Fluvial Geomorphology Modeling

Susitna-Watana Hydroelectric Project

FERC No. 14241

Alaska Energy Authority

[Draft: 5/18/12]

Technical Memorandum

May 18, 2012

TABLE OF CONTENTS

1. INTRODUCTION

This technical memorandum documents the ongoing development of the procedure for modeling the fluvial geomorphology of the Susitna River below Watana Dam. The overall goal of the study is to model the effects of the proposed Susitna-Watana Hydroelectric Project (Project) on the fluvial geomorphology of the Susitna River. 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 to the Susitna River fluvial geomorphology modeling and provide an opportunity for stakeholders and other study leads to provide feedback on modeling approach development to ensure that the needs of all parties are being met, to the extent practical.

Specific topics covered include:

- Issues/questions that need to be addressed,
- Overall modeling approach,
- Description of the considerations and selection process for the models,
- Interaction/linkage of the fluvial geomorphology modeling with other studies and models,
- Spatial and temporal considerations for model application, and
- Assumptions, limitations and uncertainties of the proposed modeling approach.

2. ISSUES/QUESTIONS TO BE ADDRESSED

The purpose of the fluvial geomorphology studies is to assess the potential impact of the Project on the dynamic behavior of the river downstream of the proposed dam, with particular focus on potential changes in instream and riparian habitat. 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 (i.e., 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 Studies:

- 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. To develop the modeling approach, specific issues that need to be addressed have been identified. These specific issues have been further differentiated into reach-scale and local-scale issues since the scale influences the proposed approach.

2.1. 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.
- Changes in both the bed material (sand and coarser sizes) and wash load (fine sediment) 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 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 bed profile, channel dimensions, and potentially hydraulic roughness.

2.2. 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 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 as 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 fines supplied during backwater connection with the main stem.

    — 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 bed load deposits at tributary mouths that may alter tributary access or tributary confluence habitat.

2.3. Synthesis of Reach-Scale and Local-Scale Analyses

The final step in the effort will be the synthesis of the reach-scale and local-scale analyses to identify potential Project-induced changes in the relative occurrence of aquatic habitat types and associated surface area versus flow relationships. In addition to the results of the hydraulic and sediment transport modeling, this synthesis will require application of fluvial geomorphic relationships to develop a comprehensive and defensible assessment of potential Project effects. Examples of this type of integrated analysis that have been successfully performed by the project team include instream flow, habitat and recreation flow assessments to support relicensing of Slab Creek Dam in California; a broad range of integrated geomorphic assessments and modeling to assist the Platte River Recovery Implementation Program in Central Nebraska; and ongoing work to support the California Department of Water Resources and Bureau of Reclamation to design restoration measures for the San Joaquin River in the Central Valley of California downstream of Friant Dam.

3. OVERALL MODELING APPROACH

The proposed modeling approach considers the need to address both reach-scale and local-scale assessments 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 one-dimensional (1D) models to address reach-scale issues and two-dimensional (2D) models to address local-scale issues is proposed. Considering the broad physical expanse of the Susitna River system, the general hydraulic and sediment transport characteristics of the various subreaches that make up the overall study area will be evaluated using 1D computer models and/or established hydraulic relationships. The 2D models will be used to evaluate the detailed hydraulic and sediment transport characteristics on smaller, more local scales where it is necessary to consider the more complex flow patterns to understand and quantify the issue(s). The 2D models will be applied to specific detailed study sites that are representative of important habitat conditions and the various channel classification types. These sites will be chosen in coordination with the Instream Flow, Riparian Instream Flow, Ice Processes and Fish studies to facilitate maximum integration of available information between the studies.

The proposed approach to integrating 1D modeling at the reach-scale and 2D modeling at the local–scale will provide the following advantages:

- 1D modeling will allow for efficient assessment of the hydraulic conditions and sediment transport balance over the length of the study reach downstream of Watana Dam.

