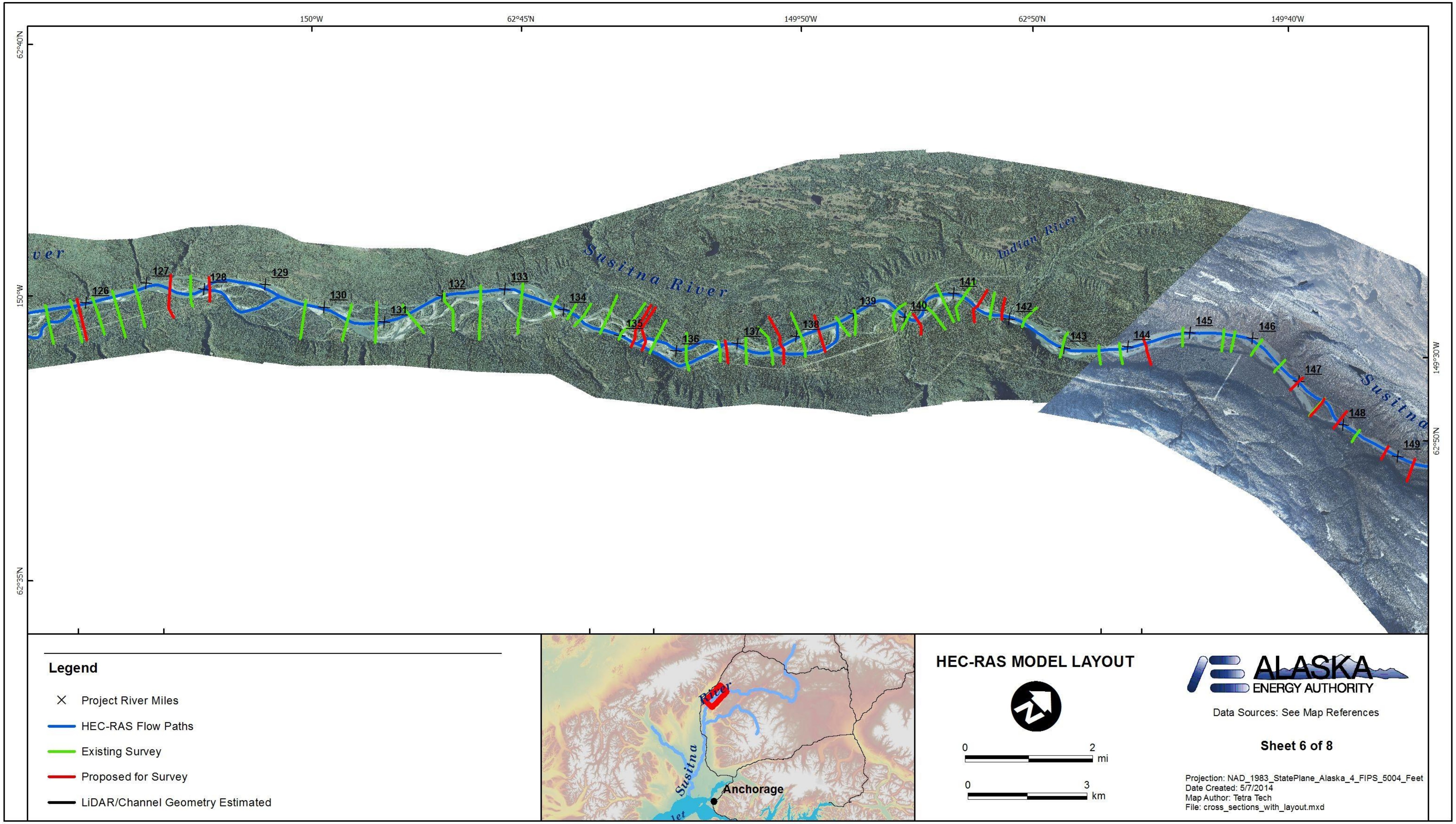

Figure 2.2-6. Survey and Model Cross Sections from PRM 125 to PRM 149.

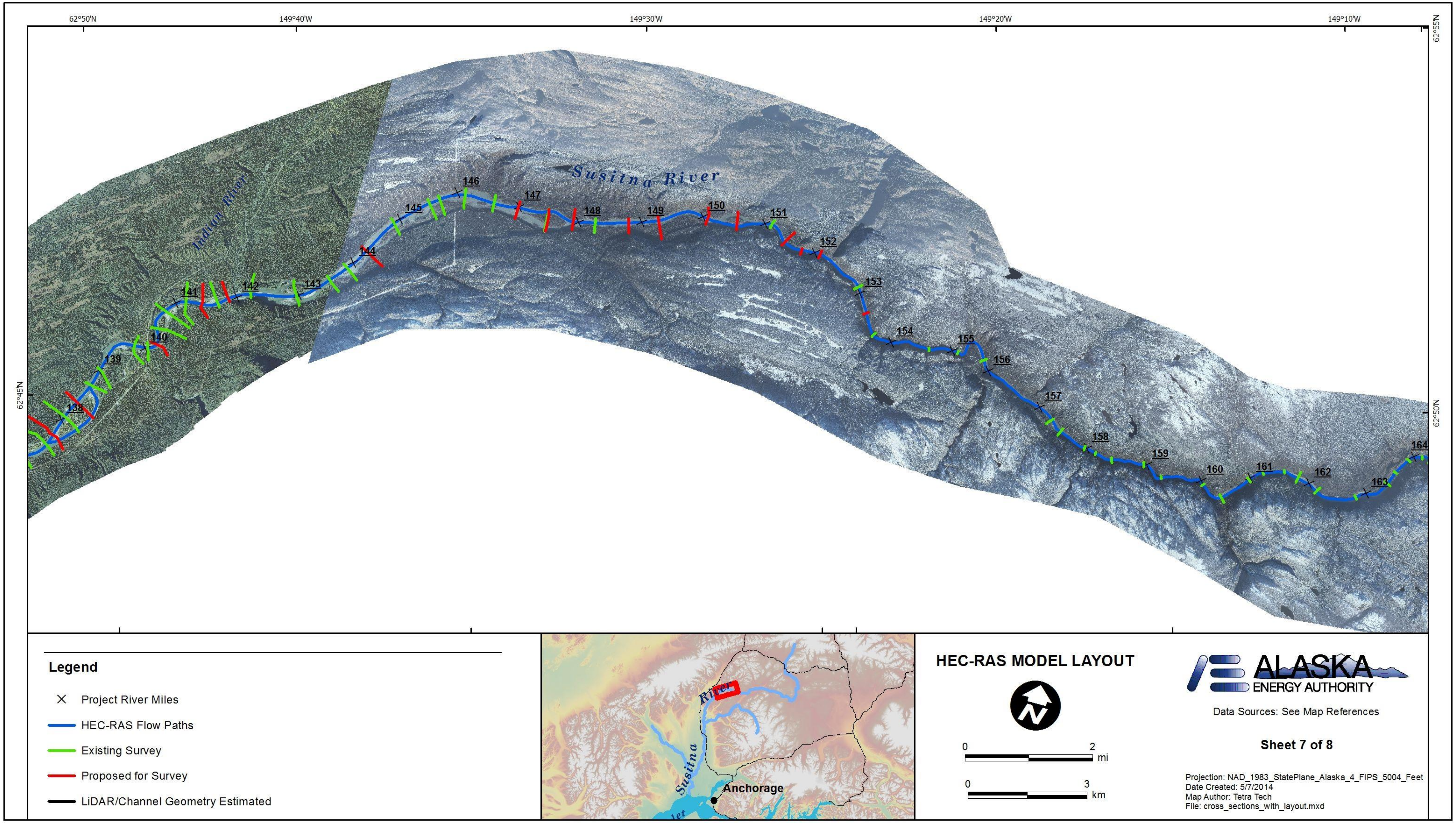

Figure 2.2-7. Survey and Model Cross Sections from PRM 138 to PRM 164.

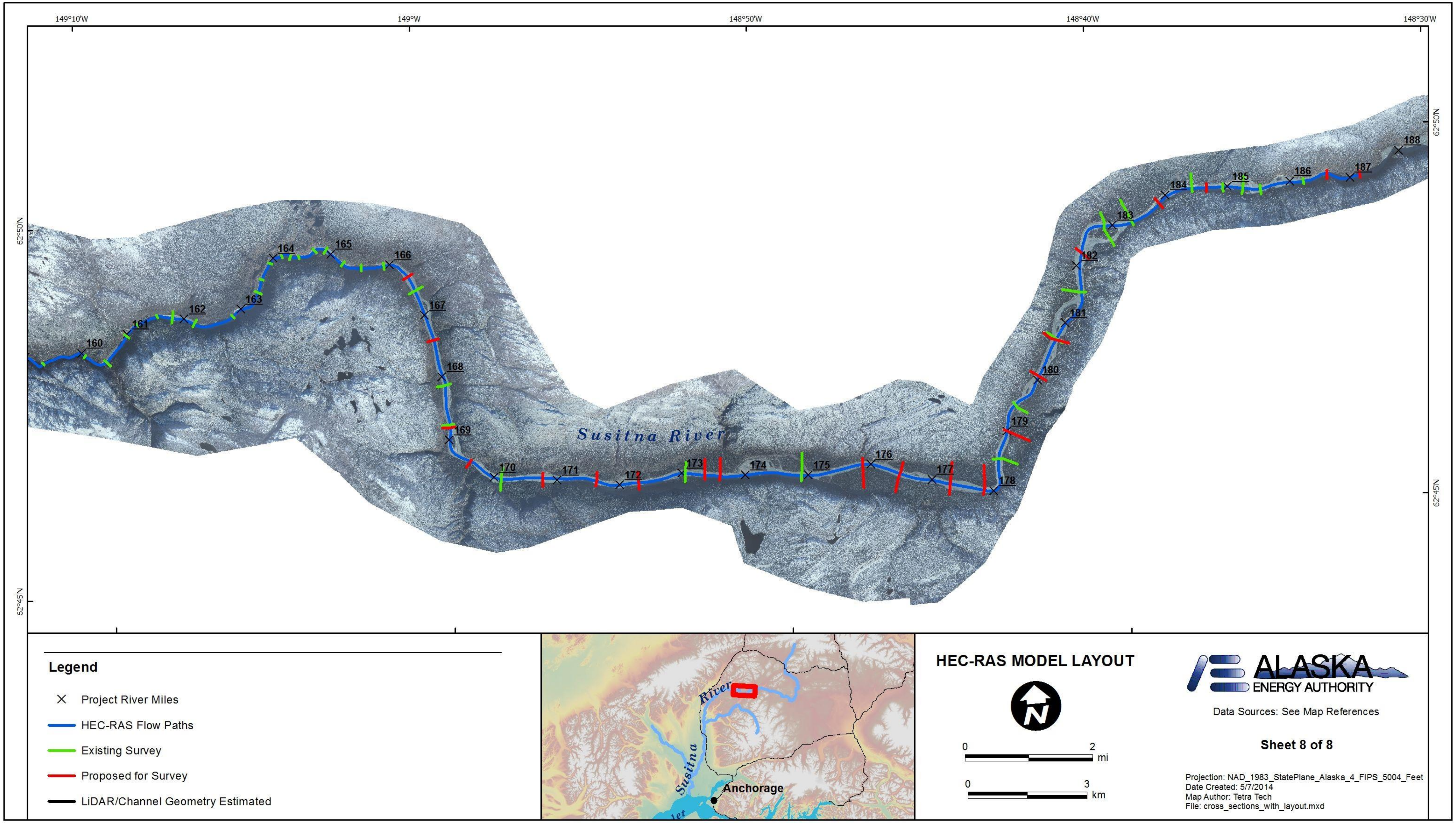

Figure 2.2-8. Survey and Model Cross Sections from PRM 160 to PRM 188.

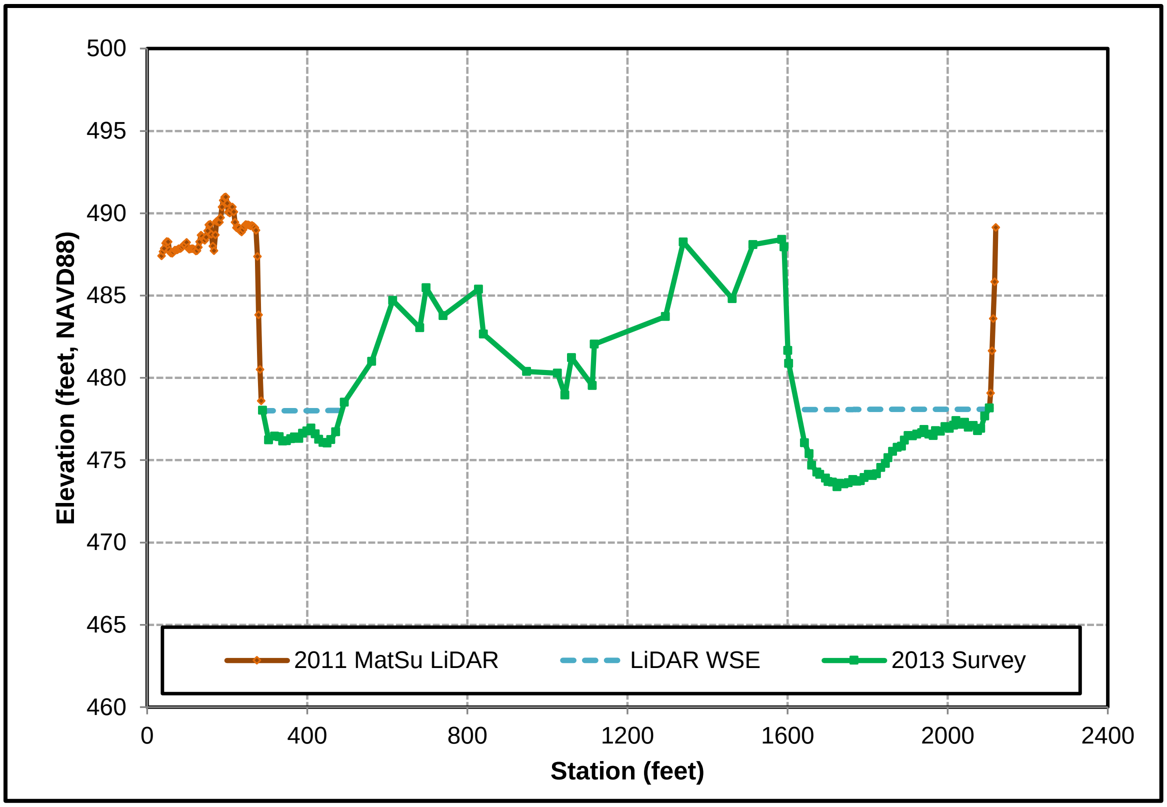

Figure 2.2-9. Example merging of bathymetric survey into LiDAR mapping to develop cross section geometry at PRM 117.9.

