# Susitna-Watana Hydroelectric Project
# (FERC No. 14241)

## Updated Fluvial Geomorphology Modeling Approach

## Technical Memorandum

Prepared for

Alaska Energy Authority

SUSITNA-WATANA HYDRO

Clean, reliable energy for the next 100 years.

Prepared by

Tetra Tech

Original Submitted June 30, 2013

Updated May 2014

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# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF ACRONYMS AND ABBREVIATIONS

| Abbreviation | Definition |
|---|---|
| 1-D | One dimensional |
| 2-D | Two dimensional |
| ADCP | Acoustic Doppler Current Profiler |
| AEA | Alaska Energy Authority |
| AOW | additional open water |
| ASPRS | American Society of Photogrammetry and Remote Sensing |
| BEI | Bank Energy Index |
| BG | Background |
| cfs | cubic feet per second |
| D | Depth |
| DHI | Danish Hydraulic Institute |
| D/S | Downstream |
| FA(s) | Focus Area(s) |
| FaSTMECH | Flow and Sediment Transport with Morphologic Evolution of Channels |
| FERC | Federal Energy Regulatory Commission |
| FHWA | Federal Highway Administration |
| GIS | Geographic Information System |
| HEC-RAS | Hydrologic Engineering Centers River Analysis System |
| HSC | Habitat Suitability Criteria |
| iRIC | International River Interface Cooperative |
| LiDAR | Light detecting and ranging |
| LWD | Large woody debris |
| MBH | Mobile Boundary Hydraulic |
| MD_SWMS | Multi-Dimensional Surface-Water Modeling System |

| | |
|---|---|
| OS | Operational Scenario |
| PDO | Pacific Decadal Oscillation |
| POC | Proof of Concept |
| PRM | Project River Mile |
| RoR | Run of River |
| RSP | Revised Study Plan |
| SPD | Study Plan Determination |
| SRH-1D (2D) | Sedimentation and River Hydraulics-One Dimension (Two Dimensions) |
| SToRM | System for Transport and River Modeling |
| TIN | Triangulated Irregular Network |
| TWG | Technical Work Group |
| U/S | Upstream |
| USACE | U.S. Army Corps of Engineers |
| USGS | U.S. Geological Survey |
| V | Velocity |
| WSE | Water-surface elevation |

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# 1. INTRODUCTION

After submittal of the Fluvial Geomorphology Modeling Technical Memorandum (Tetra Tech 2012) and the Revised Study Plan (Alaska Energy Authority [AEA] 2012), the Federal Energy Regulatory Commission (FERC) issued a Study Plan Determination (SPD) on April 1, 2013, that included three recommendations to provide additional information on the models and methods for addressing several aspects of the study plan. The recommendations were:

1. <u>Modeling in Focus Areas</u>

   *We recommend that AEA file by June 30, 2013, the proposed technical memorandum related to the selection and application of the one- and two-dimensional models (proposed for development in the second quarter of 2013.*

   *We also recommend that the technical memorandum include the following information:*

   1. *Specification of the one- and two-dimensional models to be used in the fluvial geomorphology modeling pursuant to this study as well as the aquatic habitat models pursuant to Study 8.5 (fish and aquatics instream flow);*
   2. *Location and extent of one- and two-dimensional geomorphology and aquatic habitat modeling in project reaches, focus areas, and other study sites;*
   3. *Rationale and criteria for model selection including an overview of model development;*
   4. *For fluvial geomorphology modeling only, a detailed description of the processes and methods by which ice and large woody debris (LWD) would be incorporated into the modeling approach (as described in our recommendations for incorporating large woody debris and ice processes into fluvial geomorphic modeling); and*
   5. *Documentation of consultation with the Technical Work Group (TWG), including how the TWG's comments were addressed.*

   The items in this recommendation are addressed in the following sections of this Technical Memorandum:

   - Selection of 1- and 2-D models is included in Section 3. "Selection of Hydraulic and Bed Evolution Models."
   - Application of 1- and 2-D models is included in Section 4. "Model Application."
   - Specification of the 1-D model is Section 3.1.4 "Selection of 1-D Model."
   - Specification of the 2-D model is Section 3.2.4 "Selection of 2-D Model."
   - The selected 1- and 2-D models will be used for hydraulic input to the aquatic habitat analyses and modeling as described in Section 4.3.1.2 "Hydraulic Modeling for Habitat Analysis."
   - Location and extent of 1- and 2-D models is included in Section 4.1 "Models and Survey Extent." Project reaches are described in Section 4.1.1 "Reach-Scale Model," Focus Areas are described in Section 4.1.2 "Local-Scale Focus Area Models," and other study sites (tributaries) are described in Section 4.1.3 "Other Tributary Models."

- Rationale and criteria for model selection are included in Sections 3.1.2 "Selection Criteria for 1-D models" and 3.2.2 "Selection Criteria 2-D Models."
- Overviews of model development are Sections 3.1.1 "Overview of 1-D Model Development" and 3.2.1 "Overview of 2-D Model Development."
- See recommendation 3, below, for items related to LWD and Ice modeling.
- Documentation of consultation is Section 5. "Consultation Documentation."

2. Interaction of Geomorphic Processes in the Mainstem and Tributaries

   *We recommend the study plan be modified to include a defined approach to evaluating geomorphic changes at the confluence of the Chulitna, Talkeetna, and Susitna rivers. The evaluation should extend from the mouth of both the Chulitna and Talkeetna rivers to the potentially affected upstream reaches of these tributaries. We recommend that AEA prepare a technical memorandum detailing a proposed approach for evaluating geomorphic changes in the three rivers confluence area, including explicitly stated objectives for evaluating geomorphic changes, an overview of the technical approach, additional data collection required, models and model components to be used, and additional analyses that would be conducted to address the stated objectives. We recommend that AEA file by June 30, 2013, this technical memorandum to include documentation and consultation with the TWG, including how the TWG's comments were addressed.*

   The items in this recommendation are addressed in the following sections of this Technical Memorandum:

   - The defined modeling approach is included as Section 2.2 "Comprehensive Modeling Approach."
   - The evaluation of the Chulitna and Talkeetna Rivers, including the approach and objectives is part of Section 1.2 "Objectives."

3. Incorporating Large Woody Debris and Ice Processes into Fluvial Geomorphic Modeling

   *As noted above in our analysis and recommendations for Modeling in Focus Areas, we are recommending that AEA file a technical memorandum with additional information on AEA's proposed model selection process. We recommend that an additional provision be added to the technical memorandum requiring that AEA describe in detail how ice and LWD would be incorporated into both one- and two-dimensional modeling approaches. The technical memorandum should explicitly state where and how each of the five scenarios for incorporating ice processes into one-dimensional and/or two-dimensional fluvial geomorphology modeling would be implemented, as well as details regarding where and how LWD pieces and/or accumulations would be incorporated into two-dimensional modeling.*

   The items in this recommendation are addressed in the following sections of this Technical Memorandum:

- LWD processes and modeling methods are described in Sections 4.2.2.2 “Large Woody Debris Modeling” for 1-D modeling and 4.3.2 “Large Woody Debris Effects” for 2-D modeling.
- The five scenarios for ice modeling are described for 1-D modeling in Section 4.2.3 “Ice Effects” and for 2-D modeling in Section 4.3.3 “Ice Effects.”

This technical memorandum was developed to provide responses to the SPD recommendations. The intent is to identify the models and methods for addressing the specific comments and recommendations, recognizing that adjustments to the approaches may occur as additional information is acquired. The draft technical memorandum was included as a topic at the May 21, 2013, TWG meeting, with updates to be provided as methods are refined based on field data collection, further coordination between this and other study components, and initial model development.

The selection of the one-dimensional (1-D) and two-dimensional (2-D) models, as well as the modeling approaches, has been coordinated with the other pertinent studies and the licensing participants. As part of the coordination process, an early draft of this technical memorandum, titled Fluvial Geomorphology Modeling (Tetra Tech 2012), was posted on the AEA website in May 2012.

The fluvial geomorphology modeling team will continue to develop the modeling approaches and coordinate with other studies on modeling needs. Site reconnaissance, data collection, and field observations in the summer of 2013 will also result in additional detail and possible adjustments to the modeling approaches. The length of modeling for the tributaries will be identified in the field, and hydraulic and sediment-transport modeling domains for the Focus Areas may be extended slightly, on the order of a channel width or less, to improve boundary conditions, but no adjustments will be made to the actual Focus Area limits.

An Instream Flow Study - Technical Team Meeting (IFS-TT: Riverine Modeling) was held on November 13-15, 2013 to review and discuss riverine modeling and study integration efforts. During this meeting, a Proof of Concept (POC) exercise was proposed to demonstrate modelling coordination between studies. The coordination involved Fish and Aquatics IFS (Study 8.5), Fluvial Geomorphology Modeling (Study 6.6), Ice Processes (Study 7.6), Water Quality Modeling (Study 5.6) and Groundwater (Study 7.5). The IFS-TT POC meetings were held April 15 – 17, 2014 to review and discuss the riverine models, describe model linkages, and prove via demonstration that the modeling process is conceptually sound. This revised TM provides updates to several topics including final 1-D and 2-D model selection (Sections 3.1.3.5, 3.1.4.2 and 3.2.4.2), treatment of selection of representative years including consideration of Pacific Decadal Oscillation (PDO) (Sections 2.2 and 3.4.1.1), provide additional detail on tributary modeling (Sections 4.1.1 and 4.2), clarify that application of 2-D models may not be required for all Focus Areas for all scenarios (Sections 2.1 and 4.1.3) and presentation of text, figures and tables that describe the POC efforts for 2-D hydraulic modeling (Attachment A). The updated figures and text, including Attachment A, were largely derived from materials presented during the POC meetings (see AEA 2014).

## 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 flow rates 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 significant question in any instream flow study. In other words, is the channel morphology in a state of dynamic equilibrium such that the distribution of habitat conditions will be reflected by existing channel morphology or will changes in morphology occur that will influence the relative distribution or characteristics of aquatic habitat over the term of the license (Bovee 1982)? This key issue prompts four overall questions that must be addressed by the geomorphology study:

- Is the system currently in a state of dynamic equilibrium?
- If the system is not currently in a state of dynamic equilibrium, what is the expected evolution over the term of the license?
- Will the Project affect the morphologic evolution of the Susitna River compared to pre-project conditions?
- If the Project will alter the morphology of the river, what are the expected changes over the term of the license?

The methods and results from the geomorphology study and the fluvial geomorphology modeling study will address these questions. These studies will be coordinated to:

- determine how the river system functions under existing conditions;
- determine how the current conditions form and maintain a range of aquatic and channel margin habitats; and
- identify the magnitudes of changes in the controlling variables and how these will affect existing channel morphology;

The fluvial geomorphology modeling will include a range of analyses for Existing and with-Project scenarios. These analyses will be used to:

- develop calibrated models to predict the magnitudes and trends of geomorphic response to the Project;
- apply the models to estimate potential for channel change for with-Project operations compared to existing conditions;
- support coordination with the geomorphic and other studies to integrate model results with understanding of geomorphic processes and controls to identify potential Project effects; and
- support the evaluation of potential Project effects by other studies that relate to channel and hydraulic results throughout the river corridor over the license period

To develop the modeling approach, specific issues that need to be addressed have been identified. These issues have been further differentiated into reach-scale and local-scale issues since the scale influences the proposed approach. The reach-scale modeling of the Susitna River will be performed using 1-D models, as they are well suited for long term simulations over long river reaches. Reach-scale results will address channel morphologic change on the order of $10^1$ to

$10^0$ x the Susitna River width and subdivide the flow between channel, left floodplain, and right floodplain. The 1-D models will be used to assess reach-scale sediment-transport conditions, potential changes in bed and water-surface elevations, changes in channel profile, and potential changes in bed material gradation. The 1-D models will also provide boundary conditions for the local-scale modeling (i.e., the Focus Areas) that will be performed for relatively short reaches of the Middle Susitna River Segment using 2-D models.

The detailed results of the 2-D models will provide more localized information on changes in hydraulic and bed conditions over a range of flows for existing and with-project conditions. The local-scale results within Focus Areas will provide results over a range of scales. For the main channel the element size will be on the order of $10^{-1}$ x the Susitna River width, but results can be integrated to obtain channel average results ($10^0$ x width). Model refinement must be greater in areas of appreciable geometric change or where velocity magnitude and direction change rapidly. In these areas model refinement will be between $10^{-1}$ and $10^{-2}$ x Susitna River width. A high level of refinement is required for detailed habitat analysis in the lateral features. These areas will be analyzed at the $10^{-2}$ x Susitna River width. Floodplain and island areas tend to have higher flow resistance and the shallow, low velocity conditions do not require as detailed of a resolution in the models. These areas will be modeled at scales ranging from $10^0$ to $10^{-1}$ x Susitna River width.

- The fluvial geomorphology modeling will include evaluation of existing conditions compared to four operational scenarios over the 50-year term of the license. The four operational scenarios include maximum load following, base load, intermediate load following, and Run of River (RoR). These scenarios are described as: Max Load Following OS-1: The Maximum Load Following OS-1 scenario is based on the assumption that the entire load fluctuation of the Railbelt would be provided by the Susitna-Watana Project, and that all other sources of electrical power in the Railbelt would be running at base load. This assumed condition is not realistic for an entire year, and the results of this condition should be conservative with respect to assessing downstream impacts of load following.
- Base Load: This scenario assumes that the Project is operated to support the Railbelt base load and does not operate in a load following mode.
- Intermediate Load Following: This scenario represents an intermediate condition between the Maximum Load Following OS-1 and the Base Load scenarios in which the Susitna – Watana Project provides a portion of the load fluctuation of the Railbelt (the portion of the load fluctuation that the Project would supply has not been determined).
- Run of River: In this scenario the Project is operated to match outflow from the reservoir with inflow to the reservoir. The exception would be during the initial filling of the reservoir when inflow would exceed outflow. The major difference between this scenario and the pre-Project condition would be the trapping of the vast majority of the sediment load in the reservoir under the Run of River scenario.

### 1.1.1 Reach-Scale Issues

Reach-scale issues refer to aspects of the system that involve the overall behavior and general characteristics of the Susitna River over many miles. Each reach represents a spatial extent of the

Susitna River that has a consistent set of fluvial geomorphic characteristics. Reach-scale issues include:

- Historical changes in the system and the existing status with respect to dynamic equilibrium (i.e., the overall sediment-transport balance).
- Changes in both the bed material (sand and coarser sizes) and wash (fine sediment) load sediment supply to the system due to trapping in Watana Reservoir.
- Long-term balance between sediment supply and transport capacity and the resulting aggradation/degradation response of the system for pre- and post-Project conditions.
- Changes in bed material mobility in terms of size and frequency of substrate mobilized due to alteration of the magnitude and duration of peak flows and sediment supply by the project.
- Project-induced changes in supply and transport of finer sediments that influence turbidity.
- Potential for changes in channel dimensions (i.e., width and depth) and channel pattern (i.e., braiding versus single-thread or multiple-thread with static islands) due to the Project and the magnitude of the potential change.
- Project-induced changes in river stage due to reach-scale changes in hydrology, bed profile, channel dimensions, and potentially hydraulic roughness.
- Characterization of the types, amounts, and features of LWD both in terms of supply and the overall effects of LWD on sediment transport.
- Changes in ice cover effects on sediment mobilization.

### 1.1.2 Local-Scale Issues

Local-scale issues refer to aspects of the system that involve the specific behavior and characteristics of the Susitna River at a scale associated with site-specific geomorphic and habitat features. Local-scale issues are addressed using a more detailed assessment over a smaller spatial area; however, these analyses must draw from and build upon the understanding and characterization of the system behavior determined at the reach scale. Local-scale issues include:

Processes responsible for formation and maintenance of the individual geomorphic features and associated habitat types. Potential changes in geomorphic features and associated aquatic habitat types that may result from effects of Project operation on riparian vegetation and ice processes. Effects of changes in flow regime and sediment supply on substrate characteristics in lateral habitat units. Changes in upstream connectivity (breaching) of lateral habitats due to alteration of flow regime and possibly channel aggradation/degradation. These changes may induce further changes in the morphology of lateral habitats, including:

- potential for accumulation of sediments at the mouth;
- potential for accumulation of fine sediment supplied during backwater connection with the mainstem;
- potential for changes in riparian vegetation that could alter the width of lateral habitat units.

Project effects at representative sites on the magnitude, frequency, and spatial distribution of hydraulic conditions that control bed mobilization, sediment transport, sediment deposition, and bank erosion.

Potential for change in patterns of bedload deposits at tributary mouths that may alter tributary access or tributary confluence habitat.
Potential for changes in accumulation of LWD and related effects on hydraulics, erosion, scour, and sediment transport.
Relating potential changes in ice cover and ice jams and the related potential effects on hydraulics; flow distribution between the main channel, lateral features, and floodplains; sediment transport; and erosion.

## 1.2 Objectives

The objective of this technical memorandum is to document the procedures for modeling the fluvial geomorphology of the Susitna River below Watana Dam. The overall goal is to model and evaluate the potential Project effects of the proposed Susitna-Watana Hydroelectric Project on the fluvial geomorphology of the Susitna River and tributaries, and provide input to other team members for evaluating potential Project effects on habitat. The results of this and other geomorphology studies will be used in combination with geomorphic principles and criteria/thresholds defining probable channel forms to predict the potential for alterations of channel morphology. The purpose of this technical memorandum is to explain the proposed approach, including which models will be used, for the Susitna River fluvial geomorphology modeling.

Specific objectives include:

- Identify the 1-D sediment-transport model that will be used for reach-scale modeling and 2-D sediment-transport model that will be used for local-scale modeling, including
    - Providing the rationale and criteria for model selection;
    - Specifying the selected models; and
    - Providing an overview of model development of the selected models.
- Identify the location and extent of the 1-D and 2-D models that will be performed.
- Provide a description of the processes and methods for incorporating ice and LWD into the 1-D and 2-D geomorphic modeling.
- Describe the modifications to the study plan for evaluating geomorphic changes at the confluence of the Susitna, Chulitna, and Talkeetna Rivers.

As with the reach-scale 1-D sediment-transport analysis of the Susitna River, the objectives for evaluating geomorphic change at the Three Rivers Confluence are to compare existing conditions to with-Project scenarios related to 1) hydraulic interactions; 2) sediment-transport interactions; 3) channel form (aggradation, degradation, and width), and to relate these outcomes to potential Project effects.

There are no additional analyses for the Three Rivers Confluence anticipated beyond what is currently planned for the 1-D modeling of the Susitna River because the Chulitna and Talkeetna Rivers will be included as tributary reaches in the 1-D modeling. The reach-scale 1-D modeling of the Susitna, Chulitna, and Talkeetna Rivers will provide information on potential Project effects on hydraulics, sediment transport, and channel form through the analysis of:

- Velocity

- Depth
- Water-surface elevation
- Sediment loads
- Effective discharge
- Coincident flows and stage
- Aerial photo analysis of channel change
- Bed material gradation
- Aggradation and degradation
- Channel profiles
- Channel width
- Channel plan form

### 1.2.1 May 2014 Revision Objectives

The overall objectives of this revision to the Modeling Approach TM is to document modifications to procedures for modeling fluvial geomorphology of the Susitna River below Watana Dam as well as the IFS-TT POC meetings held April 15-17, 2014. The primary types of modeling include reach-scale bed morphology modeling of the Susitna River from Watana Dam to Susitna Station, local-scale bed morphology modeling at Focus Areas in the Middle River, and local-scale hydraulic modeling to support habitat analyses of the Focus Areas. The modifications involve each of these types of modeling, and the specific objectives of this revision are:

- Identify the final selected 1-D bed morphology model (Sections 3.1.3.5 and 3.1.4.2)
- Identify the final selected 2-D bed morphology and hydraulic model (Section 3.2.4.2)
- Provided more detail on the modeling approach for the tributaries (Section 4.1.1 and 4.2)
- Update the consideration of Pacific Decadal Oscillation in the determination of representative years (Sections 2.2 and 4.4.1.1)
- Clarify that the 2-D models may not be applied at all Focus Areas for all scenarios (Sections 2.1 and 4.1.3)
- Describe the local-scale hydraulic model development and results for the POC (Section 4.5 and Attachment A).

# 2. OVERALL MODELING APPROACH

## 2.1 Background

The proposed modeling approach considers the need to address both reach-scale and local-scale conditions and the practicality of developing and applying various models based on data collection needs, computational time, analysis effort, and model limitations. Based on these considerations, an approach that uses 1-D models to address reach-scale issues and 2-D models to address local-scale issues will be used. A comparison of the capabilities of 1-D and 2-D models is provided in Table 2-1. Based on these capabilities and the need to evaluate potential Project effects over the majority of the system and at small habitat scales, a combination of 1-D and 2-D modeling approaches is required. Considering the broad physical expanse of the Susitna River system, the general hydraulic and sediment-transport characteristics of the various geomorphic reaches that make up the overall study area will be evaluated using 1-D computer models. The 2-D models will be used to evaluate the detailed hydraulic and sediment-transport characteristics at locations where it is necessary to consider the more complex flow patterns to understand and quantify flow distribution, habitat, breaching, and erosion/deposition issues related to changing hydrology, sediment supply, ice, and LWD conditions.

The 2-D models will be applied to the 10 Focus Areas that are representative of important habitat conditions and the various geomorphic reaches and associated channel classification types. Though the 2-D models will be developed for the 10 Focus Areas, there may be cases in which the results of the 1-D modeling are sufficient to determine Project effects for specific Focus Areas for certain scenarios. The 1-D model may be used to screen system response and determine whether the detailed 2-D modeling is required. These sites were chosen in coordination with the Fish and Aquatics Instream Flow, Riparian Instream Flow, Ice Processes, and Fish and Aquatic Resources studies to facilitate maximum integration of available information between the studies (see Sections 6.6.4.1.2.4, 8.5.4.2.1.2, and 8.6.3.2 of the Revised Study Plan (RSP), AEA 2012; R2 Resource Consultants 2013a, 2013b).

In addition to the reach-scale 1-D models for existing and with-project conditions, 1-D models will be developed for a selected subset of tributaries to provide sediment inputs to both the reach-scale model and the 2-D Focus Area models. These tributaries will be evaluated using models developed with cross section and bed material data collected near the mouth. Temporary gages and stage-discharge relationships at selected tributaries from other studies will provide a basis for estimating the flow record, and the models will be used to evaluate sediment loads. Because it is not practical to develop these models for all tributaries, a subset of tributaries will be modeled, and the resulting information will be used to develop sediment supplies for other ungaged tributaries (Note: Tributary water inflows will be provided by the Fish and Aquatics IFS Study 8.5). The reach-scale model will be used to develop boundary conditions for the 2-D models that include water-surface elevation versus discharge rating curves for the downstream boundary, and the sediment supply at the upstream boundary.

Section 4, Model Application, provides locations and extents of the reach-scale 1-D model, local-scale 2-D models, and tributary models. Integration of the 1-D reach-scale modeling with the local-scale 2-D Focus Area modeling will provide the following advantages:

- The 1-D model will allow for efficient assessment of the hydraulic conditions and sediment-transport balance over the length of the study reach between Watana Dam and Susitna Station.
- The 1-D model reaches will extend up the Chulitna and Talkeetna Rivers to more fully represent these sediment sink/sources and to evaluate potential Project effects on the morphology and flooding potential of these tributary channels.
- The 1-D model uses cross-sectional data that are being obtained as part of the Open-Water Flow Routing portion of the Instream Flow studies plus additional cross sections to represent stream-wise variation in planform and profile.
- The 1-D model will provide the boundary conditions for the 2-D model in the Focus Areas, including starting water-surface elevations and upstream sediment supply.
- The 1-D model will provide reach-scale evaluation of potential sediment-transport effects due to changes in LWD amounts.
- The 2-D model applied at the Focus Areas, which are also being evaluated for the ice processes and riparian instream flow studies, will allow for the fullest level of integration of these efforts, particularly as they relate to assessments of potential changes in channel width and pattern.
- The 2-D model will provide additional information on erosion and sedimentation processes related to ice jam surge, channel and lateral features blockage by ice, and flows diverted onto floodplain areas by ice jams.
- The 2-D model at the Focus Areas will provide an understanding of the hydraulic conditions and sediment-transport processes that contribute to formation of individual habitat types.
- The 2-D model at the Focus Areas will be used to evaluate flow conditions and bed mobilization around LWD obstructions.
- The 2-D model provides a much more detailed and accurate representation of the complex hydraulic interaction between the main channel and the lateral habitats than is possible with a 1-D model.

## 2.2 Comprehensive Modeling Approach

As described above, 1-D modeling will be used to evaluate reach-scale channel morphology and 2-D modeling will be used at the focus areas for channel morphology and habitat analyses. These models require input (boundary conditions) on inflowing water and sediment, and downstream water surface (stage-discharge relationships). Sediment sampling will provide bed material gradations for the 1- and 2-D morphology modeling and field observations and calibration will be used to establish roughness values for all the morphology and hydraulic models. Therefore, the various types of models will need to be conducted in a sequence where certain models or analyses provide input to other models. For example, the dam operations and flow routing models will be used to provide flow hydrographs to the 1- and 2-D morphology models and the 2-D hydraulic models will provide hydraulic results for the habitat analysis models.

Table 2.2 illustrates the series of four types of models that will comprise the majority of the fluvial geomorphology modeling component of the study. For each of these model types the hydrology, sediment, hydraulic, and geometric (channel and floodplain) input and results are summarized. The source of the input information is identified when it is provided by another study component. The type of information that will be used by other study components is identified for the fluvial geomorphic modeling results.

A prerequisite for the 1-D reach-scale morphology models is to determine the sediment supplied by each of the tributaries. Table 2.2 shows 1-D Tributary Sediment Modeling is the first modeling task. This modeling will be conducted for a range of flows to develop sediment rating curves at all tributaries located at Focus Areas, selected tributaries in the Lower Susitna River Segment for sediment supply and limited habitat analyses, and other selected tributaries in the Middle Susitna River Segment for sediment supply only. The range of tributaries will be used to develop sediment inflow for other tributaries throughout the model domain. Some of these tributaries will also be analyzed to provide information for the aquatic habitat and barrier studies.

The 1-D reach-scale morphology modeling will be run for a 50-year continuous flow record for Existing conditions and with-Project operational scenarios. The inflows to the model are the outflows from the dam for these conditions plus tributary inflows. Similarly, sediment passing the dam site will be included at the upstream limit of the model for these four conditions. Tributary sediment inflow will also be included. The only hydraulic boundary condition for this model is the stage-discharge relationship at the Susitna Station gage. The existing (2012 and 2013) channel and floodplain geometry will be the starting condition and the model will simulate potential channel change throughout the 50-year license period.

The reach-scale modeling will provide information to the 2-D local-scale morphology modeling efforts and to other study components. Local-scale models will be developed at the Focus Areas representing conditions at years-0, -25, and -50. If bed elevations or channel widths change over the 50 year period, the reach-scale model results will not only be used to alter the future (years-25 and -50) geometry, but will provide future downstream stage-discharge and upstream sediment supply rating curves to the local-scale models. The geometry and rating curve information must all be changed to maintain consistency between the models and to maintain internal consistency of the specific local-scale model. Because the local-scale models will be run for approximate 6-month open-water hydrographs, AEA does not anticipate that the rating curves will change appreciably. This assumption will be tested by evaluating the reach-scale model results and a shifting rating curve could be used if necessary.

The reach-scale models will also provide information to other studies. For example, aquatic and riparian habitat studies will use stage-discharge information at specific locations over the 50-year license period. There may also be the need to incorporate future channel change into the River1D ice model or flow routing models. This would only be necessary if the magnitude of geometric change would significantly affect the results of these studies.

The 2-D local-scale morphology models of the focus areas will not be run for the full 50-year period, but will be run for initial conditions and at years 25 and 50. These short duration runs (~6 months) will be performed for a range of hydrologic conditions including wet, average, and dry years with warm and cool PDO. It was determined that open water flows are not significantly affected by PDO (ISR Study 6.6, Appendix E) and separate warm and cool PDO years will not be included in the representative wet, average, and dry annual hydrographs. This range of hydrologic conditions will be used to interpret the local-scale morphology models and compare Existing and with-Project conditions in the main channel, secondary channels, other lateral features, islands, and floodplain areas. Just as the channel changes in the reach-scale models are used to develop the future geometry of the local-scale morphology models, the local-scale morphology model results will be used to modify lateral feature geometry in the 2-D local-scale hydraulic models.

The local-scale hydraulic models are necessary because they have much greater mesh refinement than can be achieved in the morphology models and they are steady-state models run for a range of flows rather than dynamic models run for seasonal hydrographs. The habitat analyses require a sequence of steady flows that can be applied to the range of flow magnitudes, durations, and timings of the analysis scenarios. The 2-D hydraulic modeling provides depth, velocity, water-surface elevation and other parameters for the range of flows throughout the local-scale model domains. These data will be used by the aquatic habitat, riparian habitat, and barrier studies to evaluate potential Project effects.

Though not specifically included in Table 2.2, additional 2-D morphology modeling will be conducted for a range of ice blockage and breakup conditions to evaluate erosion and deposition potential. The specific conditions for these simulations will be coordinated with input from agencies and other study components. Also not included in the table are changes in LWD that may occur over time. Descriptions of ice and LWD effects on sediment transport and model simulations are described in Section 4.2 for reach-scale modeling and 4.3 for local scale modeling.

# 3. SELECTION OF HYDRAULIC AND BED EVOLUTION MODELS

Many computer programs are available for performing movable boundary sediment-transport simulations. The choice of an appropriate model for this study depends on a number of factors, including: (1) the level of detail required to meet the overall study objective, (2) the class, type, and regime of flows that must be modeled, (3) characteristics of the bed material and wash load and, and (4) data necessary for model development and calibration. In addition, because of the wide range of sediment sizes present in the Susitna River, both the 1-D and 2-D models must be capable of routing sediment by size fractions, and ideally be capable of addressing deposition of fine sediments (wash load).

A variety of candidate models were evaluated for application on the Susitna River. The models fall into three categories of availability: (1) public domain, (2) commercial, and (3) proprietary. Public domain models are often developed by federal agencies or at universities and are available without cost. While they typically include a user interface, a commercial interface may also be available for these models. Commercial models are also available, though there are costs associated with acquiring the initial license, annual renewals, and support. Proprietary models are available only by contracting with the developer to perform an analysis. Proprietary models were not included as candidates. The candidate models for the 1-D and 2-D portions of the study are discussed below.

## 3.1 1-D Models

Most 1-D movable-boundary, sediment-transport models are designed to simulate changes in the cross-sectional geometry and river profile due to scour and deposition over relatively long periods of time. In general, the flow record of interest is discretized into a quasi-unsteady sequence of steady flows of variable discharge and duration. For each model time-step and corresponding discharge, the water-surface profile is calculated using the step-backwater method to compute the energy slope, velocity, depth, and other hydraulic variables at each cross section in the network. The sediment-transport capacity is then calculated at each cross section based on input bed material information and the computed hydraulics, and the aggradation or degradation volume is computed by comparing the transport capacity with the upstream sediment supply (i.e., the supply from the next upstream cross section for locations not identified as an upstream boundary condition). The resulting aggradation/degradation volume is then applied over the cross-sectional control volume (i.e., the sub-channel concept), and the shape of the cross section is adjusted accordingly. The computations proceed from time-step to time-step, using the updated cross-sectional and bed material gradations from the previous time-step.

The 1-D sediment-transport models should not be applied to situations where 2-D and 3-D flow conditions control the sediment-transport characteristics because they do not consider secondary currents, transverse movement and variation, turbulence, and lateral diffusion; thus, the 1-D models cannot simulate such phenomena as point bar formation, pool-riffle formation, and planform changes such as river meandering or local bank erosion. The 1-D models typically distribute the volume of aggradation or degradation across the entire wetted portion of the channel cross section after each time-step; thus, the effects of channel braiding are not directly considered. The 1-D models are, however, useful in evaluating the general sediment-transport characteristics and overall event or long term sediment balance of a given reach, and they are useful in providing boundary conditions for local-scale 2-D models.

### 3.1.1 Overview of 1-D Model Development

The following steps will be followed to develop the 1-D sediment-transport model. With few exceptions (as noted) the model development will be very similar regardless of the selected model. An overview of calibration and validation is included below. Additional information on model parameterization, calibration, validation, and sensitivity analysis will be provided in the study reports. Review and quality control procedures will be implemented throughout the model development process and are not indicated as individual steps. The steps are:

1. Determine the overall model layout.
    - Downstream boundary selected at a location of known stage-flow conditions.
    - Upstream boundary location(s) of known discharge and sediment supply information.
    - Tributaries that will be modeled geometrically with sediment routing.
    - Flow change locations of tributaries that are modeled as flow and sediment inputs.
    - Identification of split flow reaches around islands or in multiple-channel locations.
2. Develop cross-sectional data.
    - Determine cross section locations to represent the channel network.
    - Obtain channel cross-sectional geometry from land and bathymetric survey data.
    - Extend surveyed channel cross sections over islands and into floodplains using land-based survey and light detecting and ranging (LiDAR) data.
    - Determine channel and floodplain flow distances between cross sections.
3. Develop flow resistance (roughness) data for cross sections.
    - Channel base roughness based on bed material size.
    - Adjust base roughness to account for other sources of flow resistance such as channel irregularities, obstructions (including LWD), bed forms, and channel sinuosity. Note: project-related changes in amounts of LWD and sediment size can be related to flow resistance values.
    - Channel bank and floodplain (overbank) roughness based on land use, vegetative ground cover, and obstructions using field observations and aerial photography.
4. Develop bed and bank material gradation and layer information.
    - Surface sampling,
    - Subsurface sampling, and
    - Bank material samples.
5. Develop inflow hydrographs and sediment inflows for existing and with-project conditions.
    - For quasi-unsteady models, develop step hydrographs for the main channel and tributary inputs.
    - For fully unsteady models, use complete flow hydrographs.

- Develop sediment inflow rating curves based on tributary models or gaging station records that include sediment measurements.