- The 1D model uses cross-sectional data that are being obtained as part of the Flow Routing and Instream Flow studies. (Note that some supplemental cross sections may be required for the 1D sediment transport model.)
- The 1D model will provide the boundary conditions for the 2D model, including starting water-surface elevations and upstream sediment supply.
- 2D modeling applied at the detailed study sites that are also chosen 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 with and pattern for this study.
- 2D modeling at the detailed study sites will provide an understanding of the hydraulic conditions and sediment transport processes that contribute to formation of individual habitat types.
- 2D modeling 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 1D model.

A comparison of the capabilities of 1D and 2D models is provided in Table 3.1.

Table 3.1. 1D versus 2D Model Capabilities

Consideration	1D Models	2D 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
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		X
Transverse hydraulic gradients		X
Bed deformation		X

4. SELECTION OF HYDRAULIC 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 project objective, (2) the class, type and regime of flows that must be modeled, (3) characteristics of the bed material and wash load 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 1D and 2D 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 will be evaluated for application on the Susitna River. Potential candidate models for the 1D and 2D portions of the study are discussed below.

4.1. 1D Models

Most 1D 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 time periods. In most cases, the flow record of interest is divided into a quasi-unsteady sequence of steady flows of variable discharge and duration; although some models include the capability to perform unsteady sediment transport simulations. For large rivers such as the Susitna, the unsteady aspect for sediment transport is probably not significant because the time scale of typical transport changes is much longer than the time scale for changes in the flows that drive the hydraulic conditions. In quasi-unsteady modeling the water-surface profile at each cross section is calculated for each time-step and corresponding discharge using the step-backwater computational procedure. The associated energy slope, velocity, depth and other hydraulic variables along with the input bed material characteristics are used to calculate the sediment transport capacity. 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-section control volume (i.e., the sub-channel concept) and the shape of the cross section is adjusted accordingly. Because the sediment transport calculations are performed by size fraction the models are capable of simulating bed-material sorting and armoring. The computations then proceed to the next time-step and the calculations are repeated using the updated cross sections and bed-material gradations.

1D sediment transport models have limitations. They should not be applied to situations where 2D and 3-dimensional (3D) flow conditions control the sediment transport characteristics of interest. The models do not consider secondary currents, transverse sediment movement, lateral variations in transport rates, turbulence and lateral diffusion; thus, the models cannot simulate such phenomena as point bar formation, pool-riffle formation, and planform changes such as river meandering or local bank erosion. The 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. In spite of these limitations, 1D models are appropriate for efficiently evaluating the general sediment-transport characteristics and 1D channel dynamics, including the overall sediment transport balance at the reach-scale. 1D models also provide boundary conditions for the more localized 2D models.

1D models that are being considered for this study include the widely-used U. S. Army Corps of Engineers (USACE) HEC-RAS (version 4.1; USACE 2010a), the Bureau of Reclamations SRH-1D (version 2.8; USBR 2011), DHIs MIKE 11 (version 2011; DHI 2011), and Mobile Boundary Hydraulics HEC-6T (version 5.13.22_08; MBH 2008). A summary of each of these models including potential benefits and limitations is provided in Table 4.1 and the following sections.

4.1.1. HEC-RAS

HEC-RAS, version 4.1.0 (USACE 2010a) is a publicly available and widely-used software package developed by 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 the HEC-6 (USACE 1993) and HEC-6T models (Mobile Boundary Hydraulics 2008). In HEC-RAS, the sediment-transport potential is calculated 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 stream and river channels that could result from modifications to the frequency and duration of the water discharge and stage, upstream and tributary sediment supply and channel geometry. Benefits of the HEC-RAS software include widespread industry acceptance, public availability and ease of use. Potential limitations of the program for sediment-transport simulations include excessive computer run-times, file-size output limitation, and the inherent problems associated with 1D modeling of aggradation and degradation that results from the algorithm used to distribute the changes in sediment volume across the cross section (in this case, the assumption of equal adjustment at all points along the wetted portion of the bed).