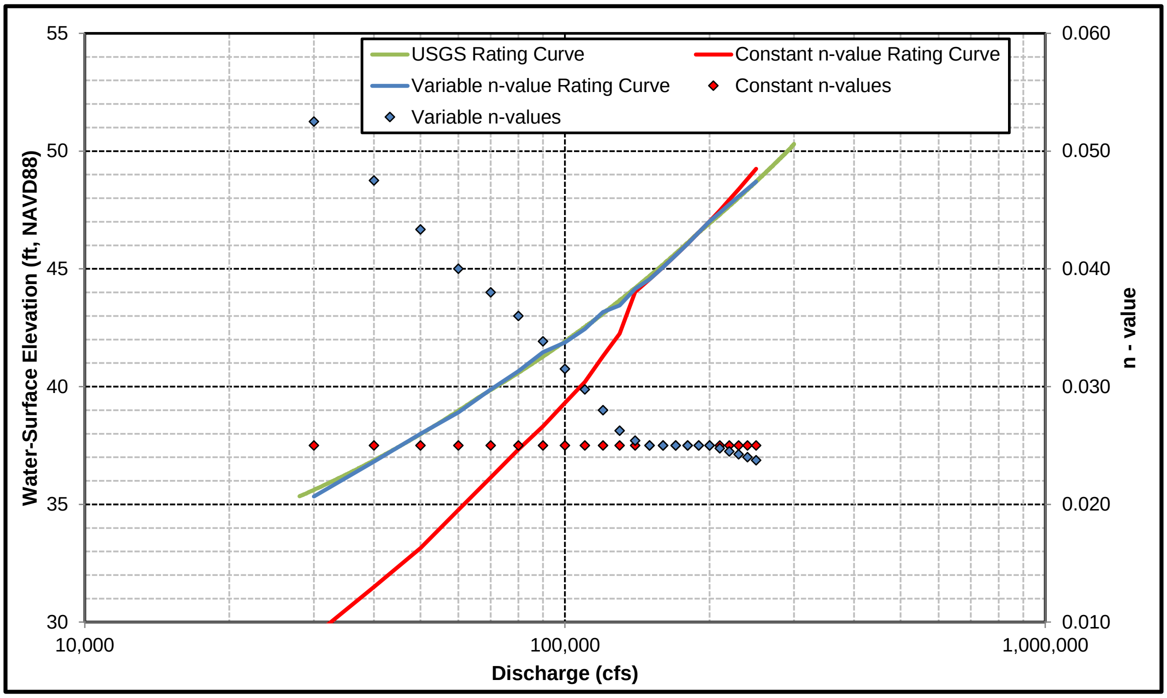

Figure 2.2-10. Downstream boundary condition developed for 1-D BEM at PRM 29.9.

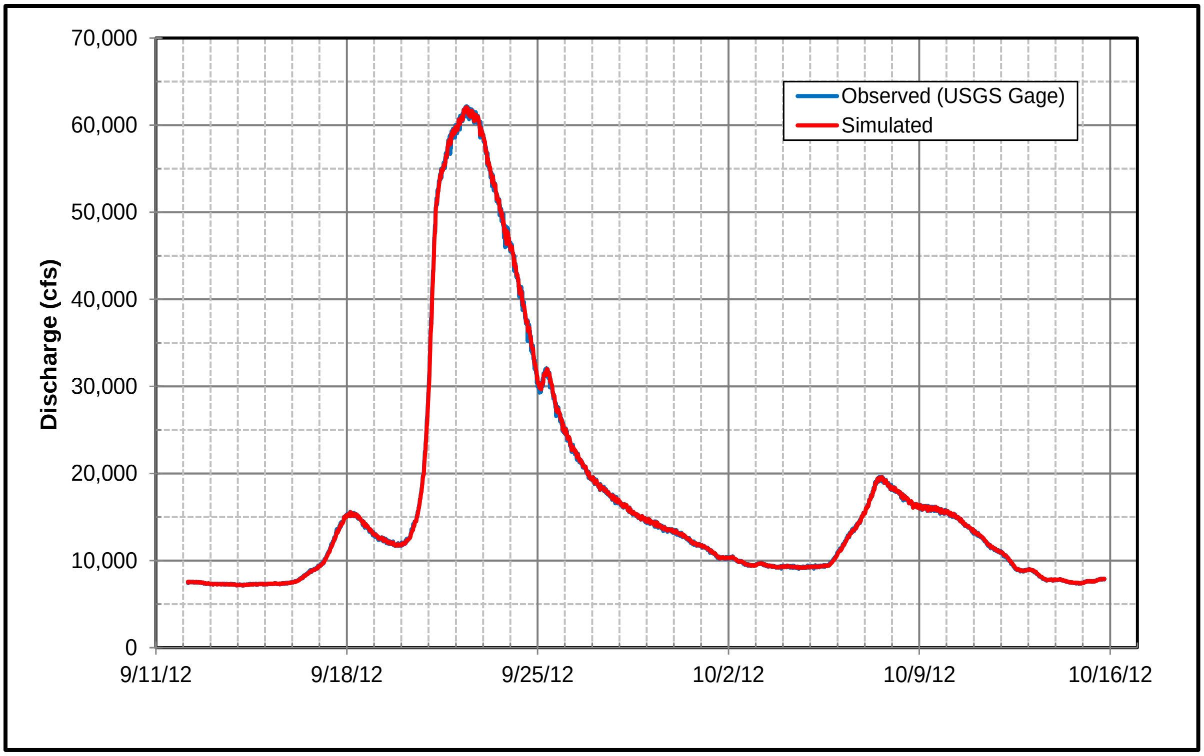

Figure 2.4-1. Observed and simulated discharge at Tsusena Creek (PRM 184.9) for the calibration event.

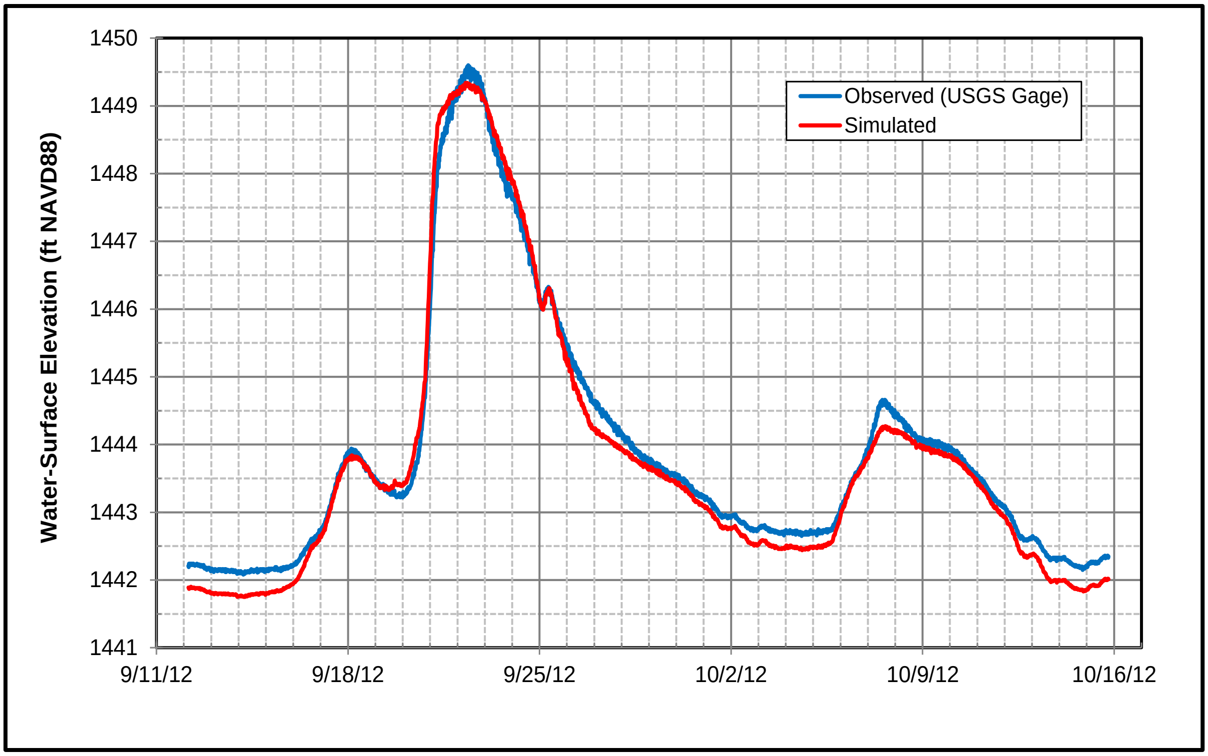

Figure 2.4-2. Observed and simulated water-surface elevation at Tsusena Creek (PRM 184.9) for the calibration event.

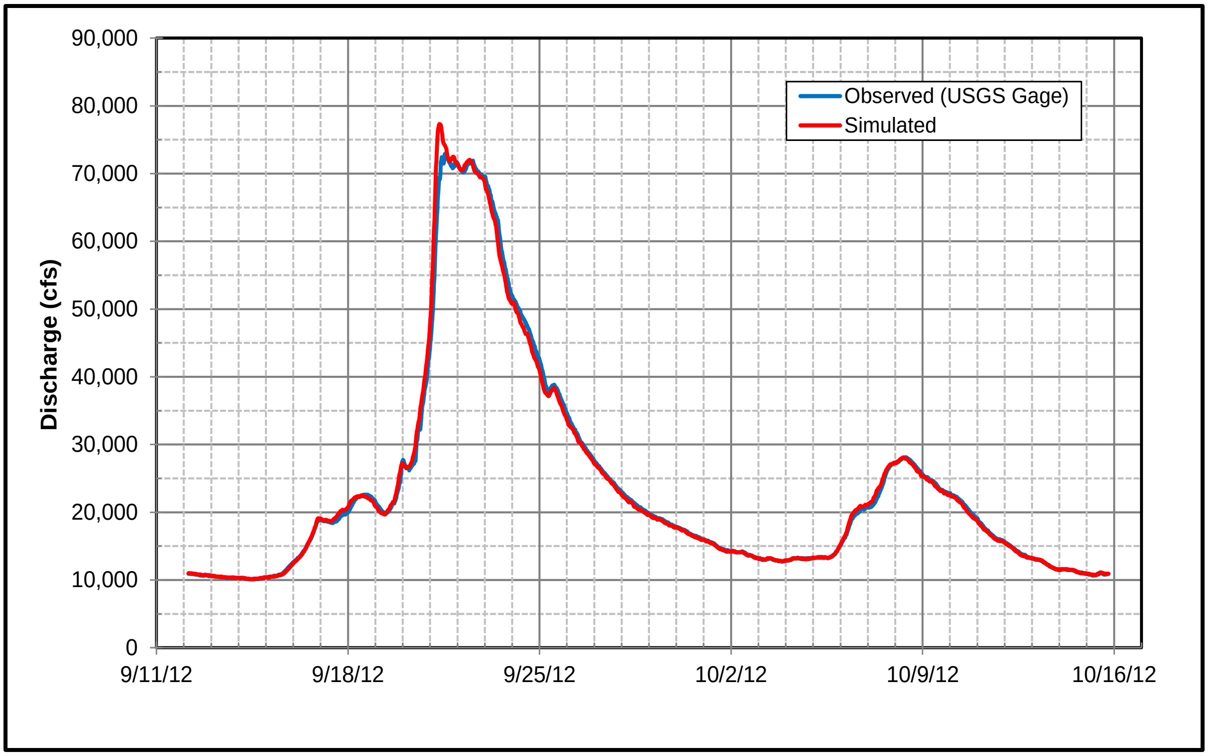

Figure 2.4-3. Observed and simulated discharge at Gold Creek (PRM 140.0) for the calibration event.

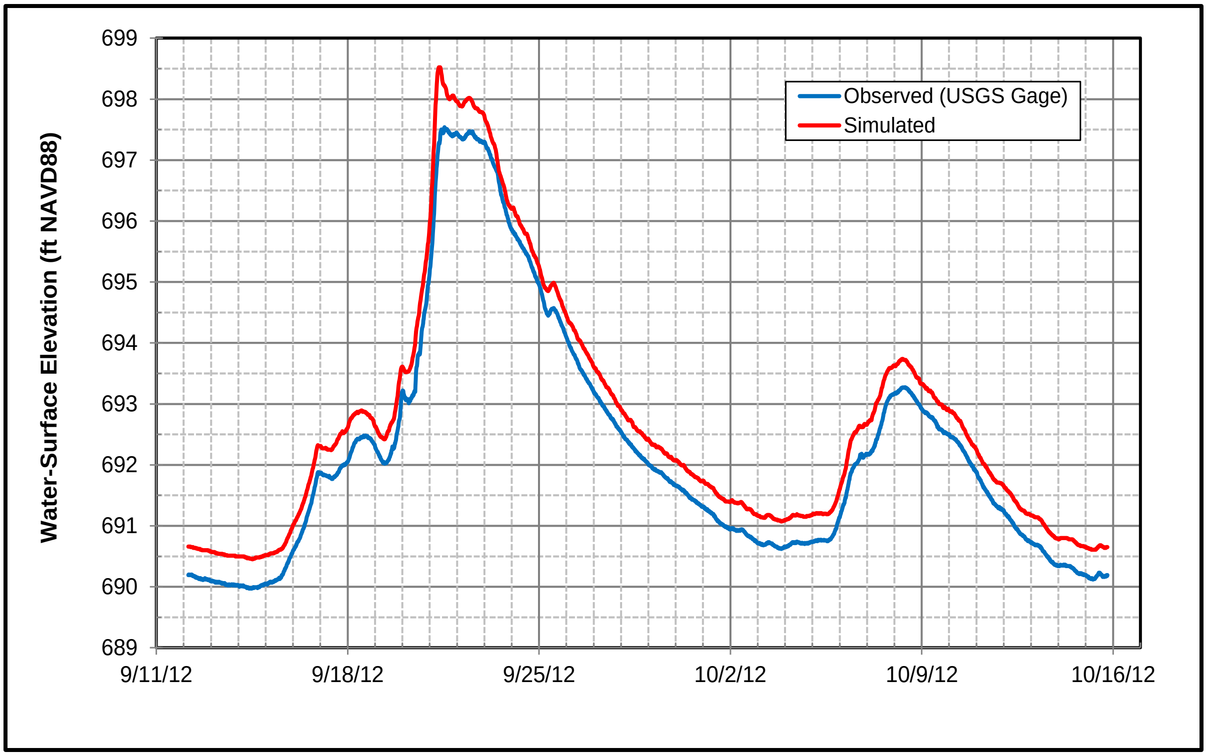

Figure 2.4-4. Observed and simulated water-surface elevation at Gold Creek (PRM 140.0) for the calibration event.