6. Other considerations.
    - Bridge constrictions and geometries.
    - Ineffective flow areas around bridges and other rapid expansion and contraction areas.
    - Use of depth- or flow-variable roughness input.
7. Test the hydraulic model over a range of flow conditions.
    - Evaluate cross-sectional spacing to determine the need for interpolated cross sections.
    - Review for potential geometric input errors in reach lengths or station-elevation data in areas of appreciable change or instability in hydraulic results.
8. Calibrate and validate the hydraulic model.
    - Adjust flow resistance input values (within reasonable limits) to calibrate the hydraulic results using available data including:
        - Water-surface elevations at the time of cross-sectional survey,
        - Water-surface elevations collected at other flows,
        - Gaging station records,
        - Water level loggers at Focus Areas and other locations,
        - Discharge and velocity measurements including main channel and lateral features, and
        - High water marks reported from extreme flood events.
9. Test the sediment-transport model.
    - Conduct a sediment-transport time-step sensitivity analysis to evaluate appropriate computational time steps for different flow magnitudes.
10. Calibrate and validate the sediment-transport model.
    - Adjust sediment input values, bed layer properties, sediment-transport time step (within reasonable limits) to calibrate the hydraulic results using available data including: 1) Gage station measurements sediment loads, specific gage plots, flow area, width, depth, and velocity measurements, 2) Comparison cross sections, and 3) Longitudinal profiles.
11. Run and evaluate the results of the sediment-transport simulations.

### 3.1.2 Selection Criteria for 1-D Models

The criteria for selecting a 1-D model for this project are primarily based on required functionality given the specific conditions of the Susitna River and its tributaries. There are several desirable characteristics as well, which may influence the decision if models are otherwise similar in their capabilities and performance. The desirable characteristics include: public domain, high level of experience with the model, and advanced graphical user interface for model input and review of results.

The required characteristics include:

- The model must accommodate sufficiently large number of cross sections to model over 100 miles of river including split flow reaches.
- The model must be capable of storing sufficiently large number of hydrograph ordinates to model flows over the 50-year license period.
- The model must be capable of simulating sufficient number and range of sediment sizes to represent the range of materials.
- Sediment-transport calculations must be performed by size fraction, especially to simulate bed material sorting and armoring processes in coarse bed channels.
- The model must include either (or both) the Parker (1990) or Wilcock and Crowe (2003) bedload sediment-transport equations, as these are the most applicable to the range of coarse bed conditions in the Susitna River and tributaries.
- Closed loop sediment-transport capability must be included to model sediment transported around islands and in multiple channel reaches. This is especially common in the Lower Susitna River Segment but is also important in the Middle River.

### 3.1.3 Potential 1-D Models

The 1-D models that are being considered for this study are:

- U.S. Army Corps of Engineers' (USACE) Hydrologic Engineering Centers-River Analysis System (HEC-RAS), version 4.1.0 (USACE 2010),
- U.S. Bureau of Reclamation's Sedimentation and River Hydraulics-One Dimension (SRH-1D), version 2.8 (Huang and Greimann 2011),
- Danish Hydraulic Institute's (DHI's) MIKE 11, version 2011 (DHI 2011a),
- Mobile Boundary Hydraulics' (MBH's) HEC-6T, version 5.13.22_08 (MBH 2010), and
- U.S. Army Corps of Engineers' (USACE) Hydrologic Engineering Center-River Analysis System (HEC-RAS), version 5.0.0 (Beta release, March 2014).

#### *3.1.3.1 HEC-RAS Version 4.1.0*

HEC-RAS, version 4.1.0 (USACE 2010) is a publicly available software package developed by the USACE to perform steady flow water-surface profile computations, unsteady flow simulations, movable boundary sediment-transport computations, and water quality analysis. HEC-RAS includes a Windows-based graphical user interface that provides functionality for file management, data entry and editing, river analyses, tabulation and graphical displays of input/output data, and reporting facilities. The sediment-transport module is capable of performing sediment-transport and movable boundary calculations resulting from scour and deposition over moderate time periods, and uses the same general computational procedures that were the basis of HEC-6 and HEC-6T (USACE 1993; MBH 2010). In HEC-RAS, the sediment transport potential is estimated by grain-size fraction, which allows for simulation of hydraulic sorting and armoring. This model is designed to simulate long term trends of scour and deposition in streams and river channels that could result from modifying the frequency and duration of the water discharge and stage, sediment supply, or direct modifications to channel geometry. Benefits of the HEC-RAS software include widespread industry acceptance, public availability, and ease of use. Potential limitations of the program include excessive computer run-times, file size output limitations, and the inherent problems associated with 1-D modeling of aggradation and degradation by equal adjustment of the wetted portion of the bed that can result in unrealistic channel geometries. Another significant limitation of using HEC-RAS for this project is that it does not currently incorporate “looped” networks (split flows around islands), which are common in the Middle and Lower Susitna River segments.

#### *3.1.3.2 SRH-1D*

SRH-1D (Huang and Greimann 2011) is a publicly available, mobile-boundary hydraulic and sediment-transport computer model for open channels that is capable of simulating steady or unsteady flow conditions, internal boundary conditions, looped river networks, cohesive and non-cohesive sediment transport (Ruark et al. 2011), and lateral inflows. The hydraulic and sediment-transport algorithms in SRH-1D are similar to those in HEC-RAS 4.1.0 and HEC-6T except that it also includes the capability to perform fully unsteady sediment-transport simulations. Advantages of SRH-1D include robust algorithms for hydraulic conditions and sediment routing, including sediment sorting. Potential disadvantages include limited testing for a broad range of conditions outside the U.S. Bureau of Reclamation and the lack of graphical user interface, which complicates data input and display of output.

#### *3.1.3.3 MIKE 11*

DHI’s MIKE 11 is a commercial software package developed for 1-D dynamic modeling of rivers, watersheds, morphology, and water quality. The model has the ability to solve the complete non-linear St. Venant equations (in only the streamwise direction) for open channel flow, so the model can be applied to any flow regime. MIKE 11 provides the choice of diffusive and kinematic wave approximation and performs simplified channel routing using either the Muskingum or Muskingum-Cunge methods. The program includes a module for simulating erosion and deposition of non-cohesive sediments. Advantages of MIKE 11 include its robust hydrodynamic capabilities (though not necessarily better than HEC-RAS), the user-friendly graphical interface, and good reporting and presentation capabilities. Disadvantages primarily stem from the commercial nature of this model and associated high cost of the software license. The MIKE 11 model does not include either the Parker (1990) or Wilcock and Crowe (2003) sediment-transport equations, which are favored for simulating bed material transport and sorting processes in coarse bed channels.

#### *3.1.3.4 HEC-6T*

HEC-6T is a commercially available program that was developed by William A. Thomas, former Chief of the Research Branch at the USACE Hydrologic Engineering Center. Mr. Thomas planned, designed, wrote, and applied the publically available version of HEC-6; HEC-6T is a commercial enhancement of the original version. HEC-6T is a DOS-based program that includes a Windows-based graphical user interface for input data manipulation and post-processing of simulation results. Limitations of this program include reduced capabilities for modeling numerous ineffective flow areas as compared to HEC-RAS 4.1.0 and limited capabilities of the graphical user interface. The model uses a quasi-unsteady flow representation. Advantages of HEC-6T are its wide application experience, looped channel capability, and large number of sediment-transport equations (including both Parker and Wilcock and Crowe), sediment sizes, and hydrograph ordinates. This model includes algorithms to limit the potential for unrealistic cross-sectional geometry. Model input is limited to 5,000 cross sections, which should be more than sufficient for the analysis of the Susitna River and tributaries as an average 250-foot cross-sectional spacing, which is less than half the channel width for much of the river, would be able to cover nearly 240 miles of channel. This software is relatively inexpensive; the fact that it is commercial is not a significant limitation. The fluvial geomorphology modeling team has extensive experience with this program.

#### *3.1.3.5 HEC-RAS Version 5.0.0*

Through an agreement with staff at HEC, the HEC-RAS software, version 5.0.0 was made available for application to this Project. While the software is currently a Beta Release (March 2014), HEC plans to make it publicly available in the summer of 2014. The description for HEC-RAS version 4.1.0 (Section 3.1.3.1) also applies to version 5.0.0 with two exceptions. The new release does incorporate looped network capabilities, the exclusion of which was considered a significant limitation of the earlier version and was the reason for eliminating version 4.1.0 from use on this Project. The looped network capability, or split-flows, allows for separate reaches to be defined around islands. Flow is routed separately through each reach around an island with individual water-surface profiles, maintaining flow continuity, and balancing energy or water surface at the upstream flow split (junction). This is essential for large flow splits where water-surface elevations can differ significantly between the channels. This capability was available for steady- and unsteady-flow analyses in the earlier version of HEC-RAS, but sediment routing was not accommodated. Multiple bifurcations (secondary flow splits from primary flow splits) are supported in the hydraulic calculations but are not allowed for sediment routing. Since only major flow splits will be simulated this is not considered to be a limiting factor. Unlike HEC-6T and HEC-RAS version 4.1.0, HEC-RAS version 5.0.0 incorporates sediment routing with full unsteady hydrodynamics. This feature is desirable because flow routing effects are automatically simulated using main channel and tributary flow hydrographs without the need for additional preprocessing required in the quasi-unsteady formulations. The fluvial geomorphology team has extensive experience with the unsteady-flow and split-flow capabilities of HEC-RAS and significant experience with quasi-unsteady sediment routing, so the team experience with the combined unsteady-flow and sediment routing capability is considered moderate to high.

### 3.1.4 Selection of 1-D Model

An initial selection of the 1-D bed evolution model was presented in the original Modeling Approach TM. Subsequent to that selection, improvements in the available models has resulted in a different model being identified for the final selection. The final selected model, as described in section 3.1.4.2, has the capability to perform sediment transport modeling under unsteady flow conditions.

#### *3.1.4.1 Initial Selection of the 1-D Model*

Specific model characteristics and selection criteria are summarized in Table 3-1 along with an evaluation of each candidate model relative to the criteria. Based on the information provided above and experience with these models, the geomorphology study team will use HEC-6T for the reach-scale sediment-transport analysis. HEC-6T is capable of modeling looped networks, which eliminated HEC-RAS from consideration. It also includes both the Parker (1990) and Wilcock and Crowe (2003) sediment-transport relationships, which eliminated MIKE 11. The advantages of HEC-6T over SRH-1D include a high level of team experience with the model and its broader range of project applications. An advantage of SRH-1D is full unsteady flow analysis that can directly simulate flow attenuation. This is not an overriding consideration as quasi-unsteady analyses have been used successfully for many large rivers. The selection is supported by the modeling team's confidence that HEC-6T is capable of effectively and efficiently modeling the processes that are important for this scale of geomorphic analysis.

#### *3.1.4.2 Final Selection of the 1-D Model*

The discussion provided in the preceding section did not account for the availability of HEC-RAS version 5.0.0, which addresses the lack of looped network functionality in version 4.1.0. Run times for long-term simulations can be significant for unsteady hydraulics, but initial tests using version 5.0.0 indicate that this is not a cause of concern. Because HEC-RAS version 5.0.0 simulates sediment routing through looped networks, has the desirable feature of coupled sediment routing with unsteady-flow simulation, and has excellent graphical output capabilities, this model will be used for reach-scale fluvial geomorphology modeling unless some significant limitation is discovered during application. The model has been tested by the USACE HEC on three river/reservoir systems so this is not considered as likely. The dynamic nature will also facilitate connection between the reach-scale and local-scale 2-D models where downstream flow-stage rating curves and upstream flow and sediment hydrographs computed with HEC-RAS will be used as inputs to the Focus Area 2-D models for years 0, 25, and 50 simulations of the representative hydrologic conditions (wet, average and dry) and operation scenarios (existing conditions, maximum load following, base load, intermediate load following, and Run of River).

## 3.2 2-D Models

The 2-D models provide a much more detailed and accurate representation of the flow field than 1-D models because they predict both the magnitude and direction (in the horizontal plane) of the velocity, whereas 1-D models only predict magnitude of velocity in the downstream direction. Because the 2-D models input includes the complete bed topography at the resolution of the mesh, they also provide a more accurate representation of velocity, flow depth, and water-surface elevation throughout the model domain. In contrast, 1-D models assign a single water-surface elevation across each cross section. The velocity distribution can be estimated based on the distribution of conveyance across the cross section. The 2-D models vary water-surface elevation and distribute velocity based on the equations of motion (continuity and Newton's second law) and, therefore, account for flow conditions up- and downstream of the location of interest. As a result, 2-D models are superior in defining detailed hydraulic conditions in areas of special interest such as key habitat units.

The 2-D models are often categorized based on the solution technique and grid structure. Finite difference models use a regular grid, which simplifies the solution but limits the level of detail that can be achieved. Finite element and finite volume models use an irregular mesh that allows for more detail in areas of interest or in areas where there is appreciable variability. A subset of finite element models uses a curvilinear grid, which shares advantages and disadvantages of both regular grid and irregular mesh. For the requirements of this project, only models that use an irregular mesh are considered because of the highly variable channel and floodplain configurations (main channel, secondary channels, side sloughs, upland sloughs, tributaries, islands, and floodplains) and the need to provide accurate and detailed results for habitat evaluation.

The 2-D sediment-transport models are much more in their infancy. Publicly available 2-D sediment-transport models had very limited capability. One of the earliest available models, STUDH (McAnally 1989) could only be used to simulate a single grain-size of fine sediment for evaluating sand transport. Models with capability to simulate coarse beds and multiple grain-size analyses are much more recent.

The 2-D hydraulic models of a specific location should be developed to accurately represent the geometry (bathymetry and topography) and variability of flow resistance, with appropriate boundary conditions. The mesh should include greater detail in areas with appreciable variability in geometry, velocity magnitude, velocity direction, depth, and roughness. The required boundary conditions include downstream water-surface elevation and upstream discharge (mainstem and tributary sources). The model boundaries should be located where flow is generally one-dimensional, although this requirement is not absolute and the effects can be reduced by extending the model limits up- or downstream from the areas of interest. 2-D sediment-transport models must include from good quality hydraulic modeling capability, and they must accurately represent surface and subsurface sediments, sediment depths, erodibility, and appropriate starting and boundary conditions. 2-D models are fully dynamic, which is a requirement for sediment routing, though many can be operated in a steady state. A sediment-transport simulation routes the sediment through the network and adjusts the elevation of the grid points (nodes) due to erosion and deposition. Modeled changes in node elevations provide a feedback on the hydraulic simulation due to changes in flow depth and conveyance. Unlike 1-D models, which aggrade or degrade the wetted portion of each cross section in concert, 2-D models adjust nodes individually based on the spatial variability of velocity, depth, sediment supply, and sediment-transport capacity.

### 3.2.1 Overview of 2-D Model Development

The following steps will be followed to develop the 2-D hydraulic and sediment-transport models of the Focus Areas. The model development and application will be similar regardless of the selected model. An overview of model calibration and validation is included below. Additional information on model parameterization, calibration, validation, and sensitivity analysis will be provided in the study reports. Review and quality control procedures will be implemented throughout the model development process and are not indicated as individual steps. The steps are:

1. Determine the overall model layout.
    - Downstream boundary stage-flow conditions developed from 1-D model,
    - Upstream (i.e., inflowing) discharge and sediment supply from 1-D model, and
    - Tributary flow and sediment input from tributary models.
2. Develop geometric base data.
    - Data from TIN (Triangulated Irregular Network) surface representation from land and bathymetric survey including necessary breaklines, and
    - Data from LiDAR bare earth data set for unsurveyed island and floodplain areas.
3. Develop model network.

- Determine node and element locations and configurations to accurately represent geometry (bathymetry and topography) and changes in roughness. This may be either a network of triangular or a combination of triangular and quadrilateral elements, depending on the selected model.
- Refine the network in areas of appreciable change or areas of significant habitat interest.
- Determine the node elevations from the geometric data.
- Review mesh quality to assure that element size transitions and other modeling requirements are reasonably met. These include:
    - Increased mesh refinement where there is appreciable geometric change or where velocity magnitude or directions changes occur.
    - Identifying where additional model refinement is needed is somewhat based on experience and judgment. Large element sizes may miss large-scale flow separation (circulation) or may have numerical instabilities (oscillating or greatly changing velocities).
    - If the instabilities are too large the model will terminate. Areas of instability are easily identified in the model results and these areas will be refined.
    - The model results will also be reviewed to determine if there are currents that are not "reasonably" depicted based on experience and these areas will be refined.

4. Develop flow resistance (roughness) and turbulence stress data.

    - Channel base roughness based on bed material size.
    - Adjust base roughness to account for other sources of flow resistance such as obstructions (including LWD) and bed forms. Note: project-related changes in amounts of LWD and sediment size can be related to flow resistance values. Also note that LWD will be simulated by including large debris areas as part of the geometry.
    - Channel bank and floodplain (overbank) roughness based on land use, vegetative ground cover, and obstructions using field observations and aerial photography.
    - Turbulence stress data, such as eddy viscosity coefficients, are used to incorporate internal flow stresses. Reasonable values depend on each model's numerical representation of these stresses. ADCP data will be used to calibrate these coefficients.

5. Develop bed and bank material gradation and layer information.

    - Surface sampling,
    - Subsurface sampling, and
    - Bank material samples.

6. Develop water and sediment inflows for existing and with-project conditions.

    - For fully unsteady models, use complete flow hydrographs.
    - Steady flow simulations will be performed for habitat analysis based on the range of flows in the simulation record.

- Develop sediment inflow rating curves based on tributary models and from the 1-D reach-scale model.

7. Other considerations.
    - Ice jam breakup hydrographs.
    - Ice jam blockage of main channel or lateral features causing redistribution of flow.
    - LWD as obstructions or changes in roughness.
    - Erodibility of floodplain areas.
8. Test the hydraulic model over a range of flow conditions.
    - Further evaluate mesh quality and the need for additional mesh refinement for areas with appreciable changes in velocity magnitude or direction to adequately capture flow transitions.
9. Calibrate and validate the hydraulic model.
    - Adjust flow resistance input values (within reasonable limits) to calibrate the hydraulic results. Calibration and validation will be performed using available data including:
        - Measured water-surface elevations throughout the focus areas during site survey and water-surface elevations measured at other times.
        - Measured velocities collected using acoustic Doppler current profiler along selected cross sections and longitudinal profiles. Note that flow resistance values in 2-D models are often lower than comparable 1-D models because 2-D models directly account for processes that 1-D models must treat as lumped flow resistance parameters.
        - Water level loggers.
        - Discharge distribution between main channel and secondary channels.
        - High water mark information if available.
10. Test the sediment-transport model.
    - Conduct a sediment-transport time-step sensitivity analysis to evaluate appropriate computational time steps for different flow magnitudes. These tests identify the longest stable time-step for model applications.
11. Calibrate and validate the sediment-transport model.
    - Adjust sediment inflow rates and sizes, bed layer properties, sediment-transport time step (within reasonable limits) to calibrate the hydraulic results using available data including:
        - Main channel bed level changes observed in the 1-D modeling,
        - Comparisons of cross sections using 1980s and current data and between the 1-D and 2-D models, and
        - Longitudinal profiles.
12. Run and evaluate the results of the sediment-transport simulations.

### 3.2.2 Selection Criteria of 2-D Models

The criteria for selecting a 2-D model for this project are primarily based on required functionality based on the specific conditions of the Middle Susitna River Segment. As with 1-D models, there are also several desirable characteristics that may influence the decision if models are otherwise similar in their capabilities and performance. The desirable characteristics include: public domain, high level of experience with the model, moderate to fast execution speed, and advanced graphical user interface for model input and reviewing results. The required characteristics include:

- Capability for sufficiently large number of elements to model the Focus Areas at the required spatial resolution.
- Flexible mesh (irregular mesh) to accurately depict geometric and hydraulic variability.
- Capability to simulate a sufficient number and range of sediment sizes to represent the range of materials in each Focus Area.
- Sediment-transport calculations must be performed by size fraction, especially to simulate bed material sorting and armoring processes in coarse bed channels.
- The model must include either (or both) the Parker (1990) or Wilcock and Crowe (2003) bed-load sediment-transport equations, as these are the most applicable to the range of coarse bed conditions in the Susitna River and tributaries.
- The model must be numerically stable under a wide range of flow conditions, especially as portions of the network wet and dry.

### 3.2.3 Potential 2-D Models

Potential 2-D models that are being considered for this study are:

- U.S. Bureau of Reclamation’s SRH-2D, version 3 (Lai 2008; Greimann and Lai 2008),
- USACE’s Adaptive Hydraulics ADH, version 4.3 (USACE 2013),
- U.S. Geological Survey’s (USGS) Multi-Dimensional Surface-Water Modeling System (MD_SWMS) suite, which includes SToRM or System for Transport and River Modeling and FaSTMECH or Flow and Sediment Transport with Morphologic Evolution of Channels models (McDonald et al. 2005; Nelson et al. 2010),
- DHI’s MIKE 21, version 2011 (DHI 2011b),
- River2D modeling suite (Steffler and Blackburn 2002; Kwan 2009), and
- RiverFLO-2D model (Hydronia 2012).

#### *3.2.3.1 SRH-2D*

The U.S. Bureau of Reclamation’s SRH-2D (Lai 2008) is a finite-volume, hydrodynamic model that computes water-surface elevations and horizontal velocity components by solving the depth-averaged St. Venant equations for free-surface flows in 2-D flow fields. SRH-2D is a well-tested 2-D model that can effectively simulate steady or unsteady flows and is capable of modeling subcritical, transcritical, and supercritical flow conditions. The model uses an irregular mesh composed of a combination of triangular and quadrilateral elements. SRH-2D incorporates very robust and stable numerical schemes with a seamless wetting-drying algorithm that results in minimal requirements by the user to adjust input parameters during the solution process. A potential limitation of this software is that the mobile bed sediment-transport module is currently not publically available; however, Tetra Tech has gained permission to use the sediment-transport module on a number of other projects. Contact with the model developers indicates that permission would be granted for use in this study. The public download version of the model (Greimann and Lai 2008) includes a morphology module that calculates bedload transport capacities at each model node based on user-defined bed material sediment gradations, but does not simulate routing of that sediment and related adjustments to the channel bed. The advanced version of SRH-2D also includes a second module that uses the capacities from the morphology module to perform sediment-routing calculations and associated bed adjustments. Based on guidance from the model developers and confirmed by Tetra Tech's use of the model for other studies, the maximum practical model size is about 16,000 elements, which could be a potential limitation in applying the model to larger-scale areas. This size limitation only applies to sediment routing simulations so much more detailed networks can be developed to support habitat simulations. Another potential limitation of the model is that sediment gradations are limited to eight size fractions, though the sizes are user specified so the size-class intervals can be tailored to the site conditions. SRH-2D uses the Manning equation for flow resistance, and does not provide a mechanism to vary the Manning coefficient with depth and discharge. In some cases, such as relatively shallow flow over a coarse bed, the hydraulic roughness can vary appreciably with depth. In these cases, other flow resistance equations that incorporate the roughness height relative to the flow depth may be preferable. The program performs wetting and drying by turning on and off elements. This approach is stable for the finite-volume method. The model is publicly available, with no associated licensing cost.

#### *3.2.3.2 ADH*

The USACE ADH program was developed by the Coastal and Hydraulics Laboratory (Engineer Research Development Center) to model saturated and unsaturated groundwater, overland flow, 3-D Navier-Stokes flow, and 2-D or 3-D shallow-water, open-channel flow conditions. ADH is a depth-averaged, finite-element hydrodynamic model that has the ability to compute water-surface elevations, horizontal velocity components and sediment-transport characteristics (including simulations to predict aggradation and degradation) for subcritical and supercritical free-surface flows in 2-D flow fields. The ADH mesh is composed of triangular elements with corner nodes that represent the geometry of the modeled reach with the channel topography represented by bed elevations assigned to each node in the mesh. A particular advantage of the ADH mesh is the ability to increase the resolution of the mesh—and thereby the model accuracy—by decreasing the size of the elements during a simulation in order to better predict the hydraulic conditions in areas of high hydraulic variability. However, use of the adaptive mesh option often results in excessively long simulation run times (several days per run) that could be impractical for this study. The model uses either the Manning or roughness height flow resistance equations. Additionally, the wetting and drying algorithm in this model has significant numerical stability limitations when applied to shallow, near-shore flows that occur in rivers like the Susitna River. The ADH model does not include either the Parker (1990) or Wilcock and Crowe (2003) sediment-transport equations, which are favored for coarse bed channels and simulating armoring processes. The model is publically available.

#### *3.2.3.3 MD_SWMS/SToRM*

The USGS's MD_SWMS model (McDonald et al. 2005) is a pre- and post-processing application for computational models of surface-water hydraulics. This system has recently been incorporated into a public-domain software interface for river modeling distributed by the International River Interface Cooperative (iRIC) (Nelson et al. 2010). iRIC is an informal organization made up of academic faculty and government scientists whose goal is to develop, distribute, and provide education for the software. iRIC consists of a graphical user interface that allows the modeler to build and edit data sets, and provides a framework that links the interface with a range of modeling applications. The graphical user interface is an interactive 1-D, 2-D, and 3-D tool that can be used to build and visualize all aspects of computational surface-water applications, including grid building, development of boundary conditions, simulation execution, and post-processing of the simulation results. The models that are currently included in iRIC are FaSTMECH and SToRM, which are part of the MD-SWMS package, as well as NAYS, MORPHO2D, and a Habitat Calculator for assessing fish habitat under 2-D conditions. Of these models, SToRM is the most relevant for modeling the Susitna River for purposes of this project, primarily because it uses an unstructured triangular mesh (in contrast to the curvilinear mesh required for FaSTMECH) and provides both steady-flow and unsteady-flow capability. NAYS is a fully unsteady, 2-D model designed for a general, non-orthogonal coordinate system with sophisticated turbulence methods that can evaluate the unsteady aspects of the turbulence, and MORPHO2D is 2-D model capable of analyzing the interactions between sediment transport and vegetation and between surface water and groundwater. Both NAYS and MORPHO2D were developed in Japan, and have not been widely used or tested in the U.S. The SToRM model blends some of the features of finite volumes and finite elements, and uses multi-dimensional streamline upwinding methods and a dynamic wetting and drying algorithm that allows for the computation of flooding. Subcritical, supercritical, and transcritical flow regimes (including hydraulic jumps) can be simulated. The program includes advanced turbulence models and an automatic mesh refinement tool to better predict the hydraulic conditions in areas of high hydraulic variability. The most recent version of the SToRM model does not include the capability to model sediment-transport, but the program authors are currently working on implementing sediment-transport algorithms that may be available for use in this study (J. Nelson, pers. comm., 2012). MD_SWMS has been successfully applied to a number of rivers in Alaska, including the Tanana River near Tok (Conaway and Moran 2004) and the Copper River near Cordova (Brabets 1997); some of the modules are currently being validated using high-resolution scour data from the Knik River near Palmer. This modeling package is publicly available, with no associated licensing cost.

#### *3.2.3.4 MIKE 21*

Developed by DHI, MIKE 21 is a commercial modeling system for 2-D free-surface flows that can be applied in rivers, lakes, coastal, and ocean environments It has the ability to simulate sediment transport and associated erosion and deposition patterns. The software includes a Windows-based graphical user interface as well as pre- and post-processing modules for use in data preparation and analysis of simulation results, and reporting modules that have graphical presentation capabilities. MIKE 21 has the ability to model a range of 2-D mesh types that include Single Grid, Multiple Grid, Flexible Mesh, and Curvilinear Grid. The MIKE-21 model uses either Manning number (numerically similar to Manning n), or Chezy flow resistance equations, but does not include roughness height. Wetting and drying are element-based with a transitional condition where a layer of water is maintained on dry nodes until the element is fully dry. The model does not include either the Parker (1990) or Wilcock and Crowe (2003) sediment-transport equations, which are favored for coarse bed channels and simulating armoring processes. MIKE-21 is commercially available with a relatively expensive licensing cost compared to other available models.

#### *3.2.3.5 River2D Modeling Suite*

River2D is a 2-D, depth-averaged finite-element hydrodynamic model developed at the University of Alberta and is publically available from the university with no associated licensing cost. The River2D suite consists of four programs: R2D_Mesh, R2D_Bed, River2D, and R2D_Ice, each of which contains a graphical user interface. The R2D_Mesh program is a pre-processor that is used to develop the unstructured triangular mesh. R2D_Bed is used for editing the bed topography data and R2D_Ice is used to develop the ice thickness topography at each node for simulating ice-covered rivers. Following mesh development, the hydrodynamic simulations are run using the River2D program, which also includes a post-processor for visualizing the model output. River2D is a very robust model capable of simulating complex, transcritical flow conditions using algorithms originally developed in the aerospace industry to analyze the transitions between subsonic and supersonic conditions (transonic flow).

Many 2-D models become numerically unstable due to wetting and drying of elements; however, River2D uniquely handles these conditions by changing the surface flow equations to groundwater-like flow equations in these areas. The model computes a continuous free surface with positive (above ground) and negative (below ground) water depths, which allows the simulation to continue without changing or updating the boundary conditions, increasing model stability. The transmissivity of the subsurface flow is essential for the wetting and drying algorithm but can create surface-flow continuity issues. The model uses only roughness height for flow resistance. For some conditions, such as in vegetated banklines or floodplains, the Manning roughness equation is often preferable.

River2D also has the capability to assess fish habitat using the PHABSIM weighted-usable area approach (Bovee 1982). Habitat suitability indices are input to the model and integrated with the hydraulic output to compute a weighted useable area at each node in the model domain.

River2D Morphology (R2DM) is a depth-averaged, two-dimensional hydrodynamic-morphological and gravel transport model developed at the University of British Columbia. The model was developed based on the River2D program, and is capable of simulating flow hydraulics and computing sediment transport for uni-size and mixed-size sediment using the Wilcock-Crowe (2003) equation over the duration of a hydrograph. R2DM can be used to evaluate the changes in grain-size distributions, including fractions of sand in sediment deposits and on the bed surface. The number of size classes is set at 12 and the sediment sizes are preset in the software ranging from 0.125 mm to 256 mm. The sediment-transport module has been verified using experimental data, and was successfully applied to the Seymour River in North Vancouver, British Columbia (Smiarowski 2010). River2D is available in the most recent version of iRIC (version 2.0).

#### *3.2.3.6 RiverFLO-2D*

RiverFLO-2D is a commercial two-dimensional, depth-averaged finite-element hydrodynamic and mobile-bed model developed by Hydronia LLC. The model uses triangulated mesh (irregular grid) and efficient wetting and drying methods. The wetting and drying algorithm includes partially wet elements by assigning nodes with positive depth as zero velocity. The model used Manning equation to represent surface roughness. RiverFLO-2D is commercial at moderate cost (approximately $5,000) including the SMS interface. The model includes eight sediment-transport equations but does not include Parker (1990) or Wilcock and Crowe (2003). The sediment is represented by a single (median) particle size except for the Van Rijn equation which also includes $D_{90}$. Without a particle size gradation or multiple layers, armoring processes cannot be simulated. This is a significant shortcoming for evaluating potential Project effects. This model is commercially available.

### 3.2.4 Selection of 2-D Model

Initial model selection narrowed the potential models to two candidates, SRH-2D and River2D. After testing the two models, the final 2-D bed evolution model selection was determined.

#### *3.2.4.1 Initial Selection of the 2-D Model*

Table 3-2 provides a summary of the 2-D models, their characteristics, and limitations. Four of the six models can be eliminated based on the model selection criteria (Section 3.2.2). SToRM was eliminated as it does not currently include sediment transport. ADH, MIKE 21, and RiverFLO-2D were eliminated because they do not include either the Parker (1990) or Wilcock and Crowe (2003) sediment-transport equations and RiverFLO-2D does not include sediment gradations. Based on river conditions and project requirements, two of the models (SRH-2D and River2D) are good candidates for sediment-transport analyses related to the project. The SRH-2D model includes both of the desired sediment-transport relationships and the River2D model includes Wilcock and Crowe (2003). Other differences between the models include the method for specifying flow resistance, approach for wetting and drying of elements, and limits on model size (number of elements). SRH-2D only includes the Manning equation and River2D only includes roughness height for estimating hydraulic roughness. Because there are situations where either approach for flow resistance has advantages, this difference was not a deciding factor.

Wetting and drying is a significant issue for 2-D modeling because model instability can be significant when areas of the model are added or eliminated from the network as the water-level changes. Experience with SHR-2D indicates that it performs very well for wetting and drying in shallow areas along the margins of the channel. When the centroid of the element is dry, the element is eliminated and it is reintroduced into the network when the centroid is rewetted. River2D does not eliminate elements from the model, but converts nodes to a subsurface flow controlled by the transmissivity and storativity. Without including transmissivity, the entire mesh needs to be submerged. These parameters should be set such that the amount of flow traveling below the surface is negligible, but can be adjusted to improve transient analysis. If transmissivity is too high, surface-flow continuity could be a problem, especially for simulating low-flow conditions or when large portions of the network are “dry.”

Neither model has significant size limitations for hydraulic simulations; both can accommodate more than 100,000 elements. SRH-2D is limited to approximately 16,000 elements for sediment routing simulations, which may be a limitation for the Focus Areas. Significantly larger numbers of elements will be included for habitat simulations, as needed. Although the number of sediment size classes in SRH-2D is limited to eight, they are user specified so they can be adjusted based on site conditions. River2D has 12 size classes, but are preset in the model and sizes greater than 256 mm or less than 0.125 mm are not included. The fluvial geomorphology team has considerable experience using the SRH-2D model for both hydrodynamic and mobile boundary simulations. Other team members have experience using the ice and habitat functionality of River2D. The SRH-2D model does not compute habitat suitability indices directly, but the output can be readily used for that type of analysis with spreadsheet and GIS tools, a procedure that has been used by the modeling team for many projects. Although River2D's groundwater approach for element wetting and drying is a concern given the potential range of flows needed for sediment-transport analysis, it is not known if this will create continuity problems for the specific simulations that are required for this study. River2D will be one of the tools used for the ice processes modeling. This factor and the habitat functionality that has been incorporated directly into the model represent advantages of using River2D for the project.

Because of the uncertainty in how the models will perform, the geomorphology modeling team members recommend testing the SRH-2D and River2D models for sediment transport and habitat analysis at one Focus Area to assess their capabilities and limitations with respect to the characteristics of the Susitna River and the specific questions that must be answered by the modeling. The primary criteria for making the final model selection will center on the ability of the model to produce representative flow and sediment-transport results for existing conditions, including flow continuity, comparisons to observed velocities and depths, overall flow distribution, sediment-transport capacity, bed evolution, and armoring. Other criteria will include ease of model development, limitations on model size and spatial resolution, execution speed, and convenience performing post-run analyses. Since these models use essentially the same basic types of data, the outcome from the proposed test will not affect the data collection plan.