4.1.2. SRH-1D

SRH-1D (Huang and Greimann 2011) is a 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 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 under a broad range of conditions outside the Bureau of Reclamation and the lack of graphical user interface that complicates data input and manipulation and display of output.

4.1.3. MIKE 11

Danish Hydraulic Institute's (DHI) MIKE 11 is a proprietary software package developed for 1D 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 the reporting and presentation capabilities. Disadvantages primarily stem from the proprietary nature of this model and high cost of the software license.

4.1.4. HEC-6T

HEC-6T was written by William A. Thomas, former Chief of the Research Branch at the USACE Hydrologic Engineering Center (HEC). Mr. Thomas planned, designed, wrote and applied the publically available version of HEC-6; HEC-6T is a proprietary 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 and limited capabilities of the graphical user interface. This software is relatively inexpensive: the fact that it is proprietary is not a significant limitation.

4.1.5. 1D Model Selection Process and Initial Evaluation

Based on the above information and experience the Geomorphology Study team has with these models, the Geomorphology Study team tentatively proposes to use HEC-6T for the reach-scale sediment transport analysis. This proposal is based on confidence gained through previous studies that HEC-6T is capable of effectively and efficiently modeling the processes that are important for this scale of geomorphic analysis. The selection of the 1D (as well as the 2D) model will be coordinated with the other pertinent studies and the stakeholders. This technical memorandum is part of the coordination process. Specific model-selection criteria are identified in Table 4.1 along with an evaluation of each candidate model relative to the criteria.

Table 4.1. Evaluation of 1D Models

Evaluation Criteria	Models			
	HEC-RAS	SRH-1D	MIKE 11	HEC-6T
General				
Proprietary/cost	No	No	Currently Investigating	$3000
Full or quasi unsteady for sediment transport simulation	Quasi	Both	Currently Investigating	Quasi
Ice for fixed bed	Yes	No	Currently Investigating	No
Ice for moveable bed	Currently Investigating	No	Currently Investigating	No
Number of transport equations supported	7	13	10	18
Supports user defined transport equation	No	No	Currently Investigating	Yes
Closed loop capability	Not Currently	Yes	Yes	Yes
Experience with model	High	Limited	Limited	High
Model Size Limitations				
# of cross sections	No limit	No limit	No limit	5000
# of hydrograph ordinates	40000	Not indicated	Currently Investigating	No Limit
# of sediment sizes	20	Not indicated	Currently Investigating	20
Sediment Sizes Supported				
Wash load (silts, clays)	Yes	Yes	Yes	Yes
Considers settling and resuspension	Yes	Yes	Yes	Yes
Sand	Yes	Yes	Yes	Yes
Gravel and cobble	Yes	Yes	Yes	Yes

4.2. 2D Models

Potential 2D models that are being considered for this study include the Bureau of Reclamation's SRH2-D (version 3 [Lai 2008; Greimann and Lai 2008]), USACE's Adaptive Hydraulics (ADH version 3.3 [USACE 2010b]), the U.S. Geological Survey's (USGS's) MD_SWMS (McDonald et al. 2005), and DHIs MIKE 21 (version 2011 [DHI 2011]).

4.2.1. SRH-2D

The 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 2D flow fields. SRH-2D is a well-tested 2D model that can effectively simulate steady or unsteady flows and is capable of modeling subcritical, transcritical and supercritical flow conditions. The model uses an unstructured arbitrarily shaped 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. Preliminary contact with the model developers indicates that permission would be granted for use in this study. This version of the model (Greimann and Lai 2008) includes a "Morphology" module that calculates bed load 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. 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.

4.2.2. 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, 3D Navier-Stokes flow, and 2D or 3D 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 2D 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. 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 model is publically available.