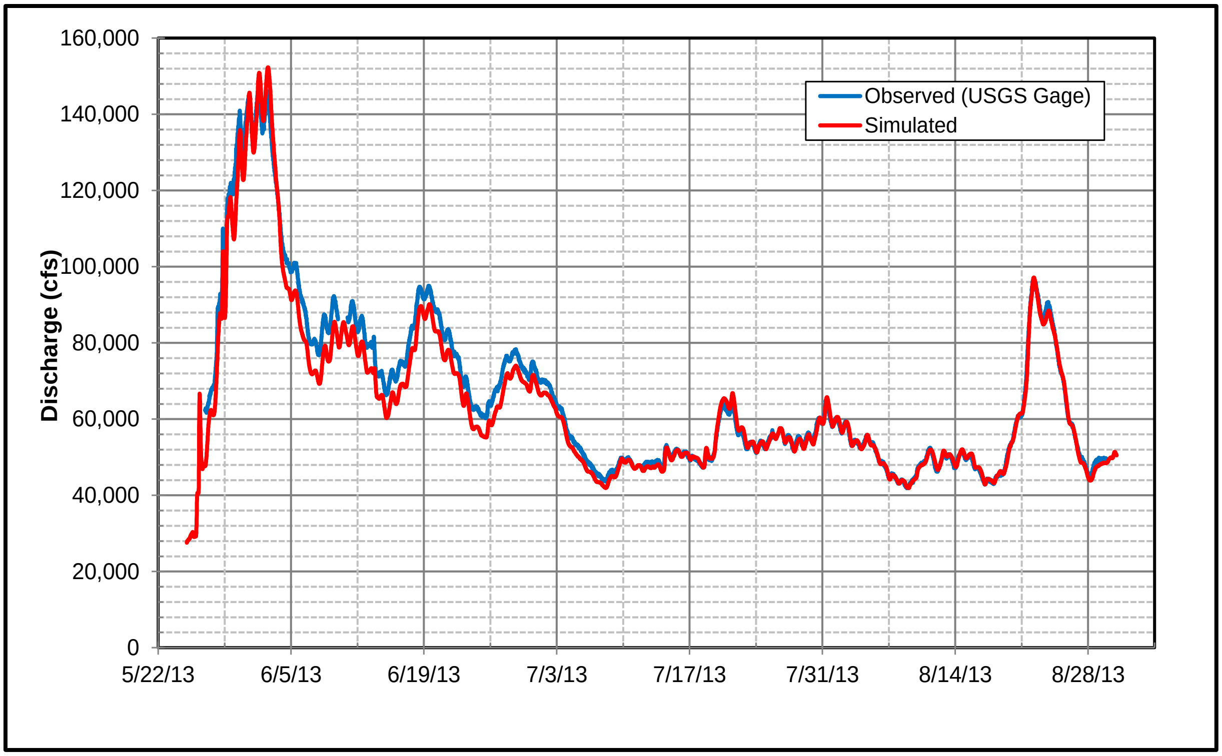

Figure 2.4-5. Observed and simulated discharge at Sunshine (PRM 88.0) for the calibration event.

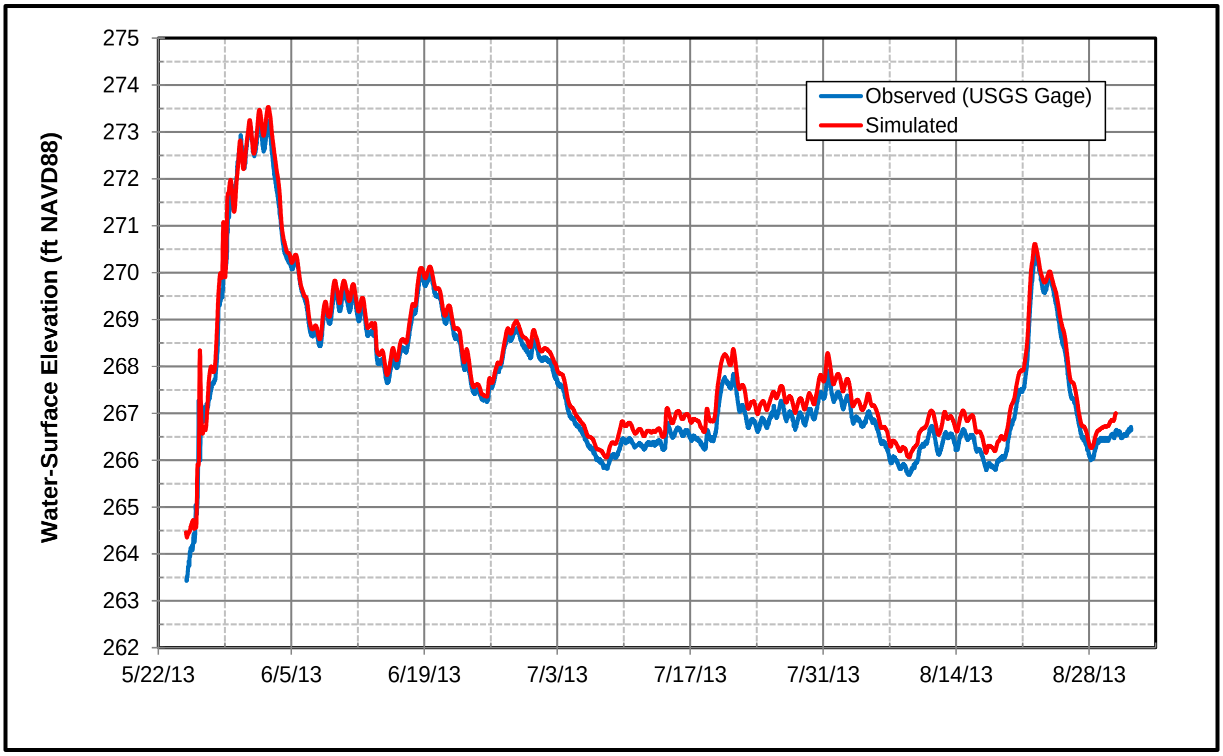

Figure 2.4-6. Observed and simulated water-surface elevation at Sunshine (PRM 88.0) for the calibration event.

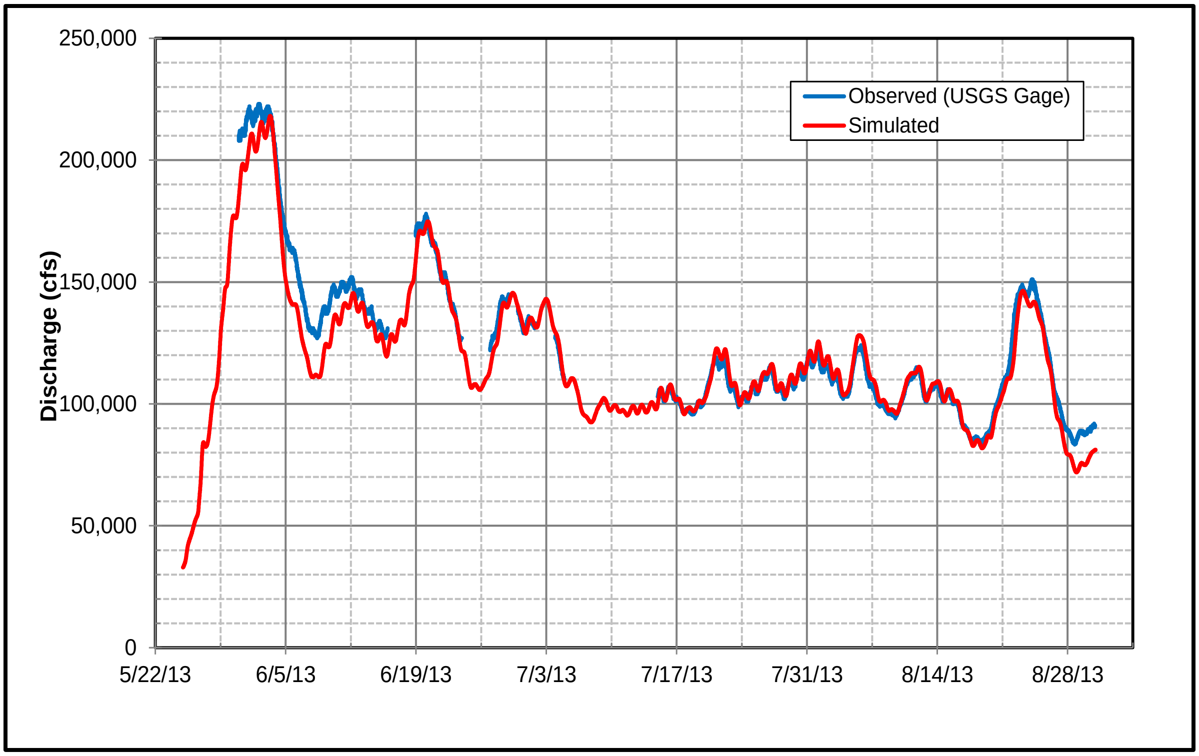

Figure 2.4-7. Observed and simulated discharge at Susitna Station (PRM 29.9) for the calibration event.

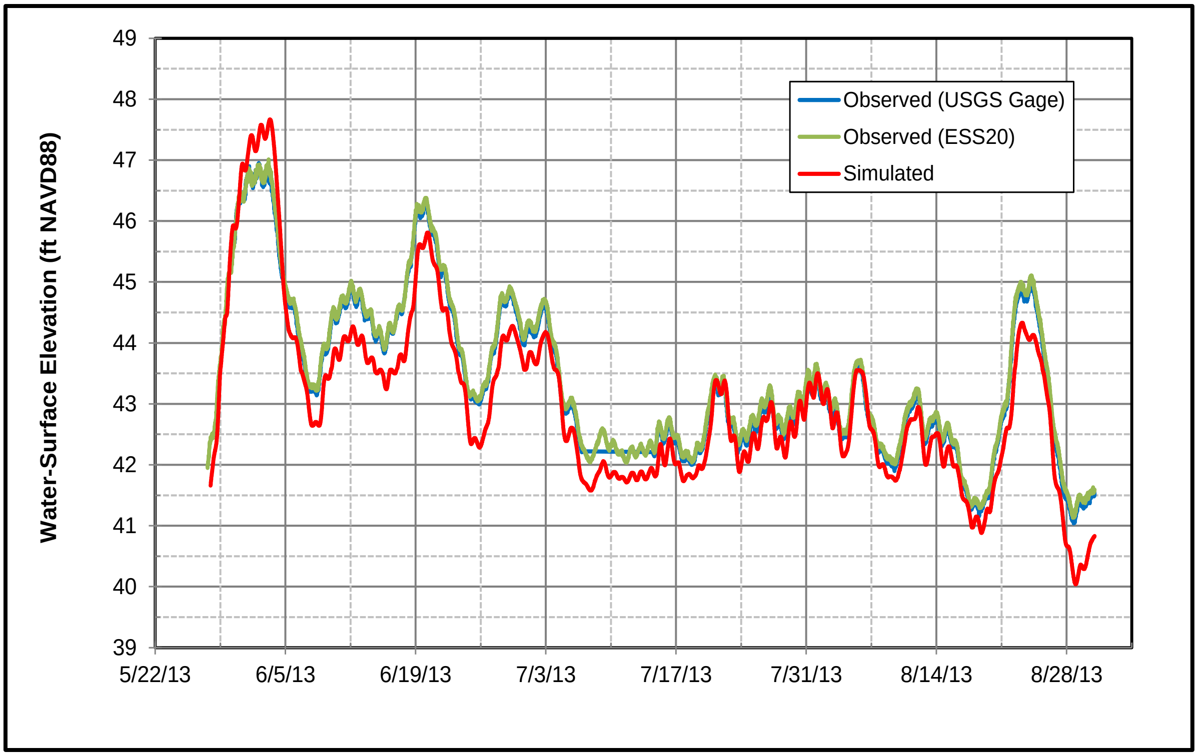

Figure 2.4-8. Observed and simulated water-surface elevation at Susitna Station (PRM 29.9) for the calibration event.

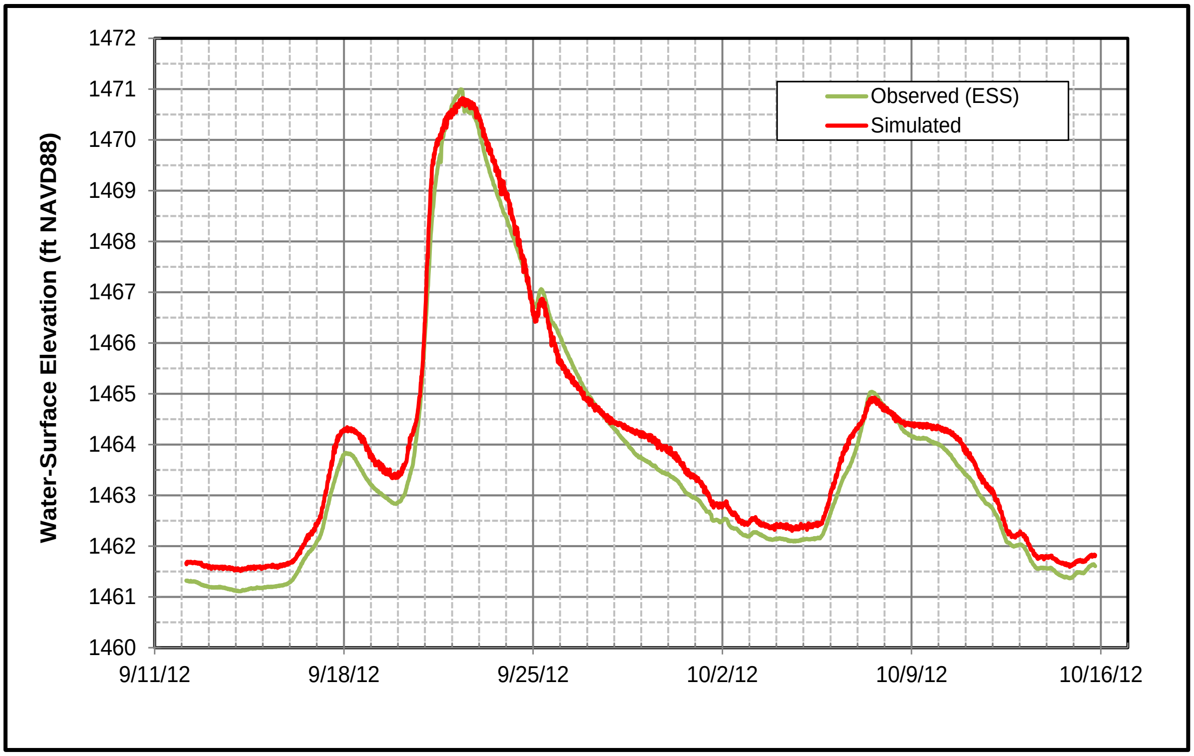

Figure 2.4-9. Observed and simulated water-surface elevation at ESS70 (PRM 187.2) for the calibration event.