#### *3.2.4.2 Final Selection of the 2-D Model*

During testing of SRH-2D and River2D sediment transport simulations two limitations of River2D were identified that preclude its use for bed morphology modeling at the Focus Areas. River2D does not allow multiple sediment inflow boundaries so only main channel sediment supply can be included and tributary sediment supply is not. River2D also has limited functionality in defining the sediment input at the upstream boundary. Either a constant sediment input or a percentage of the computed transport capacity is prescribed at the inflow boundary. Because the sediment supply needs to be defined by the reach-scale modeling for the range of operational conditions, neither of these options are acceptable. SRH-2D does not have these limitations and can use a sediment rating curve, defined sediment hydrograph, or the transport capacity option as input. Therefore, the SRH-2D model was selected for mobile bed modeling of the Focus Areas.

The hydraulic modeling at the Focus Areas can be performed with either River2D or SRH-2D to provide input hydraulics for the habitat analyses performed in the Fish and Aquatics (Study 8.5) and Riparian (Study 8.6) Instream Flow Studies. The hydraulic output includes primary results of water-surface elevations, flow velocity, and flow depth, and secondary results (calculated from the primary results) such as Froude number, shear stress, and critical particle size. The Proof of

Concept hydraulic analyses were conducted with SRH-2D (Section 4.5 and Attachment A) and were used by Study 8.5 to test the interaction between hydraulic model output and habitat availability. The study team members concerned with riverine modeling and results (Fish and Aquatic IFS, Ice Processes, Fluvial Geomorphology modeling) met to decide on the 2-D modeling approach for open-water local scale modeling. It was concluded that both models would work for the habitat modeling and that neither one is superior to the other. The River2D model may be more visually appealing given its ability to portray standing water and potential groundwater sources directly, although it would still require close interaction with the groundwater lead. While SRH-2D does not explicitly depict groundwater and standing water, these sources can be incorporated into the model structure. It was concluded that SRH-2D would be used for open-water hydraulic modeling of the Focus Areas.

# 4. MODEL APPLICATION

The selected models will be used to address hydraulics, sediment transport and morphology at reach and local scales. This section describes the application of the individual models to address specific aspects of the study and the interaction between the models.

The overall river will be simulated using a 1-D reach-scale model applied to existing and with-project operation scenarios. The reach-scale model will extend from the Watana Dam (Project River Mile [PRM] 187.1) site down to Susitna Station (PRM 29.9) and will include portions of the Talkeetna and Chulitna rivers as tributary reaches. Local-scale modeling will be performed with 2-D models at each of the 10 Focus Areas. Both the reach-scale model and the local-scale models require sediment loading from tributaries, so 1-D models will be developed to simulate hydraulics and sediment-transport capacity as a basis for estimating sediment rating curves. In the Middle Susitna River Segment, sediment input will be evaluated for tributaries at the Focus Areas to evaluate delta formation, investigate potential fish barriers, and analyze habitat. The results from tributary analyses at Focus Areas will be supplemented by analyzing sediment supply from other tributaries. Some Lower Susitna River tributaries will be modeled with 1-D models to support habitat evaluation, and to develop sediment input for the reach-scale model. Not all tributaries in the Middle River and Lower River Segments will be modeled, but a sufficient range of tributary conditions will be evaluated to develop sediment input for the tributaries that are not directly modeled.

## 4.1 Models and Survey Extent

### 4.1.1 Tributary Models

As identified in Section 2.2, the 1-D reach-scale models and 2-D local-scale models require as input sediment supplied by tributaries. In the original version of this Technical Memorandum (dated June 30, 2013) 20 tributaries were selected for hydraulic and sediment transport modeling; after coordinating with the Fish Passage Barriers in the Susitna Tributaries Study and agency staff during the March 19, 2014 Fisheries Technical Meeting, Unnamed Tributary 115.4 was eliminated and 5 additional tributaries were selected (Table 4-1). The 5 additional Middle River tributaries are Chinook Creek, Fourth of July Creek, Sherman Creek, Fifth of July Creek, and Deadhorse Creek. All five are outside of Focus Areas  Chinook Creek is located within Devils

Canyon (Geomorphic Reach MR-4); the other four are located in the Middle Susitna River Segment downstream of Devils Canyon (Geomorphic Reach MR-6). Of the 24 total selected tributaries, 19 are located along the Middle Susitna River Segment and the remaining 5 are located along the Lower Susitna River Segment. The Middle River tributaries (see Figure 4-19) include short reaches in the downstream portions of the channels to determine sediment inputs to the reach-scale model. In the Lower River tributaries (see Figure 4-20), local-scale sediment-transport models will be developed for the mouth and approximately 1-mile reaches upstream to determine potential morphologic effects of with-Project scenarios and to provide sediment inputs to the reach-scale model.

### 4.1.2 Reach-Scale Model

Figures 4-1 through 4-8 show the cross sections and channel network for the Susitna River 1-D model that, as previously discussed, extends from the Watana Dam site (PRM 187.1) to Susitna Station (PRM 29.9). The figures show two types of cross sections: (1) cross sections shown in green have been surveyed, and (2) cross sections shown in red are identified for potential future surveys. The lateral extent of the cross sections approximately encompasses the 500-year floodplain. Only the below-water, in-channel areas have been/will be surveyed directly. The remaining extent has been/will be developed using detailed LiDAR data. The cross sections identified for potential future surveys represent requests compiled from the Fluvial Geomorphic Modeling Study, the Fish and Aquatics IFS (Study 8.5), and the Ice Processes (Study 7.6). Pending evaluation of intermediate model runs and further review of the need for additional cross sections by the study leads, all of the identified future cross sections may not be surveyed.

The Terrascan (Tetra Tech customized software) ground classification algorithm were used to create the bare-earth model from the LiDAR data. The bare-earth class was developed from the set of returns classified as ‘Only’ and ‘Last of Many’ by an iterative method. First, a rectangular filter was passed over the “Unclassified” points and a set of local low points was selected to seed the bare-earth class. Then all the unclassified points were compared to the triangulated surface defined by the set of bare-earth points and those that were found be close enough to fall within a certain angle and distance of the surface were added to the bare-earth class (ASPRS Class 2). The process was repeated with the expanded bare-earth class until the number of points being added to the bare-earth class declines.

The figures also show flow paths (blue lines) and junctions for flow splits and combinations. When flow splits around islands or there are significant and distinct flow paths, the model includes separate reaches. The most complex area of reaches occurs between the Yentna River confluence and PRM 44.5 (Figure 4-1). This area is quite complex from a 1-D modeling perspective; thus, some simplification was required, especially between PRMs 34 through 38.

Tributaries that are modeled only as point-source flow and sediment input do not require junctions, but tributaries that are modeled as reaches do. Tributaries that are being modeled as reaches are the Talkeetna and Chulitna Rivers. The Yentna River is being modeled as a flow/sediment input based on flow data from the upstream gage and sediment rating curves. Based on the discussion at the June 14, 2012, Water Resources TWG meeting and review comments and recommendations in the April 1, 2013, Study Plan Determination, the Three Rivers Confluence area (Susitna, Talkeetna, and Chulitna confluence) can be adequately modeled for purposes of this study with the 1-D sediment-transport model (Figure 4-4). Figure 4-4 shows (1) the cross sections that have been surveyed (green), and (2) cross sections with topography derived from LiDAR and channel geometry estimated (black). The USGS gage on the Talkeetna River reach is at the upstream limit of the survey reach (PRM 4.8), and this is the upstream extent of the model. Ten cross sections were surveyed on the Talkeetna River.

The modeled reach of the Chulitna River extends approximately 18.4 miles upstream to the USGS gage. Only two cross sections on the Chulitna River have been surveyed; the geometry of the remaining sections is based on LiDAR-derived topography and estimated channel geometry. Model topography that was developed from the LiDAR data were collected during low flows of approximately 12,400 to 13,100 cfs. The surveyed bathymetry from the lower Chulitna River were used to guide adjustments to the low-flow channel to account for the missing topography below the water surface in the LiDAR data. The LiDAR data were used to estimate water-surface slope (elevation drop over channel distance). Using slope, roughness, discharge, and flow top-width, AEA estimated the flow area and average depth at each cross section. The channel form from the surveyed cross sections were used to guide the development of the below water channel shape. This approach was feasible because the LiDAR was collected at relatively low flow when depths were shallow on this wide and braided section of the Chulitna River.

### 4.1.3 Local-Scale Focus Area Models

In addition to the large-scale 1-D model of the Middle and Lower Susitna River segments, local-scale 2-D models are also being developed for the 7 Focus Areas below PRM 146 in the Middle River for which data were collected in 2013. Data will be collected for the three additional focus areas above PRM 146. The 2-D models will be available for detailed modeling for scenarios and conditions in specific Focus Areas where the detailed 2-D modeling is warranted for determination of Project effects. It may not be necessary nor reasonable to apply the 2-D model for all scenarios at all Focus Areas. The results of the 1-D Bed Evolution model can be used to help identify the cases in which the application of the 2-D model is warranted. The 10 Focus Areas are shown in Figures 4-4 through 4-8 and are designated by the downstream PRM as FA-104 (Whiskers Slough), FA-113 (Oxbow 1), FA-115 (Slough 6A), FA-128 (Slough 8A), FA-138 (Gold Creek), FA-141 (Indian River), FA-144 (Slough 21), FA-151 (Portage Creek), FA-173 (Stephan Lake Complex), and FA-184 (Watana Dam). Each of the Focus Areas is shown in detail in Figures 4-9 through 4-18. At each of the Focus Areas, detailed survey (land and bathymetric) are being performed including the areas along the water’s edge and below water. Some floodplain survey are also being performed, but the primary topographic data source for the floodplain areas is the LiDAR data (see Section 4.1.1 for discussion of development of bare-earth model). The survey and LiDAR data are being used to generate a detailed TIN surface-representation of the area that will be the basis for assigning elevations to the nodes of the 2-D model networks.

The Riparian Instream Focus Areas (FAs) that are co-located with the geomorphology FAs (FA-104 (Whiskers Slough), FA-115 (Slough 6A), FA-128 (Slough 8A), FA-138 (Gold Creek), and FA-173 (Stephan Lake Complex)) extend into the vegetated islands and floodplain areas adjacent to the channel (Figures 4-9 through 4-18). The 2-D hydraulic and sediment-transport model will include main channel, secondary channels, sloughs, tributaries, islands and floodplains. The 2-D model limits will extend up to one channel width upstream and downstream from the Focus Area limits to reduce boundary condition effects within the primary area of interest, though in many cases the model limits will coincide with the FA limits. In most cases, surveyed cross sections are located relatively close to the Focus Area limits and can be used to extend the models. At

FA-104 (Whiskers Slough) (Figure 4-9), the 2-D model will be extend approximately one channel width up- and downstream of the FA. At FA-113 (Oxbow 1) (Figure 4-10), the model downstream boundary will be located at PRM 113.6. The upstream boundary of FA-113 (Oxbow 1) is coincident with the downstream boundary of FA-115 (Slough 6A) (Figure 4-11) and these FAs will probably be included in a single 2-D model. If the combined model is too large, then two overlapping models will be developed to provide coverage of the areas. The upstream boundary of FA-115 (Slough 6A) is suitable as the upstream model boundary.

Neither the upstream nor downstream boundary of FA-128 (Slough 8A) (Figure 4-12) is ideal, but neither can be improved significantly within a reasonable distance of the FA boundary. As a result, the model boundaries is located approximately one channel width up- and downstream to reduce boundary condition effects.

The upstream boundary of FA-138 (Gold Creek) (Figure 4-13) is suitable for 2-D modeling, but the downstream boundary is not. The model boundary was, therefore, moved downstream approximately one channel width and rotated perpendicular to flow.

The downstream model boundary at FA-141 (Indian River) (Figure 4-14) is located approximately one channel width downstream to move the boundary condition away from the mouth of Indian River. The upstream boundary is suitable as a 2-D model boundary. Both the upstream and downstream model boundaries will be located approximately one channel width from the boundaries at FA-144 (Slough 21) (Figure 4-15). The upstream boundary at FA-151 (Portage Creek) (Figure 4-16) is close to the mouth of Portage Creek, so extending the model boundary upstream is being considered, though the variable river width at this location may also present additional challenges. The downstream model boundary at FA-151 (Portage Creek) is located approximately one channel width from the FA boundary. The downstream boundary of FA-173 (Stephan Lake Complex) (Figure 4-17) is suitable for 2-D modeling and the upstream model boundary was moved approximately one-half channel width upstream. Both of the boundaries at FA-184 (Watana Dam) (Figure 4-18) are adequate for 2-D modeling, and moving either could create modeling challenges because moving the downstream boundary would put it into the Tsusena Creek delta and moving the upstream boundary would put it into a widened area with channel bars.

Eight of the Focus Areas encompass 11 tributaries including: Portage Creek, Indian River, Skull Creek, Gash Creek, Slash Creek, Whiskers Creek, and 5 unnamed tributaries (Figure 4-19, Table 4-1). Each of the tributary mouths and a nominal reach length are included in the Focus Area models to simulate delta processes and tributary bed response. The length of the reaches were determined in the field, but ranged between approximately 60 to 500 feet. Except for Portage Creek, which was inaccessible in 2013 due to land access limitations, up to five cross sections were surveyed in each tributary to develop sediment input rating curves to the Focus Area models. Determination of sediment loading from the tributaries is discussed further in the next section.

## 4.2 Tributary Sediment Supply Modeling

Hydraulic models of tributaries surveyed in 2013 have been developed using HEC-RAS software (Table 4-1, Figure 4-19, Figure 4-20). The surveyed cross sections provided needed geometric inputs. Where coupled measurements of flow and stage were available, these data were used to calibrate the simulated steady-flow water-surface profile. A range of flows for each tributary was developed to encompass the minimum and maximum hourly flows in the flow series developed for the 61-year extended flow period. These flows were input to the calibrated model to calculate associated hydraulics.

To support the preliminary 1-D bed evolution model simulations (Section 4.5.1.3.1), bed material load sediment rating curves were developed for Indian River and Gold Creek to provide for calculation of tributary sediment supply. At these two tributaries, the sampled bed material gradations were coupled with the reach-averaged hydraulic results from the HEC-RAS models to calculate sediment transport capacity. Sediment transport was measured at both tributaries during water year 1984 (Knott et al. 1986), and these measurements were compared to the calculated sediment rating curve. It was determined that the bed-load transport equation developed by Parker et al. (1982) provided the closest fit to the measurements. This procedure will be applied to the other 22 tributaries to develop bed material load sediment rating curves. As the reach-scale 1-D bed evolution model is refined, the sediment loading from the tributaries will be evaluated to confirm the transport equations provide sediment loadings that allow for balancing reach-scale sediment budgets.

## 4.3 Reach-Scale 1-D Modeling

### 4.3.1 Bed Evolution and Hydraulic Modeling

The 1-D model will be used to simulate bed evolution throughout the model domain for existing conditions and with-Project operational scenarios. Inclusion of the Chulitna and Talkeetna rivers as modeled reaches will allow direct evaluation of potential Project effects on hydraulic and sediment-transport conditions in the lower portions of these tributaries. This approach provides a more complete evaluation of potential Project effects on these tributaries than would be achieved by treating them only as point-source water and sediment inputs. For example, morphological characteristics of the Chulitna River indicate that this tributary reach is a potential sediment source or sink; treating it as a modeled reach allows for simulation of bed lowering (source) or sediment accumulation (sink). Similarly, the Talkeetna River as a modeled reach will allow simulation of changes in both water-surface elevations and channel geometry. Flow and sediment input will be based on the gaging station records and measurements for the Chulitna and Talkeetna rivers.

The 1-D modeling will compute bed and water-surface elevations, flow depths and velocities throughout the modeled reaches of the mainstem Susitna River and tributaries under each scenario. These data will provide input for evaluating habitat conditions, changes in lateral habitat connectivity, and the potential for developing barriers at tributaries. The model will also provide information to assess changes in bed material composition and effects on fine material transport (wash load) and turbidity. The model will include the transition from an extremely low sediment supply at the dam to the longitudinally increasing sediment loads through tributary inputs and entrainment of existing bed material. The results of the 1-D modeling will be also be used to evaluate changes in effective discharge, which, along with the flow-frequency analyses and potential for changes in vegetation from the riparian instream flow study, will be used to evaluate potential changes in channel width. The Riparian Instream Flow Study will provide data on area and elevation for zones of woody vegetation recruitment. These elevations will be correlated to flow recurrence, which in turn will be used to evaluate morphologic changes along the margins of the main channel, secondary channels, side sloughs, upland sloughs, and tributaries. Data from the Riparian Instream Flow Study, the Fish and Aquatics Instream Flow Study analysis of changes in hydrology operational scenarios, and 1-D sediment-transport analysis provide a basis for adjusting the channel width in the 1-D model throughout the simulation.

As noted in Section 3.1.1 (Overview of 1-D Model Development) the sediment-transport model will be calibrated based on available information. Ideally, the calibration would involve simulating an extended time period with model geometry derived from the beginning of that period and comparison of the model result as at the end of the period with current geometry. This possibility has been considered in this case because a survey was conducted in the 1980s. Ideally, the model would be run from the 1980s to present as a calibration step. However, AEA is not taking this approach because the survey data from the 1980s was deemed insufficient to develop a 1980s model. AEA will, however, will perform a 30 year run of the 1-D bed evolution model with the current geometry as the initial condition and compare the magnitude of channel change in areas where 1980s data are available. Based on this comparison, model parameters may be adjusted to provide better agreement between the documented and modeled magnitude and location of channel change over the 30 year period..

Another useful tool for assessing variability and trends in channel morphology is specific gage analyses at the long-term USGS gages. These plots are based on measurements of discharge and water-surface elevation through time. At low flow the water surface will closely track bed elevation change and the specific gage plot will identify trends and variability in bed elevation through time. Although limited by the number of available cross sections, channel bed profiles will also be used to assess the channel morphologic change since the 1980s. Although the available information may not be sufficient for a precise calibration of the sediment-transport model, it will be adequate to evaluate potential Project effects as these will be relative comparisons of Existing conditions to the simulated operational scenarios.

It is anticipated that adjustments will be made to the channel width in the with-Project scenario runs at up to five times during each simulation. Long-term width change (narrowing) is expected to occur along the Susitna River based on reductions in ~2-year recurrence interval flows for the with-Project scenarios. Using typical downstream hydraulic geometry relationships, bankfull channel width is proportional to bankfull discharge to the 0.5 power (Leopold and Maddock 1953), though other values of the exponent have been proposed. For example Parker (2010) indicates a power of 0.461 for gravel-bed rivers. A consistent flow frequency ($Q_2$) or effective discharge is used to predict the eventual equilibrium width for the new hydrologic regime.

With a target channel width determined for the new hydrologic regime, we will need to estimate the rate of width change over the 50-year license period. The rate of width adjustment may be greatest in the initial years after closure, so the time interval for simulating width change may be shorter during the initial periods of the simulation and increase with time during the simulation. The rate of width adjustment may also be limited by the supply of sediment available for deposition in the channel margins. This potential limiting factor will be checked and if necessary, the rate of width change modified. One approach for developing the width versus time relationship is the application of rate law, which is an exponential decay function (Graf 1977, Wu et al. 2012). Rate law is not a process-based approach, but is a useful relationship for describing geomorphic response due to a disturbance. We will coordinate with the other study team members and agencies to agree on an amount of channel width change expected to occur over the 50-year license period. For example, the Middle Susitna River Segment may be deemed to reach 80 percent of the ultimate width change and the Lower Susitna River Segment may reach 60 percent. The rate law equation would be used to determine the channel width for intermediate time periods. These channel widths will be imposed on the reach-scale models during the simulation and ultimately on the local-scale 2-D models for future (years-25 and -50) conditions.

The reach-scale models will be run for a 50-year period, corresponding to the length of the FERC license. This 50-year period was selected from the 61-year record in coordination with the Technical Team. The selection of the 50-year period was presented in Study 6.6 ISR Section 5.2.1 and Appendix E. AEA will incorporate at least one large, relatively rare (i.e., 50- to 100-year recurrence interval) event if one does not already occur in the selected model period. Although it is likely (64% chance) that at flood exceeding the 50-year recurrence flow is contained within any selected 50-year period, if that event is not present it could be included to account for operational effects on this flood. Similarly, there is a 40% chance of a 100-year event occurring in a 50-year period, so this event could be included for similar reasons. The final decision to include such event(s) will be coordinated with the Technical Team.

The simulation time-steps in the 1-D sediment-transport model will vary with discharge to optimize the balance between model stability and total simulation time. The length of the discharge-dependent time-steps will be determined in the early phases of the modeling through a series of tests with the initial, baseline model that will identify the maximum stable time-step for each range of discharges using procedures similar to those spelled out in USACE (1992).

In addition to simulating a long term, continuous period of flows, it will also be possible to include rare flood events associated with unusual climatic conditions or ice-jam breakup to understand conditions that form or maintain the existing habitats and how those conditions may be altered by the project. For these conditions, an appropriate time step will be determined on a case-by-case basis. For example, a time step ranging from several hours to 1 day may be appropriate for a flood event; however, the time step necessary to model breaking of an ice jam may need to be on the order of minutes.

### 4.3.2 Large Woody Debris Effects

#### *4.3.2.1 Large Woody Debris Mapping*

The effects of LWD on sediment transport and bed evolution will be evaluated using data from 2012 aerial photography to define baseline conditions, and the amounts of LWD will be reduced proportionally within each reach based on the changes in supply as a result of the Project.

The 2012 aerial photographs (1-foot pixel resolution) were used as a base to digitize existing LWD within the Geomorphic Feature classifications (Table 4-2). Portions of LWD features that extend into the listed GeomFeat polygons in the Middle and Upper River (RM 99 to RM 260) were digitized, but LWD that is contained wholly within vegetated islands (VI), additional open water (AOW) or background (BG) areas will not be digitized because these features will have little or no effect on hydraulic conditions in the channel. All wood in the Middle and Upper River (RM 99 to RM 260) are being digitized, but only a sub-sample of the wood in the Bar

Island Complex features in the Lower River is being digitized to obtain representative wood densities on these mobile features.

Individual Pieces: LWD at least 25 feet long that are wholly within, or extend into, the designated geomorphic features will be digitized as single segment line features from the root wad or thickest end (start of line) to the thinnest end of the LWD (end of line). Digitizing is being conducted on a 1:1000 scale within ArcMap. In log jams (see below), individual pieces that are over 25 feet in length and are discernible and were digitized.

The following attributes were assigned to each individual LWD feature:

RootWad (Y or N) – Is there a visible root wad, defined as visible thickened end, on the piece of LWD? (This is a judgment call because the resolution of the photos is not always sufficient to be definitive.)
Jam (Y or N) – Is the LWD contained within a log jam, defined as three or more touching pieces of visible/digitized LWD?
Local_Scr – Is the LWD definitively from a local (adjacent bank) source, generally determined to be a local source if the LWD extends perpendicular to, or at an oblique angle from, the vegetated bank into the flow (e.g., not parallel to the bank), or if the piece of large wood has the majority of the branches intact, indicating that it was not transported very far from its source.
Channel Position – The channel position of the wood will be identified in the following categories:

- BJ – Bank Adjacent – adjacent to vegetated bank at the side of a channel
- AB – Apex of Bar – at the apex of a bar
- DB – Downstream end of Bar – at the downstream end of an unvegetated bar
- SB – Side of a Bar – along the side or in the middle of an unvegetated bar
- MDC – Middle of the Channel – within the wetted channel
- HSC – Head of a Side Channel – spanning the head of a side channel
- SPC – Span Channel – spanning a small channel at a location other than the head of the channel
- BG – Biogeomorphic, e.g., contained in beaver dams

Image Date – the date of the aerial photograph image that was used for digitizing
Length (ft) – length of the piece of LWD as calculated within ArcMap from length of line feature

Log Jams: In addition to single pieces, if there are large log jams that contain small, un-differentiated pieces of wood, the area of these log jams are being digitized as a polygon feature. Single, distinguishable pieces of LWD within these polygons are being digitized as line features as described above. The following attributes are being recorded for log jam features:

RM_ID – Identifier coded as RM-XXX with XXX being sequential number in an upstream direction
Channel Position – same as used for individual pieces of wood, described above
Image Date – the date of the aerial photograph image that was used for digitizing
Area (sq-ft) of the polygon that is identified with ArcMap

#### *4.3.2.2 Large Woody Debris Modeling*

One of the objectives of the geomorphology study (AEA 2012, Section 6.5.1.1) is to "Assess Large Woody Debris Transport and recruitment, their influence on geomorphic forms and, in conjunction with the Fluvial Geomorphology Modeling Study, effects related to the Project." The geomorphology study is evaluating large woody debris sources, loading, and transport in the Susitna River. Loading from upstream and major tributaries will be evaluated for pre- and with-Project scenarios. The fluvial geomorphology modeling study will also provide input on the potential Project effects on large woody debris input. Bank erosion rates under the existing and with-Project scenarios will be evaluated using the Bank Energy Index (BEI) (Mussetter et al. 1995; Mussetter and Harvey 1996), a semi-quantitative index of the total energy applied to the channel banks. One- and 2-D modeling results will be used to compute the BEI values. The BEI values will be correlated to existing bank erosion rates at specific locations. With-Project bank erosion rates will be estimated using this correlation to estimate LWD recruitment.

At the reach-scale, large woody debris increases overall flow resistance, reduces velocity, and reduces sediment transport (Smith et al. 1993, Shields and Grippel 1995; Assani and Petit 1995; Buffington and Montgomery 1999). The cumulative drag force of debris in a particular reach will be distributed over the reach by equating area-distributed drag force to the equivalent shear stress to compute an incremental increase in flow resistance associated with the LWD (Hygelund and Manga 2003). For existing conditions, the amount of debris, type of obstruction, size, and other attributes will be used to evaluate the contribution of debris to total flow resistance. The input flow resistance coefficients will then be modified in the Project-conditions models to reflect changes in LWD due to the Project by proportioning the amounts of debris and the resulting total flow resistance based on the altered LWD supply. Depending on the relative LWD supply, effects on reach-average hydraulics may be negligible in some areas, but could be significant in others. In general, LWD supply from upstream of the dam will be eliminated by the Project, but LWD supplied from tributaries downstream from the dam will be unchanged. If bank erosion rates decrease based on the BEI analysis, then this supply will also be reduced.

Existing debris characteristics, including size, height and frequency, will be evaluated both in the field and by analyzing aerial photography, as described above. For large clusters and large individual pieces, height and size can also be evaluated using the LiDAR data.

### 4.3.3 Ice Effects

As part of the ice processes study for the Susitna River, "predictive ice, hydrodynamic and thermal modeling using River1D is planned for the Middle River between the proposed dam and the Three River Confluence near Talkeetna" (Section 7.6.3.2, AEA 2012). Additional ice-related, reach-scale modeling will be performed as part of the fluvial geomorphology modeling study. It is tentatively assumed that the existing bed material is stable (i.e., below incipient motion conditions) under ice conditions, due to reduced velocities and shear stresses associated with low river flows and the ice cover. The validity of this assumption under both existing and with-Project conditions will be tested by performing an incipient motion analysis using shear stress results from the River1D modeling. Should the results indicate that substantial sediment transport should occur at the reach scale, the 1-D model will be adjusted to incorporate appropriate rates of sediment transport for ice covered conditions. AEA anticipates this could be accomplished by extending the simulation period, and adjusting flow magnitudes and durations of the 1-D modeling to account for sediment transported under these conditions.

1-D dynamic modeling will also be performed of ice jam breakup surges to develop inflow hydrographs for 2-D dynamic models. The 1-D modeling will be performed using HEC-RAS and will be similar to dam break simulations of the rapidly released water stored above the ice jam. The 2-D simulations of ice jam surges are discussed in Section 4.3.3.

### 4.3.4 Summary of Reach-Scale Model Results

The reach-scale, 1-D modeling will provide a basis for assessing Project effects on the following issues:

- Existing status and potential Project effects with respect to dynamic equilibrium with respect to sediment transport.
- Changes in both the bed material (sand and coarser sizes) and wash (fine sediment) load under with-project conditions.
- Long-term balance between sediment supply and transport capacity, and the resulting aggradation/degradation response of the system.
- Changes in bed material mobility.
- Changes in effective discharge.
- Changes in flow distribution within multiple channel reaches.
- Project-induced changes in supply and transport of finer sediments that influence turbidity.
- Potential for changes in channel dimensions (i.e., width and depth) and channel pattern (i.e., braiding versus single-thread or multiple-thread with static islands).
- Project-induced changes in river stage due to reach-scale changes in hydrology, bed profile, channel dimensions, and hydraulic roughness.
- Characterization of the types, amounts, and features of LWD both in terms of supply of LWD and the overall effects of LWD on sediment transport and channel morphology.
- Changes in ice cover effects on sediment mobilization.
- Boundary conditions for the 2-D local-scale modeling.
- Hydraulic parameters to calculate Bank Energy Index and estimate bank erosion rates.

## 4.4 Local-Scale 2-D Modeling

The 2-D hydraulic modeling is being performed at the Focus Areas to support habitat analysis using steady flow simulation performed over the range of discharges that occur in the study reach. Sediment-transport modeling is inherently unsteady because the sediment is routed through the system and the bed deforms in response to changes in flow and sediment supply. Boundary conditions for all of the 2-D model simulations, including downstream water-surface elevations, and upstream flow and sediment supply, will be obtained from 1-D modeling results. For open-water conditions the downstream flow-stage and upstream flow-sediment supply rating curves will be developed from the 1-D sediment-transport models and upstream flow rates will be from the 1-D open-water flow routing models. For ice cover conditions AEA will develop upstream flow and downstream flow-stage boundary conditions from the River1D models developed by the Ice Processes Study.

The flexible mesh formulation that is available in the SRH-2D model is ideal for obtaining detailed results in areas of significant change or interest. Large channels require less detail than small channels, and floodplains generally require the lowest resolution because the topographic and hydraulic variability is often the lowest for floodplain areas. In developing the models, the mesh will be refined, as necessary, to capture the effects of appreciable topographic or flow resistance variability. Figure 4-21 shows an example of a fine mesh, though the level of detail is varied throughout the model domain to provide greater mesh refinement in areas of anticipated geometric or hydraulic change. An example of a coarse mesh is shown in Figure 4-22. This level of mesh resolution may be required for 2-D morphology modeling to reduce computer simulation time. For the 2-D sediment-transport models, the element sizes will be as large as practicable, but with sufficient detail to represent variability in bathymetry, topography, roughness, and bed composition.

Areas with significant habitat value will be identified by the aquatic habitat team members, and these areas will be modeled at a level of mesh resolution sufficient to describe the variability in hydraulic conditions that is necessary for the habitat analysis. Figure 4-23 is an example of the mesh requirements of the 2-D hydraulic models used for aquatic habitat analysis. Based on input from the aquatic and riparian habitat analysis teams, it is anticipated that the mesh resolution of approximately 2 m will be used in key areas of the habitat analysis. Element sizes of up to 10 m will be used for the main channel, and up to 30 m elements in floodplain areas. The element sizes will transition smoothly between these ranges to maintain good mesh quality. These general guidelines represent starting values for the spatial resolution that will be refined and adjusted as necessary throughout the model development phase. The level of mesh refinement will be determined first for hydraulic requirements and then the fine 2 m mesh will be used in areas of detailed habitat analysis. The mesh examples in Figures 4-21 and 4-22 do not fully meet the element size criteria outlined above because greater detail will be incorporated in the lateral features and habitat areas.

### 4.4.1 Bed Evolution and Hydraulic Modeling

#### *4.4.1.1 Morphology Modeling of Focus Areas*

Due to the intensive computational requirements of 2-D sediment-transport modeling and the potentially long execution times, it is not practical to run the 2-D Focus Area sediment-transport models over a multi-year time-frame. These models will be run over a select set of three seasonal hydrographs to assess river behavior during typical wet, average, and dry annual runoff seasons, and warm or cool Pacific Decadal Oscillation (PDO). If PDO significantly affected hydrology there may have been the need to identify separate wet, average and dry years for each climate condition resulting in up to six seasonal hydrographs required for 2-D Focus Area sediment transport modeling. It was determined that open water flows are not significantly affected by PDO (ISR Study 6.6, Section 5.2.1 and Appendix E Evaluation of 50-Year Simulation Period, Pacific Decadal Oscillation, and Selection of Representative Annual Hydrographs). Therefore, the three selected annual hydrographs for wet (1981), average (1985) and dry (1976) (ISR Study 8.5 Appendix J) conditions are applicable to both warm and cool PDO climate conditions for open water sediment transport analyses at the Focus Areas. The specific seasonal hydrographs were selected by categorizing each year in the 61-year extended record and selecting a representative year from each subset. The criteria for identifying the runoff categories and the specific hydrographs from each category were determined in coordination with the other study teams and agencies. Because of the nature of the 2-D model formulation, the time increment for 2-D mobile-boundary simulations is typically on the order of seconds to insure model stability; however, results are reported at longer time intervals to limit output file size.

Riparian vegetation plays a key role in the development of islands and lateral habitats, primarily by protecting surfaces from erosion and promoting sediment deposition. Vegetation can also contribute to channel narrowing by encroaching onto bars and islands, causing riverward growth of banks through trapping of sediments. Conversely, changes in the flow regime and/or ice processes can alter riparian vegetation patterns, including the extent, species composition and age-classes, providing a feedback mechanism between the processes. As a result, the influence of riparian vegetation on the morphology of the Susitna River is an important consideration in these studies. The riparian instream flow and geomorphology studies will be closely coordinated because of the interactions described above. The teams is developing an understanding of the interactions between the processes that are responsible for creation and maintenance of the islands and lateral habitats by coordinating their respective study approaches and integrating the study results. Estimates of the ages of island and floodplain surfaces from the Riparian Instream Flow Study, based on dendrochronology combined with the inundation results from the 2-D modeling, will greatly facilitate this effort by helping to identify rates of sediment deposition and reworking of these surfaces. The turnover analysis based on overlay of aerial photos from the 1950s, 1980s and current conditions will also provide quantification of existing lateral floodplain accretion and erosion rates.