4.2.3. MD_SWMS/SToRM

The USGS Multi-Dimensional Surface-Water Modeling System (MD_SWMS; McDonald et al. 2005) is a pre- and post-processing application for computational models of surface-water hydraulics. The system provides a graphical user interface (GUI) that allows the modeler to build and edit data sets. MD_SWMS also provides a framework that links the GUI with the modeling applications. The GUI is an interactive 1D, 2D and 3D 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 package includes a number of different modeling applications including SToRM (System for Transport and River Modeling). SToRM uses an unstructured triangular mesh and provides both steady-flow and unsteady-flow capability. The 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, sediment transport algorithms for cohesive and non-cohesive sediment mixtures, transport of suspended and dissolved substances and an automatic mesh refinement tool to better predict the hydraulic conditions in areas of high hydraulic variability.

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.

4.2.4. MIKE 21

Developed by DHI, MIKE 21 is a proprietary modeling system for 2D 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 GUI as well as pre- and post-processing modules for use in data preparation, analysis of simulation results and reporting modules that have graphical presentation capabilities. MIKE 21 has the ability to model a range of 2D mesh types that include Single Grid, Multiple Grid, Flexible Mesh, and Curvilinear Grid. The primary limitation to MIKE-21 is that is proprietary software and is relatively expensive as compared to other available software.

4.2.5. 2D Model Selection Process and Initial Evaluation

The selection of the 2D will be coordinated with the other pertinent studies and the stakeholders. This technical memorandum is part of the coordination process. Specific model selection criteria are identified in Table 4.2 along with an evaluation of each candidate model relative to the criteria.

Table 4.2. Evaluation of 2D models

Evaluation Criteria	Models			
	SRH-2D	ADH	MD_SWMS/SToRM	MIKE 21
General				
Proprietary/cost	No	No	No	Currently Investigating
Unsteady flow capability	Yes	Yes	Yes	Yes
Ice for fixed bed	No	No	No	No
Ice for moveable bed	No	No	No	No
Number of transport equations supported	13	2	Currently Investigating	10
Supports user defined transport equation	No	Yes	Currently Investigating	Currently Investigating
Relative execution speed	Fast	Slow	Currently Investigating	Fast
Model stability	High	Moderate	Currently Investigating	Currently Investigating

Experience with model	High	High	Limited	Limited
Moveable boundary simulation	Yes	Yes	Yes	Yes
Grid Structure/Model Formulation				
Finite element (FE)/Finite Volume (FV)	FV	FE	FV/FE	FV/FE
Grid structure	Flexible mesh	Flexible Mesh	Flexible Mesh	Currently Investigating
Model Size Limitations				
# of grid elements	16000	Unlimited	Currently Investigating	Unlimited
Sediment Sizes Supported				
Wash load (silts, clays)	No	Yes	Yes	Yes
Considers settling	No	Yes	Yes	Yes
Sand	Yes	Yes	Yes	Yes
Gravel and cobble	Yes	Yes	Yes	Yes

4.3. Tributary Delta Model

Tributary confluences are areas of interest for determining the potential Project effects on sediment transport and morphology. Alternation of mainstem flow regime has the potential to change the elevation at which tributary sediments are initially deposited since the main stem may be at a different stage when the tributaries are at peak flow. Additionally, the ability to mobilize and transport bed load delivered by tributaries may also be altered. Changes in the configuration of sediments deposited at the tributary confluences can affect the ability of fish to access the tributaries and the extent of clear water habitat associated with some tributary confluences. Modeling sediment transport and deposition processes at select tributary mouths will therefore be necessary.

The tributaries to be modeled will be determined in conjunction with AEA, the Instream Flow and Fish studies and the stakeholders based on fish use and the potential for Project effects. The Geomorphology Study team tentatively proposed modeling a subset of tributary confluences with the Susitna River that represent the range of conditions among all of the tributaries. Modeling of the larger tributary confluences, such as the Talkeetna, Chulitna and the Yentna is not anticipated because it would require relatively large-scale 2D modeling and a large commitment of resources that would detract from the studies in more critical areas. If issues are ultimately identified that require modeling of these areas a plan will be developed at that time.