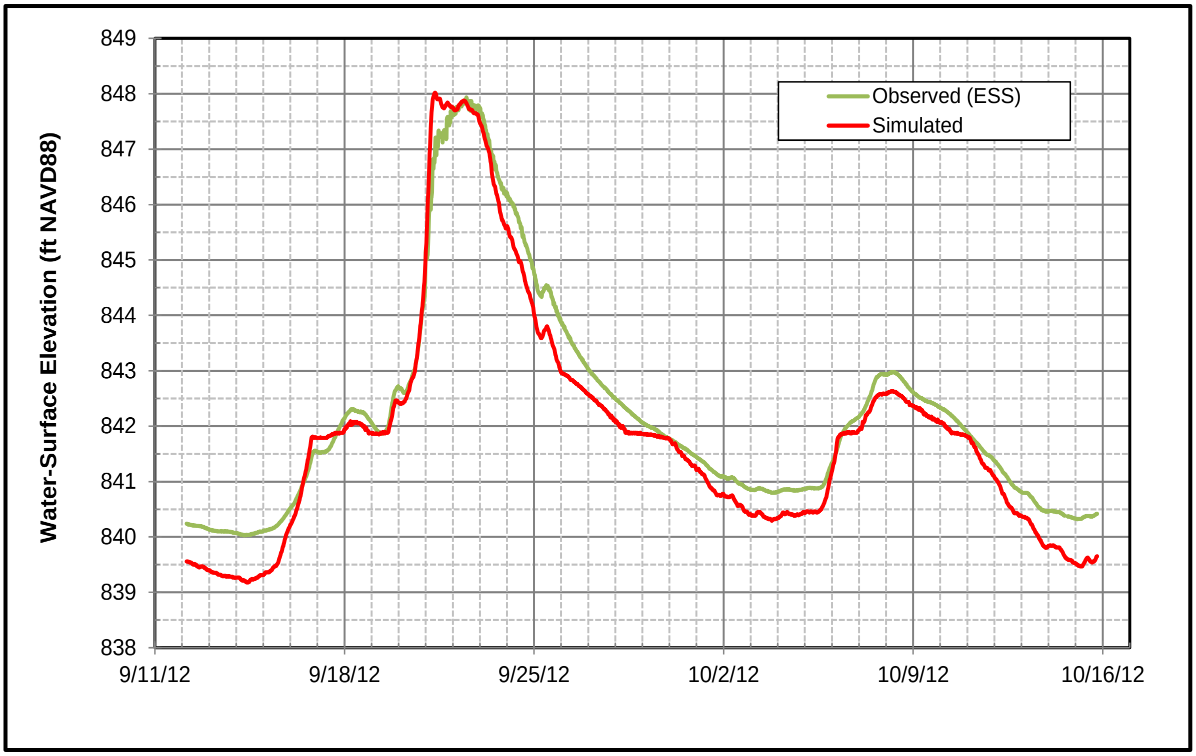

Figure 2.4-10. Observed and simulated water-surface elevation at ESS55 (PRM 152.1) for the calibration event.

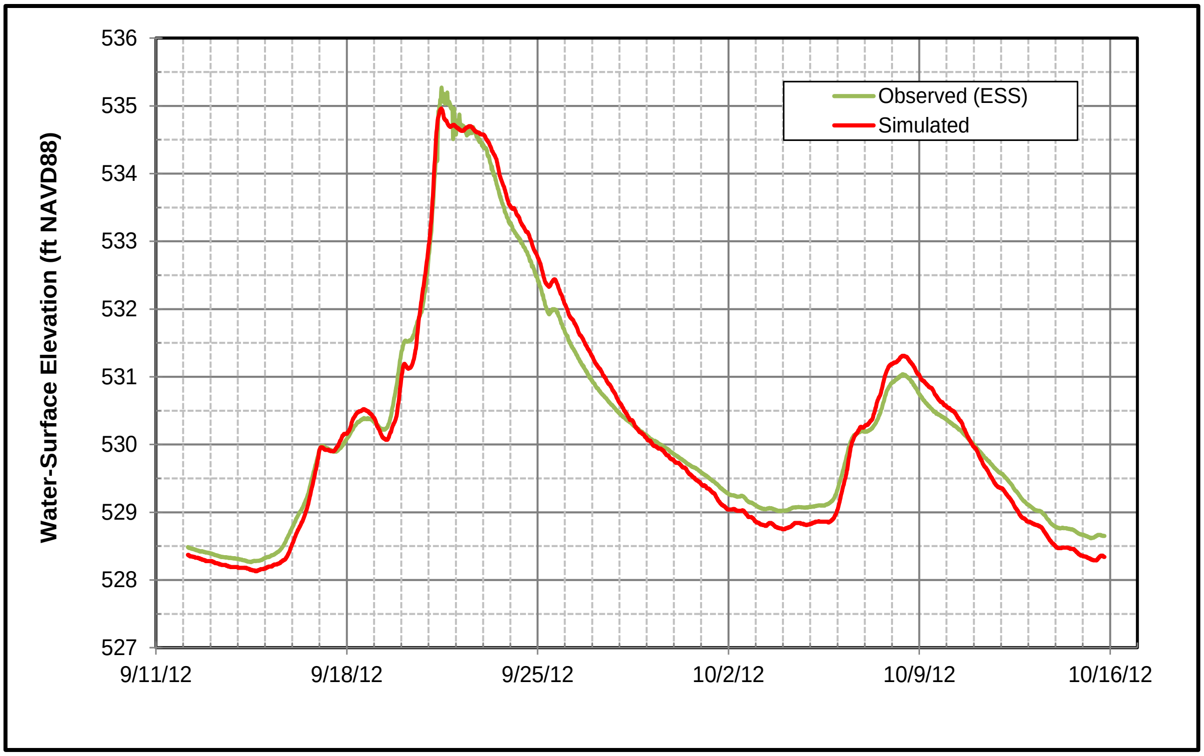

Figure 2.4-11. Observed and simulated water-surface elevation at ESS50 (PRM 124.1) for the calibration event.

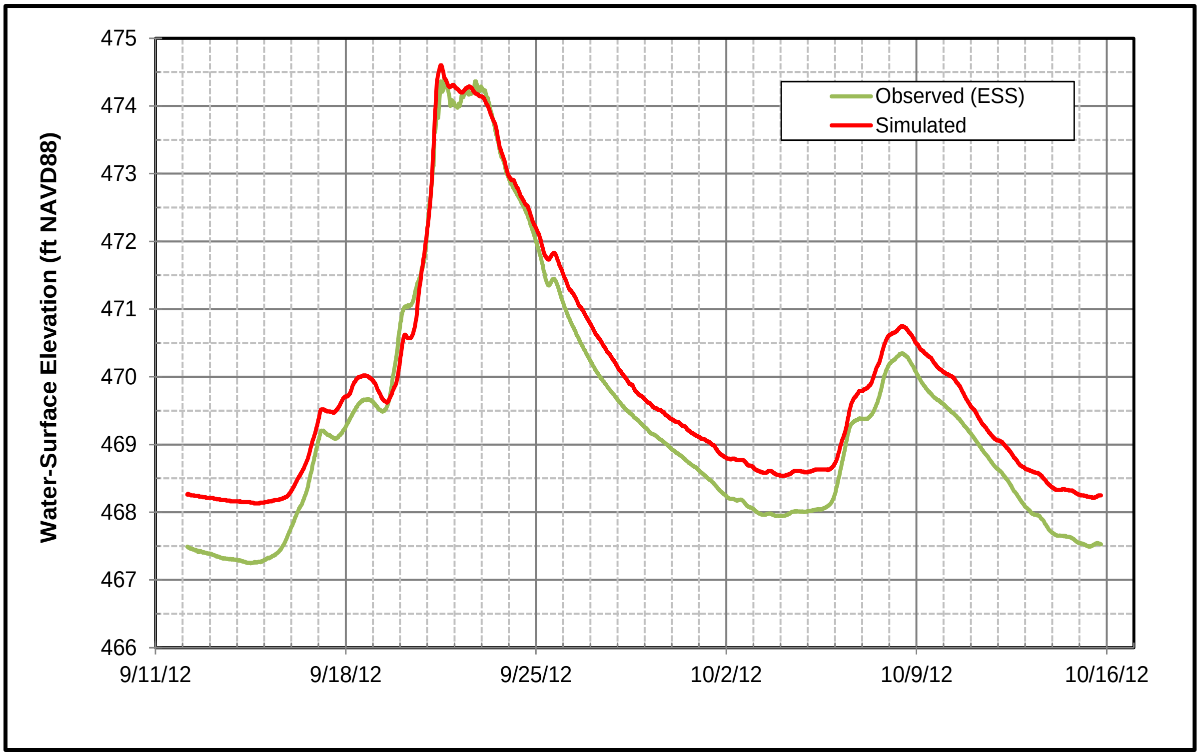

Figure 2.4-12. Observed and simulated water-surface elevation at ESS45 (PRM 116.1) for the calibration event.

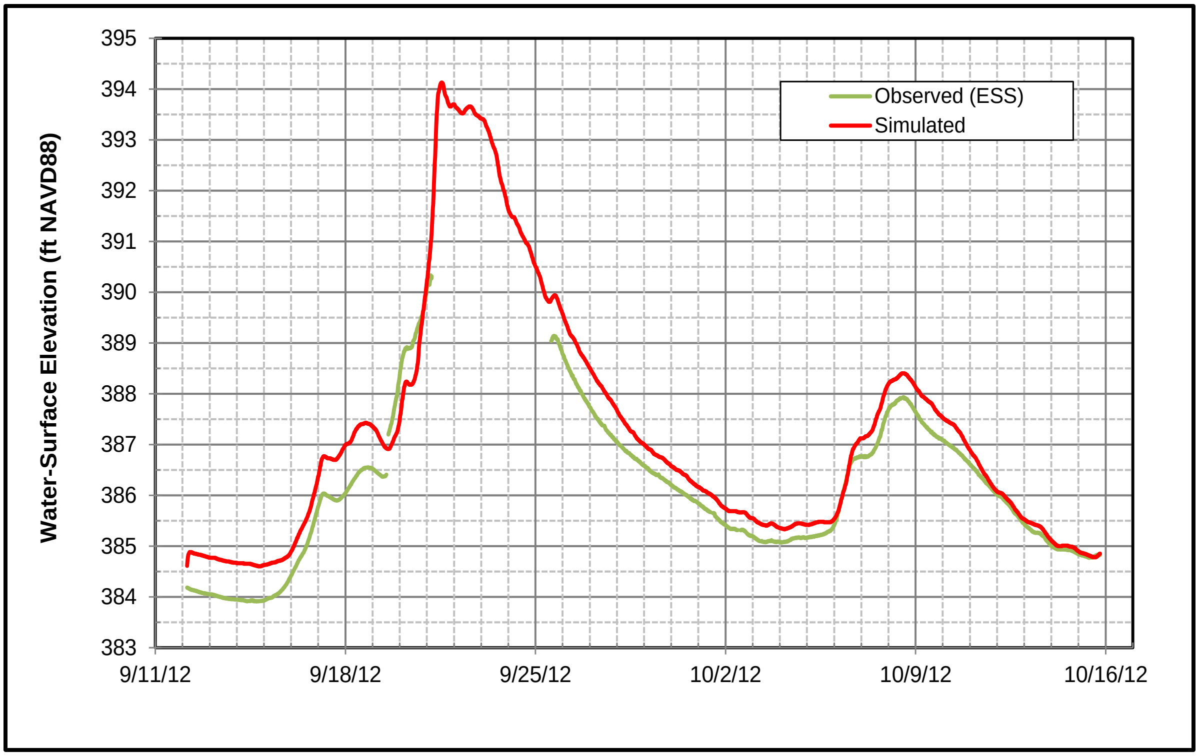

Figure 2.4-13. Observed and simulated water-surface elevation at ESS40 (PRM 107.1) for the calibration event.