The 2-D morphology modeling will include the analyses of the existing channel geometry with existing hydrology as a baseline for comparison. The existing channel geometry will then be combined with the hydrology for the range of operational scenarios. These results will be used to evaluate potential, initial Project effects on sediment transport and bed morphology, including changes in bed composition and flow distribution to lateral channels. Runs will also be performed using the projected 25- and 50-year channel geometry and with-Project hydrology. The future channel geometry will include main channel bed level changes from the 1-D model. Width change in the main channel that was incorporated in the 1-D modeling results will also be included in the 2-D models. Changes in sediment supply and downstream boundary conditions will be incorporated from the 1-D modeling. Vegetation encroachment and changes in lateral features will also be incorporated into the 2-D morphology models. These models will be run for the three seasonal hydrographs to be used in the development of the detailed hydraulic models.

#### *4.4.1.2 Hydraulic Modeling for Habitat Analysis*

Output from the 2-D hydraulic models will be provided to the habitat analysis teams in tabular (either ASCII or spreadsheets, as appropriate) format for each flow condition. The output values for the required hydraulic variables that include depth, velocity, and water-surface elevation, will be provided at each node along with the associated geo-referenced horizontal coordinates and elevations. Additional hydraulic parameters (such as Froude number and shear stress) can be computed from the output variables. These will be selected in consultation with the Instream Flow Habitat study and agencies. The range of flows will be determined in coordination with the instream flow habitat study and can be adjusted, as necessary, during the modeling phase. Habitat will be calculated at each node by combining the Habitat Suitability Criteria (HSC) for each species and life stage with the hydraulic data. The method of calculation depends on the hydraulic model used for the simulations. For the ice-covered period, the River2D model was selected for use on many habitat indices may be calculated directly, though GIS may still be required for some. For the open-water period, the focus of this Technical Memorandum, the SRH-2D model was selected and a Geographic Information System or GIS-based approach will be used to calculate habitat indices. There will be several steps required to convert the model output from hydraulic data to habitat data.

The 2-D modeling will include steady-state analyses of either the existing channel or projected future topography. Results for the existing channel topography will provide the baseline for comparison of potential Project effects. Where appropriate, the existing-conditions topography will be adjusted to represent the projected channel form at year-25 and at the end of the 50-year license period, and the models will be re-run to provide a basis for assessing Project effects. The future channel geometry in the 2-D models will include main channel bed level changes from the 1-D model. Predicted width changes in the main channel will also be incorporated, based on the 1-D model results and additional, off-line analyses that consider Project-related changes in the effective discharge analysis, riparian vegetation, and sediment supply. Projected changes in secondary channels and other lateral features will also be incorporated into the models where appropriate. Through this process, model output will be provided for the habitat analysis for existing conditions, initial, with-Project conditions associated with the change in hydrology, and the projected longer-term (50-year) changes in channel morphology combined with operational hydrology.

In summary, the geomorphic modeling will provide the following information:

Existing (year 0) geometry, vegetation, and bed composition:

- Steady-state simulations over a range of discharges, and
- Hydraulic variables including depth, velocity, and water-surface elevation tied to geo-referenced horizontal coordinates (x, y) as input to the habitat analysis.

The same output as the previous bullet for with-project operational scenarios to represent interim conditions after Project implementation, but before long-term channel adjustments.

The same output as the previous bullet based on Project future-conditions geometry, vegetation, and bed composition for with-project operational scenarios to represent conditions at year-25 and at the end of the 50-year Project license.

The future conditions 2-D models will be developed through a combination of the 1-D model results, 2-D morphology modeling results, and coordination with the other study teams and the agencies.

### 4.4.2 Large Woody Debris Effects

The data described in Section 4.2.2.1 will also be used to develop 2-D modeling scenarios to assess the effects of changes in the amount and distribution of LWD on local hydraulic and sediment-transport conditions. Projected changes in the size and location of large woody debris will be simulated by adjusting mesh resolution, bed elevations, and the relative erodibility of the affected area. If a large jam is likely to be removed or become smaller with time, the roughness would be reduced and modeled bed elevation will be lowered. The hydraulic effects of large woody debris can also be simulated by locally adjusting flow resistance without changing elevation. In either case, erosion due to the acceleration of flow around the obstruction can be simulated. This erosion is not a complete representation of the scour that can occur at large woody debris accumulations because scour is also related to vertical flow, vortices, and turbulence that are not simulated by the 2-D models. Where appropriate, the additional local scour will be estimated using scour equations developed for other applications. For example, a recently developed equation for abutment scour would be useful for evaluating scour around large log jams. This equation, described in the Federal Highway Administration (FHWA) HEC-18 bridge scour manual (Arneson et al. 2012), relates obstruction shape, bed material mobility, unit discharge upstream, and unit discharge adjacent to the obstruction to potential scour depth. The equation is conservative, as it is intended for design of bridge foundations, but the magnitude of the conservatism can also be determined (Lagasse et al. in press).

### 4.4.3 Ice Effects

Ice processes influence both the channel morphology and riparian vegetation. For example, ice can prevent vegetation from establishing on bars by annually shearing off or uprooting young vegetation. Similarly, ice can scour vegetation from the banks, increasing their susceptibility to erosion. Both of these influences can affect channel morphology. Ice jams can also directly influence the channel morphology by diverting flows onto the floodplain where new channels can form, particularly when the downstream water-surface elevations are low, allowing the return flows to headcut back into the floodplain. Ice can also move bed material that would not be mobilized under open-water conditions by rafting large cobbles and boulders.

The Geomorphology and Ice Processes studies are working together to identify the key physical processes that interact between the two. A significant portion of the influences of ice processes on morphology are directly related to their effects on riparian vegetation. The Geomorphology and Ice Process studies are also coordinating with the Riparian Instream Flow study to identify and interpret evidence of ice conditions such as ice scarring locations and elevations on trees. Additional influences of ice processes beyond the riparian vegetation issues that will be incorporated directly into the fluvial geomorphology modeling include:

- Simulation of the effects of surges from ice jam breakup on hydraulics, sediment transport and erosive forces using unsteady-flow 2-D modeling with estimates of breach hydrographs.
- Simulation of the effects of channel blockage by ice on the hydraulic and erosion conditions resulting from diversion of flow onto islands and the floodplain.
- Use of the detailed 2-D model output to assess shear stress magnitudes and patterns in vegetated areas, and the likelihood of removal or scouring.
- Use of the detailed 2-D model output to assess shear stress magnitudes and patterns in unvegetated areas, and the likelihood of direct scour of the boundary materials.
- Application of the 2-D model to investigate whether ice jams are a significant contributor to floodplain and island deposition as a result of ice jams inundating these features and causing sedimentation.

The analyses of ice-affected morphologic change will rely on observations and information from the Ice Processes Study, the Riparian Instream Flow Study, and geomorphology field work. The results of 1-D and 2-D simulations, performed by the Ice Processes Study, will also be used. The information to be developed for both existing and with-Project scenarios will include: (1) size, location, and frequency of ice jams, (2) location, extent, and duration of bank attached ice, (3) location, extent, and duration of ice blockage in main versus secondary channels, (4) model output from 1-D and 2-D ice model simulations, (5) estimates of fine-sediment concentrations during ice cover conditions, and (6) field observations of the impacts of ice movement or flow diversion on floodplain areas. The types of analyses and specific conditions to be evaluated will be coordinated with the other study teams and agencies as information from the 2013 field season is evaluated.

Although sediment transport in ice-affected conditions is not fully understood, Ettema (2010) indicates that bed-load and suspended load equations are able to represent these conditions and that for a given discharge sediment transport potential is less than for open water conditions due to reduced velocity and shear stress. He indicates that bed-load equations compared well with measurements in ice-covered conditions and that expected increases in suspended bed-material load transport, due to temperature effects on water density, viscosity, and particle fall velocity, are supported by lab and field studies. Suspended load is often supply limited, so an increase in this sediment-transport component may depend more on supply than on transport capacity. Ice jams and breakup may exert significant impact on unregulated rivers (Ettema 2010) and where water discharge fluctuates appreciably, such as during winter operation of hydropower dams, ice cover formation and presence may also have significant effects (Ettema 2010; Zabilansky et al. 2002).

The 2-D modeling will be used to evaluate the effects of altered hydrology and ice conditions on local erosion, mobilization, and sedimentation processes. The hydraulic results from the River1D and River2D modeling performed as part of the ice processes study will be reviewed to evaluate whether general mobilization of the bed is possible during ice-cover conditions.

Using ice jam breakup hydrographs, unsteady 2-D models will be used to evaluate the hydraulics and sediment transport for these dynamic flow conditions. The hydrographs will be developed with unsteady hydraulic routing using HEC-RAS modeling similar to dam-break modeling. Blackburn and Hicks (2003) provide information on simulating ice jam breakup surges and indicate that unsteady-flow, hydraulic routing is applicable to this type of simulation. The location and height of blockages created by ice dams will be determined through coordination with the Ice Processes and Riparian Instream Flow study teams. The unsteady dam break capabilities of the HEC-RAS model will be used to simulate the release of ponded water upstream of the ice dam to generate a flow hydrograph that will be input to the unsteady 2-D models when the flood wave reaches the downstream Focus Area.

Ice cover typically increases active flow area and decreases velocity and bed-load transport. Bank-attached ice can redistribute flow within a channel. As shown in Figure 4-24, in multiple channel areas, partially or completely blocked channels can redistribute flow between channels. Channel blockage can also divert flow onto islands and floodplains. Figures 4-25 through 4-31 show the locations and descriptions of ice jams in 2012 and in the 1980s. This type of information will provide a basis for selecting the FAs where additional 2-D erosion modeling will be performed to evaluate ice effects. We anticipate that three or four FAs will be selected.

Full blockage will be simulated using altered geometry and partial blockage will be modeled with a combination of altered geometry and high flow resistance. These methods will be used to evaluate erosion potential of vegetated and unvegetated areas with ice conditions. The specific locations and characteristics of ice jams will be coordinated with the other study teams and agencies.

Diversion of flow onto vegetated floodplain areas may also contribute to floodplain sedimentation. Data from winter operation of gages and other field measurements or observations will be used to estimate fine-material concentrations. Depending on the material size and type of channel blockage, the fine-material diverted onto vegetated areas may be trapped by vegetation and accumulate on the floodplain surface. The 2-D models will not simulate the accumulation directly, but the results can be post-processed to estimate rates of accumulation and floodplain accretion. This will be done by computing the unit discharge of fine sediment (unit discharge of flow times the fine sediment concentration) delivered to floodplain areas based on the proportion of Rouse-type suspended sediment profiles extending above the top-of-bank. As vegetation will trap some of this sediment, rates of accretion can be estimated. The Fluvial Geomorphology Modeling Study will work with data collected by the Riparian IFS (Study 8.6) team to evaluate historical rates of sediment accretion to validate the above analytical approach. With-Project accretion rates will be proportioned based on comparison of the expected overbank flows and sediment concentrations with existing conditions flow and sediment concentrations. This procedure will utilize the sediment delivery index (SDI) which will scale the Pre-Project sediment accretion rate developed in the Riparian IFS (Study 8.6) to estimate the post-Project sediment accretion rate based on the change in sediment load and frequency of inundation between pre- and post-Project conditions. The SDI procedure was presented at the Riparian Modelers Technical Team Meeting held meetings held 29 – 30, 2014.

### 4.4.4 Summary of Local-Scale Model Results

The local-scale, 2-D modeling will provide information on:

- Existing status and potential Project effects with respect to changing morphology in lateral features.
- Detailed hydraulic input to habitat modeling for existing and with-Project conditions.
- Changes in bed material composition.
- Changes in bed material mobility.
- Changes in flow distribution.
- Project-induced changes in supply of finer sediments into floodplains.
- Project-induced changes in river stage on delta formation at tributary mouths.
- Effects of LWD on sediment transport and channel morphology.
- Changes in ice effects on sediment mobilization, lateral features, and floodplains.
- Hydraulic parameters to estimate Bank Energy Index and bank erosion rates.

## 4.5 Summary of Hydraulic Analyses for Proof of Concept

The IFS-TT POC meetings that were completed in April 15-17, 2014 (see AEA 2014) included a demonstration of the integration between 2-D hydraulic analyses (open water and ice covered) and fish habitat analyses. These areas of integration were of significant interest because the detailed spatial information from the hydraulic analyses is combined with habitat indices in a GIS platform to determine spawning and rearing habitat availability. Other areas of spatial integration for habitat availability in the GIS software were groundwater sources and upwelling, substrate mapping, water quality and temperature, breaching flows, and bed mobilization. This section outlines the approach, summarizes the hydraulic results that are input for the habitat analyses, and provides example results for one flow condition. Detailed discussion and results are included as Attachment A of this TM.

### 4.5.1 Approach

The complete Fluvial Geomorphology Modeling approach involves reach-scale bed evolution modeling, local-scale bed evolution and hydraulic modeling, and consideration of ice effects, large woody debris effects, bank erosion and channel migration, changes in substrate composition, and channel width change through sediment deposition and vegetation colonization along channel margins. The reach-scale modeling covers a 50-year period, the local scale sediment transport modeling will be conducted for representative year hydrology at three time periods (years 0, 25, and 50), and the local-scale hydraulic modeling will be conducted for a range of steady flows representing the three time periods (years 0, 25, and 50). The reach- and local-scale models will be run for existing conditions and four operational scenarios as needed. At year zero all of the scenarios have the same bathymetry, topography, substrate, and vegetative characteristics. Therefore, at year zero the range of steady flows simulated with the hydraulic model are representative of all operational conditions. The Proof of Concept was developed to demonstrate integration between studies at year zero at one Focus Area and did not need to incorporate the sediment transport or other effects for future conditions.

The selected Focus Area was FA-128 (Slough 8A) where the hydraulic analyses were performed for a range of flows using the SRH-2D hydraulic model. The model simulated flows of 2,000, 4,000, 6,000, 8,000, 12,000, 16,000, 22,000, 30,000, and 50,000 cfs. The habitat analyses were conducted for existing conditions and an operational scenario by using the applicable hydrographs and interpolating between the hydraulic results.

#### *4.5.1.1 Model Development*

Section 3.2.1 provides an overview of the steps used for 2-D modeling development. These steps include both hydraulic and sediment transport models where sediment transport is included as additional steps. The steps, and whether they were included for the POC, are shown in detail in Attachment A and are outlined below.

1. Determine the overall layout.

   The hydraulic boundary conditions were determined but flow and sediment hydrographs were not. A stage-discharge rating curve was developed for the downstream limit of the model, which extended a few hundred feet downstream of the Focus Area boundary. Upstream flows were established as the range (2,000 to 50,000 cfs) established by the IFS Study 8.5. The upstream location was set approximately 0.7 miles upstream to better simulate flows into upland Slough 8A. A proportional discharge was set for Skull Creek tributary.

2. Develop geometric base data.

   A Triangulated Irregular Network (TIN) was developed from the bathymetric and topographic surveys combined with the LiDAR bare earth points in the overbank areas. The TIN contours were compared to aerial imagery to make adjustments to the triangulation to better depict the topography. This was very important at heads of side channels, channel bars, and in areas of beaver dams. The TIN for FA-128 (Slough 8A) was comprised of approximately 2.5 million triangles.

3. Develop model network.

The SHR-2D model is constructed of triangular and quadrilateral elements with elevations assigned at nodes located at the element corners. The goal of the model network geometry is to accurately replicate the TIN geometry. The model network has additional refinement in areas of habitat interest. The elevations of the element nodes are extracted directly from the TIN. The mesh quality depends on the characteristics of the individual elements. Large change in area between adjacent elements should be avoided as well as large numbers of elements connected to a single node. It is also desirable to avoid long thin triangles and quadrilaterals to achieve good mesh quality.

4. Develop flow resistance and turbulence stress data.

   Initial values of flow resistance (Manning n) were assigned based on channel type, presence of gravel bars, and vegetation conditions. These values were selected based on typical values found in applicable reference manuals. Standard values of the turbulence stress parameters were for the SRH-2D model were assigned.

5. Develop bed and bank material gradation layer information.

   Because this is a sediment transport requirement, this step was not necessary for the hydraulic model. The substrate information Study 8.5 were used as a comparison for initial assignment of roughness.

6. Develop water and sediment inflows for existing and with-project conditions.

   For the Proof of Concept, a range of steady flows are analyzed to support the habitat analyses. For sediment transport analyses flow and sediment hydrographs will be developed.

7. Other considerations.

   The other considerations include ice and LWD effects, which were not a consideration for the POC.

8. Test the hydraulic model over a range of flow conditions.

   The model was tested for a range of flows to identify whether additional refinement was needed. Some areas were refined based on this step and incorporated in the final model.

9. Calibrate and validate the hydraulic model.

   The model calibration was performed based primarily on water-surface elevations, velocities, and flow distributions available from the detailed ADCP data collected at FA-128 (Slough 8A). These data were supplemented with water-surface elevations (water’s edge shots) collected during the bathymetric survey and topographic surveys. Other water’s edge shots were collected by the field crews.

10. Test the sediment-transport model.

    This step was not part of the POC.

11. Calibrate and validate the sediment transport model.

    This step was not part of the POC.

12. Run and evaluate the results of the sediment transport simulations.

> Although this step was not performed for sediment-transport conditions, it was performed for the hydraulic model of FA-128 (Slough 8A). When the model results were reviewed and used for habitat analyses, areas where water was expected were shown to be dry. Slough 8A was of particular concern as it has water continuously and the model results indicated that below a main channel flow of approximately 30,000 cfs much of this slough was dry. The missing component was determined to be groundwater sources. The model was run with point sources determined from data collected by Study 8.5 and the revised models provided more realistic results in Slough 8A and other areas.

As noted above, the POC model development process is presented in detail in Attachment A. The attachment includes detailed graphical and tabular results for model calibration and model results. For alternative operational scenarios, the sediment transport model will incorporate flow hydrographs and sediment input for each scenario from the reach-scale model. For future conditions (years 25 and 50), the hydraulic model will incorporate anticipated channel change for each scenario but will be run for a range of steady flows. The future conditions sediment transport runs will incorporate channel change and flow/sediment hydrographs from the reach-scale models. The future conditions modeling will incorporate changes to the model network and roughness so steps 3 and greater will be included for future conditions models.

#### *4.5.1.2 Model Results*

The hydraulic model was run for open water conditions for flows ranging from 2,000 to 50,000 cfs. Table 4-3 shows the variables provided at each element in the model network and for each flow simulation. The SRH-2D model is a finite volume model. Although the model network is developed using elevations at the nodes located at the element corners, the model uses the element centroid as the computational point, and provides primary hydraulic of velocity and depth for each element. The water-surface elevation is the element elevation plus the depth. The model computes total shear stress from the flow and roughness conditions as part of the application of the 2-D equations of fluid motion and Froude number is a standard model output. For 2-D modeling, total shear stress includes roughness from the bed (or ground) and vegetation effects. For 1-D modeling additional effects, such as channel irregularities and sinuosity must also be included in the Manning *n*-value. To separate bed stress from the total stress used in the model, an additional calculation was performed to estimate bed stress. The velocity and depth were combined with a base Manning *n* of 0.03 was used to estimate bed stress. The equation is a combination of Manning equation (English units) and the shear stress equation, which results in:

$$\tau = \frac{\gamma}{Y^{(1/3)}}\left(\frac{Vn}{1.486}\right)^2 \qquad (4.1)$$

This equation provides identical results to the SHR-2D output when the element Manning n is used along with the point velocity and depth. Flow resistance in vegetated areas is dominated by vegetation and Manning *n*-values of greater than 0.10 are common. By substituting a Manning *n* of 0.03, the shear on the ground is separated from the drag caused by the vegetation. Both values of shear stress have meaning and were provided as output for the habitat analyses.

Although sediment transport is not being considered for the POC, bed scour is an important factor for habitat analyses. This was addressed by calculating the critical particle size based on the shear stress using Shields relationship.

$$D_{crit} = \frac{\tau}{K_s(\gamma_s - \gamma)} \tag{4.2}$$

For a specific hydraulic condition, the $D_{crit}$ value represents the largest size than could be mobilized as bed load. A Shields parameter, $K_s$, of 0.03 if often used to represent incipient motion. By using a value of 0.045 the bed is bed would be mobilized, which is more representative of scour potential in the habitat area. The remaining piece of information to determine scour is the actual particle size present at the location. This was provided by the substrate mapping performed as part of Study 8.5. The substrate size was compared to $D_{crit}$ to determine the potential for bed mobilization and scour. If the actual median particle size ($D_{50}$) is greater than $D_{crit}$, then mobilization does not occur. Conversely, if the median size is smaller than $D_{crit}$ then mobilization is occurring.

Attachment A includes more detailed description of model development, calibration, and model output over the range of discharges. For this summary, output from the 30,000-cfs run is included to spatially illustrate the hydraulic results. The 30,000-cfs flow was selected because it occurs nearly every year, and probably mobilizes much of the main channel bed (Tetra Tech 2013). Figures 4-32 through 4-37 show color-filled contour maps of the hydraulic results. Figure 4-32 is the water-surface elevation, Figure 4.33 is flow depth, Figure 4.34 is vertically averaged flow velocity, Figure 4.35 is bed shear stress, Figure 4.36 is critical particle size, and Figure 4.37 is Froude number.

The water-surface elevation plot (Figure 4-32) shows that several side channels are connected (breached) to the main channel. Slough 8A is not breached at the upper end, but has a small amount of flow from a 22 cfs point source located in the slough outside the Focus Area. The value of 22 cfs was selected using data provided by Study 8.5 and is preliminary. At the heads of side channels, the water-surface contour generally aligns perpendicular to the side channel and diagonal to the main channel. This indicates that the head of the side channel is acting as a control, which is consistent with field observations. The surveys of the side channel heads appears to be detailed enough to define the hydraulic controls, especially since the flows in the side channels were reproduced when the model results were compared with ADCP measurements (see Attachment A). This figure also illustrates significant elevation differences between the main channel and side channels. For transects that cross the channel and floodplain perpendicular to the river corridor, side channels have water-surface elevations one to four feet lower than in the main channel. For example the 578-foot contour (lower edge of the yellow color fill) shows a water surface in the main channel differing by nearly 0.5 feet from the right side of the channel to the left, this difference is maintained in the large side channel (moving further river left), and then increases to 1.5 feet in the small side channel and then to approximately 5 feet in the far left side channel downstream of Slough 8A. This illustrates the value of using 2-D modeling in the Focus Areas.

The flow depth plot (Figure 4-33) shows depths at variable contour intervals to make the figure more legible. Flow depths are generally greater than 6 feet in the main channel and less than 6 feet in the side channels. Figure 4-33 also shows the breaching discharges splitting to the side channels, all of which accumulate in the channel along the left side of the floodplain. Near the downstream boundary, the side channel has collected sufficient flow that the total flow is conveyed approximately equally between the two branches, though the water surface in the two branches differs by as much as a foot (Figure 4-32). There is approximately 15,500 cfs in the right channel compared to approximately 14,500 cfs in the left channel. For flows less than

30,000 cfs more flow is conveyed in the right channel and by 50,000 cfs more flow is conveyed in the left channel (as shown in Attachment A).

Figure 4-34 shows the velocity contours, also at intervals selected to improve legibility. The main channel and primary side channel have velocities greater than 6 ft/s, except along channel margins and the large mid-channel bar where velocities are less than 5 ft/s. The smaller side channels have velocities less than 6 ft/s with considerable areas less than 3 ft/s. Slough 8A has velocities predominantly less than 1 ft/s with some areas slightly greater than that value.

Figure 4-35 shows shear stress. As shown in Equation 4.1 shear stress is dominated by velocity and roughness, so where velocity is high shear stress is high. In the commonly referenced shear stress equation, $(\tau = \gamma YS)$, the slope term for gradually varied flow is energy slope, which is a function of depth, velocity and roughness. Therefore, the highest shear stress values correlate to high velocities. Although high velocity tends to occur in deep areas of the main channel, it also occurs in shallower, steep areas in other channels. Quite low values of shear stress occur in many of the side channels and especially in Slough 8A.

From Equation 4.2, $D_{crit}$ is directly proportional to shear stress. Because sediment sizes range over orders of magnitude, $D_{crit}$ is plotted in Figure 4-36 in mm using the Phi scale. The critical size in the in the main channel is between 32 and 64 mm. The measured $D_{50}$ of surface materials on bar and island heads in the middle river ranged from approximately 40 to 80 mm and the $D_{50}$ of the subsurface materials ranged from 20 to 45 mm. This indicates a likelihood of main channel bed mobilization at this flow if the bar/island heads are representative of the main channel. Additional data have been collected as part of winter sampling to better quantify main channel bed materials that are not directly measurable during open-water flow conditions. Critical particle sizes are much smaller in the side channels. Bed mobilization and scour is still possible in these channels depending on the sizes of the materials present. This is done by comparing the substrate mapping to the $D_{crit}$ size as part of the habitat analyses in Study 8.5.

Figure 4-37 shows Froude number over the model domain. Froude number is proportional to velocity and inversely to the square root of depth. As is expected in this relatively steep system, the Froude number in larger channels is around 0.6. In backwater areas with flat energy slopes and low velocities the Froude numbers drop to 0.3 and less. High Froude numbers, 0.8 to 1.1, occur at some side channel heads indicating that the channel head geometry is controlling flow into side channels at 30,000 cfs. The high Froude number at the upstream boundary results from approximate geometry in the area outside the Focus Area and illustrates the need to move boundaries outside the area of interest.

In addition to the model development and calibration information, Attachment A includes results from the range of flows run and supplied to Study 8.5. The results focus on flow depths and breaching flows to illustrate the changing hydraulic conditions throughout the Focus Area. The series of models provide reliable hydraulic conditions throughout the range of Focus Area channels and sloughs.

From the standpoint of hydraulic modeling, a major lesson learned from the POC is the need to account for other flow sources. The Skull Creek tributary is an obvious source of flow and sediment. Slough 8A has a persistent groundwater source that was incorporated into the SRH-2D model as a point source. Additional point sources (or sinks) can be included at other locations in the model domain if needed. For the 30,000-cfs run, only one source was included. For illustration purposes, other simulations shown in Attachment A include point sources at one up to two locations. If subsurface flows are identified for individual habitat areas, flows of less than 1 cfs can be introduced in the SRH-2D model and the local influence on habitat a can be addressed. As a finite volume model, SRH-2D is extremely well-suited for this type of analysis as these minor flow contributions can be tracked through the channel network, though including their local influence on habitat is the primary value.

### 4.5.1.3 Development of Bed Morphology Models

Although sediment-transport analyses were not a required component of the POC, the reach-scale morphology model below Watana Dam and the local-scale morphology model of FA-128 (Slough 8A) have progressed following the model development procedures outlined in Sections 3.1.1 and 3.2.1.

#### 4.5.1.3.1 1-D Bed Morphology Model

The reach-scale model work has progressed through Step 9 (Section 3.1.1): testing the sediment-transport model. Although the model is not fully calibrated hydraulically, preliminary hydraulic calibration and initial tests of the sediment-transport model have been conducted to evaluate the performance of HEC-RAS version 5.0.0. Testing has focused on the unsteady sediment-transport routine, coupled with split flow (closed loop) networks. The model has been run for a 10-year simulation with preliminary bed sediment gradations, inflow hydrographs, and inflow sediment relationships. The model is showing minor bed fluctuation as is consistent with comparisons between the 1981 cross section surveys and the 2012/2013 surveys. The simulation time is not excessive, and can be affected appreciably by adjusting the desired computation increment. The sediment model runs have highlighted some areas where hydraulic calibration can be improved, and these improvements are underway. Based on these preliminary results, HEC-RAS version 5.0.0 appears well suited for the reach-scale modeling.

#### 4.5.1.3.2 2-D Bed Morphology Model

Similar efforts have been made using SRH-2D for bed morphology modeling of FA-128 (Slough 8A). The effort has progressed through Step 10 (Section 3.2.1): testing the sediment-transport model. The sediment-transport model has approximately 16,000 elements compared to approximately 260,000 in the hydraulic model. The hydraulic model calibration is actually quite similar because much of the mesh refinement in the hydraulic model is required for detailed habitat analysis and is not a hydraulic necessity. The model has been tested using a 3-month portion of the representative year (1981) hydrograph including the peak flow of approximately 60,000 cfs. The sediment input includes initial rating curves for the range of sediment sizes and bed surface and subsurface gradations have also been input. The model will require approximately 5 days to simulate a 6 month open-water flow period, which was the anticipated time frame. Based on these initial results it appears that the SRH-2D bed morphology model will be capable of executing representative year pre- and post-Project conditions for the open water portion of the year in a reasonable time frame.

To perform the sediment-transport modeling, a sediment-transport rating curve and representative bed material gradations were developed and input to the model. An initial sediment transport versus discharge rating curve was developed based on the USGS sediment-transport measurements and representative sediment gradations for a range of discharges. The surface and subsurface bed material gradations were developed using the sediment samples collected in 2013 and the habitat mapping developed as part of ISR 8.5. The sediment-transport model was run over a 3-month portion of the representative year (1981) hydrograph which has a peak flow of approximately 60,000 cfs.

The initial results indicate that the predicted magnitude and patterns of aggradation/degradation match the field observations reasonable well. In addition, the model is predicting reasonable (realistic?) changes in bed material gradation over the duration of the hydrograph. These initial results indicate that the SRH-2D model is an appropriate tool for predicting changes in channel geometry.

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# 5. CONSULTATION DOCUMENTATION

The draft version of this document was made available for review on May 3, 2013 and the material was presented at a Technical Team Meeting on May 21, 2013. The minutes from the meeting were posted on June 4, 2013. The draft document, presentation, minutes, and comments (Agency and public comments with responses) are all available on the Susitna-Watana public website (www.susitna-watanahydro.org). The following additions, clarifications, and corrections to the draft document have been made in this version based on the discussions at the May 21, 2013 meeting and comments received:

Section 1.1 Background

- Expanded discussion of dynamic equilibrium of the Susitna River
- Expanded discussion of connections and objectives of the geomorphology and fluvial geomorphology modeling study components
- Introduction to simulation scales for reach- and local-scale models for main channel, side channels, other lateral features, islands, floodplains, and aquatic habitats

Section 1.2 Objectives

- Inclusion of objectives for the Three Rivers Confluence reach-scale modeling

Section 2.2 Comprehensive Modeling Approach

- Section added to discuss connections between the types of modeling that will be conducted as part of the fluvial geomorphology modeling study
- New table added (Table 2.2) that illustrates model connections, input requirements, and how results will be used by subsequent models
- Discussion of how morphologic change may need to be incorporated by other study components

Section 3.1.3.2 SRH-1D

- Corrected the number of sediment size classes

Section 3.2.1 Overview of 2-D Model Development

- Clarification of how model refinement will be related to appreciable change in velocity

Sections 3.2.3.1 SHR-1D, 3.2.3.5 River2D, and 3.2.4 Selection of 2-D Model

- Correction of number of sediment sizes in SRH-2D, River2D and related discussion

Section 4.1.2 Reach Scale Model (survey)

- Identification of cross sections that are prioritized for survey in 2013
- Discussion of how LiDAR will be used to develop channel cross sections in the Chulitna River
- Figures 4-1 through 4-11 (Figures 4-1 through 4-8 in this revised Technical Memorandum) updated to show 2013 high priority sections and low priority sections

Section 4.2 Tributary Modeling

- Expanded discussion of how some tributary deltas will be simulated with site-specific 1-D models

Section 4.3.1 Bed Evolution and Hydraulic Modeling (1-D)

- Discussion of how comparison cross sections, channel profiles, and specific gage analyses will be used for model calibration
- Discussion of suitability of the 1980s survey data for morphology modeling
- Discussion of how changes in channel width will be simulated over the 50-year license period
- Expanded discussion of potentially including 50- and/or 100-year events into the simulation alternatives

Section 4.3.3 Ice Effects

- Expanded discussion of how ice effects could be included in 1-D morphology model simulations

Section 4.4 Local-Scale 2-D Modeling

- Discussion of using 1-D model results to develop 2-D Focus Area boundary conditions and channel geometries
- Expanded discussion of mesh refinement for aquatic habitat requirements and inclusion of new figure (Figure 4-26, Figure 4-23 in this revised Technical Memorandum) illustrating the habitat areas

Section 4.4.1 Bed Evolution and Hydraulic Modeling (2-D)

- Reordered sub-sections so the order matches the order of modeling tasks
- Included Pacific Decadal Oscillation as a hydrologic condition that will be addressed
- Included year-25 as a time period for Focus Area morphology and hydraulic modeling

Section 6 References

- Added references related to channel width change

Section 7 Tables

- Table 2.2 (also Table 2.2 in current TM); added to illustrate connections between types of morphology models and results used by other study components
- Tables 3.1 and 3.2 (Table 3.1 revised in current TM to include HEC-RAS ver. 5.0.0); corrected for number of sediment size classes in SRH-1D, SRH-2D, and River2D
- Table 4.1 (Table 4.1 has been revised in current TM to include additional tributaries based in coordination with Study 9.12 and March 19, 2014 Technical Team meeting input from agencies and identify tributaries surveyed in 2013); added note about which tributaries will have data collection in 2013

Section 8 Figures

- Updated Figures 4-1 through 4-11 to show prioritized cross section surveys in 2013 (Figures 4-1 through 4-8 in this revised Technical Memorandum updated to differentiate cross sections with existing surveys (2012 and 2013) from cross sections proposed for survey (2014 and 2015) from cross sections where LiDAR topographic mapping is coupled with estimates of channel geometry)
- Updated Figure 4-11 (Figure 4-4 and 4-5 in this revised Technical Memorandum) showing cross sections on the Chulitna River that will be developed with LiDAR
- Updated Figures 4-12 through 4-21 (Figures 4-9 through 4-18 in this revised Technical Memorandum) to show habitat types at the Focus Areas
- Updated Figure 4-22 (Figure 4-19 in this revised Technical Memorandum) to show riparian focus areas based on current information
- Included new figure (Figure 4-26, Figure 4-23 in this revised Technical Memorandum) added to illustrate mesh detail requirements for aquatic habitat analyses
- Figure numbers incremented for subsequent figures

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# 7. TABLES

**Table 2-1. 1-D versus 2-D model capabilities.**

| Consideration | 1-D Models | 2-D Models |
|---|---|---|
| Sediment balance | Reach-scale | Local-scale |
| Aggradation/degradation response | Reach-scale | Local-scale |
| Changes in bed material gradation | Reach-scale | Local-scale |
| Sediment accumulation at slough mouths / localized deposition | | X |
| Bed material mobilization | X | X |
| Effective discharge | X | |
| Flushing of fines from side slough habitats | | X |
| Complex flows in floodplain and potential erosion | | X |
| Frequency and duration of overbank flooding | Reach-scale | Local-scale |
| Distribution of flow and flow patterns between channel features | Larger side channels | X |
| Distribution of flow between channel(s) and floodplains | X | X |
| Transverse hydraulic gradients | | X |
| Bed deformation (distributed aggradation and degradation) | | X |
| Ice effects on sediment mobilization and erosion | Reach-scale | Local-scale |
| Large woody debris effects | Reach-scale | Local-scale |

**Table 2-2 Model input and results for various study aspects.**

| Modeling Task | Input and Results | Hydrology | Sediment | Hydraulics | Channel & Floodplain Geometry |
|---|---|---|---|---|---|
| 1-D Tributary Sediment Modeling | Input | Range of steady flows | Bed material from site samples | Site-specific D/S stage-discharge | Existing at T = 0 (yr-0)[3] |
| | Results for: | Results for range of steady flows to develop sediment rating curves at mouth of each tributary | | | |
| | 1-/2-D Morph. | | trib. sediment rating curves | | |
| | Aquatic Habitat | | | V, D, WSE some trib. mouths | barrier/delta change some tribs. |
| | Other studies | | | | |
| | | | | | |
| 1-D Reach-Scale Morphology Modeling | Input | 50-yrs Existing & OS[1] | Existing & OS[2] | stage-discharge at Susitna Sta. | Existing at T = 0 (yr-0)[3] |
| | Results for: | Results for continuous 50-year simulations throughout 1-D modeling domain | | | |
| | 2-D Morphology | | U/S sed. rating curves at FAs | D/S stage-discharge at FAs | main channel change |
| | 1-D Ice | | | stage-discharge at 3-Rivers | main channel change[4] |
| | Flow Routing | | | | main channel change[4] |
| | Aquatic Habitat | | substrate change[4] | stage-discharge relationships | main channel change[4] |
| | Riparian Habitat | | sediment supply to overbanks | stage-discharge relationships | bar/island/floodplain change |
| | | | | | |
| 2-D Local-Scale Morphology Modeling | Input | <1-yr wet, avg., dry with PDO, Existing & OS[1] | U/S sed. rating curves at FAs for yrs-0,25,50 for Existing & OS[5] | D/S stage-discharge at FAs for yrs-0,25,50 for Existing 3 OS[5] | Existing (yr-0)[3], yrs-25,50[5] in main channel |
| | Results for: | Results for range of <1-yr simulations throughout FA modeling domain | | | |
| | 2-D Hydraulic | | bed material gradation change[4] | | lateral feature trends |
| | 2-D Ice | | | | lateral feature trends[4] |
| | Flow Routing | | | | |
| | Aquatic Habitat | | substrate change[4] | | barrier/delta change |
| | Riparian Habitat | | sediment supply to overbanks | | bar/island/floodplain change |
| | | | | | |
| 2-D Local-Scale Hydraulic Modeling | Input | Range of steady flows[6] | Bed material gradation change[7] | D/S stage-discharge at FAs for yrs-0,25,50 for Existing & OS[5] | Existing (yr-0)[3], yrs-25,50 main channel[5] and lateral features[7] |
| | Results for: | Results for range of steady flows throughout FA modeling domain | | | |
| | Ice, Flow Routing | | | | |
| | Aquatic Habitat | | | V, D, WSE, etc. throughout FAs | |
| | Riparian Habitat | | | V, D, WSE, etc. throughout FAs | |

Notes:

1 From flow routing study.
2 From gage data, sediment transport study, and reservoir sedimentation study.

3 From hydrographic survey, land-based survey, and LIDAR. (Survey by Tetra Tech for tributaries.)
4 Only if magnitude of change is sufficiently large to warrant inclusion in other study aspects.
5 From 1-D Reach-Scale morphology models.
6 From habitat study requirements.
7 From 2-D Local-Scale morphology modeling trends.