It is currently proposed that a model will be created for the tributary deltas that uses estimated bed load transport from the tributary, the topography and the bathymetry of the confluence, measurements of the characteristics of the tributary deposits, and the ability of the main stem in the area of the confluence to mobilize and transport those deposits. The approach will include field observations to characterize the sediment transport regime that will be used to identify appropriate methods of estimating bed load transport. Surveys of tributary channel geometry and sampling of bed material gradations will be coupled with an appropriate bed material transport function to calculate sediment yield rating curves. Hydrology synthesized for ungaged tributaries will be needed from other studies for each of the selected tributaries for this purpose.

The yield and topography in the area of the expected delta along with the ability of the main stem to mobilize and transport the bed material will provide a basis for characterizing how Project operations would affect the formation of tributary deposits. At this time, it is envisioned that a relatively detailed 1D hydraulic model of the main stem in the vicinity of each tributary will provide sufficient hydraulic information to evaluate the potential for, and likely extent of, additional growth of the tributary deposits into the mainstem. For complex tributary confluences that are of particular interest to the instream flow studies, local-scale 2D models can be developed and applied to support the analysis.

5. LINKAGE/INTERACTION OF FLUVIAL GEOMORPHOLOGY MODELING WITH OTHER STUDIES

The Fluvial Geomorphology Modeling Study team will interact extensively with the Flow Routing, Instream Flow, Riparian Instream Flow, Ice Processes and Fish study teams. The types of interaction will vary depending on the specific study, but a considerable amount of physical data describing the system, including transects, topography/bathymetry, substrate characterization, aerial photography, and pre- and post-Project flows generally will be shared. Selection of joint sites for detailed studies will be an important aspect of the collaboration. By selecting commons sites, the potential for exchange of information between the study teams will be maximized and ensure that the most effective and extensive use of detailed study site data will be used.

5.1. Flow Routing Study

It is anticipated that the Flow Routing Study will provide the pre- and post-Project hydrology information for all studies, including the Fluvial Geomorphology Modeling Study. This hydrology information will include mainstem pre- and post-Project flows at various points along the study area and inflows for gaged and ungaged tributaries. This information is expected to be provided for the 50 year, extended flow record.

For the Fluvial Geomorphology Modeling effort the upstream boundary condition at RM 184 will be the existing condition or pre-Project daily flows from the extended flow record. For the post-Project condition, the upstream boundary condition will be the average daily releases from Watana Dam unless load-following scenarios are evaluated. In the latter case, the Project outflows will need to be on an hourly or possibly finer time increment. Estimated daily inflows from tributaries provided by the Flow Routing Study will be input along the length of the 1D sediment transport model and may be inputs to the localized 2D models depending on the location and specific issues to be addressed.

5.2. Instream Flow Study

For the Instream Flow Study, an assessment of whether the current channel geometry and substrate characterization used in evaluation of habitats will remain relatively unchanged over the period of the license under both the pre- and post-Project conditions will be important. The Geomorphology Studies will determine whether the channel morphology is in a state of dynamic equilibrium such that the distribution of habitat conditions over the timeframe of the license (assumed to be 50 years, corresponding to the maximum FERC licensing period) will be adequately reflected by existing channel morphology. If it is determined that the river is not in a state of dynamic equilibrium, the Geomorphology Studies will provide projections of the direction and magnitude of the changes. Changes in the relative occurrence of aquatic habitat types and the associated surface area versus flow relationships that may occur as a result of the Project will be an important outcome of these studies. As part of this evaluation, pre- and post-Project changes in channel dimensions (width and depth) and the proportion and distribution of geomorphic features and habitat types will be estimated for each of the reach types delineated using the channel classification system to be developed for the Susitna River. This will provide the Instream Flow Study with an important part of the information required to evaluate the post-Project effects on aquatic habitat. Other important information to be provided by the Fluvial Geomorphology Modeling and the Geomorphology studies for the Instream Flow Study includes:

- Characterization of channel/habitat changes between 1980s and 2012.
- Evaluation of stability of islands, side channels and floodplain surfaces over the period of aerial photographic record (1951, 1983, current photos).
- Identification of zones of substrate mobilization, deposition and scour at the reach scale for pre- and post-Project flow regimes.
- Potential changes in lateral habitat connectivity due to aggradation and degradation
- Pre- and post-Project changes in spatial and seasonal patterns of the fine sediment (wash load) transport and the associated Project effects on turbidity.
- Changes in substrate composition in both the main channel and lateral habitats.
- Pre- and post-Project large woody debris (LWD) recruitment and transport.