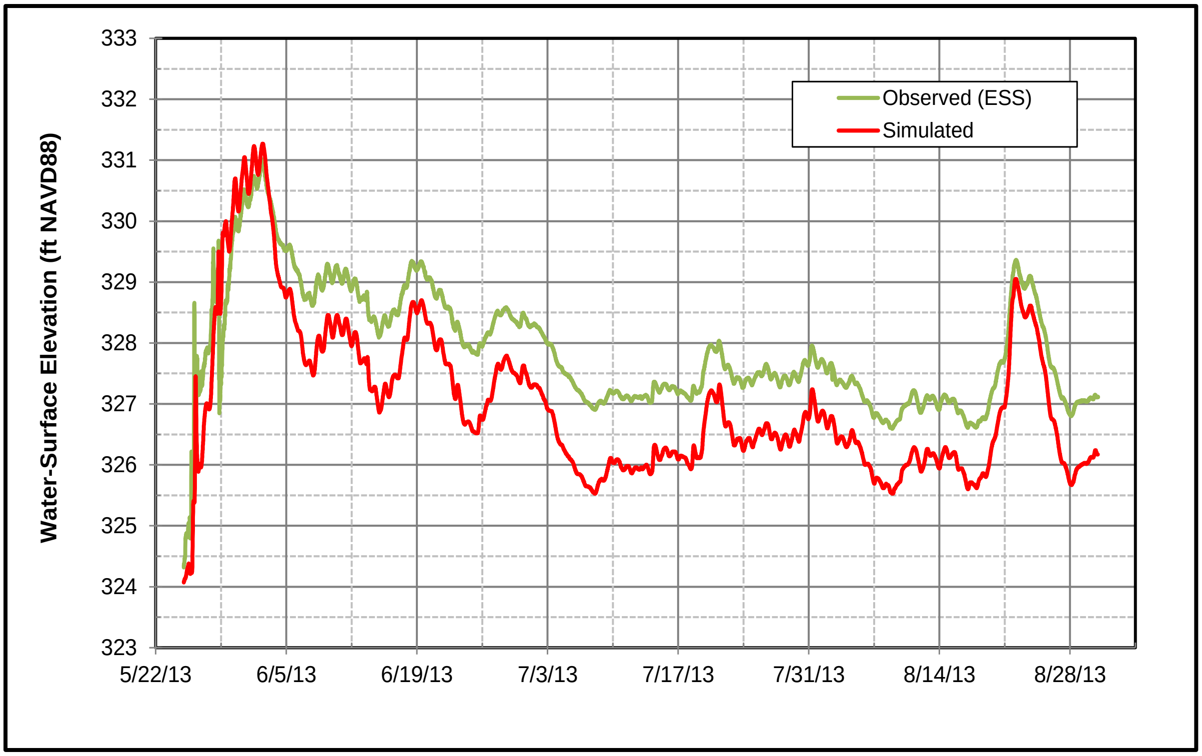

Figure 2.4-14. Observed and simulated water-surface elevation at ESS30 (PRM 98.4) for the calibration event.

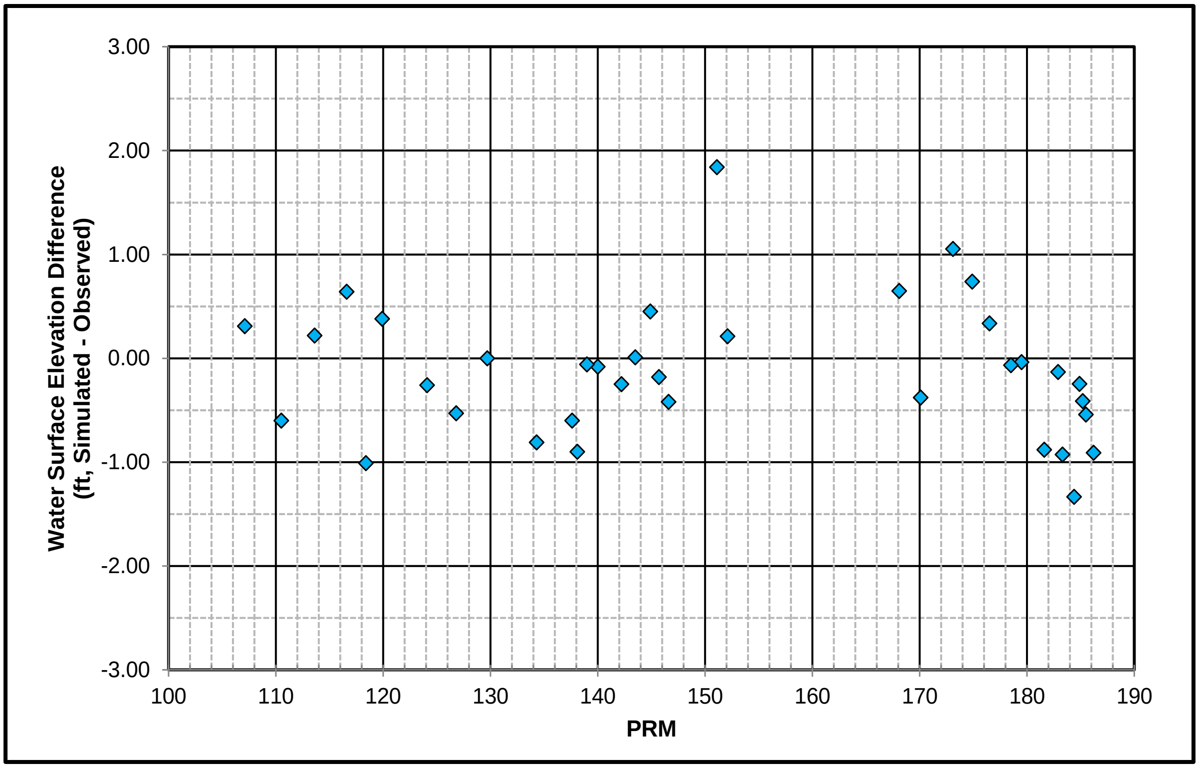

Figure 2.4-15. Middle River comparison of observed point-in-time water-surface elevations to simulated elevations during the calibration event.

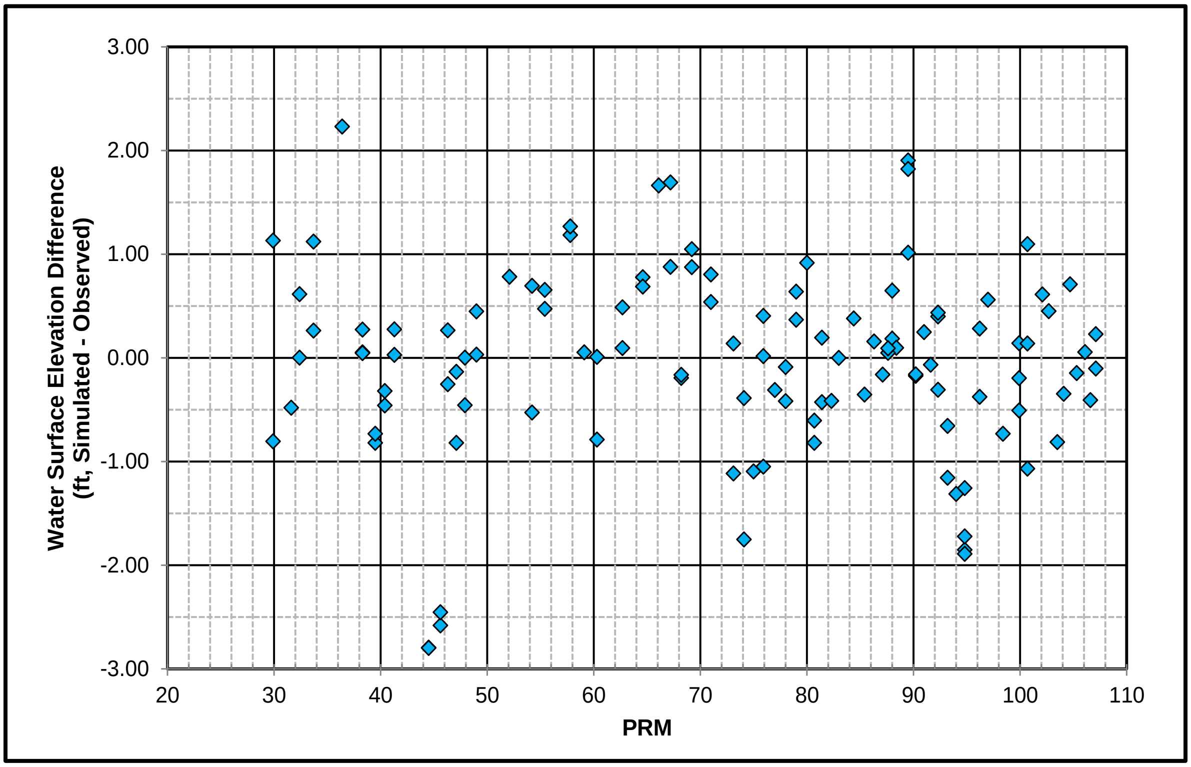

Figure 2.4-16. Lower River comparison of observed point-in-time water-surface elevations to simulated elevations during the calibration event.

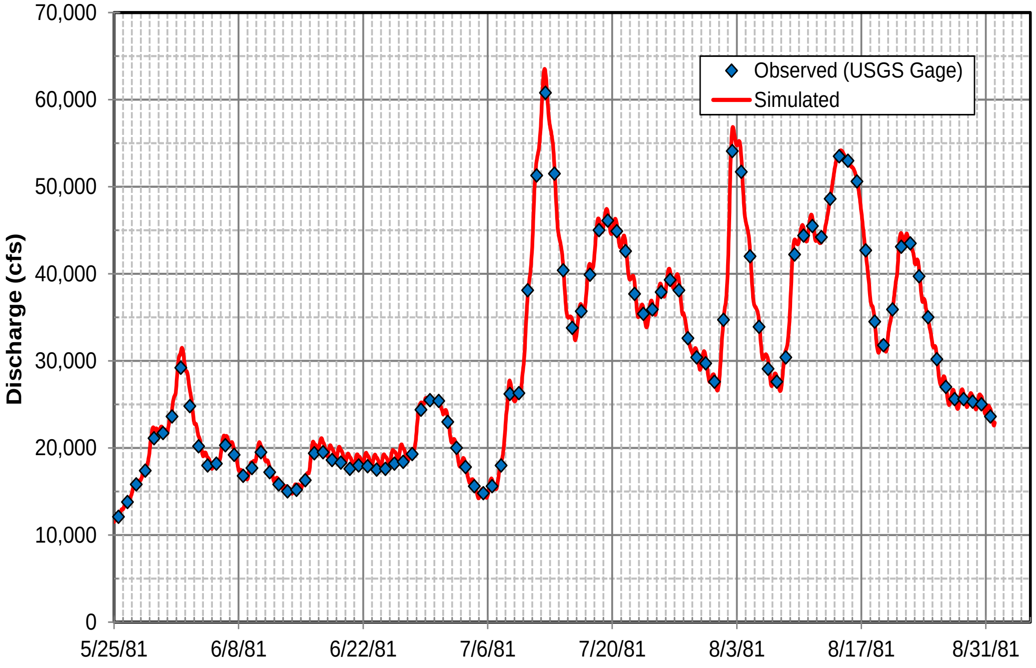

Figure 2.4-17. Observed (daily average) and simulated (hourly) discharge at Gold Creek for the validation event.

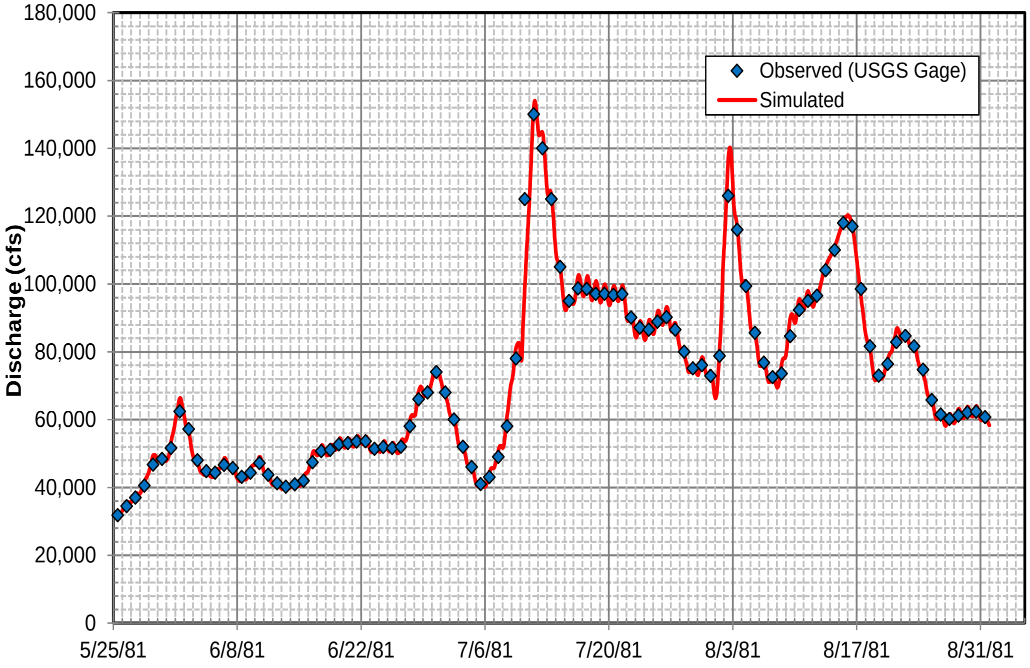

Figure 2.4-18. Observed (daily average) and simulated (hourly) discharge at Sunshine for the validation event.

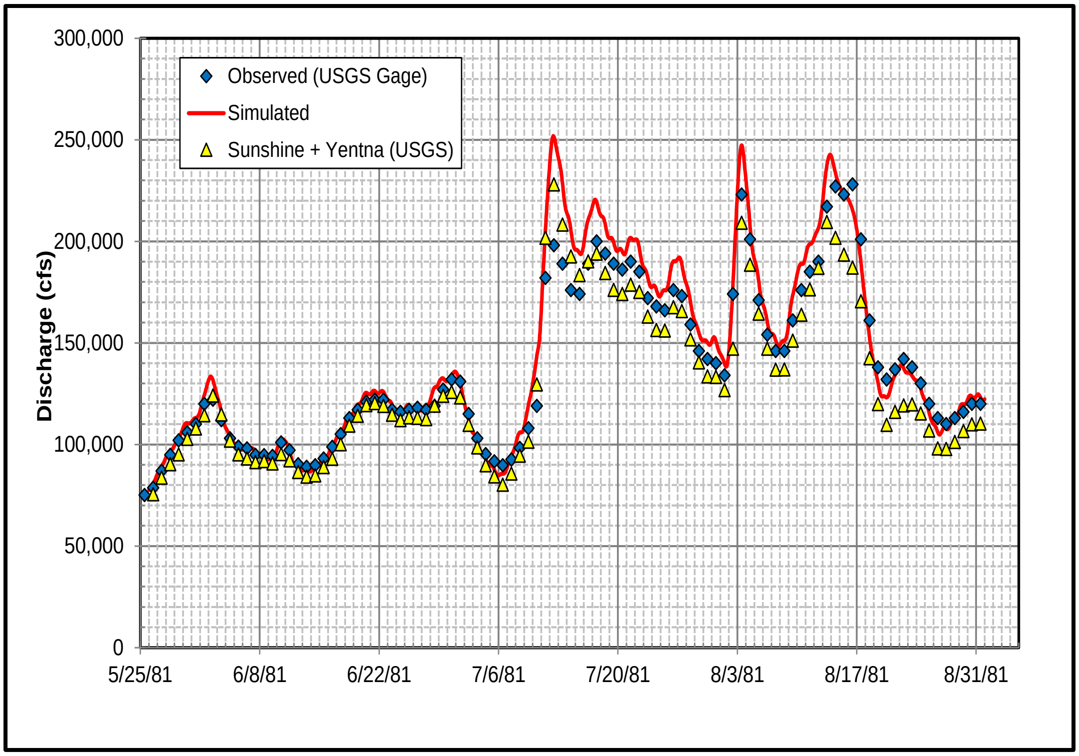

Figure 2.4-19. Observed (daily average) and simulated (hourly) discharge at Susitna Station for the validation event.