**Table 3-1. Evaluation of 1-D models**

| Model Characteristics and Evaluation Criteria | Models | | | | |
|---|---|---|---|---|---|
| | HEC-RAS V4.1.0 | SRH-1D | MIKE 11 | HEC-6T | HEC-RAS V5.0.0 |
| **General** | | | | | |
| Commercial/cost (if applicable) | ○ | ○ | ● / $8,000 | ● / $3,000 | ○ |
| Full or quasi unsteady for sediment transport simulation | Quasi | Both | Full | Quasi | Both |
| Ice for fixed bed | ● | ○ | ○ | ○ | ● |
| Ice for moveable bed | ● | ○ | ○ | ○ | ● |
| # of transport equations supported | 7 | 13 | 10 | 18 | 8 |
| Supports user defined transport equation | ○ | ○ | ○ | ● | ○ |
| Closed loop capability | ○[1] | ● | ● | ● | ● |
| Experience with model: High (H); Moderate (M); Low (L) | H | L | M | H | M-H |
| **Model Size Limitations** | | | | | |
| # of cross sections | NL | NL | NL | 5,000 | NL |
| # of hydrograph ordinates | 40,000 | NL | NL | NL | NL |
| # of sediment sizes | 20 | NL | NL | 20 | 20 |
| **Sediment Sizes Supported** | | | | | |
| Wash load (silts, clays) | ● | ● | ● | ● | ● |
| Considers settling and resuspension | ● | ● | ● | ● | ● |
| Sand | ● | ● | ● | ● | ● |
| Gravel and cobble | ●W | ●P,W | ● | ●P,W | ●W |

Notes: ● = Yes; ○ = No; NL = No Limit
P = Parker (1990), W = Wilcock & Crowe (2003) sediment transport relations
[1] Not currently available, but in development.

**Table 3-2. Evaluation of 2-D models**

| Model Characteristics and Evaluation Criteria | Model | | | | | |
|---|---|---|---|---|---|---|
| | SRH-2D | ADH | SToRM | MIKE 21 | River2D (R2DM) | River FLO-2D |
| **General** | | | | | | |
| Commercial/cost (if applicable) | ○ | ○ | ○ | ● / $20k | ○ | ● / $5k |
| Unsteady flow capability | ● | ● | ● | ● | ● | ● |
| Ice for fixed bed | ○ | ● | ○ | ● | ● | ○ |
| Ice for moveable bed | ○ | ● | ○ | ● | ● | ○ |
| Number of transport equations supported | 4 | 2 | ○[1] | 10 | 2 | 8 |
| Supports user defined transport equation | ○ | ● | ○[1] | ● | ○ | ● |
| Relative execution speed: Fast (F), Moderate (M), Slow (S) | M | S | F | F | M | F |
| Model stability: High (H), Moderate (M), Low (L) | H | M | M | H | H | H |
| Experience with model: High (H), Moderate (M), Low (L) | H | M | L | L | M | L |
| Mesh Wetting and Drying Approach: Element (E), Node/Partial (N), Sub-Surface (S) | E | N | N | E | S | N |
| Roughness Equation: Manning n (n), Chezy (C), roughness height ($K_s$), drag coefficient ($C_d$, $C_d \alpha 1/C^2$) | n | n, $K_s$ | $C_d$, $K_s$ | n, C | $K_s$ | n |
| Moveable boundary simulation | ● | ● | ○[1] | ● | ● | ● |
| **Grid Structure/Model Formulation** | | | | | | |
| Finite element (FE)/Finite Volume (FV) | FV | FE | FV/FE | FV/FE | FE | FE |
| Grid structure: Flexible Mesh (FM) | FM | FM | FM | FM | FM | FM |
| **Model Size Limitations** | | | | | | |
| # of grid elements for sediment routing, (U = unlimited) | 16k[2] | U | ○[1,3] | U | >100k | >100k |
| # of sediment sizes (NS = not specified in documentation) | 8 | NS | ○[1] | NS | 12 | 1 |
| **Sediment Sizes Supported** | | | | | | |
| Wash load (silts, clays) | ○ | ● | ○[1] | ● | ○ | ○ |
| Considers settling | ○ | ● | ○[1] | ● | ○ | ○ |
| Sand | ● | ● | ○[1] | ● | ● | ● |
| Gravel and cobble (P = Parker, W = Wilcock & Crowe) | ● P,W | ● | ○[1] | ● | ● W | ● |
| Sediment Gradation/Multiple Layers/Armoring | ● | ● | ○[1] | ● | ● | ○ |

Notes: ● = Yes; ○ = No;

[1] Not currently available, but in development.

[2] >100k elements for hydraulic modeling,

[3] Unlimited for hydraulic modeling.

**Table 4-1 Tributaries selected for modeling.**

| Tributary Name | PRM | Entering Bank | Geomorphic Reach | Focus Area | Selected in 2014 |
|---|---|---|---|---|---|
| Tsusena Creek | 184.6 | RB | MR-2 | | |
| Fog Creek | 179.3 | LB | MR-2 | | |
| Unnamed | 174.3 | LB | MR-2 | FA-173 | |
| Unnamed | 173.8 | RB | MR-2 | FA-173 | |
| Chinook Creek | 160.5 | LB | MR-4 | | X |
| Portage Creek | 152.3 | RB | MR-5 | FA-151 | |
| Unnamed* | 144.6 | LB | MR-6 | FA-144 | |
| Indian River* | 142.1 | RB | MR-6 | FA-141 | |
| Gold Creek* | 140.1 | LB | MR-6 | | |
| Fourth of July Creek | 134.3 | RB | MR-6 | | X |
| Sherman Creek | 134.1 | LB | MR-6 | | X |
| Skull Creek* | 128.1 | LB | MR-6 | FA-128 | |
| Fifth of July Creek | 127.3 | RB | MR-6 | | X |
| Deadhorse Creek | 124.4 | LB | MR-6 | | X |
| Lane Creek* | 117.2 | LB | MR-7 | | |
| Gash Creek* | 115.0 | LB | MR-7 | FA-113 | |
| Slash Creek* | 114.9 | LB | MR-7 | FA-113 | |
| Unnamed* | 113.7 | LB | MR-7 | FA-113 | |
| Whiskers Creek* | 105.1 | RB | MR-8 | FA-104 | |
| Trapper Creek* | 94.5 | RB | LR-1 | | |
| Birch Creek*[1] | 92.5 | LB | LR-1 | | |
| Sheep Creek | 69.5 | LB | LR-2 | | |
| Caswell Creek | 67.0 | LB | LR-2 | | |
| Deshka River* | 45.0 | RB | LR-3 | | |

Notes: *Tributaries analyzed in 2013.

[1] Not surveyed in 2013 due to lack of access from private landowner.

[2] Unnamed Tributary 115.4 was excluded from modeling based on 2013 observations of the absence of a depositional fan at the tributary mouth and the disconnection of the mouth from the main channel.

**Table 4-2. Large woody debris digitizing within geomorphic features.**

| Geomorphic Feature Code | Description | Lower River | Middle River | LWD Digitized? |
|---|---|---|---|---|
| MC | Main Channel | X | X | Yes |
| EXP MC | Exposed Substrate Main Channel | | X | Yes |
| SC | Side Channel | X | X | Yes |
| EXP SC | Exposed Substrate Side Channel | | X | Yes |
| SCC | Side Channel Complex | X | | Yes |
| BIC | Bar Island Complex | X | | Sub-sample[1] |
| BAB | Bar/Attached Bar | X | | |
| SS | Side Slough | X | X | Yes |
| EXP SS | Exposed Substrate Side Slough | | X | Yes |
| US | Upland Slough | X | X | Yes |
| EXP US | Exposed Substrate Upland Slough | | X | Yes |
| TR | Tributary | X | X | Yes |
| EXP TR | Exposed Substrate Tributary | | X | Yes |
| TD | Tributary Delta | X | | Yes |
| TM, MCTM, SCTM, TRTM | Tributary Mouth (Main Channel, Side Channel, Tributary) | | X | Yes |
| VI | Vegetated Island | X | X | No |
| AOW | Additional Open Water | X | X | No |
| BG | Background | X | X | No |

Notes:

1 Due to the high number of pieces of large wood on the Bar Island Complex features in the lower river, the large area of Bar Island Complex, and the likely transient nature of the wood here, these areas will be sub-sampled to obtain a density of large wood and log jams. The density of wood features will be apportioned over the total area of Bar Island Complex to estimate total wood loading.

**Table 4-3. Summary of SRH-2D model output provided to the IFS Study 8.5.**

| Parameter | Parameter Description |
|---|---|
| Point_ID | Element ID |
| Area_ft^2 | Area of element (square ft) |
| Centroid_X_ft | Easting coordinate of element centroid (ft) |
| Centroid_ Y_ft | Northing coordinate of element centroid (ft) |
| Bed_Elev_ft | Elevation of element centroid (ft) |
| Water_Elev_ft | Water-surface elevation (ft) |
| Water_Depth_ft | Water depth (ft) |
| Vel_X_ft_p_s | Velocity component in the X-direction (ft/s) |
| Vel_Y_ft_p_s | Velocity component in the Y-direction (ft/s) |
| Vel_Mag_ft_p_s | Velocity magnitude (ft/s) |
| Froude | Froude number |
| Strs_lb_p_ft2 | Shear Stress (lb/ft$^2$) |
| Dcrit_mm | Particle size of incipient motion (mm) - Shields Parameter = 0.045 |
| Bed_Strs_lb_p_ft2 | Bed Shear Stress (lb/ft$^2$) |
| Dcrit_Bed_Strs_mm | Particle size of incipient motion from bed shear stress (mm) - Shields Parameter = 0.045 and Manning n of 0.03 |

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# 8. FIGURES

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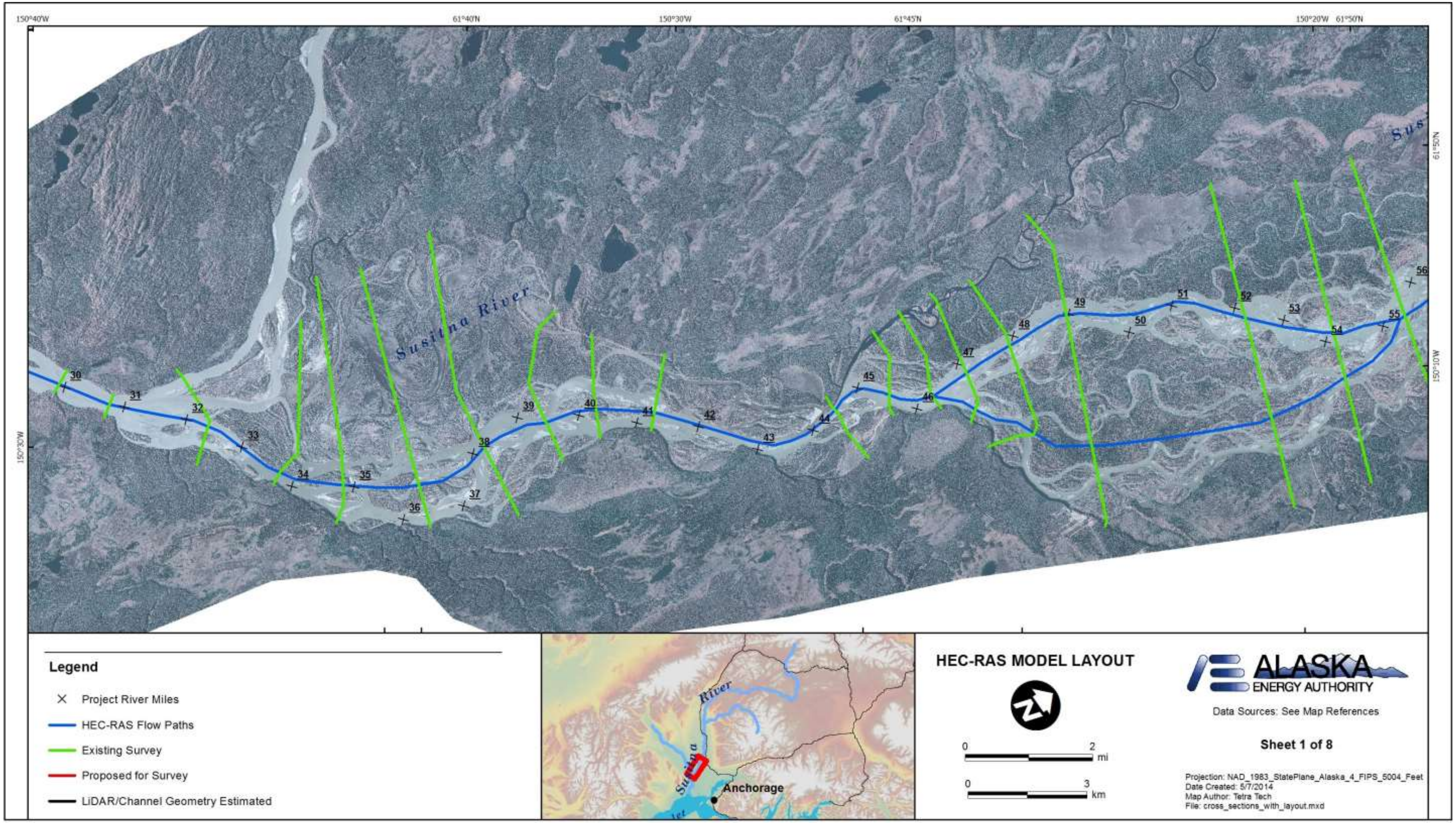