The velocity and depth measurements collected by the Instream Flow Study to characterize habitat will be used to assist in calibrating the hydraulic model(s). Data collected on the distribution of flow between the main channel and lateral habitat will also be important information to help calibrate the hydraulic portion of the 2D model.

5.3. Riparian Instream Flow Study

Riparian vegetation plays a large 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 and 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; thus, there is a feedback mechanism between the two 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 need to be closely coordinated because of the interaction described above. The collaboration will begin with coordinated the selection of the detailed study sites among the Riparian Instream Flow, Ice Processes and Geomorphology study teams. By working on the detailed study sites together the teams will develop an understanding of the interaction between the processes that are responsible for creation and maintenance of the islands and lateral habitats. 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 2D modeling will greatly facilitate this effort by helping to identify rates of sediment deposition and reworking of these surfaces. Similarly, profiling of deposited sediments in the riparian corridor to identify the types of sediments that make up the floodplain will also contribute to the understanding of the physical processes and development of the functional model for linkage of the geomorphology, riparian vegetation and ice processes.

The results of the fluvial geomorphology model along with applicable geomorphic principles will be applied to interpret model results. Understanding of the geomorphology of the system will also be used to provide a reality check on the extent of changes indicated by the modeling. Examples of the linkage between the Riparian Instream Flow Study and the fluvial geomorphology model include:

- Altering Manning's n-values to represent establishment (increased n) or removal (decreased n) of vegetation.
- Application of shear stress parameter to determine the erodibility of banks and potential influence of vegetation.
- Interpretation of flow and sediment transport patterns to determine areas of sediment deposition within and adjacent to vegetation.
- More accurate water surface elevations from the local-scale 2D model than is provided by the 1D models for periods when the flows only partially inundate the riparian corridor.
- Use of geomorphic threshold relationships to understand the potential for removal of vegetation by the flows and the potential for additional channel narrowing due to changes in the vegetation patterns.

5.4. Ice Processes Study

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. In both examples these influences affect channel morphology. Ice jams can also directly influence the channel morphology by diverting flows onto 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 normally not be mobilized by rafting large cobbles and boulders.

There will be close collaboration between the Geomorphology and Ice Process studies to identify the key physical processes that interact between the two. Working together to analyze the conditions at the detailed study sites will be a key part of this collaboration. A significant portion of the influences of ice processes on morphology are directly related to their effects on riparian vegetation, as discussed in Section 5.3. Additionally, influences of ice processes beyond the riparian vegetation issues that may be incorporated directly into the fluvial geomorphology modeling may include:

- Simulating the effects of surges from ice jam breakup on hydraulics, sediment transport and erosive forces using unsteady-flow 2D modeling with estimates of breach hydrographs.
- Simulating the effect 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 2D model output to assess shear stress magnitudes and patterns in vegetated areas, and the likelihood of removal or scouring.

- Use of the detailed 2D model output to assess shear stress magnitudes and patterns in unvegetated areas, and the likelihood of direct scour of the boundary materials.

5.5. Fish Study

The primary interaction with the Fish Study will be in the selection of the sites for detailed study. Part of the selection process will consider the use of the specific sites as well as the types of habitat present at the site by target fish species. The local-scale 2D models can be used to evaluate instream habitat quality on a spatially-distributed basis rather than the cross-sectionally-based approach used in traditional Instream Flow Incremental Methodology (IFIM) studies.