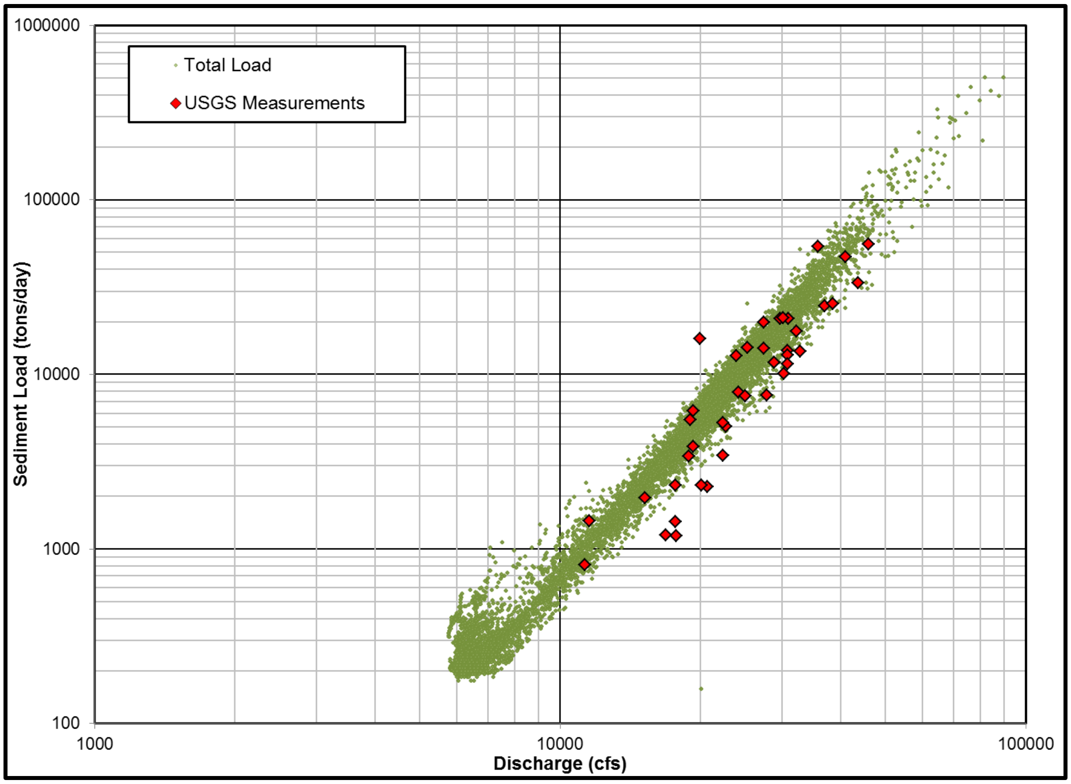

Figure 3.4-1. Susitna River near Talkeetna comparison of measured and modeled total bed material loads.

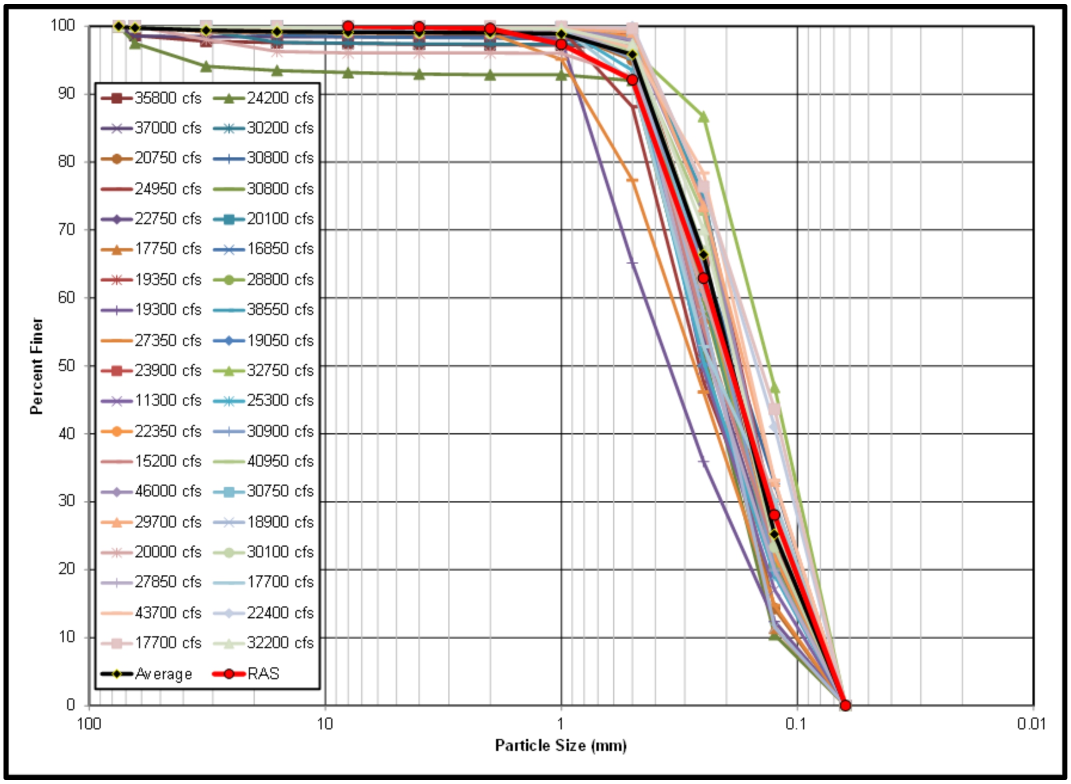

Figure 3.4-2. Susitna River near Talkeetna comparison of measured and modeled transported bed material gradations.

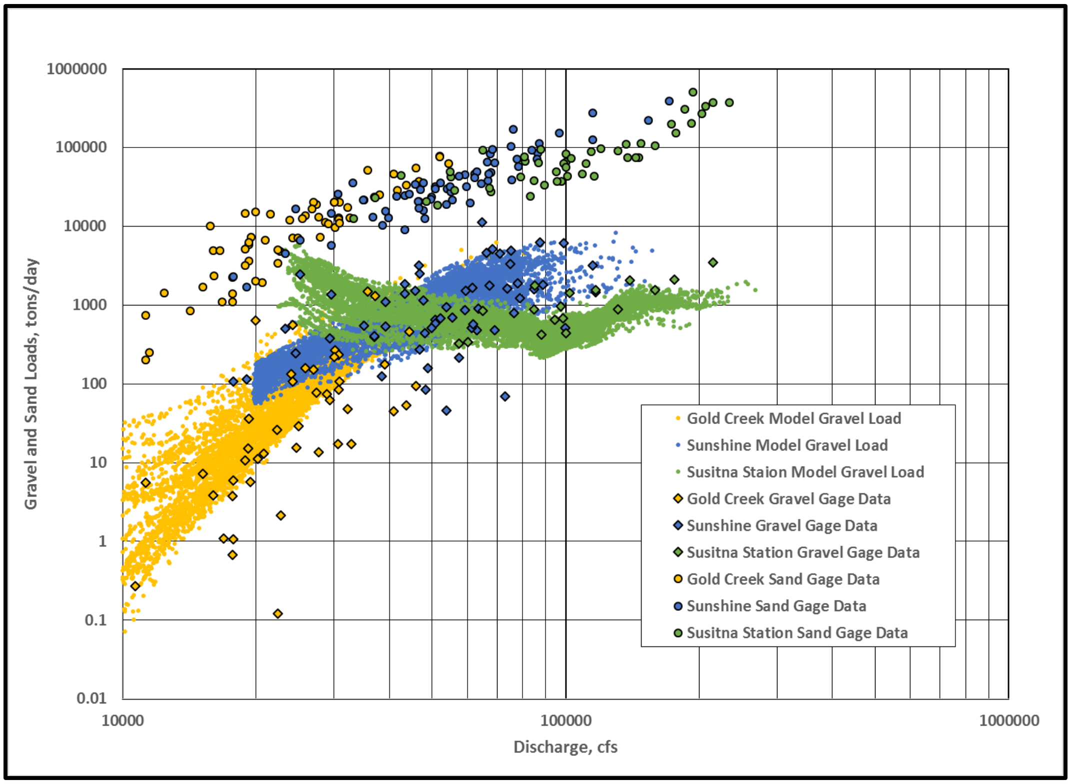

Figure 3.4-3. Susitna River comparison of measured and model transported gravel loads.

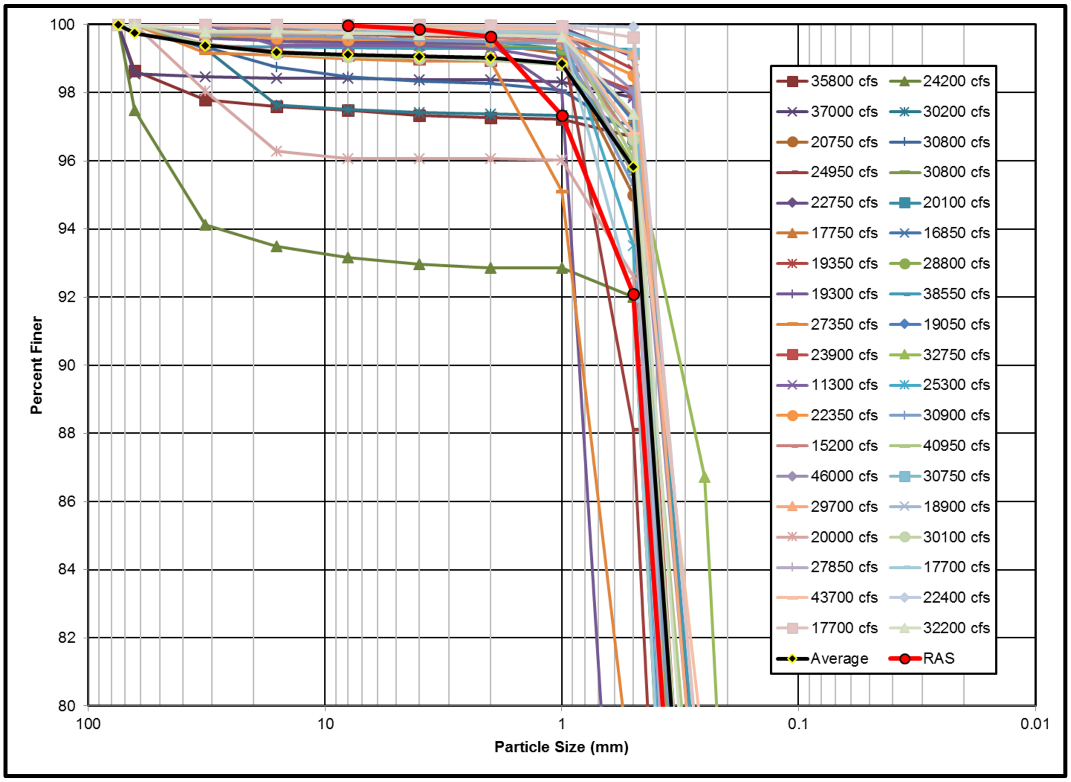

Figure 3.4-4. Susitna River near Talkeetna comparison of measured and model transported coarse material gradations.

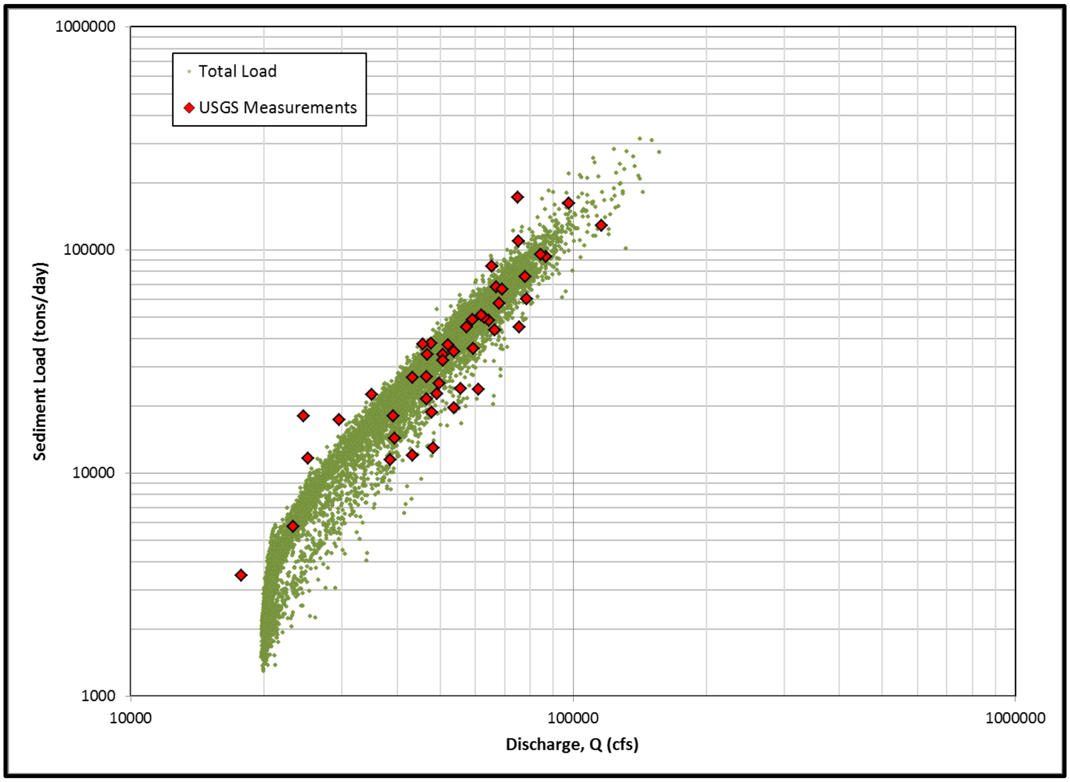

Figure 3.4-5. Susitna River at Sunshine comparison of measured and modeled total bed material loads.

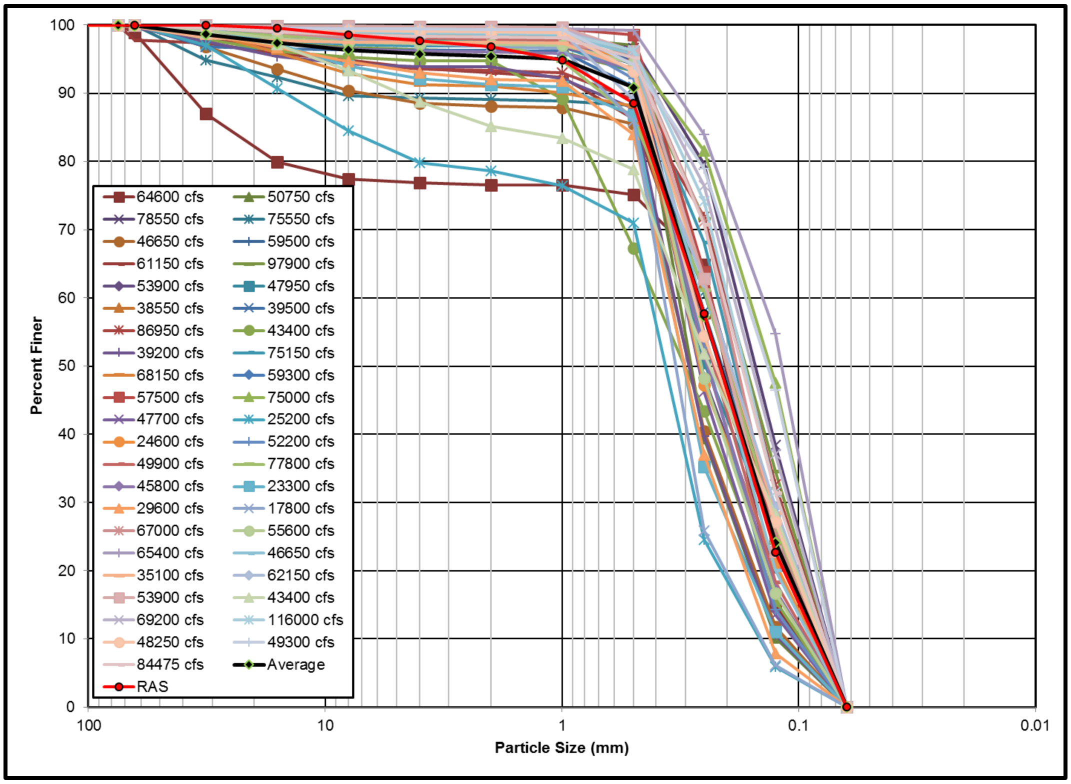

Figure 3.4-6. Susitna River at Sunshine comparison of measured and modeled transported bed material gradations.

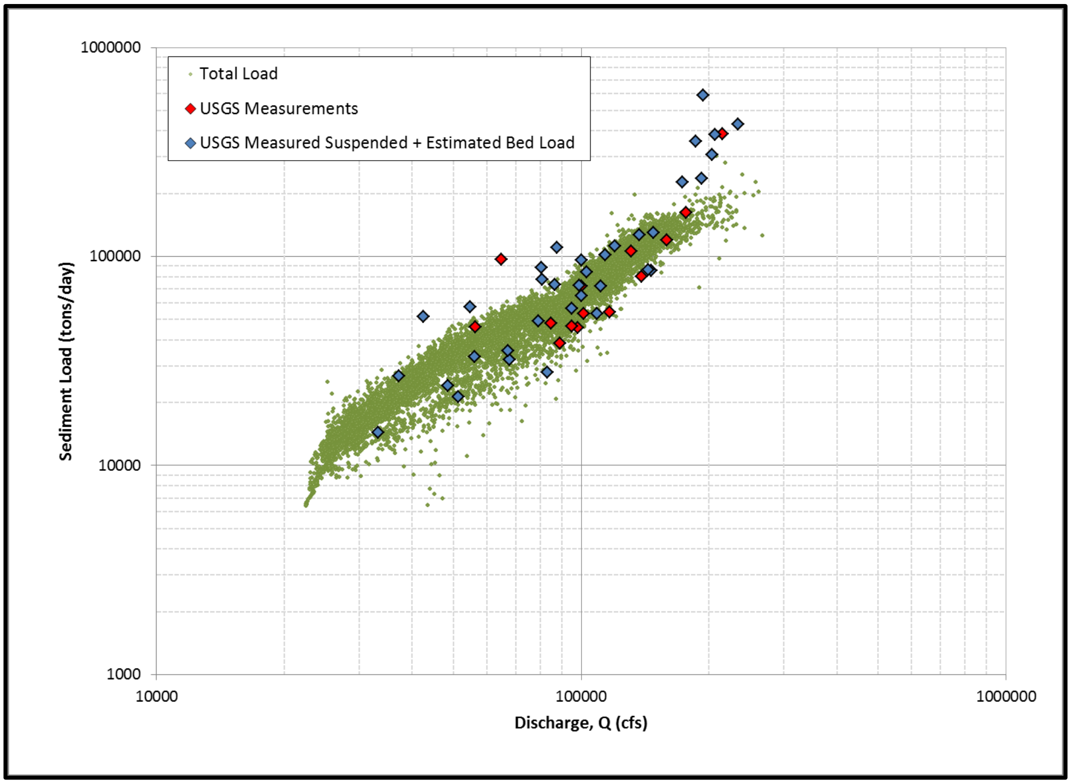

Figure 3.4-7. Susitna River at Susitna Station comparison of measured and modeled total bed material loads.

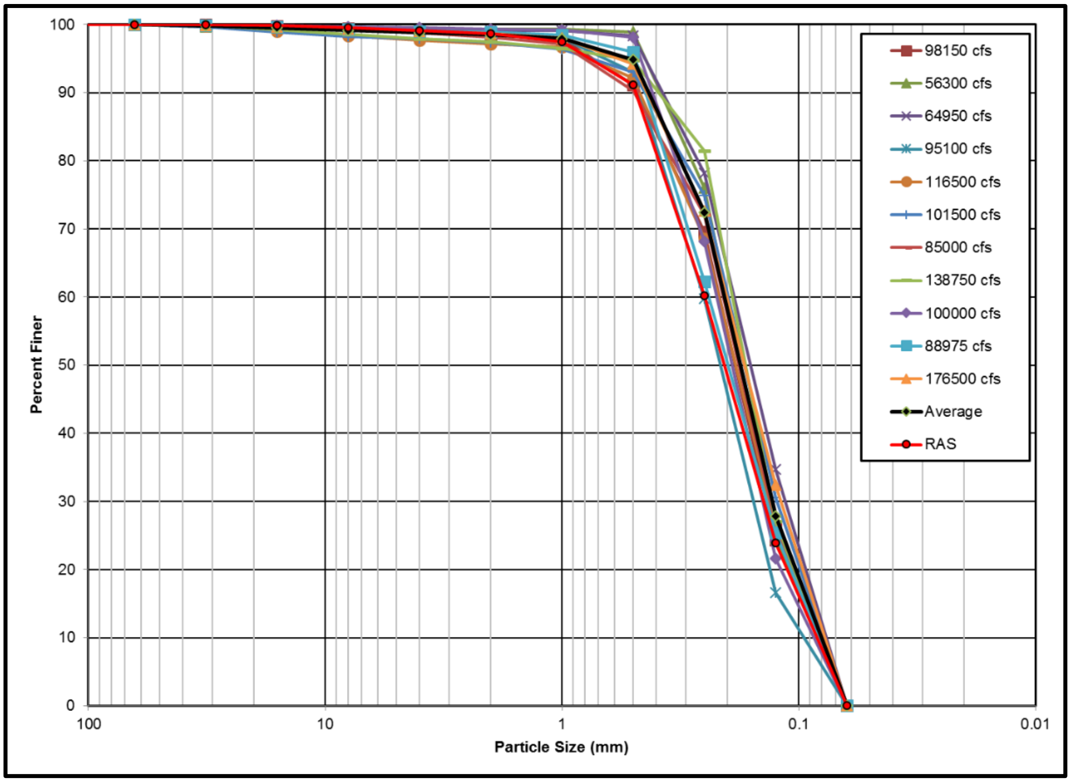

Figure 3.4-8. Susitna River at Susitna Station comparison of measured and model transported bed material gradations.

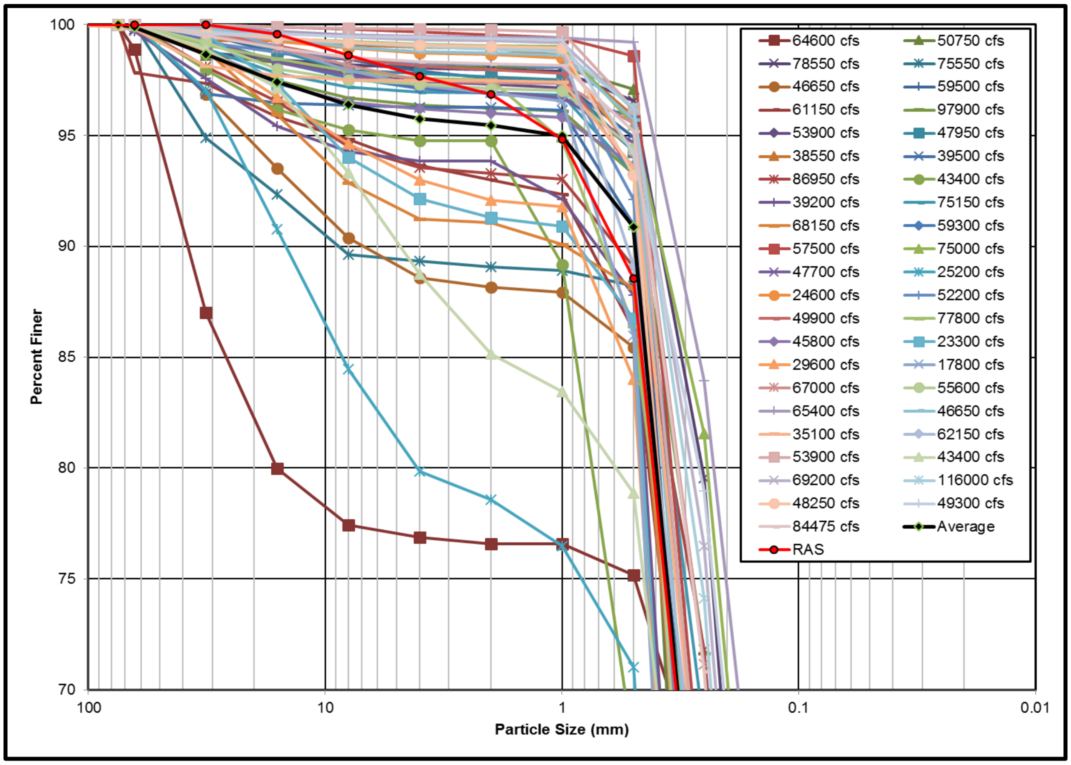

Figure 3.4-9. Susitna River at Sunshine comparison of measured and modeled transported coarse material gradations.

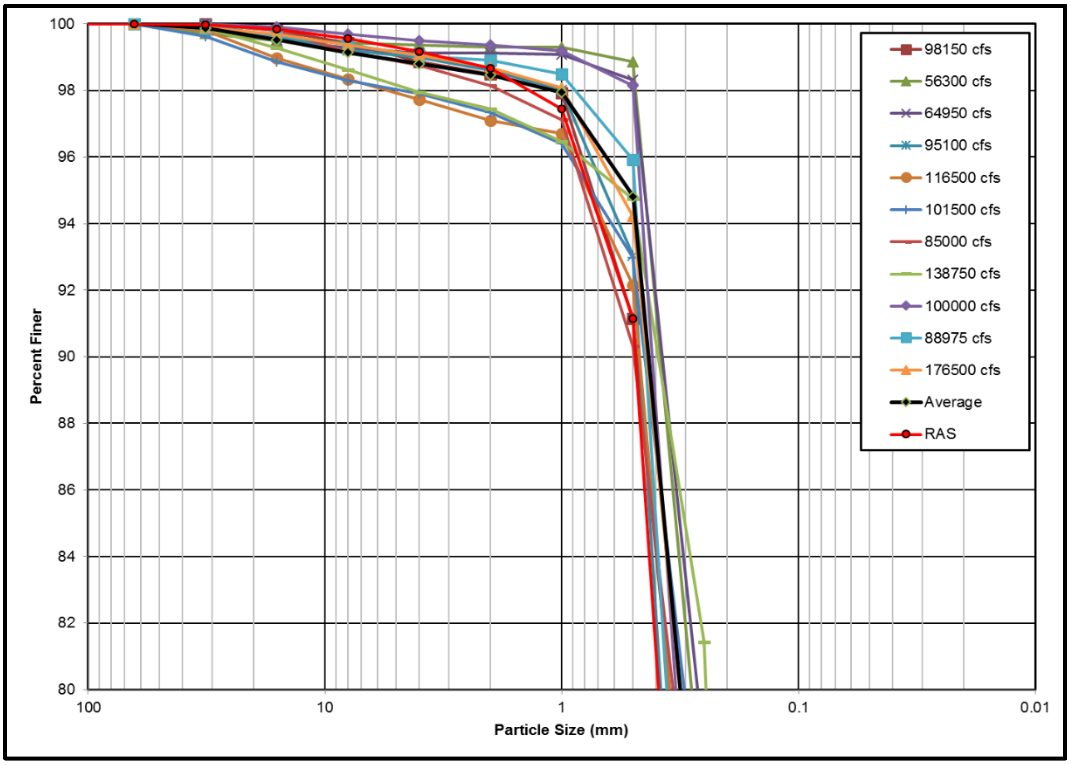

Figure 3.4-10. Susitna River at Susitna Station comparison of measured and model transported coarse material gradations.

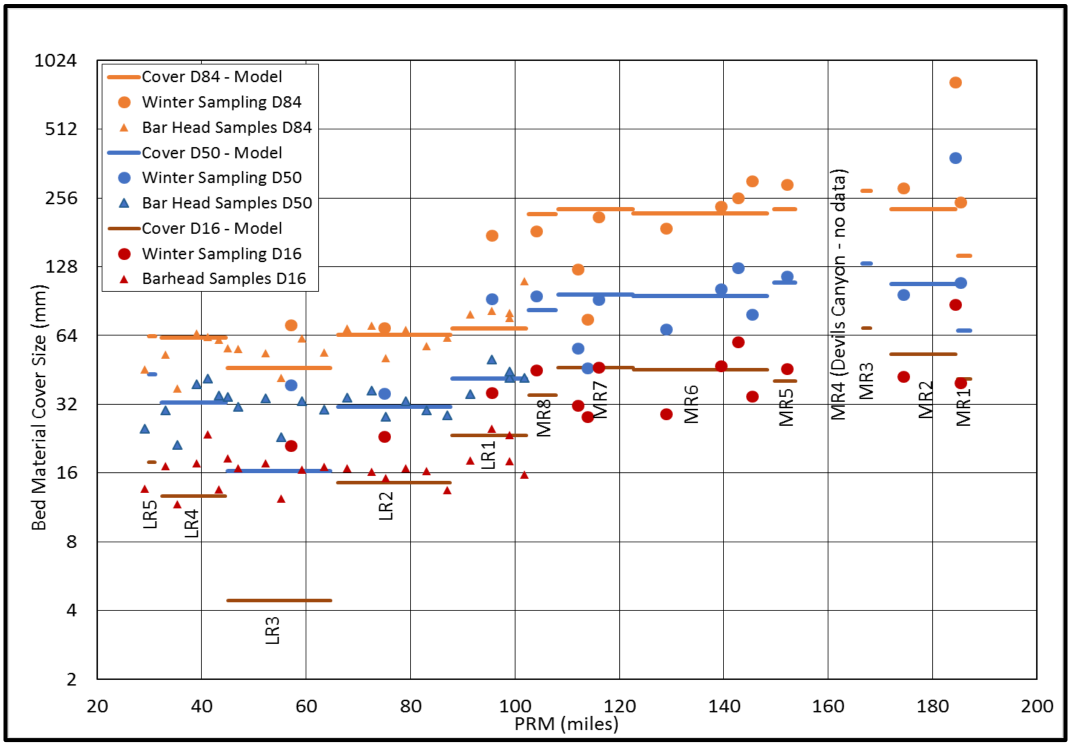

Figure 4.5-1. Comparison of model and winter bed sampling surface material sizes.

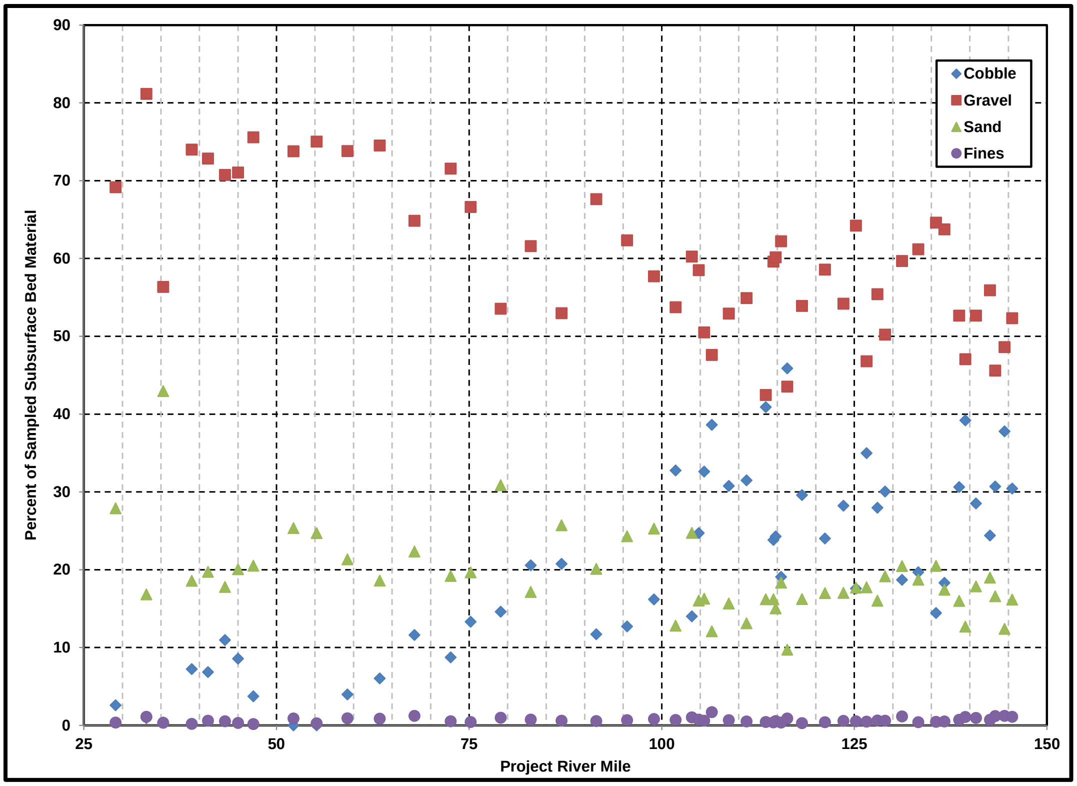

Figure 4.5-2. Composition of subsurface bar-head bed material samples.

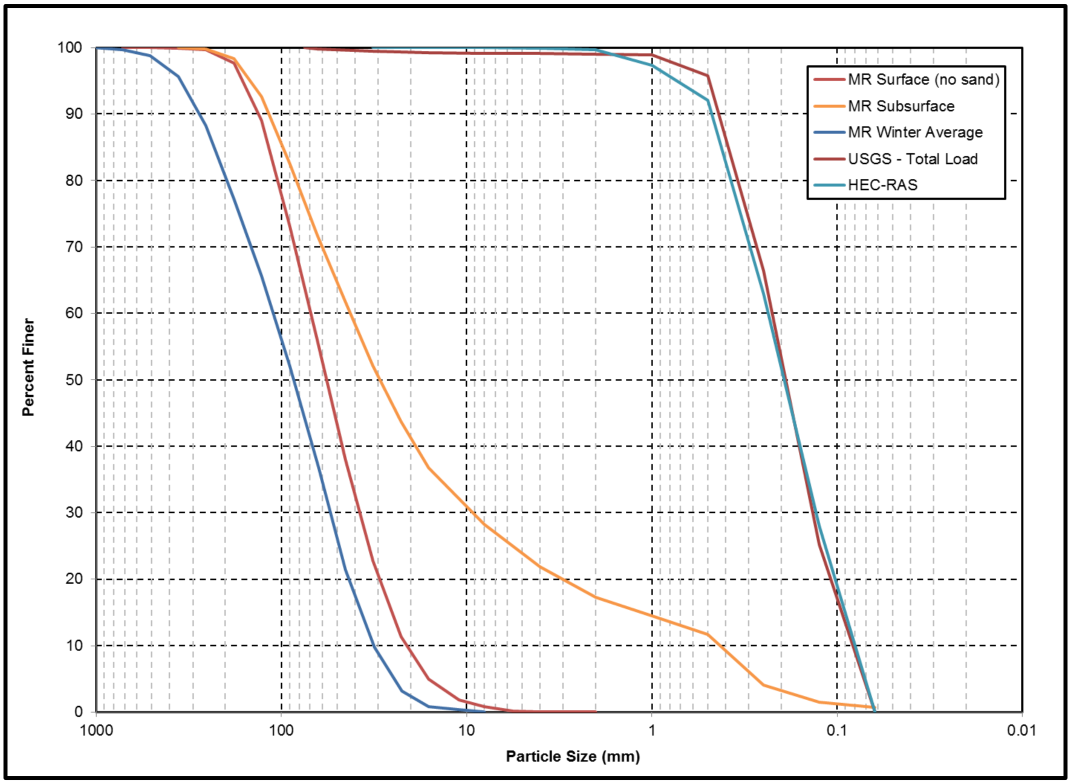

Figure 4.6-1. Middle Susitna River Segment bed material gradations and transported gradations.

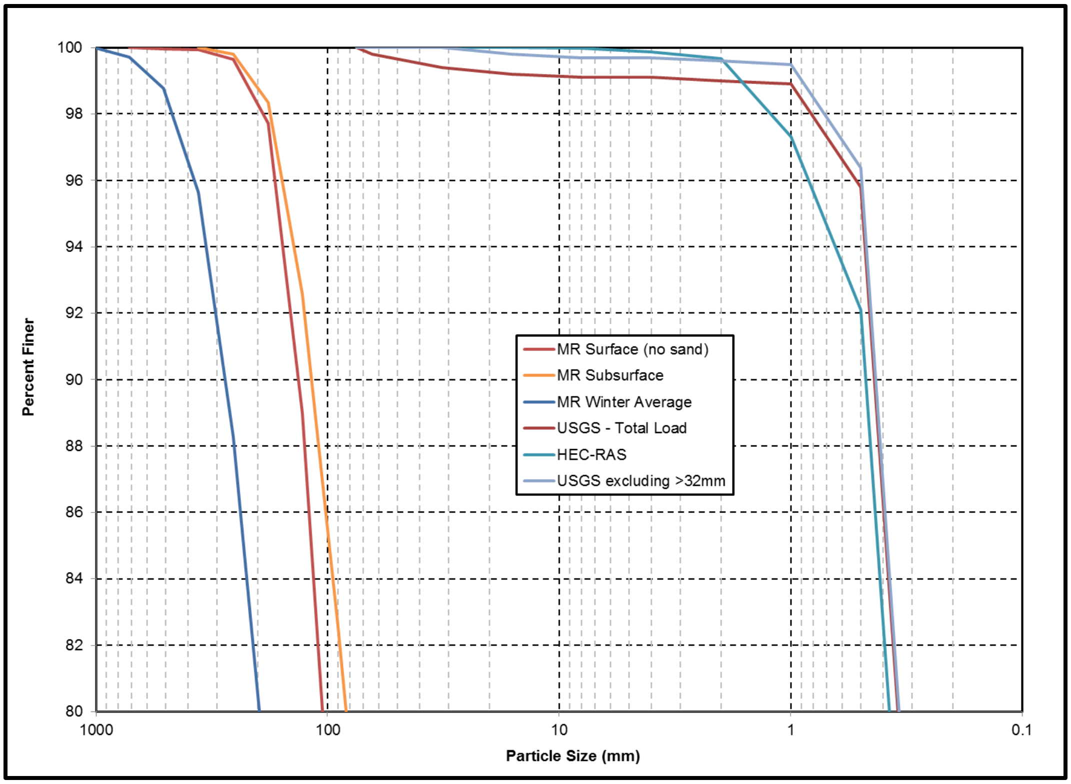

Figure 4.6-2. Detail of Middle Susitna River Segment bed material gradations and transported bed material load gradations.

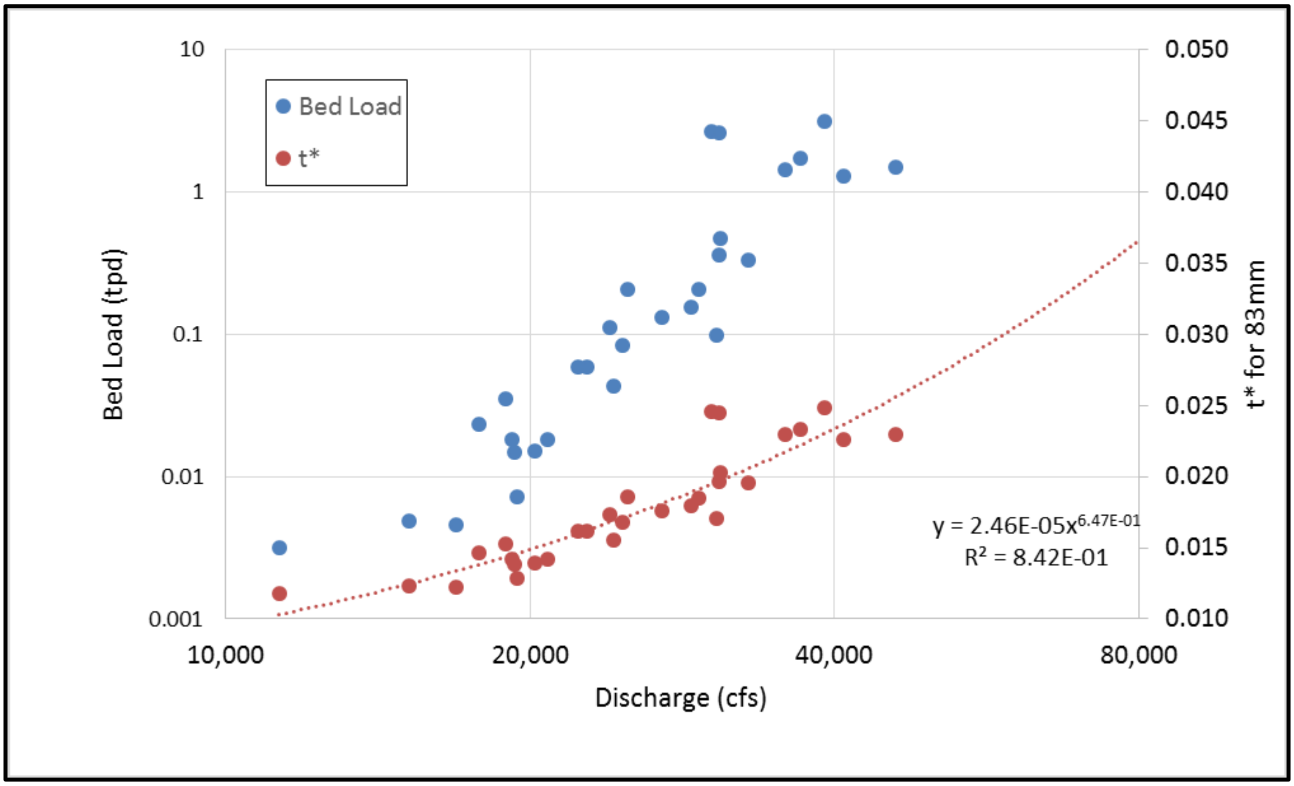

Figure 4.6-3. Middle River estimated bedload transport rates using Wilcock-Crowe and dimensionless shear stress for USGS measurements (tpd = tons per day).