**Figure 4-1. Survey and Model Cross Sections from PRM 30 to PRM 56.**

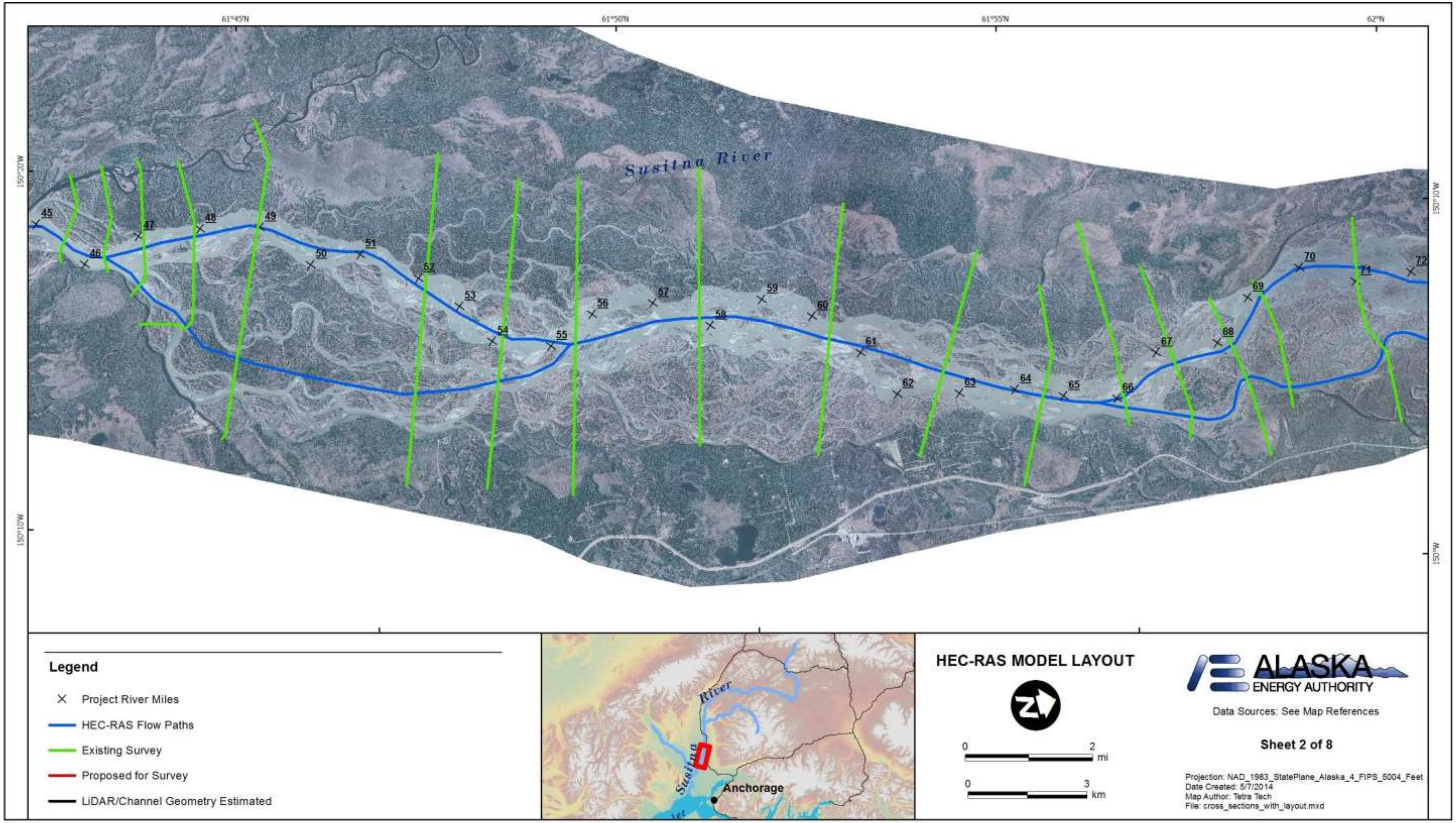


**Figure 4-2. Survey and Model Cross Sections from PRM 45 to PRM 72.**

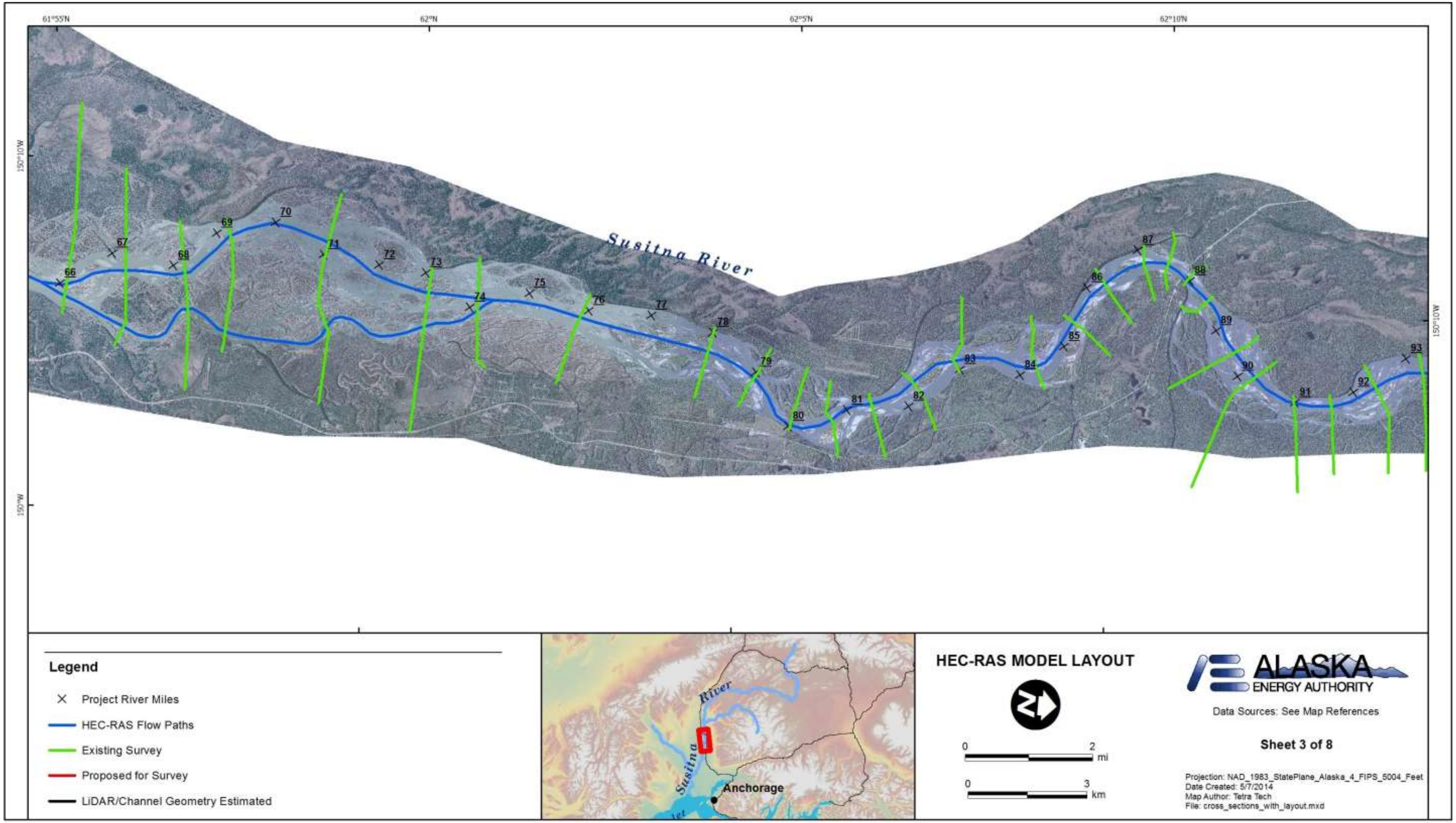


**Figure 4-3. Survey and Model Cross Sections from PRM 66 to PRM 93.**

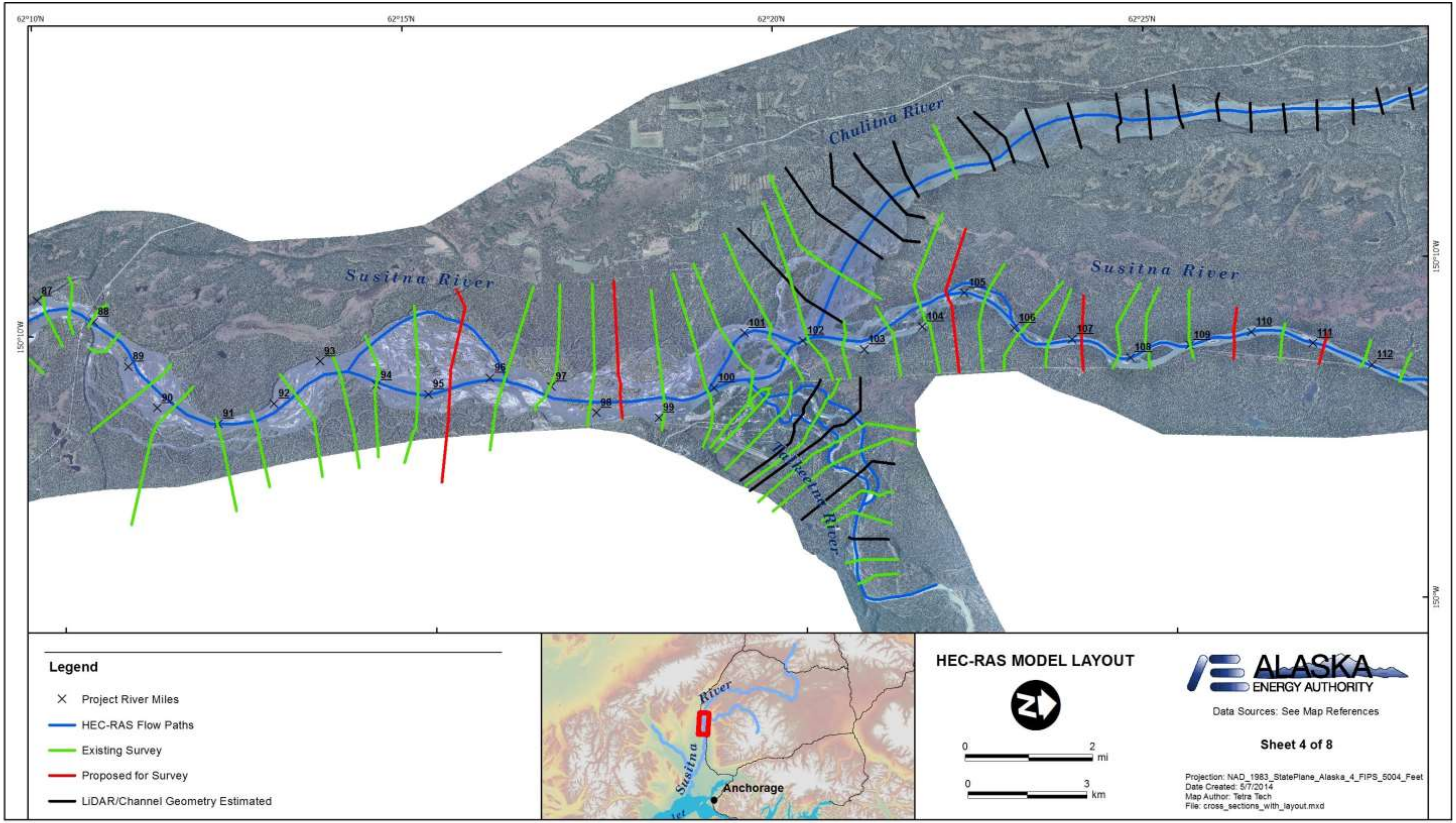


**Figure 4-4. Survey and Model Cross Sections from PRM 87 to PRM 112.**

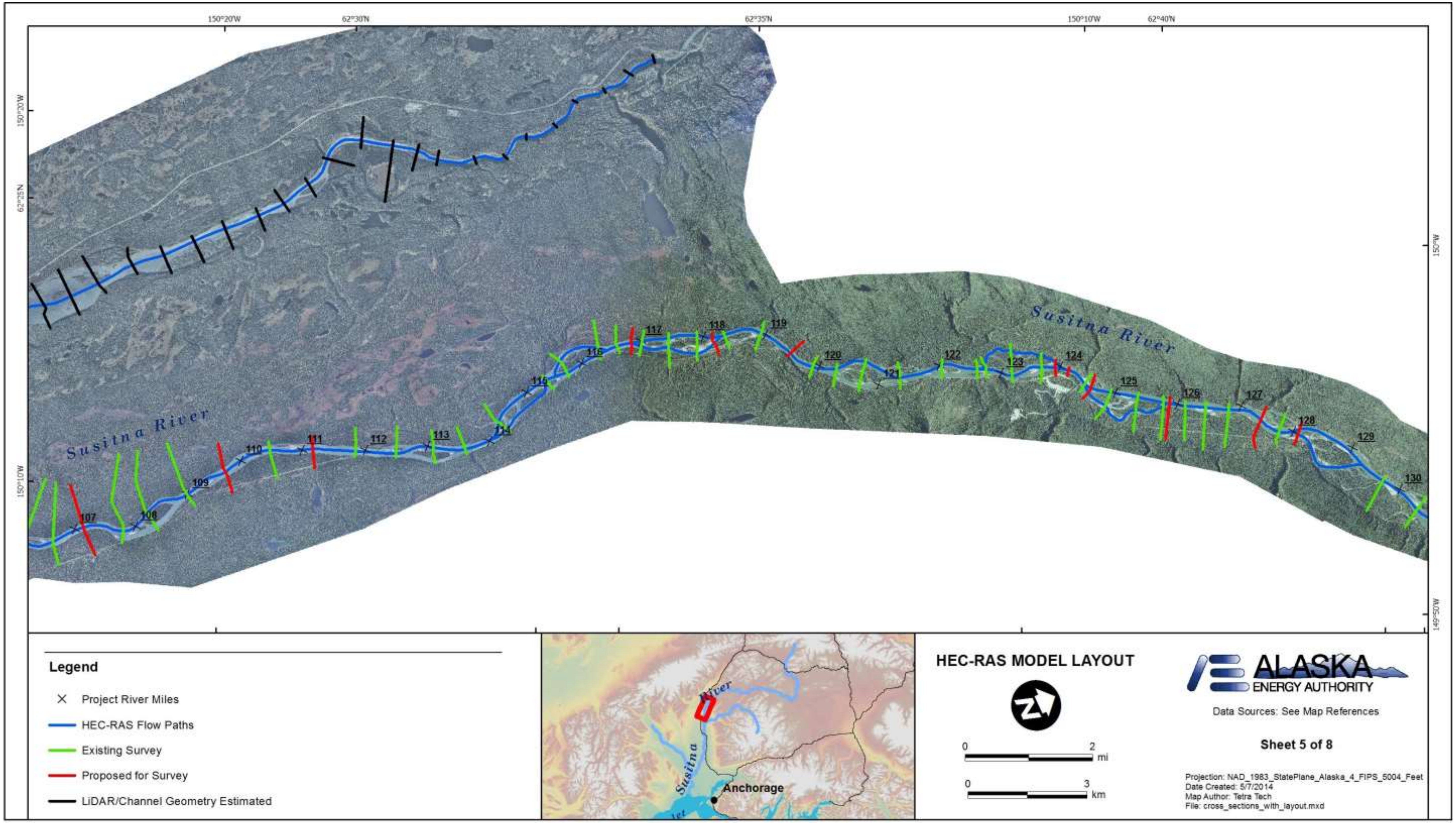


**Figure 4-5. Survey and Model Cross Sections from PRM 107 to PRM 130.**

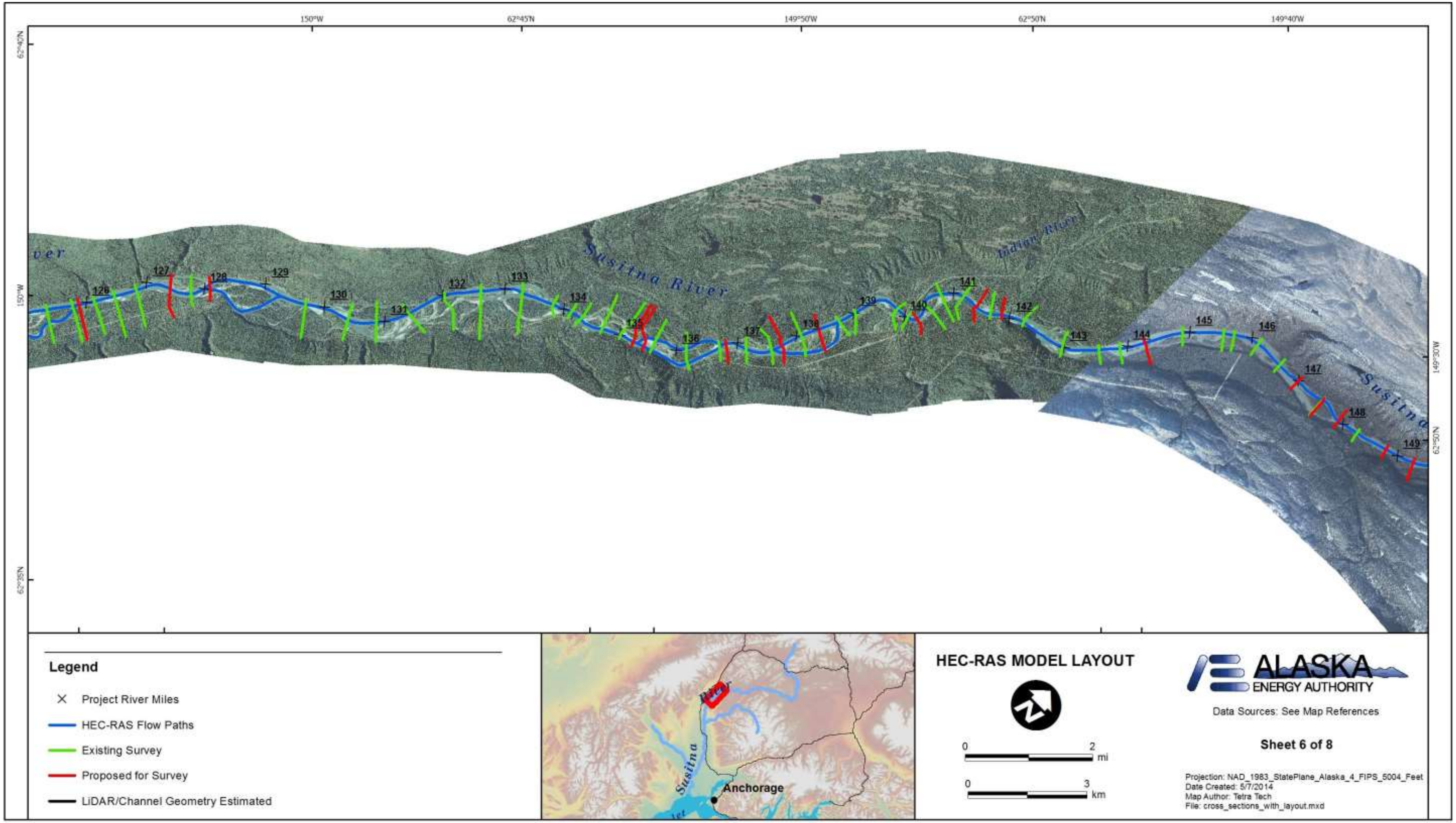


**Figure 4-6. Survey and Model Cross Sections from PRM 125 to PRM 149.**

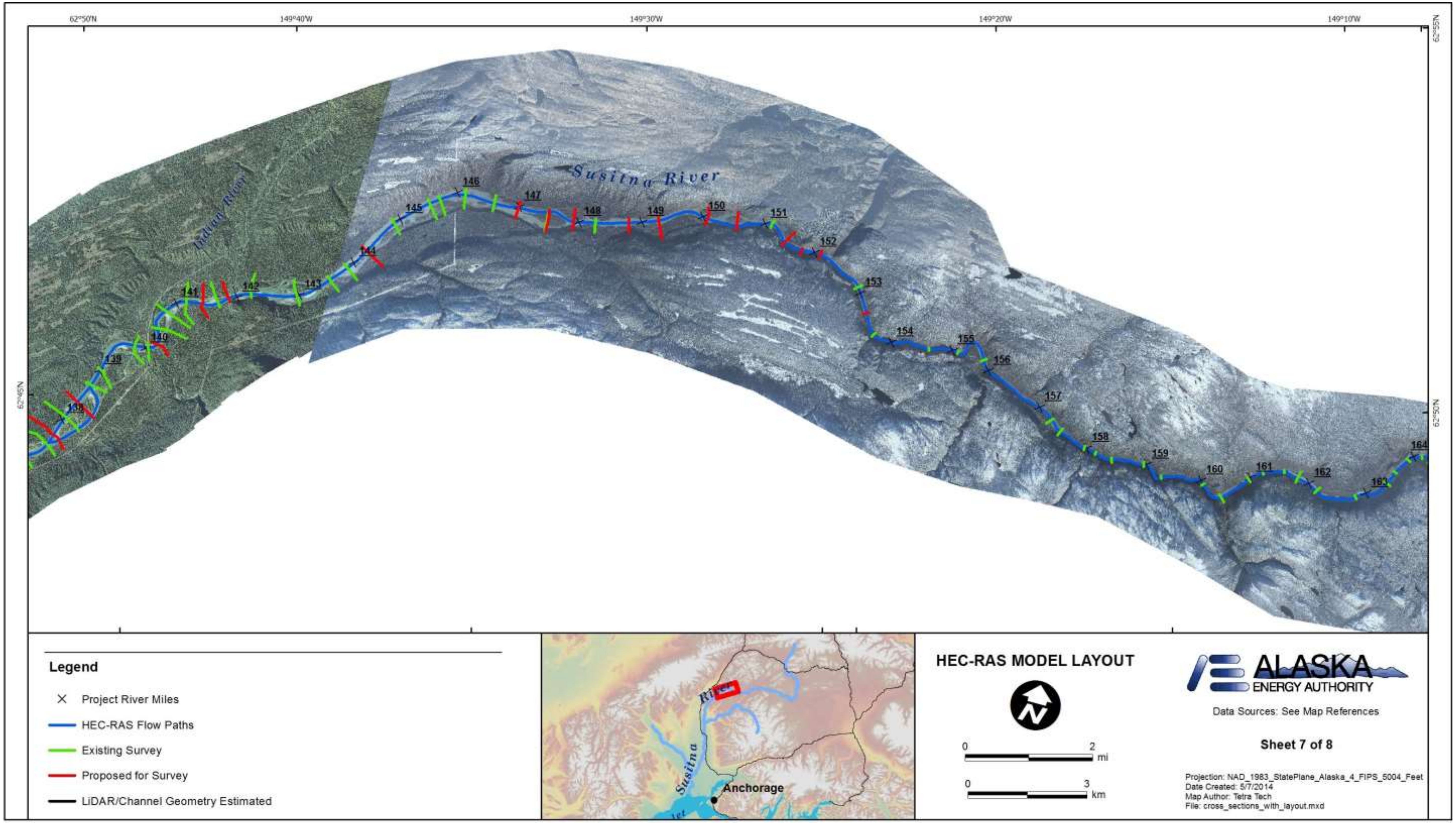


**Figure 4-7. Survey and Model Cross Sections from PRM 138 to PRM 164.**

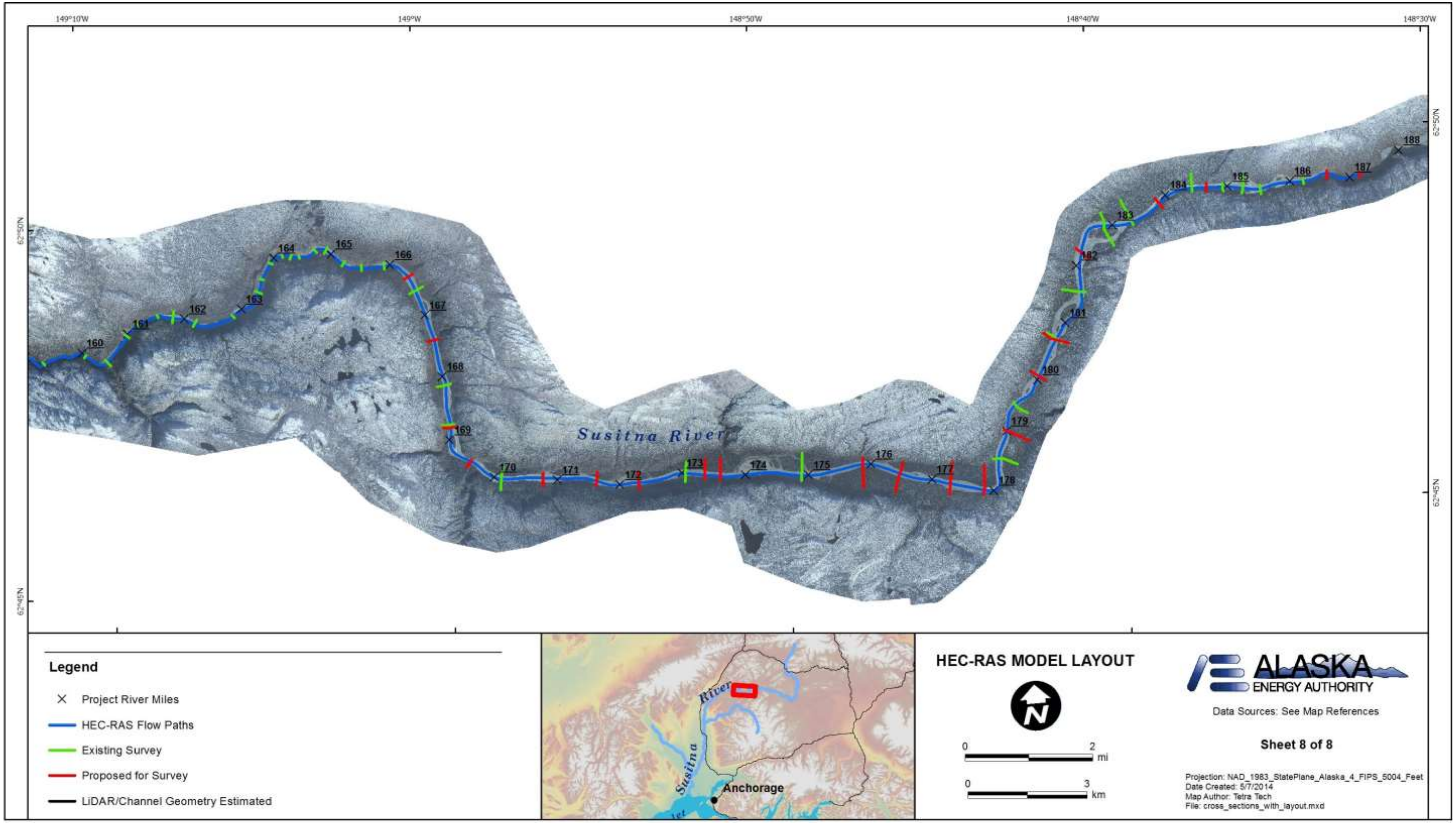


**Figure 4-8. Survey and Model Cross Sections from PRM 160 to PRM 188.**

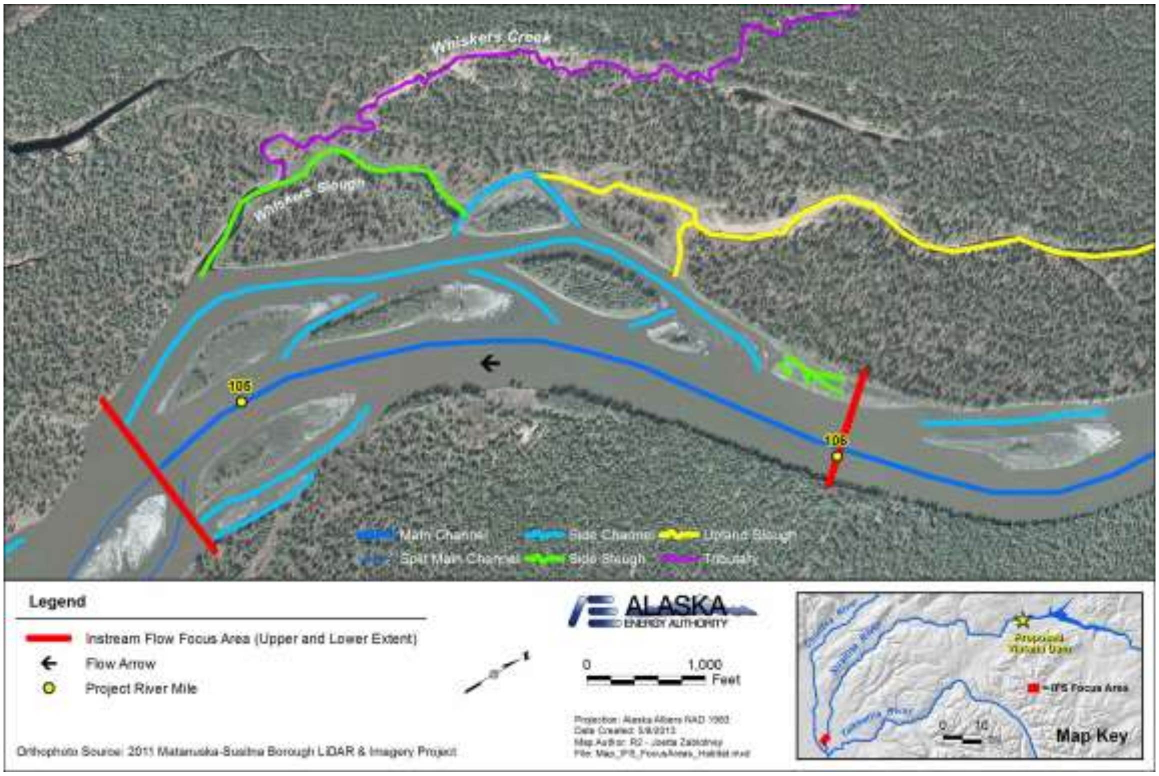


Figure 4-9. FA-104 (Whiskers Creek) (From R2 Resource Consultants Inc. 2013b).

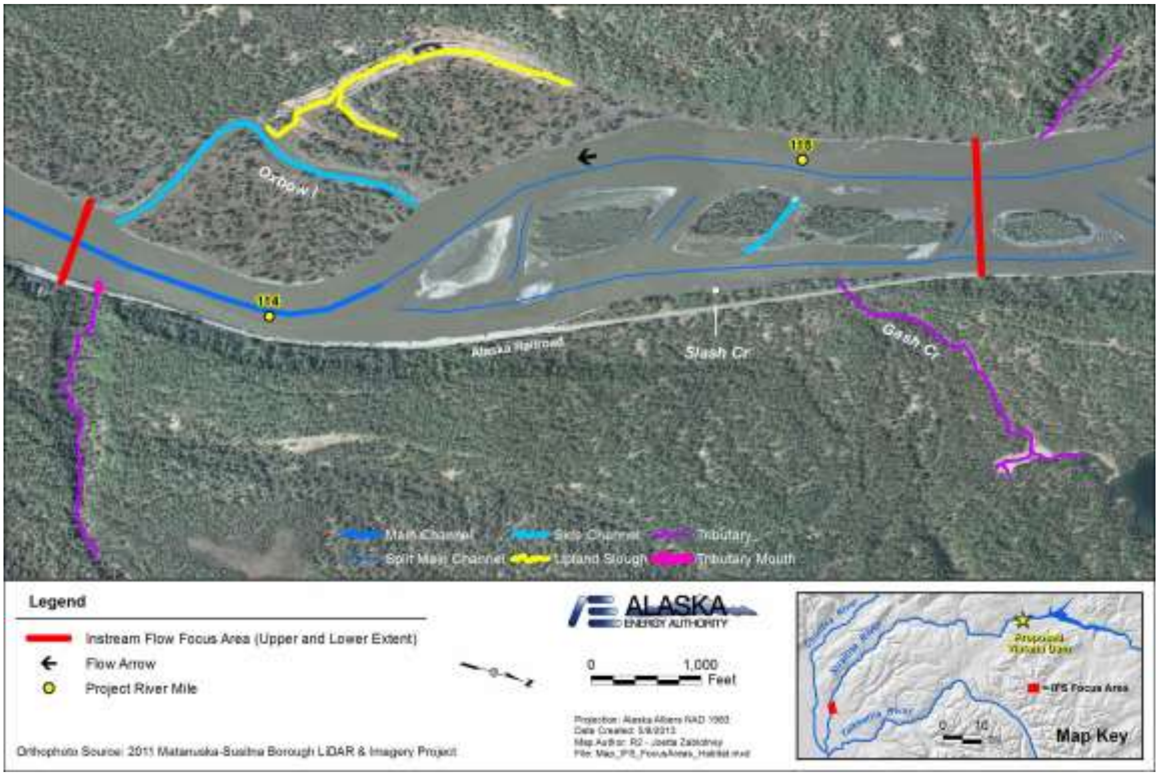


Figure 4-10. FA-113 (Oxbow 1) (From R2 Resource Consultants Inc. 2013b).

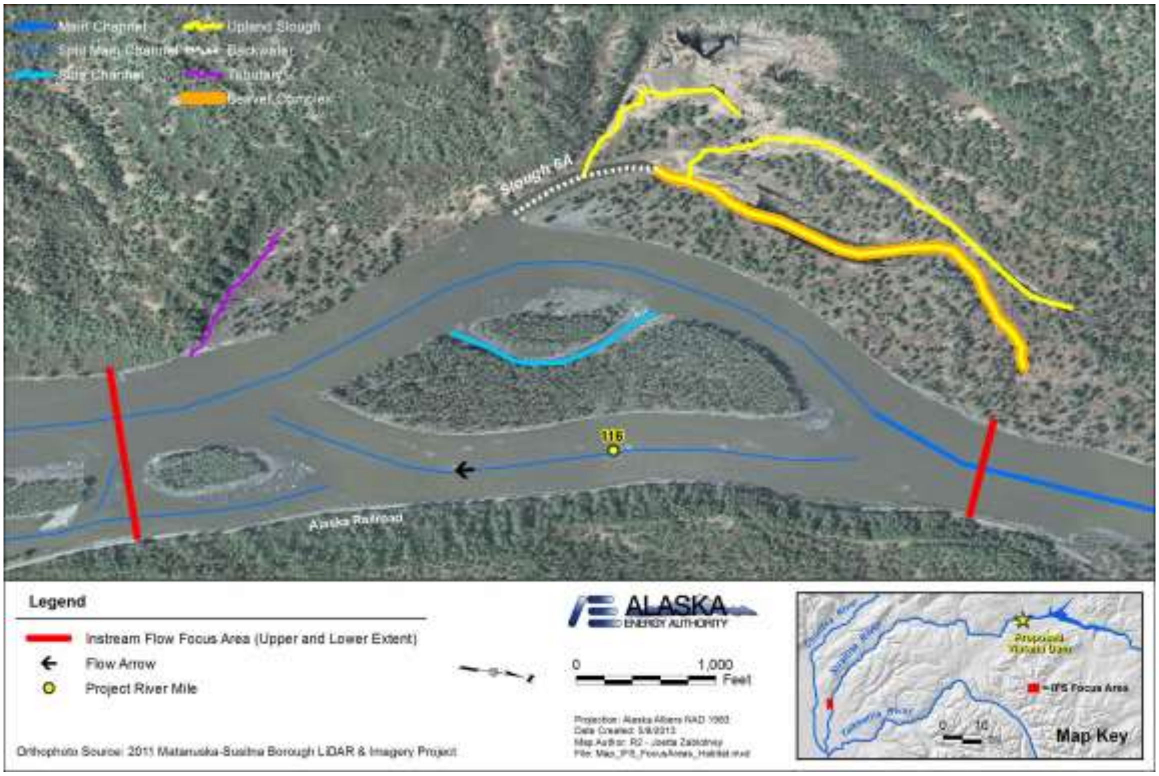


Figure 4-11. FA-115 (Slough 6A) (From R2 Resource Consultants Inc. 2013b).

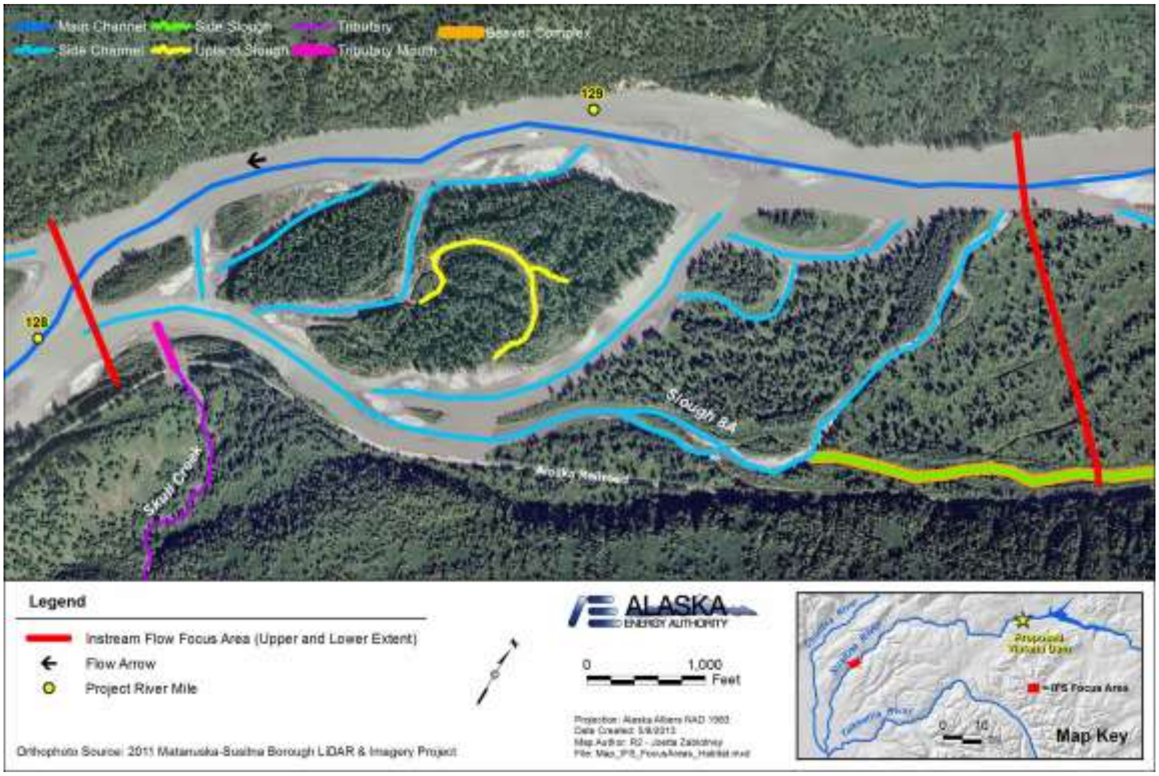


Figure 4-12. FA-128 (Slough 8A) (From R2 Resource Consultants Inc. 2013b).

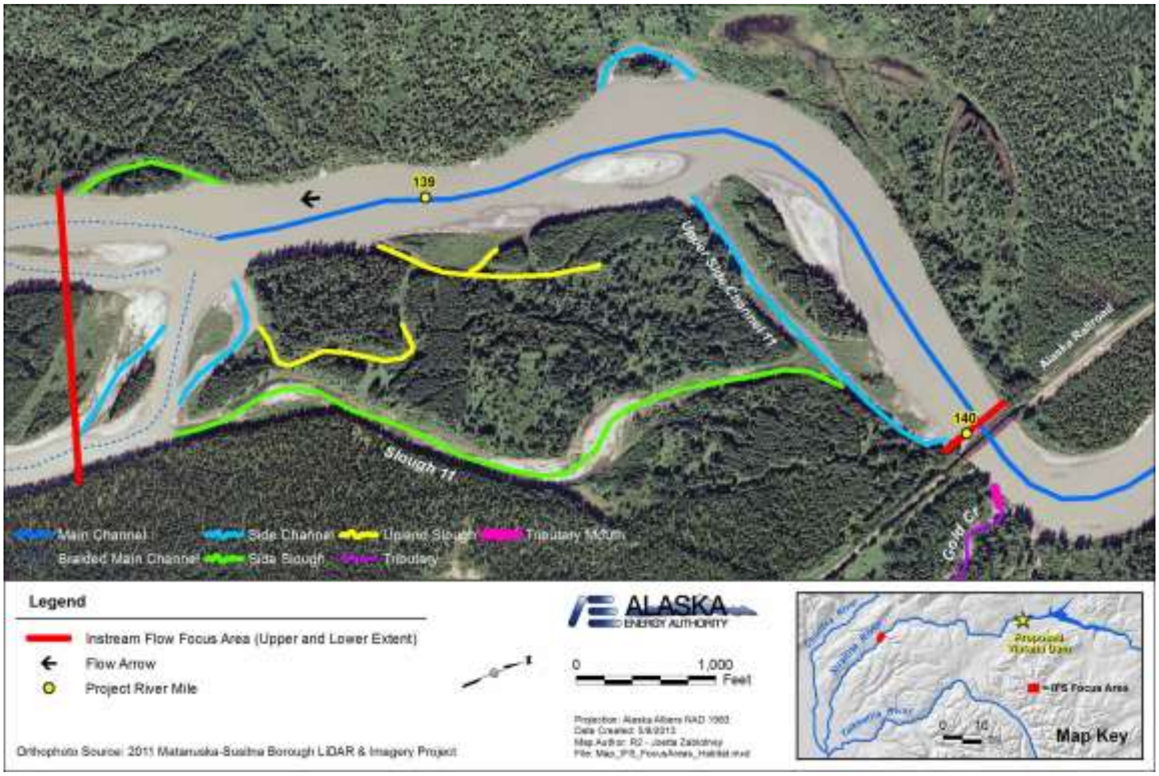


Figure 4-13. FA-138 (Gold Creek) (From R2 Resource Consultants Inc. 2013b).

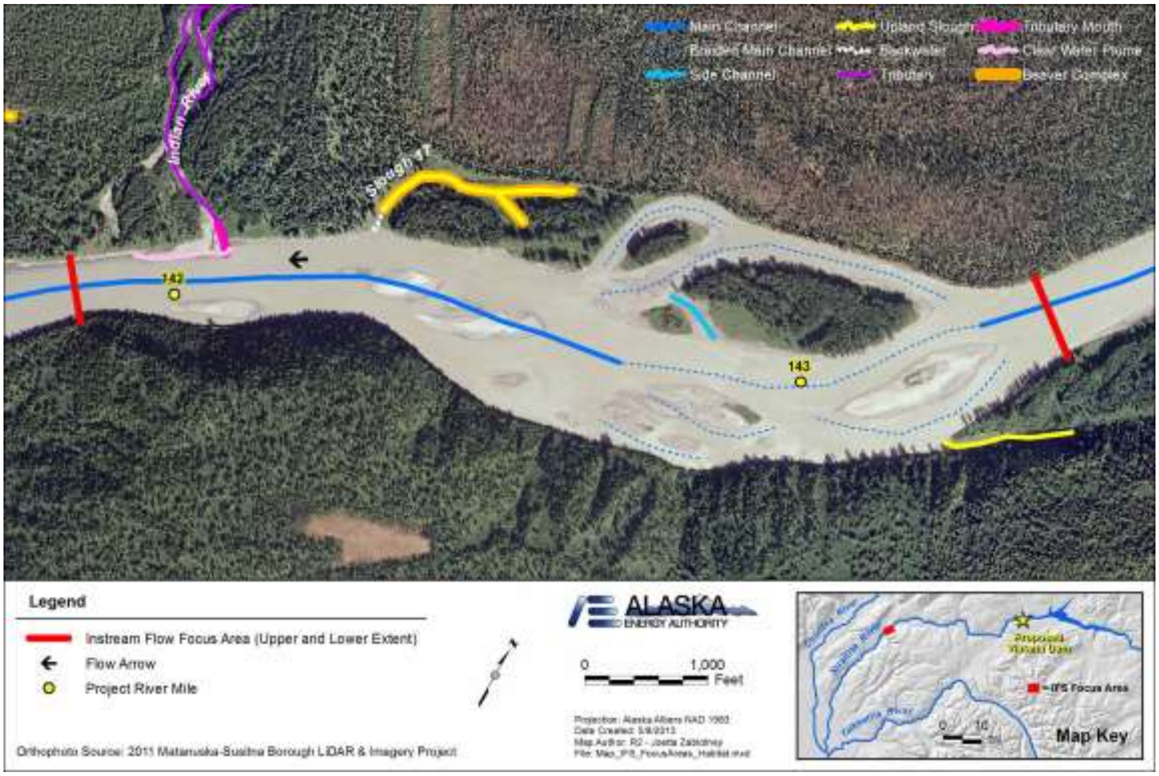


Figure 4-14. FA-141 (Indian River) (From R2 Resource Consultants Inc. 2013b).

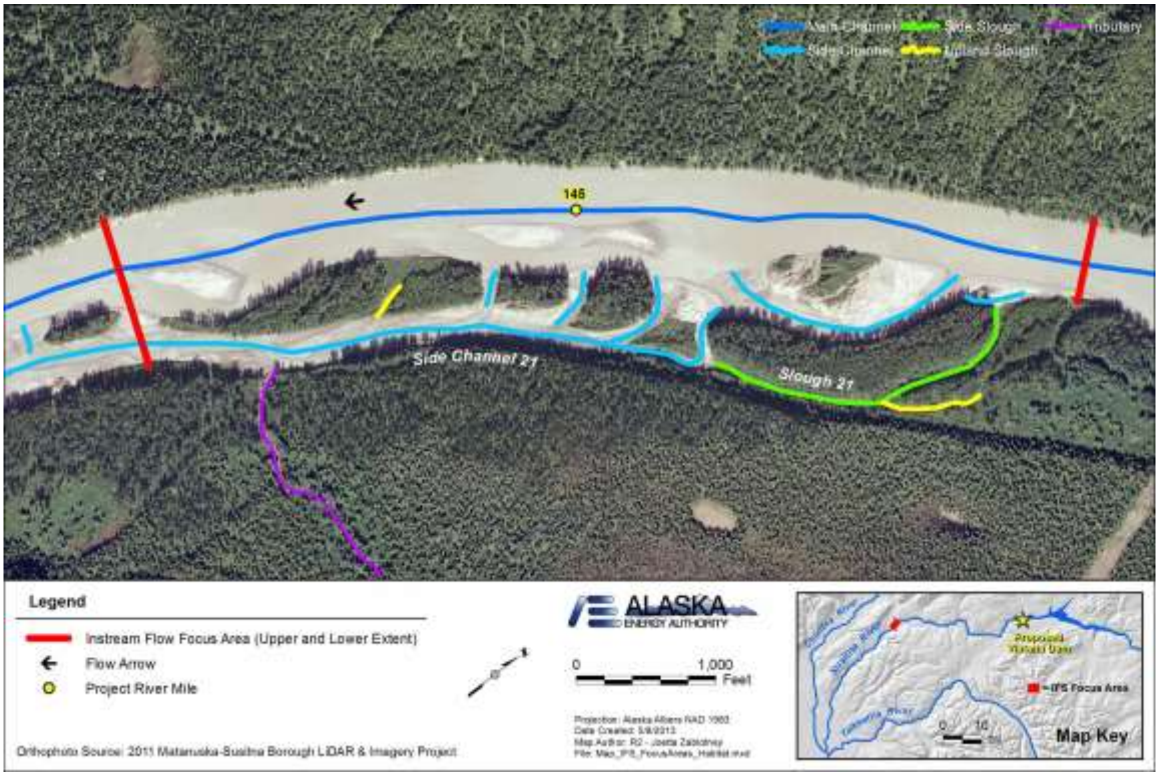


Figure 4-15. FA-144 (Slough 21) (From R2 Resource Consultants Inc. 2013b).

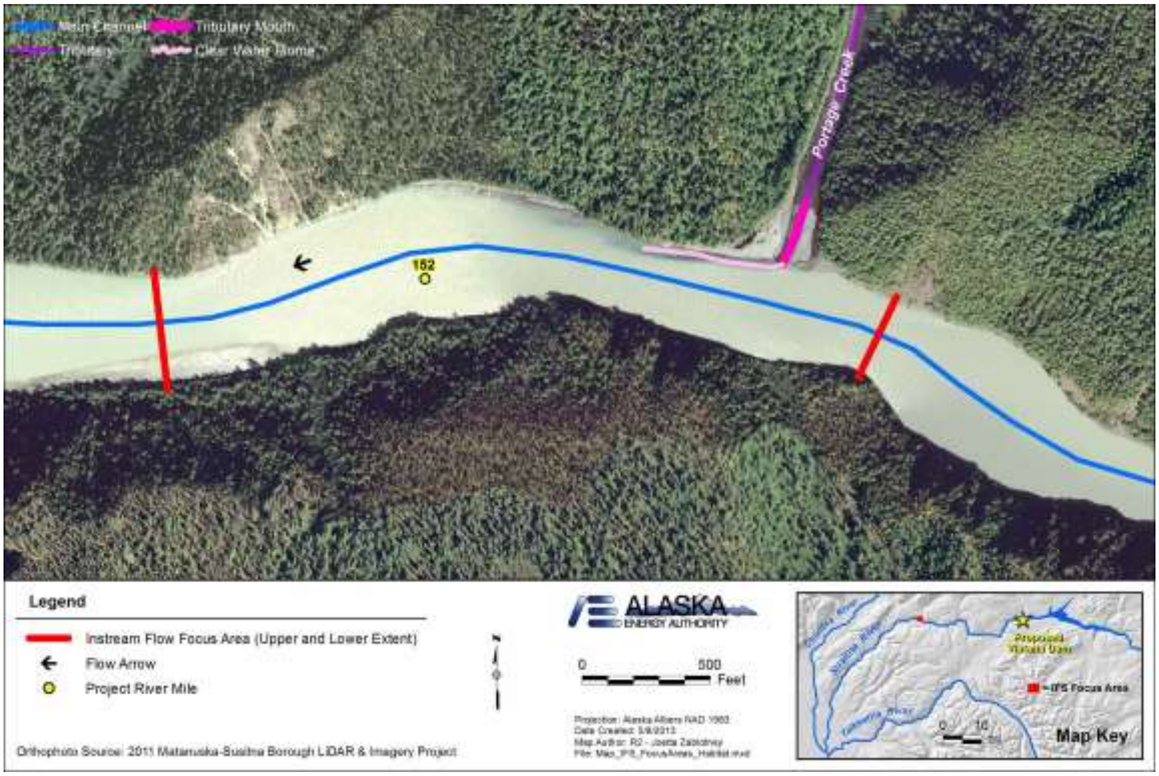


Figure 4-16. FA-151 (Portage Creek) (From R2 Resource Consultants Inc. 2013b).