6. SPATIAL AND TEMPORAL CONSIDERATIONS FOR MODEL APPLICATION

6.1. Spatial Scale

The spatial extent of the Lower River modeling effort has not been determined. The 1D modeling will be continued downstream into the Lower River to at least Sunshine Station (RM 84). The decision whether to continue the 1D modeling further downstream in the Lower River and whether detailed 2D modeling sites will be included in the Lower River will be made based on an assessment of the potential for the Project to affect channel morphology in this area. The assessment of potential Project effects in the Lower River is being conducted in 2012 as part of the Geomorphology Study. Results of this effort will be presented to and reviewed by the stakeholders, AEA and key members of other study teams (Instream Flow, Riparian Instream Flow, Ice Processes and Fish studies). This assessment will include a determination of the downstream limit for the 1D modeling and identification of any 2D modeling sites in the Lower River.

6.2. Model Time Scale

The time scale for the sediment transport model simulations is also an item that must be determined in collaboration with the other studies and stakeholders. The time scale includes the length of simulation period and the time-step of the simulation. Model execution times are often a limitation, particularly for the 2D model. In fact, this is a key consideration for developing a proposed modeling approach that combines 1D and 2D modeling. It will most likely be practical to execute the 1D model for a continuous period of several decades representing the potential length of a FERC license. On the other hand, the computational requirements for the 2D model will likely limit simulation times to no longer than individual seasonal hydrograph.

6.2.1. 1D Model

For the 1D modeling, it is currently proposed that the simulation be conducted over a continuous period that represents the potential length of a FERC license, assumed to be 50 years for purposes of developing this work plan. The use of average daily flows should provide sufficient temporal resolution unless the Project is operated in a mode that results in considerable flow fluctuations within a day; this would be the case if load-following scenarios are included. If such fluctuations are included in potential operational scenarios then portions of the hydrographs with these flow fluctuations will need to be run at a time step on the order of 1 hour or less.

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 habitats and how those conditions may be altered by the Project. For these conditions, an appropriate time step will need to 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, for breaking of an ice jam the time step may need to be on the order of minutes.

6.2.2. 2D Model

Because of the nature of the 2D model formulation the time increment for the 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. Due to the intensive computational requirements of 2D sediment transport modeling and the potentially long execution times it is currently proposed that the 2D model will be executed for individual flow seasons representing typical years (low, medium and high) when flows are expected to be sufficiently high to mobilize the bed material (most likely late spring through the summer).

Similar to the 1D model, the 2D model may be used to perform simulations of floods of given return periods or individual events caused by breaking of an ice jam to understand conditions that form or maintain the habitats and how those conditions may be altered by the Project.

7. ASSUMPTIONS, LIMITATIONS AND UNCERTAINTIES

Although the hydraulic, hydrodynamic, and sediment-transport modeling discussed in the previous sections has been successfully used for a wide variety of projects, it is important to understand the limitations and uncertainties associated with the modeling. These considerations are especially important when interpreting the model results because of the primary assumption that long term channel response of the system to the Project (i.e., changes in the flow and sediment transport regimes) can be interpreted from a combination of long term 1D modeling; short term, site specific 2D modeling; and geomorphic principles. These limitations and uncertainties are applicable to the suite of model platforms that are being considered for this study, and are itemized in the following sections.

7.1. Limitations

Limitations of the fluvial geomorphology modeling include:

- It will not be possible to run the 2D model for a 50-year or other long-term time frame. Model runs for specific flows or specific season/years will likely be the time frame for the 2D model.
- The 2D model will not model the entire length of the study area; rather, specific detailed study sites will be modeled that are representative of the range of important geomorphic and aquatic habitat conditions.

- The modeling effort will not produce a 3D surface of the channel and floodplain that can be used as a basis for cross sections in the Instream Flow Study.
- Lateral migration and bank erosion are not modeled directly.
- For both the 1D and 2D modeling, the predicted results at the up- and downstream boundary conditions, and at any tributary or distributary boundary conditions, are influenced by the user-prescribed model input.
- Calibration of the 1D hydraulic model will be limited to measured water-surface elevations and discharges, as well as aerial photography for defining inundated area, under existing and historical conditions.
- Calibration of the 1D sediment-transport model will be limited to comparative (repeat) cross section surveys, historical gage measurements and ratings (i.e., specific gage analyses) and available sediment-transport measurements.
- Calibration of the 2D modeling will be limited to hydraulic conditions (i.e., calibration to measured water-surface elevations, velocity and discharge measurements, and aerial photography to determine inundated area).