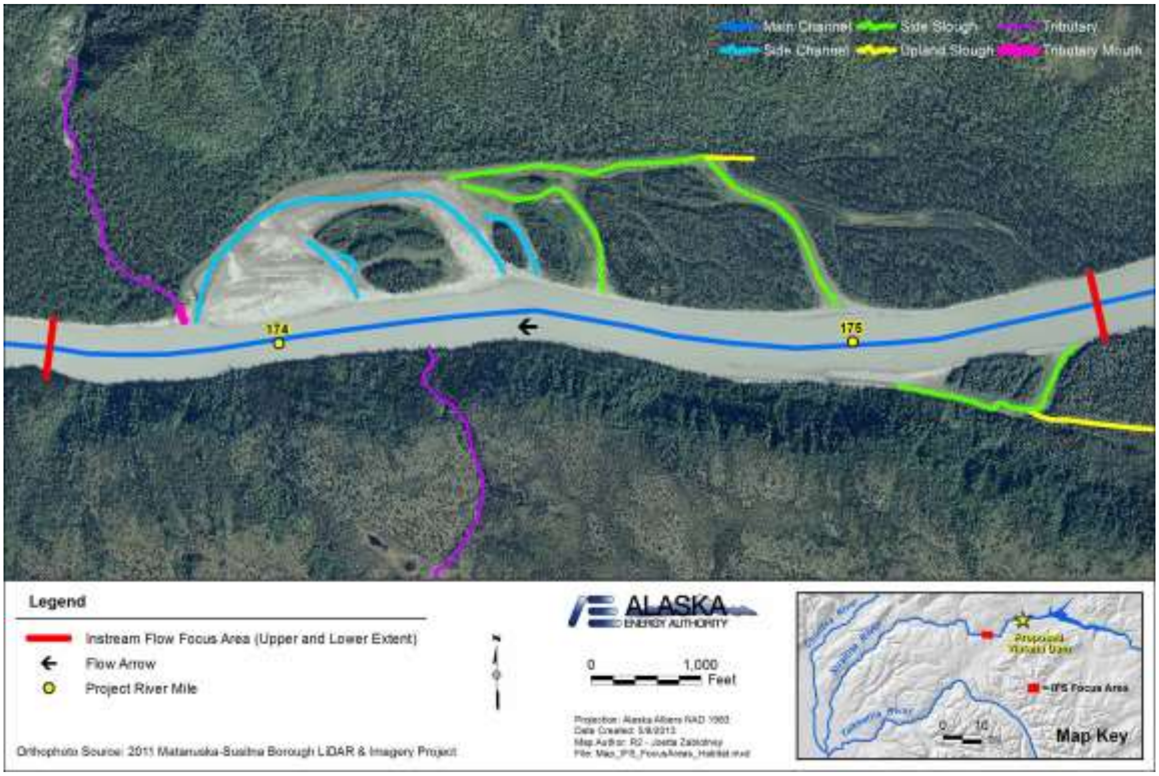


**Figure 4-17. FA-173 (Stephan Lake Complex) (From R2 Resource Consultants Inc. 2013b).**

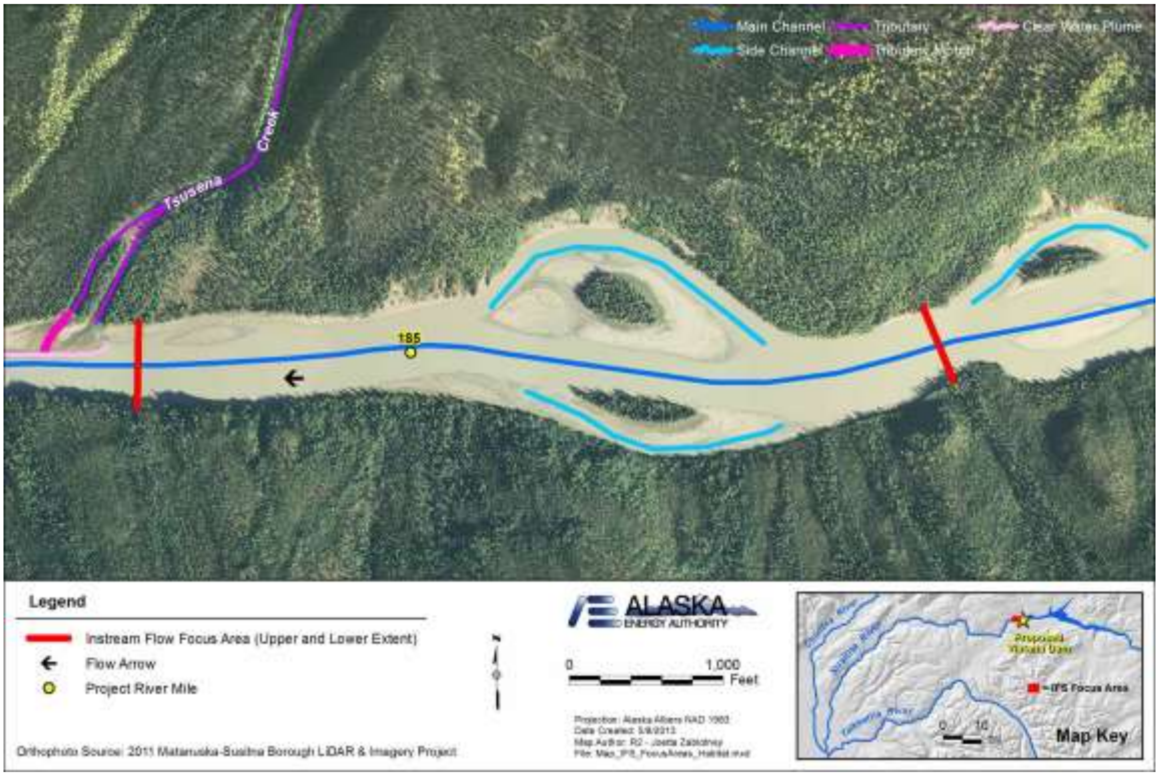


**Figure 4-18. FA-184 (Watana Dam) (From R2 Resource Consultants Inc. 2013b).**

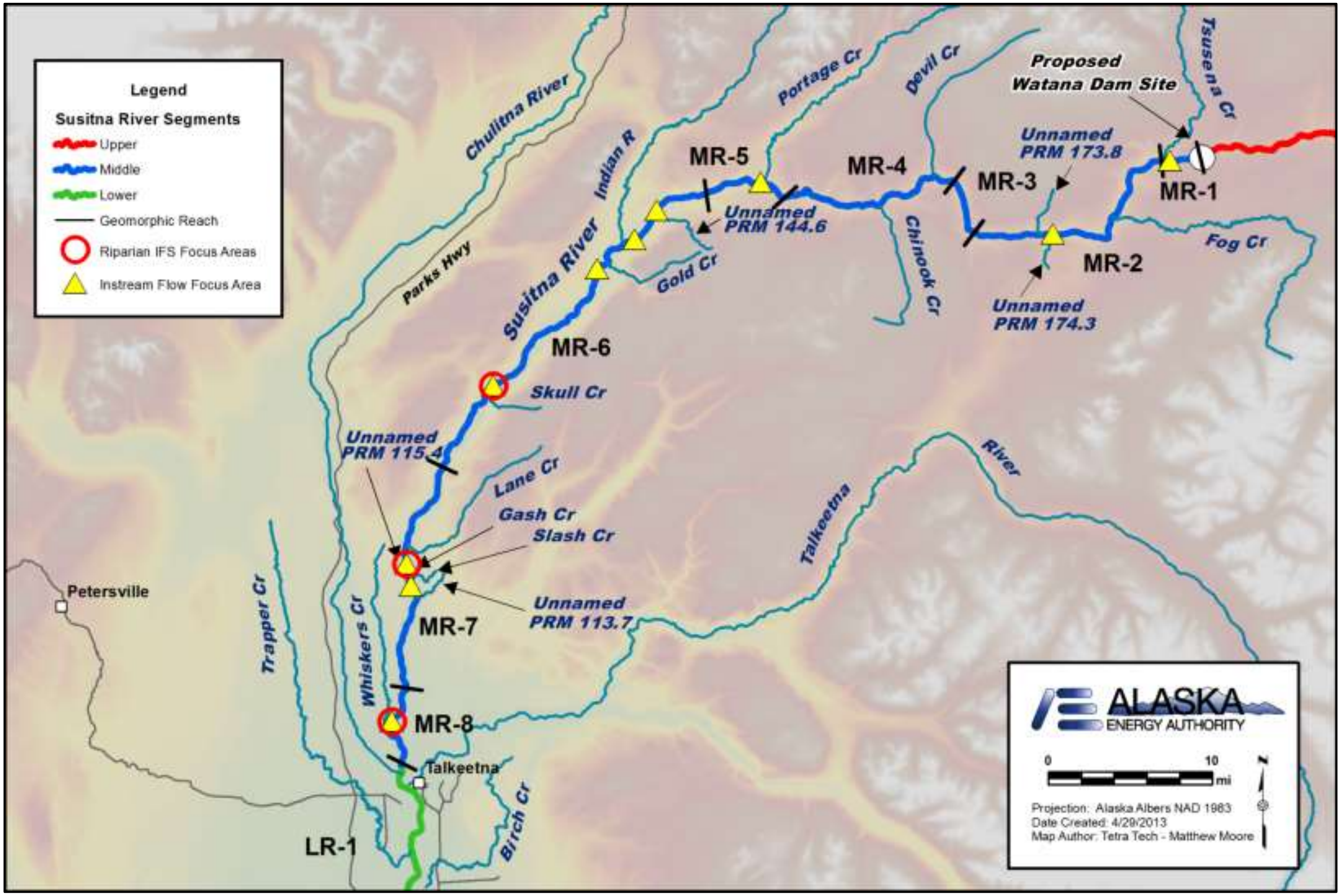


**Figure 4-19. Middle River Tributary Locations Relative to Geomorphic Reach and Focus Areas.**

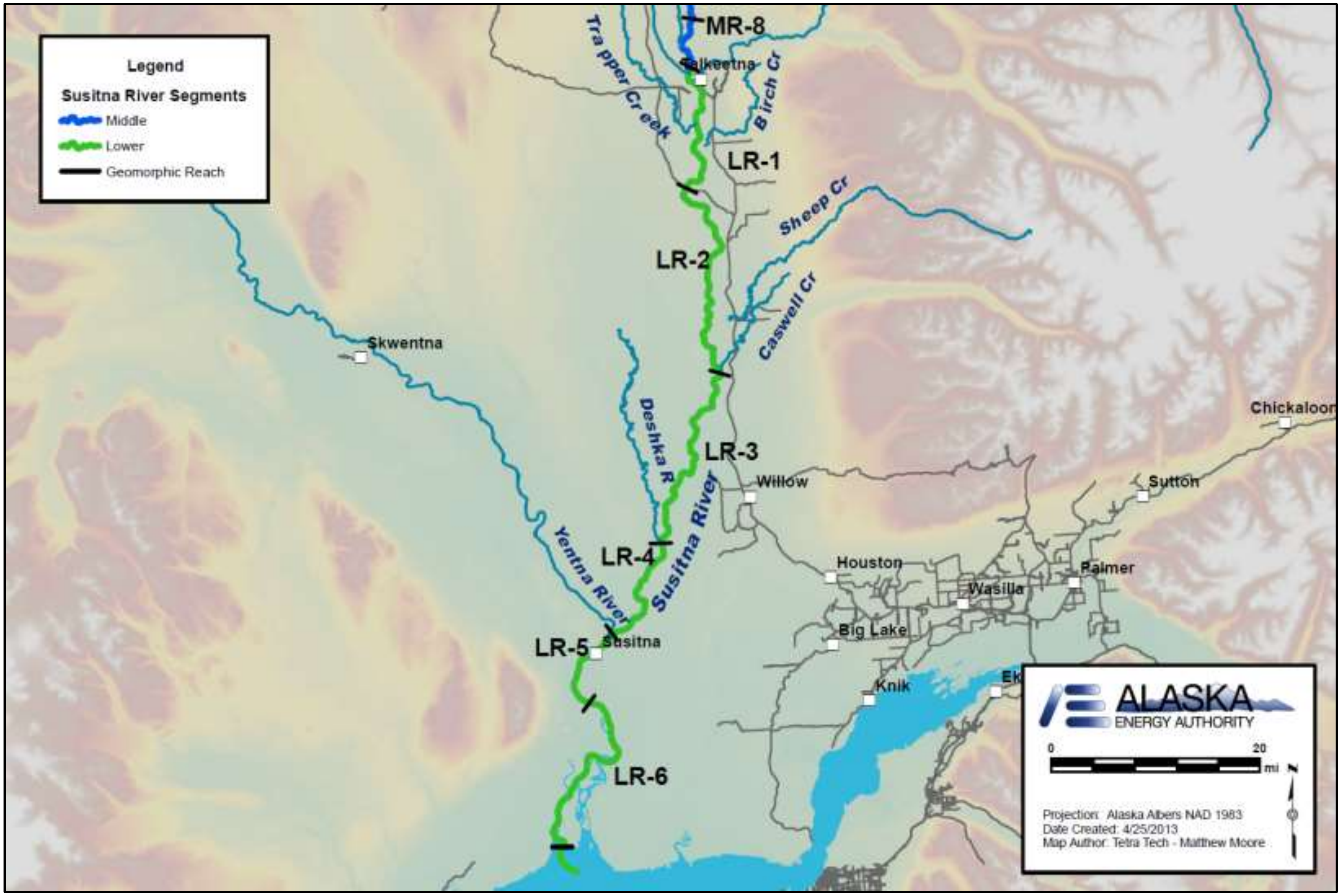
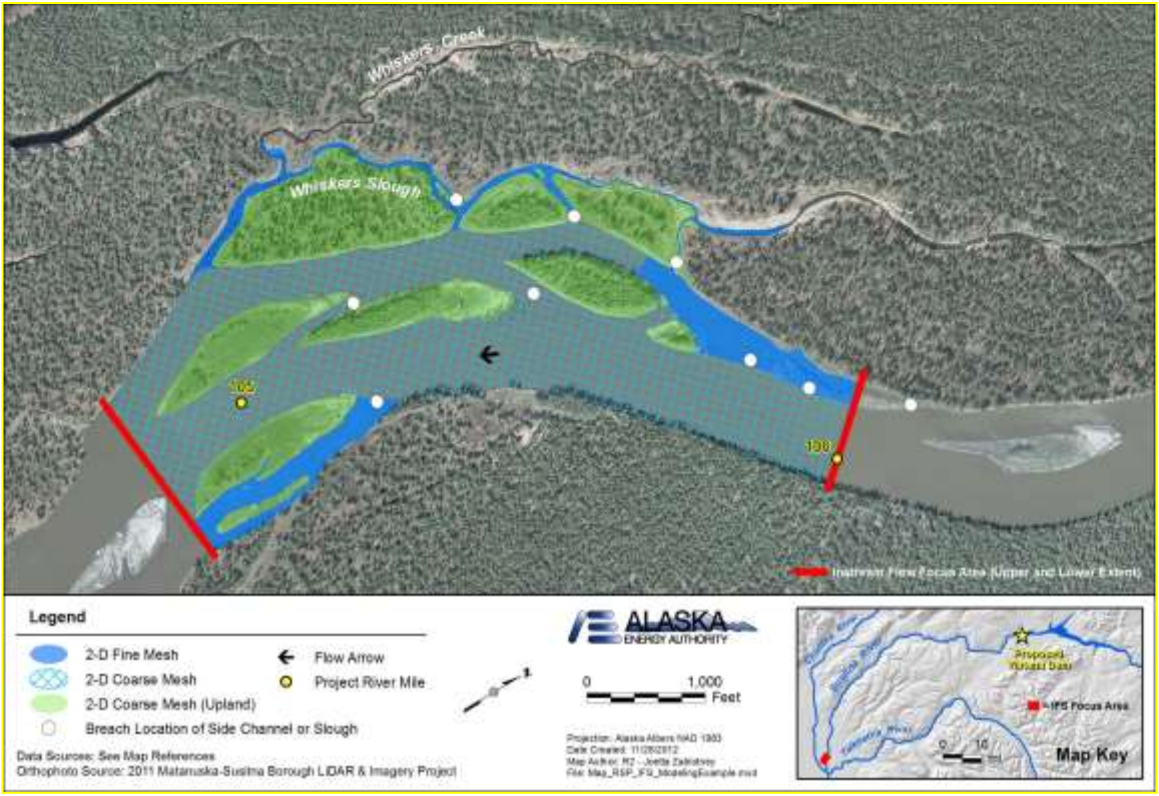


**Figure 4-20. Lower River Tributary Locations Relative to Geomorphic Reach.**

Figure 4-21. Example of Fine Mesh Applied in FA-104 (Whiskers Slough).

**Figure 4-22. Example of Coarse Mesh Applied in FA-104 (Whiskers Slough).**



Data Sources: See Map References
Orthophoto Source: 2011 Matanuska-Susitna Borough LIDAR & Imagery Project

Projection: Alaska Albers NAD 1983
Date Created: 11/28/2012
Map Author: R2 - Joetta Zablotney
File: Map_RSP_IFS_ModelingExample.mxd

Figure 4-23. Examples of mesh detail for habitat analysis requirements FA-104 (Whiskers Slough).

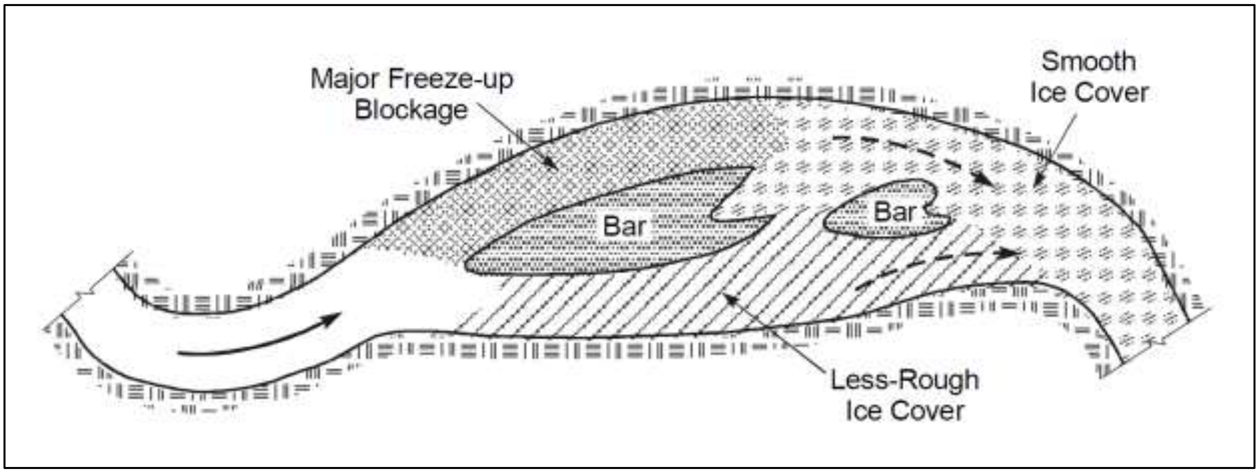


Figure 4-24. Example of Ice Blockage Altering Flow Distribution in Multiple Channel Reaches (Zabilansky et al. 2003).

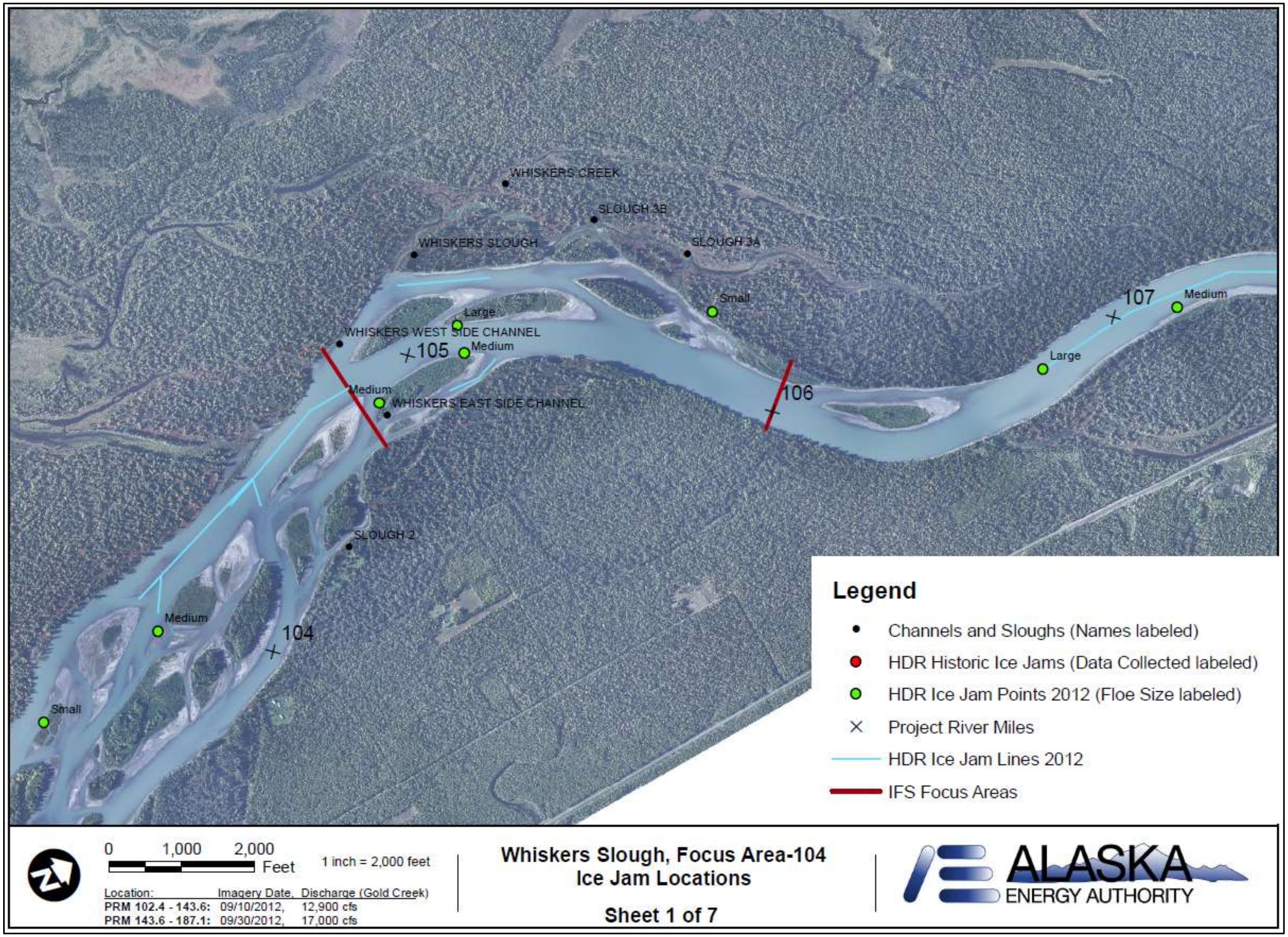


**Figure 4-25. Ice Jam Locations at FA-104 (Whiskers Slough).**

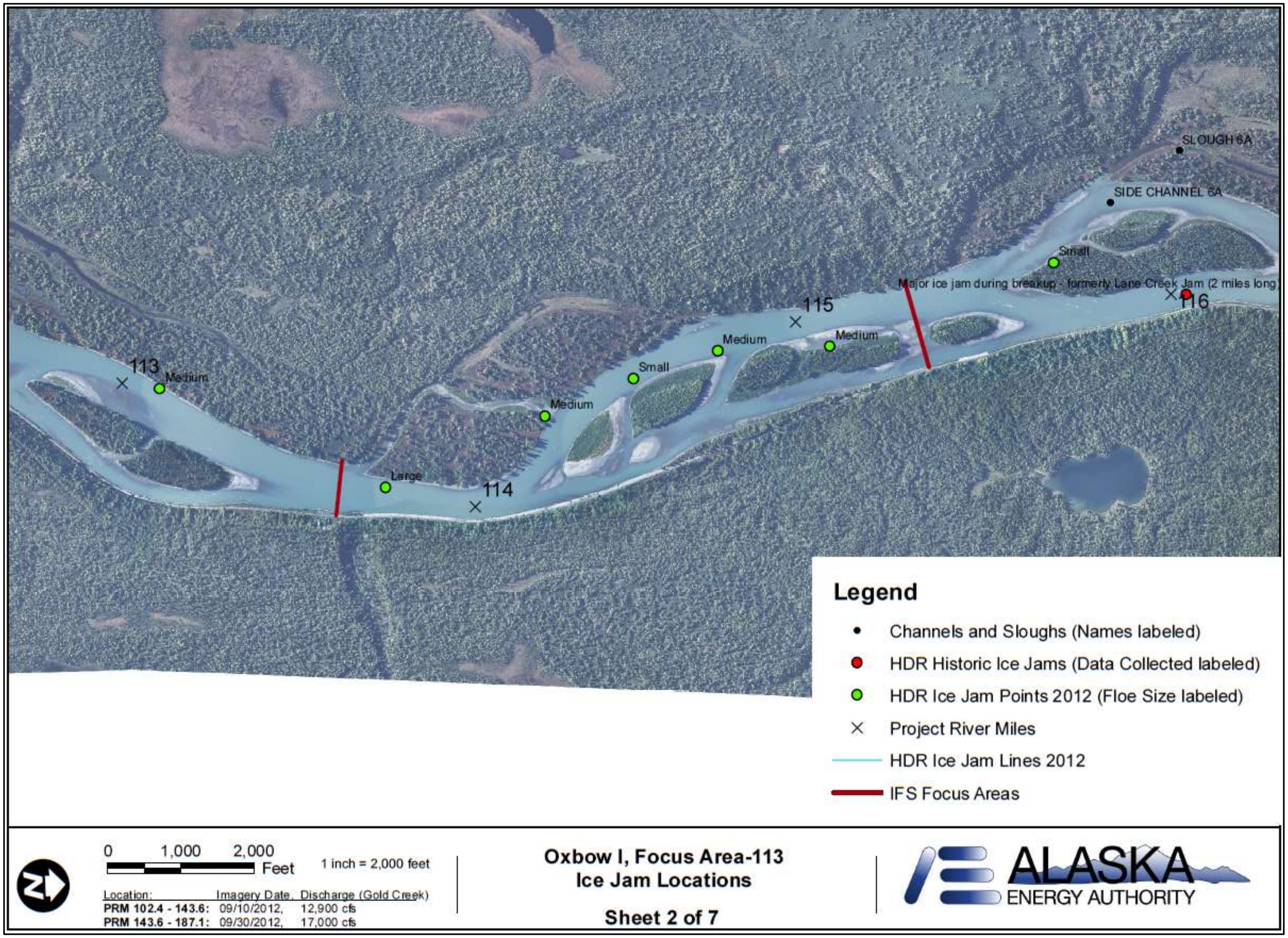


**Figure 4-26. Ice Jam Locations at FA-113 (Oxbow 1).**

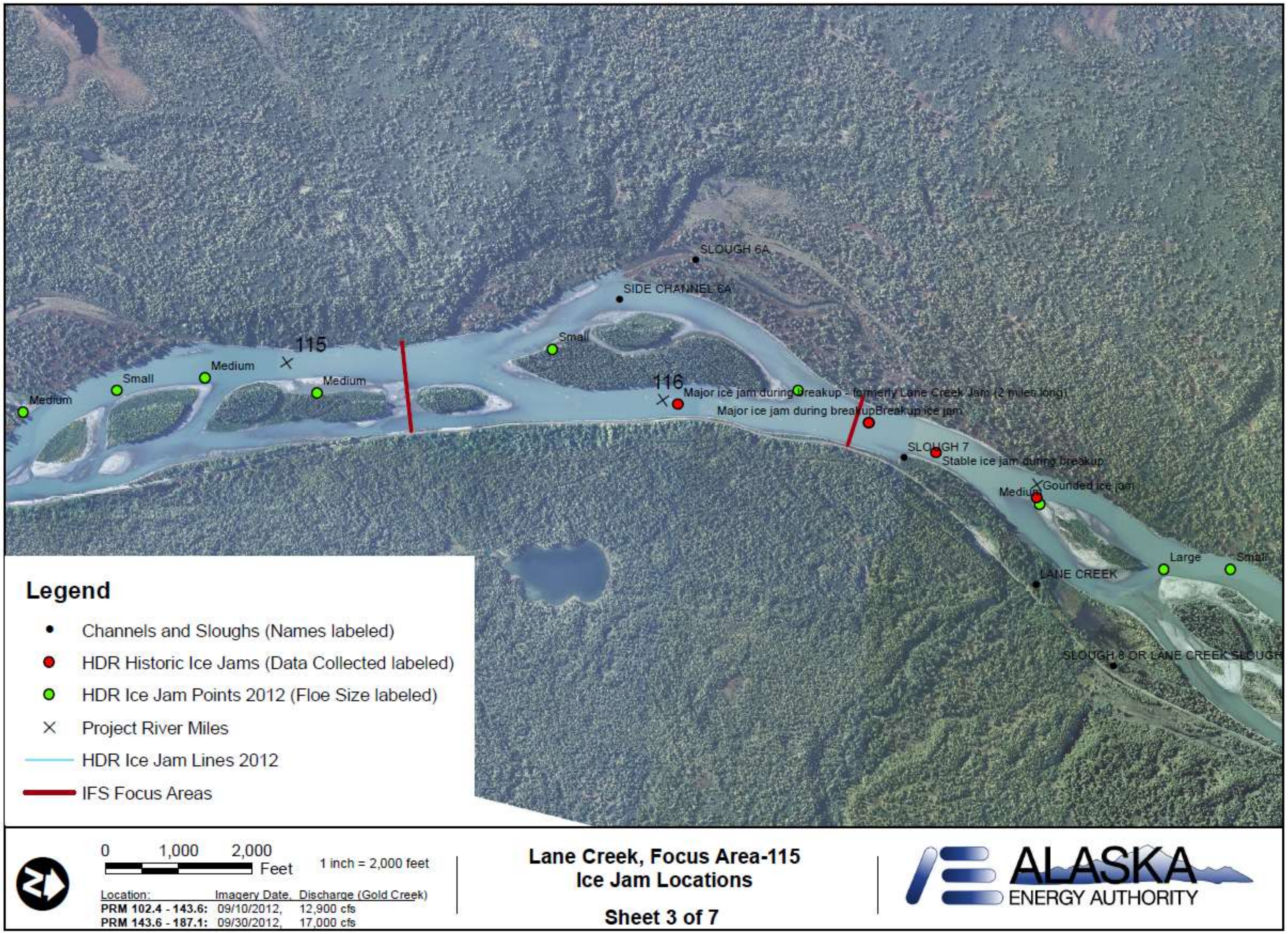


**Figure 4-27. Ice Jam Locations at FA-115 (Slough 6A).**

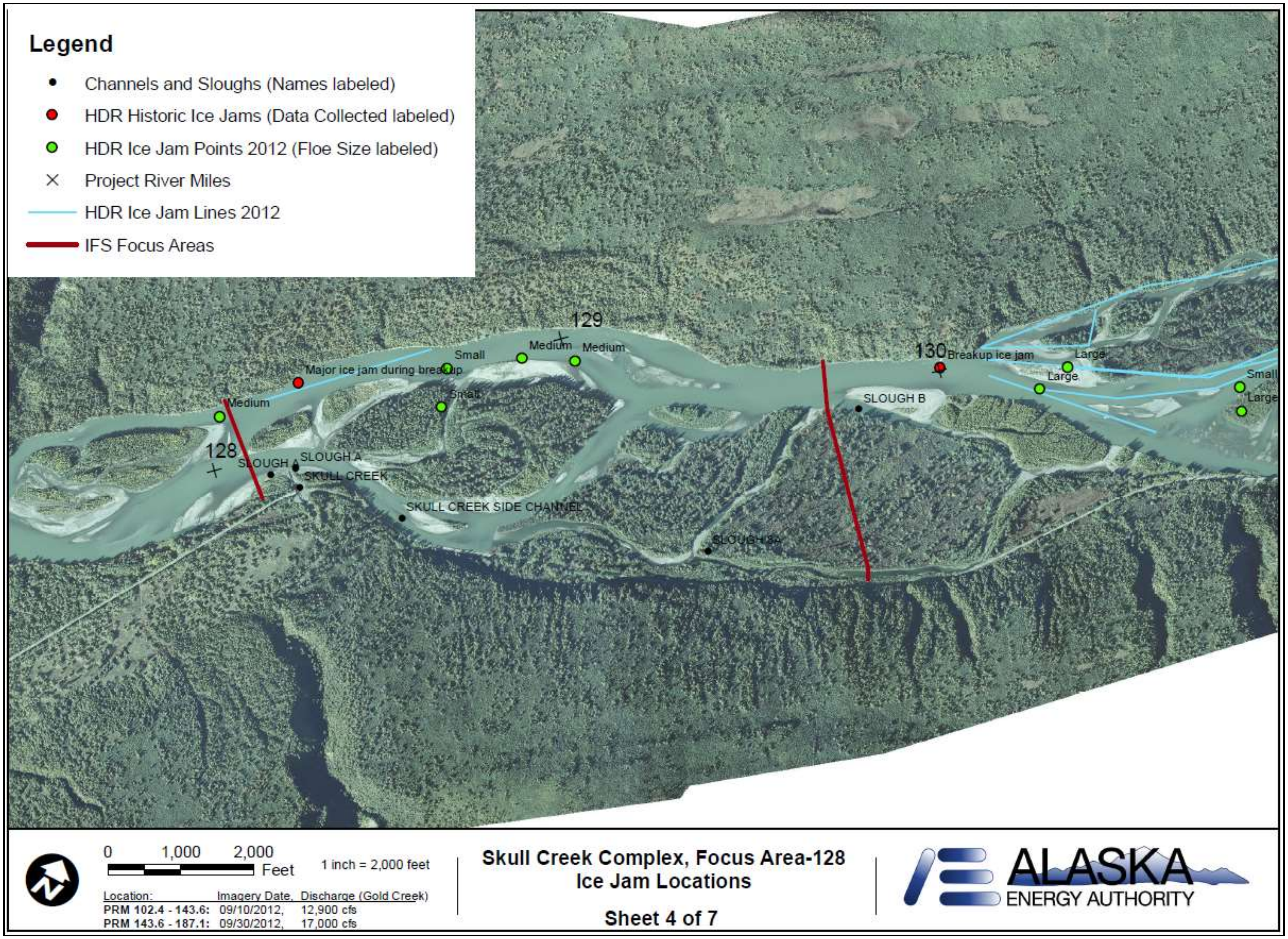


**Figure 4-28. Ice Jam Locations at FA-128 (Slough 8A).**

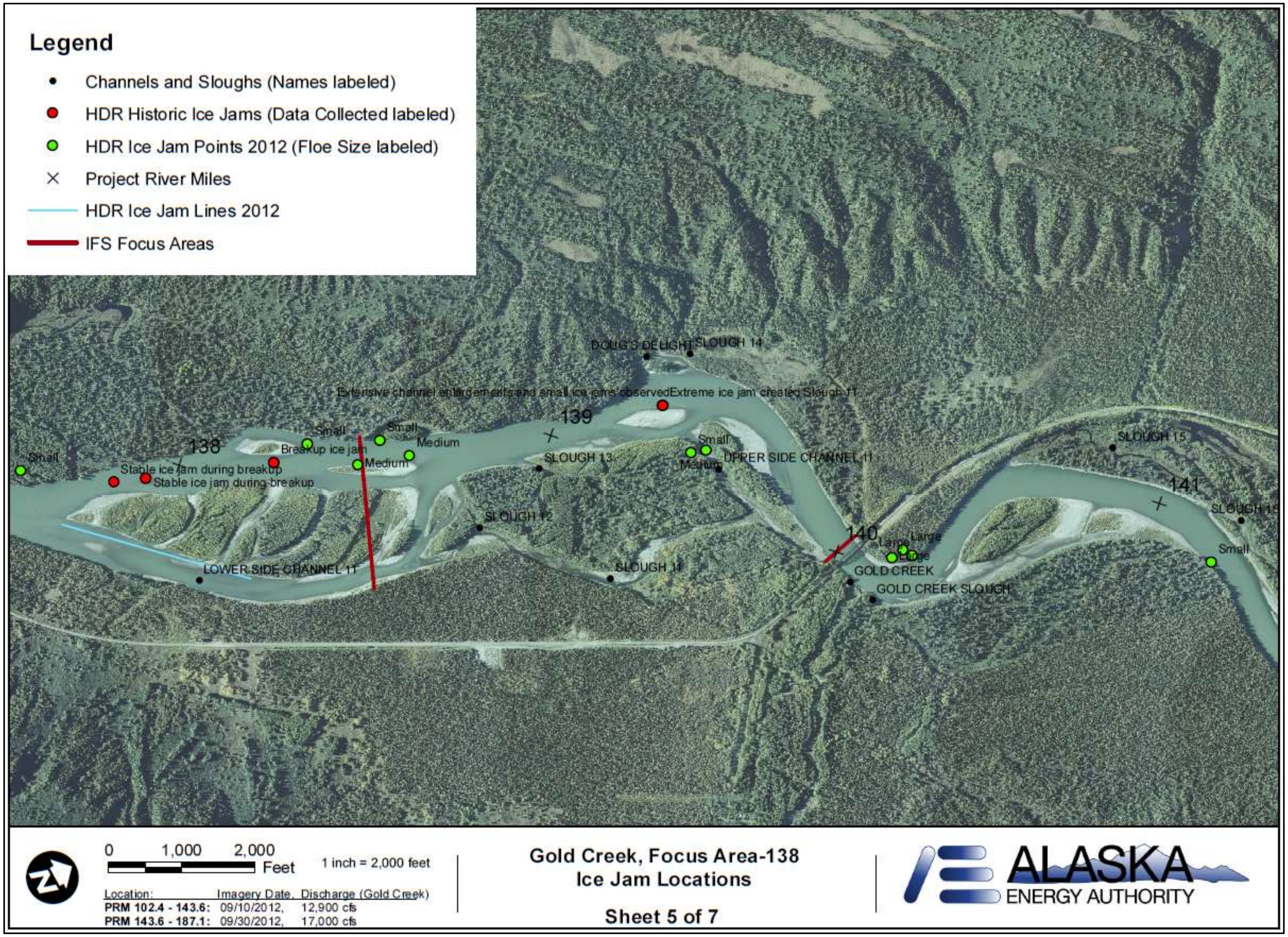


**Figure 4-29. Ice Jam Locations at FA-138 (Gold Creek).**

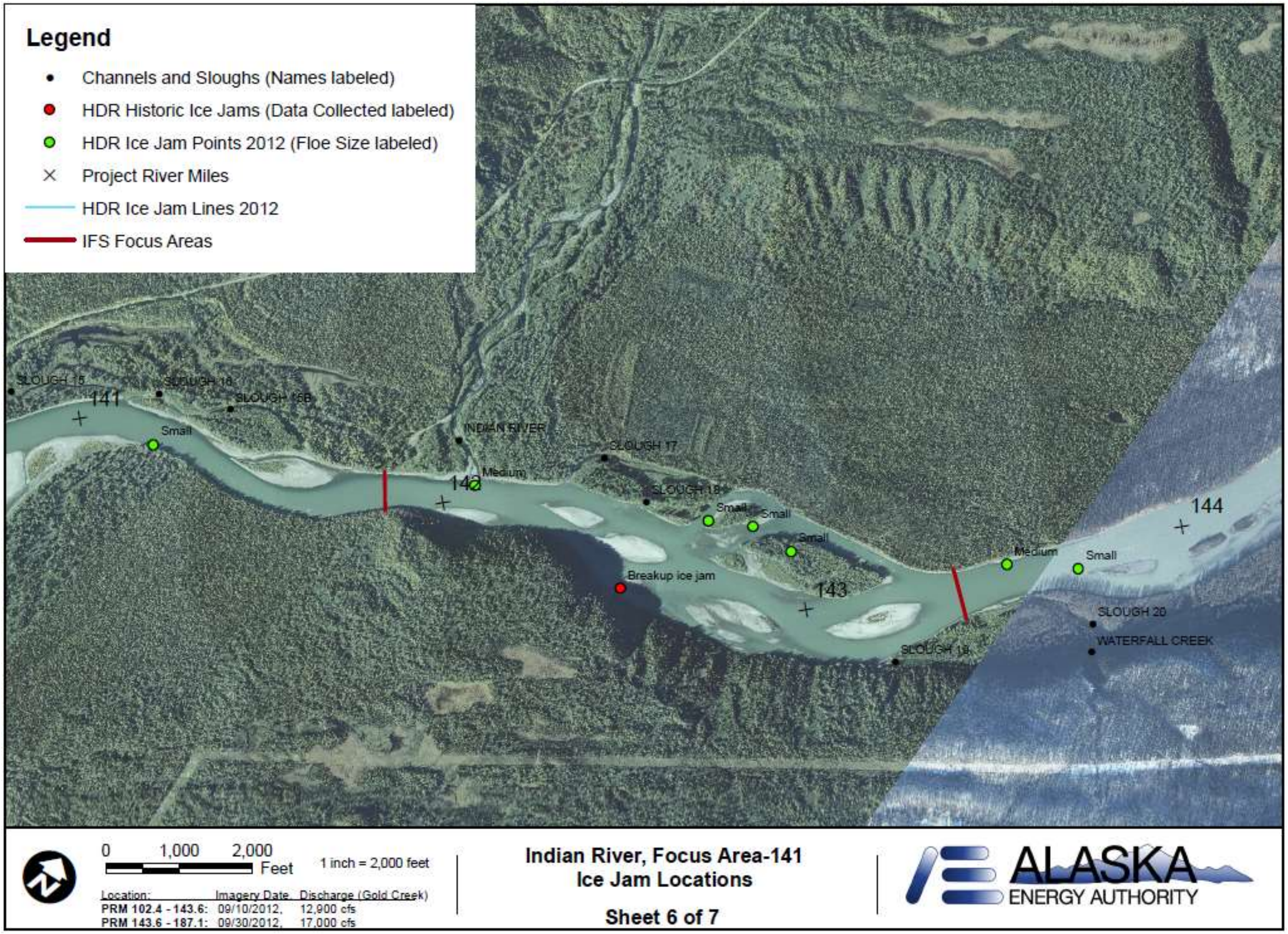


Figure 4-30. Ice Jam Locations at FA-141 (Indian River).

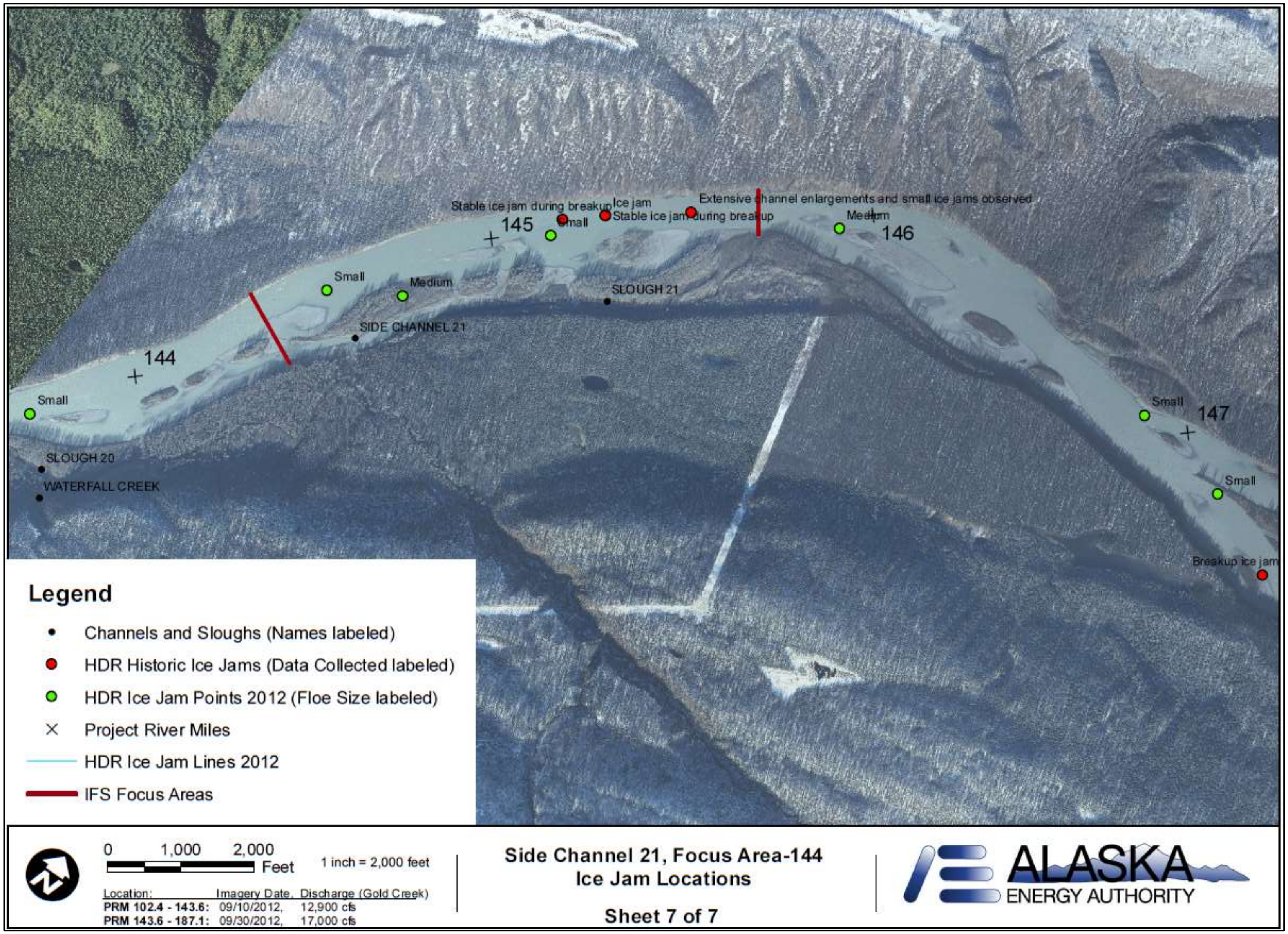


**Figure 4-31. Ice Jam Locations at FA-144 (Slough 21).**

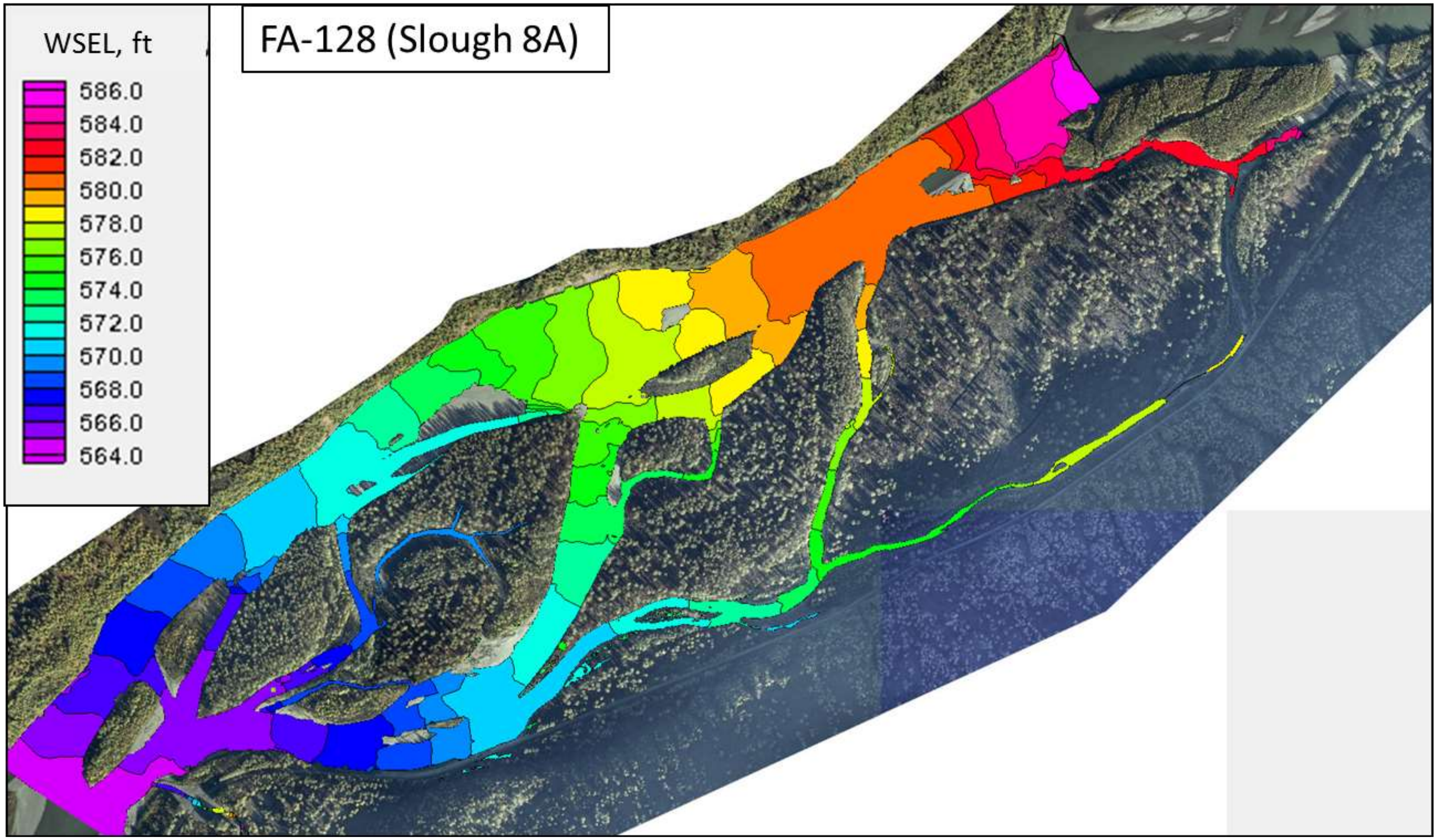


Figure 4-32. Hydraulic Model Water-surface Elevations at 30,000 cfs, FA-128 (Slough 8A).

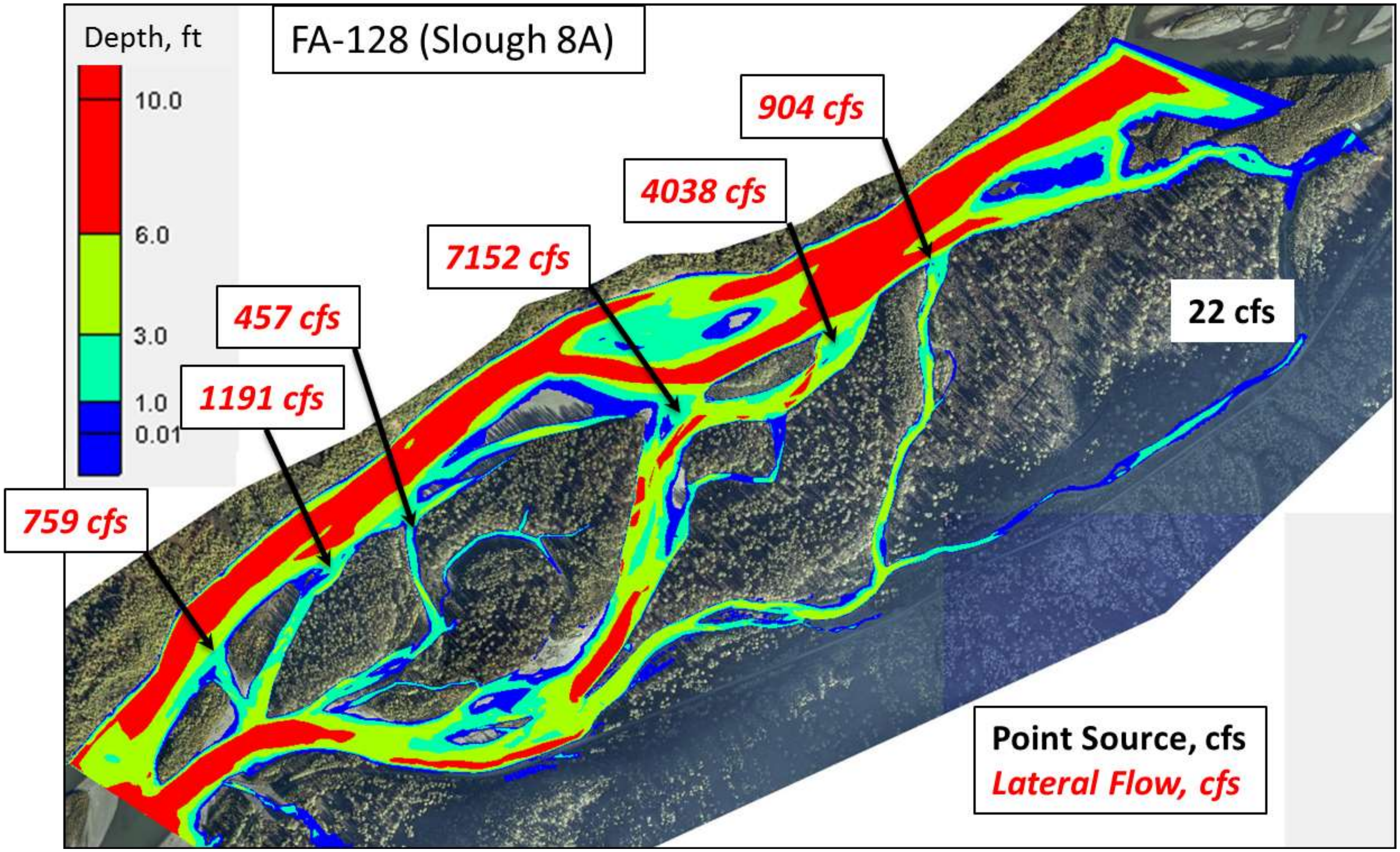


**Figure 4-33. Hydraulic Model Depth and Breaching Flows at 30,000 cfs, FA-128 (Slough 8A).**

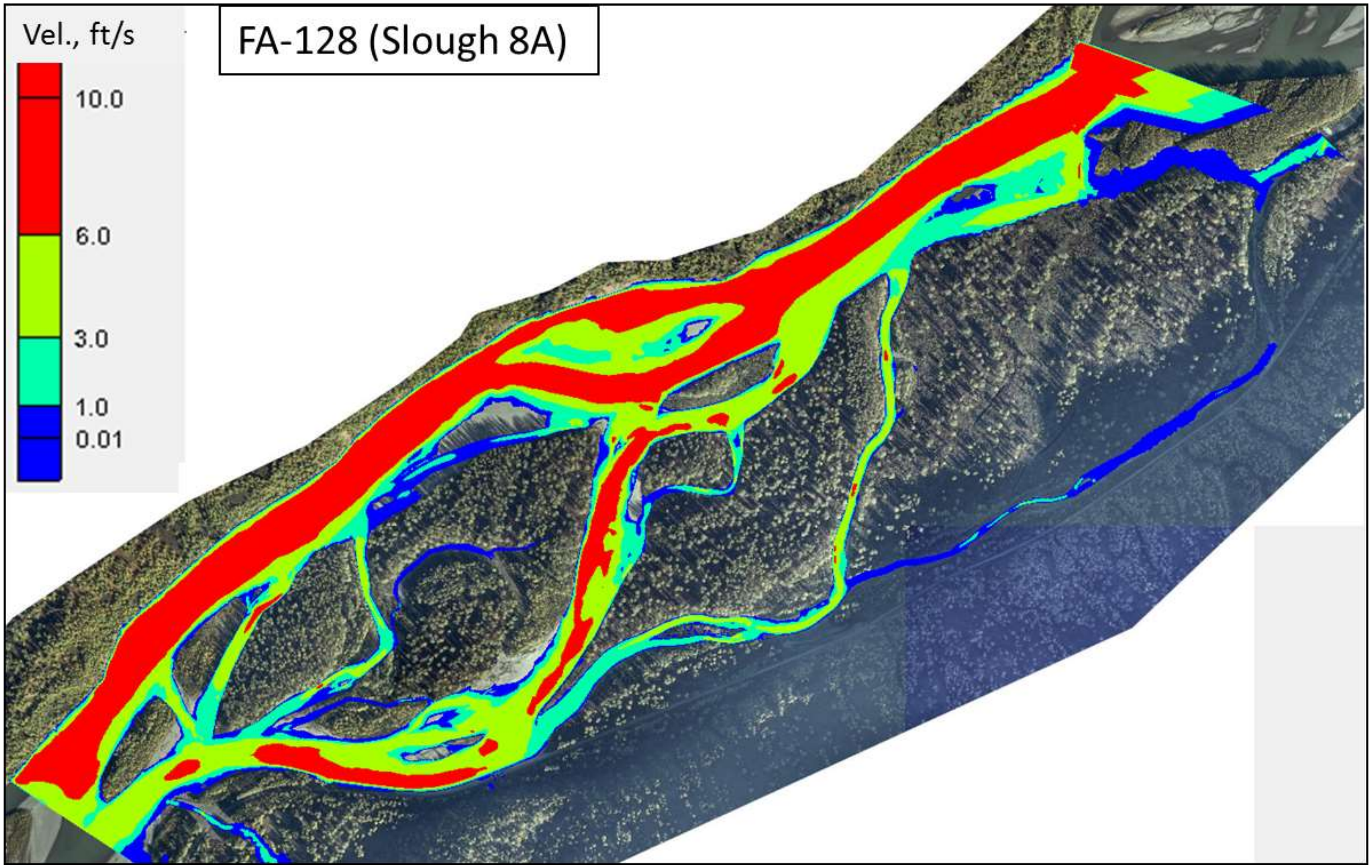


Figure 4-34. Hydraulic Model Velocities at 30,000 cfs, FA-128 (Slough 8A).

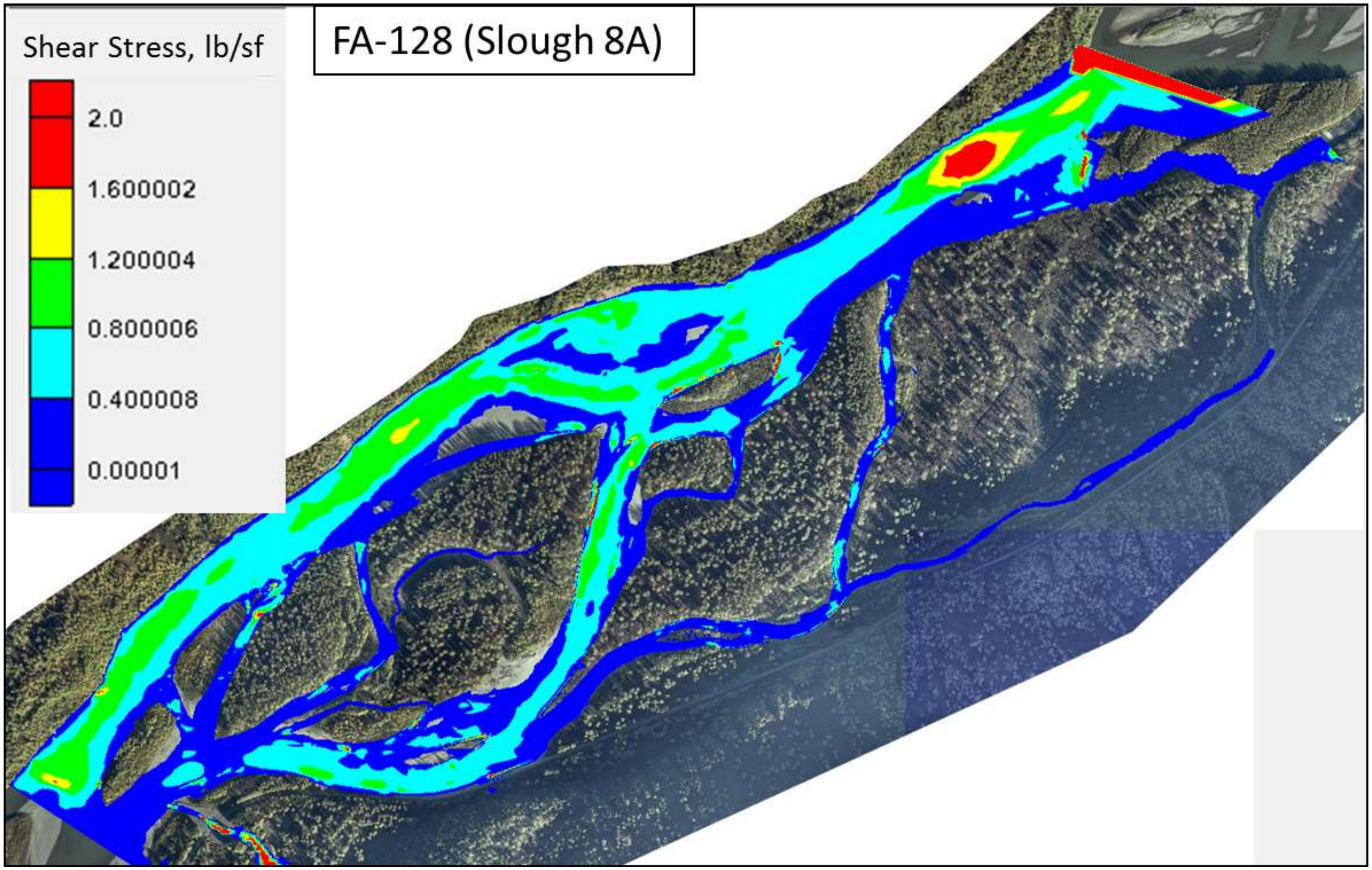


Figure 4-35. Hydraulic Model Shear Stress at 30,000 cfs, FA-128 (Slough 8A).

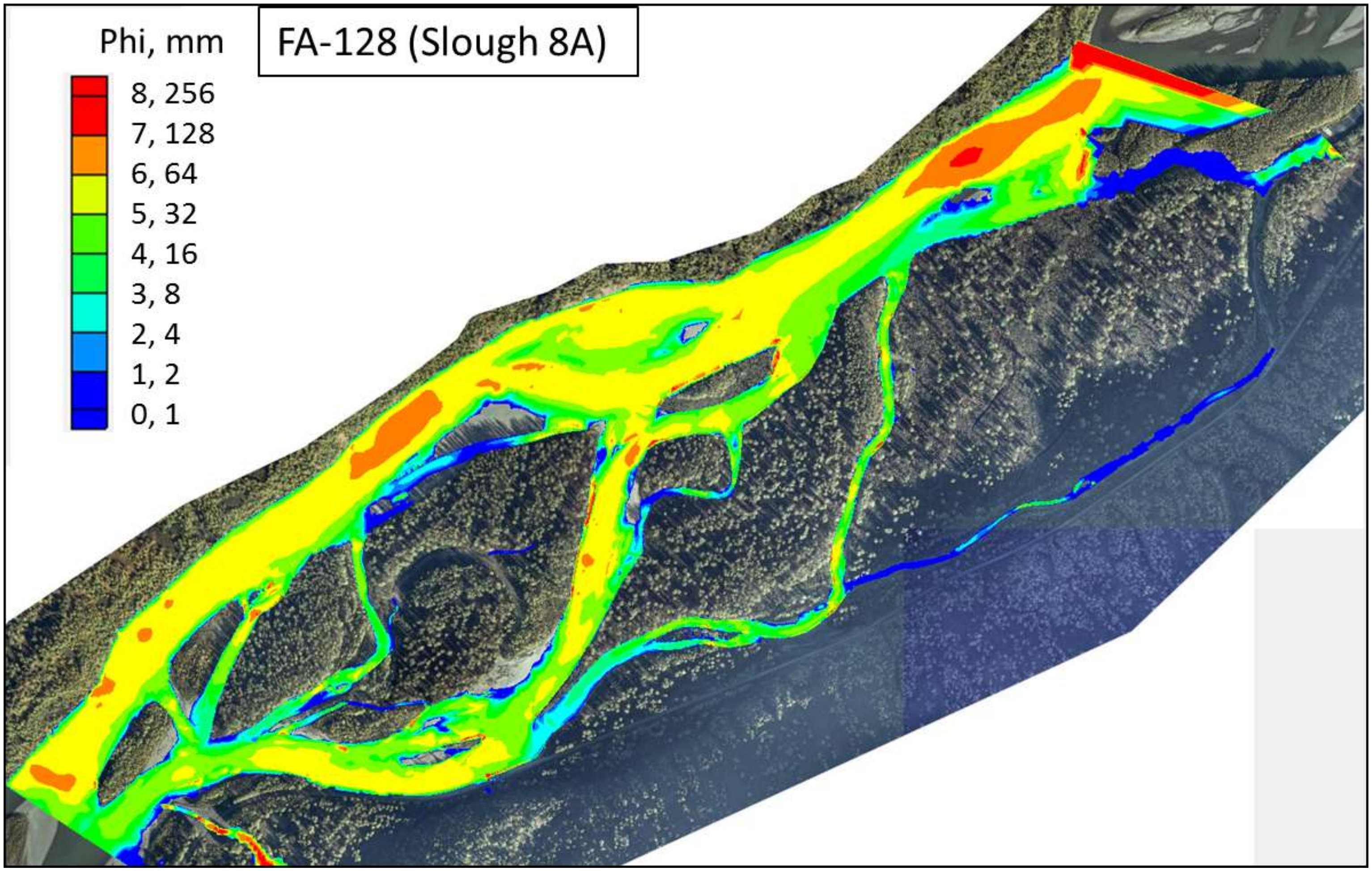


**Figure 4-36. Hydraulic Model $D_{crit}$ at 30,000 cfs, FA-128 (Slough 8A).**

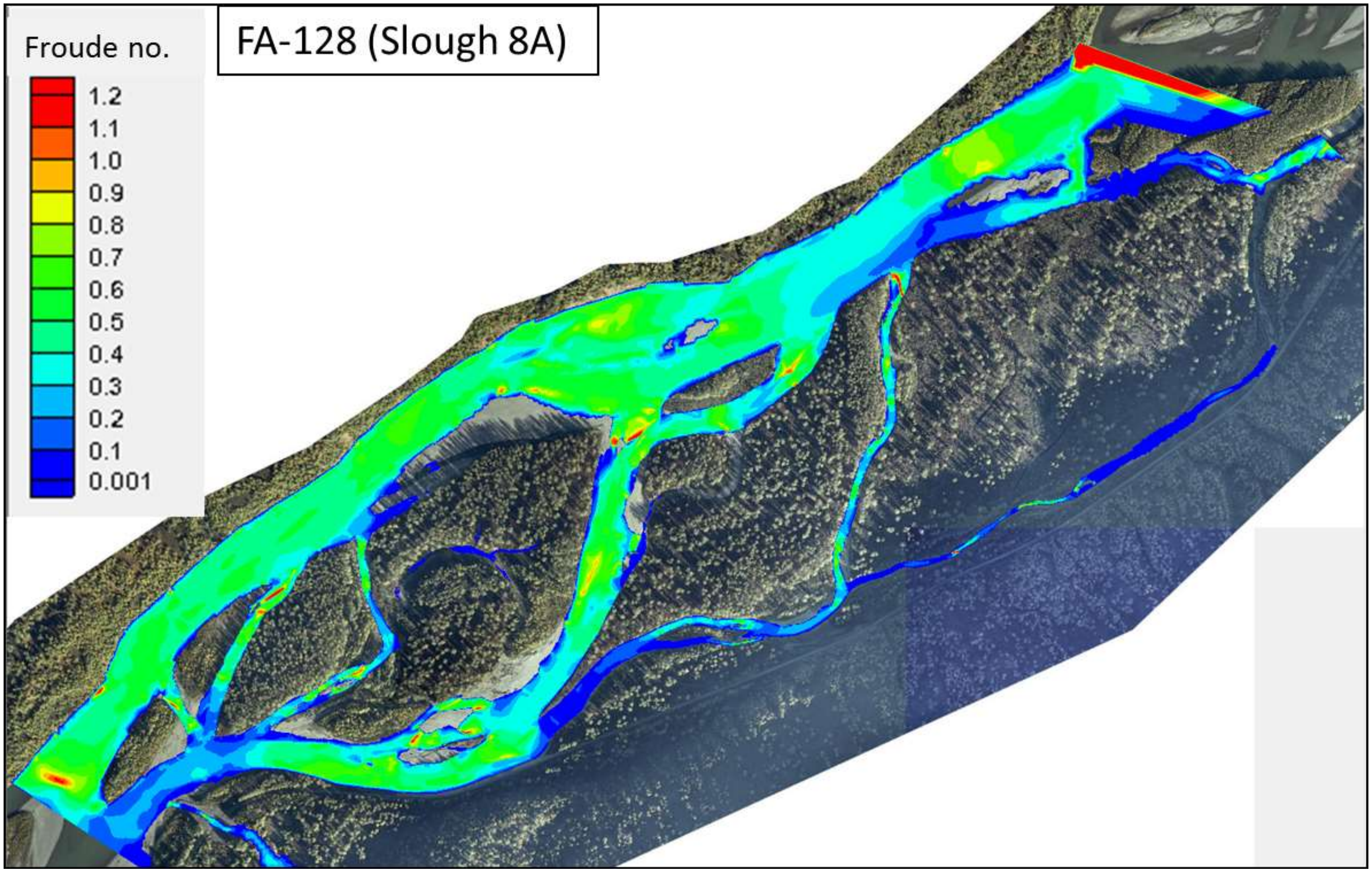


**Figure 4-37. Hydraulic Model Froude number at 30,000 cfs, FA-128 (Slough 8A).**