7.2. Uncertainties

Inherent uncertainties for the fluvial geomorphology modeling stem from data gaps. These uncertainties include:

- Sediment transport from most of the tributaries has not been measured and will have to be estimated using sediment transport relationships and mass balance considerations using locations with available sediment transport measurements.
- The vast majority of the tributaries are not gaged for flow so hydrology will have to be estimate using watershed characteristics and mass balance considerations using locations with available hydrologic records.
- Only a few stream gages have records approaching 50 years which will require missing data to be developed using correlation with other gages.
- Although the calibrated 1D hydraulic and sediment-transport model will be capable of accurately predicting the general conditions along the project reach, the ability of the model to accurately predict conditions at a specific location that is not in the vicinity of a calibration measurement is unknown.
- Because calibration of the 2D hydraulic modeling will only involve calibration to measured hydraulic conditions, only the hydraulic output is verifiable and the degree to which the 2D sediment-transport modeling is representative of actual conditions is not known.

8. REFERENCES

Bovee, K.B., 1982. A guide to stream habitat analysis using the instream flow incremental methodology. Instream Flow Information Paper No. 12. FWS/OBS-82/26. U.S. Fish and Wildlife Service, Office of Biological Services, Fort Collins, Colorado.

Brabets, T.P, 1997, Geomorphology of the Lower Copper River, Alaska: U.S. Geological Survey Professional Paper 1581, 89 p.

Conaway, J.S., and Moran, E.H., 2004, Development and calibration of two-dimensional hydrodynamic model of the Tanana River near Tok, Alaska: U.S. Geological Survey Open-File Report 2004-1225, 22 p.

Danish Hydraulic Institute (DHI), 2007a. Mike 21 Flow Model, User's Manual, Hydrodynamic Module, Danish Hydraulics Institute, 90 p.

DHI, 2007b. Mike 21 ST, Non-Cohesive Sediment Transport Module, User's Manual, Hydrodynamic Module, Danish Hydraulics Institute, 56 p.

DHI Water and Environment, 2011. MIKE 11.

DHI Water and Environment, 2011. MIKE 21 Flow Model, Hydrodynamic Module User Guide, 90p.

Greimann, B. and Y. Lai, 2008. Two-Dimensional Total Sediment Load Model Equations, ASCE Journal of the Hydraulics Division, 134(8): 1142–1146.

Huang, J.V. and Greimann, B.P., 2011. SRH-1D 2.8 User's Manual, Sedimentation and River Hydraulics – One Dimension, Version 2.8, U.S. Department of Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group. 227p.

Lai, Y.G., 2008. SRH-2D version 2: Theory and User's Manual, Sedimentation and River Hydraulics – Two-Dimensional River Flow Modeling, U.S. Department of Interior, Bureau of Reclamation, November, 113 p.

McDonald, R.R., Nelson, J.M., and Bennett, J.P., 2005, Multi-dimensional surface-water modeling system user's guide: U.S. Geological Survey Techniques and Methods, 6-B2, 136 p.

Mobile Boundary Hydraulics, 2008.

Ruark, M., Niemann, J., Greimann, B., and Arabi, 2011. Method for Assessing Impacts of Parameter Uncertainty in Sediment Transport Modeling Applications, Journal of Hydraulic Engineering, 137(6): 623–636.

U.S. Army Corps of Engineers (USACE), 1993. HEC-6, Scour and Deposition in Rivers and Reservoirs, User's Manual, Hydrologic Engineering Center, Davis, California.

USACE, 2010a. HEC-RAS, River Analysis System, User's Manual, Version 4.1.0, Hydrologic Engineering Center, Davis, California.

USACE, 2010b. Adaptive Hydraulics User Manual Version 3.3. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi.