SAMPLE SCOPE OF WORK

Two-Dimensional Hydraulic Modeling Analysis for Transportation Projects

This sample Scope of Work (SOW) provides transportation agencies with a starting point and/or template for a consultant contract SOW for a two-dimensional (2D) riverine hydraulic analysis.

This document is not legally binding in its own right, and compliance with FHWA technical guidance described in this document is voluntary only.

The types of projects that might justify two-dimensional hydraulic analysis include the partial list below. Further guidance on when 2D modeling is justified or otherwise required by Federal law or regulation can be found in Table 4.1 of FHWA HDS 7 “Hydraulic Design of Safe Bridges.”

* Hydraulic design and scour analysis for a new bridge, replacement bridge, or culvert
* Scour evaluation of a new or existing bridge
* Design of scour countermeasures
* Major and complex culvert analysis and design
* Streambank stabilization
* Design of protection for road embankments in longitudinal floodplain encroachments
* Design of multiple-opening crossings
* Floodplain impact analysis of highway projects
* Habitat analysis
* Channel rehabilitation or realignment analysis
* Sediment transport analysis
* Tidal hydraulics – For some projects it may be sufficient to represent tidal boundary conditions when modeling bridge hydraulics, while for others, the addition of wind and wave action must be considered. For more information, refer to the FHWA Primer on Modeling in the Coastal Environment <https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif18002.pdf>

This SOW is directed at the use of 2D hydraulic modeling for highways in the river environment. While some aspects of the content are applicable to coastal hydraulic modeling, the document is focused on, and intended for use in riverine settings. In coastal regions, hydraulic and hydrodynamic forces should be combined with coastal processes such as tidal generation and propagation, wave stresses created as waves break on the coast, and wind setup of the water surface. These topics are beyond the scope of this reference document.

The exact content of the SOW for a particular study will vary depending on the type of project and its purposes.

Throughout this sample SOW, instructional content for use by the Agency is provided as italicized text within boxes (such as this text). The actual SOW incorporated into a contract should delete and not include these instructions. Note also that in locations highlighted with a double underline throughout the document or where the indicator [Agency Name] appears, should be replaced with the Agency’s desired text and/or actual name of the Agency, without brackets.

# GENERAL

The Consultant shall perform the two-dimensional (2D) hydraulic modeling analysis in accordance with this Scope of Work (SOW).

## Purpose

Two-dimensional hydraulic analysis is required for this project to accurately determine the values of certain hydraulic parameters under a range of flow conditions. The parameters to be calculated include flood elevation and lateral extent, flood depth, velocity (magnitude and direction), and shear stress, among others. The resulting values will be used for the project-relevant items such as those listed below as well as other project elements not listed here:

* Verification of bridge waterway adequacy: determination of minimum bridge low chord profile, assessment of road overtopping location and magnitude, scour evaluation, etc. for a bridge design project
* Scour evaluation of an existing bridge
* Floodplain impact analysis or compliance documentation
* Design or evaluation of bridge scour for a proposed structure
* Design or evaluation of stream instability countermeasures
* Embankment protection analysis and design
* Streambank stabilization design
* Design and analysis of major and/or complex culverts
* Accurate understanding of complex flow patterns for design of multiple bridge/culvert openings either in series, in combination, or both
* Environmental permitting support and habitat analysis
* Channel rehabilitation or realignment analysis

The list above can be edited by omitting items not relevant to the particular project or adding other relevant items as needed.

## Reference Documents

The following documents are incorporated by reference into this SOW. Conformance with the requirements and recommendations of these documents is expected in the performance of the work unless written justification is provided for deviation from any relevant recommendations.

In the first bullet below, the correct title of the Agency’s manual should be entered.

The FHWA documents listed below are technical guidance or references.

* [Agency Name] Hydraulic Design Manual
* FHWA Reference Document “*Two-Dimensional Hydraulic Modeling for Highways in the River Environment”*
* FHWA HDS 2 *“Highway Hydrology”*
* FHWA HDS 7 *“Hydraulic Design of Safe Bridges”*
* FHWA HEC-18 *“Evaluating Scour at Bridges”*
* FHWA HEC-20 *“Stream Stability at Highway Structures”*
* FHWA HEC-23 *“Bridge Scour and Stream Instability Countermeasures”*

## Software Requirements

The Consultant shall obtain and maintain the software and licenses required to develop, run, edit and apply the results of the two-dimensional analyses required under this SOW. Required software includes the graphical user interface Surface-water Modeling System (SMS) together with the Sedimentation and River Hydraulics-Two Dimensional (SRH-2D) model. Supporting geospatial software such as ArcGIS, MicroStation, OpenRoads, AutoCAD Civil 3D or other comparable software may also be useful or required. Electronic work products submitted to the Agency shall be produced by the most current version of the relevant software at the time they are submitted.

The language below is intended to clarify expectations as to the software program(s) to be used for two-dimensional modeling. It may be desirable to add language that the Consultant will not pass the cost of software or licenses through to the agency as a project expense. The paragraph below calls for the use of SMS and SRH-2D, which is the modeling software currently recommended by the FHWA. The Agency may, at its discretion, require a different program or allow the Consultant to choose the software. The highlighted sentence in the next paragraph should be modified if the Agency does not intend to require the use of SMS and/or SHR-2D. The Agency may also list the acceptable geospatial software for the effort.

Note: The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturer’s names appear in this document only because the Government considers them essential to the objective of the document. The document includes them for informational purposes only and the Government does not intend them to reflect a preference, approval, or endorsement of any one product or entity.

# DATA COLLECTION

Note: Fill in appropriate entries in the highlighted locations. Many DOTs use a standard modification to the State Plane system for conversion from grid to ground. If that applies to your Agency it should be specified in the paragraph below.

## Project Vertical Datum

All elevation values depicted in the hydraulic modeling, and in the presented results of the modeling, shall be reported in the North American Vertical Datum of 1988 (NAVD 88) and in US Survey feet, unless a different vertical datum and units are specified by the [Agency name] for the specific project or study.

## Horizontal Coordinate System

The horizontal coordinate system used in the model development and in the resulting model output will be [state name] State Plane, Zone [fill in appropriate zone] in the North American Datum of 1983 (NAD83), unless a different horizontal coordinate system has been specified by the Agency for the specific project or study

## Typical Data Provided by Agency

This section and the next incorporate the assumption that the Agency will not provide survey, topographic or bathymetric data. The data provided by the Agency versus what the Consultant is to obtain depends on several factors, such as the availability of public domain digital aerial mapping of suitable quality (explained later in this SOW), the Agency’s use of in-house or on-call surveyors, etc.

The [Agency name] is responsible to provide the following:

* Record or as-built drawings of all highway and bridge facilities that fall within the model extents.
* Any available hydraulic analysis or design reports associated with highway and bridge facilities that fall within the model extents.
* Any hydraulic models (1D or 2D) that have already been developed for the reach of interest or adjacent to the reach of interest.
* Recent bridge inspection reports (topside and underwater) for bridges owned by the Agency that fall within the model extents.
* Maintenance or asset management records of major structures and drainage systems within the model extent.
* Any available design documents and/or drawings for the current project.
* Previous scour analyses.

## Additional Data Collected by the Consultant

The Consultant’s services under this SOW will include collecting, obtaining, or developing the following data in support of two-dimensional hydraulic modeling:

* Information on flood hydrology from all available official sources (streamflow gauge data; Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) reports; previous hydrology studies for the same watershed; high-water marks; anecdotal information from adjacent landowners).
* Aerial imagery (a time history of aerial photographs may be desirable to inform assessments of channel migration rates).
* Any available, topographic and/or bathymetric data for the study reach that is in the public domain (refer to Section 2.5 for accuracy requirements). The Consultant will examine available topographic data and make recommendations on suitability for modeling to the Agency.
* Site specific soil survey and geotechnical analyses (if scour analysis is performed).

If suitable topographic data are not available, the Consultant shall acquire and process topographic digital data meeting the accuracy requirements described in Section 2.5 of this SOW, with coverage throughout the model domain. If suitable bathymetric data are not available the Consultant shall acquire and process bathymetric (below water) digital data meeting the accuracy requirements described in Section 2.5, extending along the entire stream channel reach within the model domain.

## Requirements for Underlying Topographic and Bathymetric Data

The Consultant is responsible for verifying the suitability of the topographic and bathymetric data (hereafter referred to as “terrain”) that are used for assigning elevations to the two-dimensional mesh. Suitable data, at a minimum, will have the following properties:

Note: In the third bullet below, the Agency may choose to provide more quantitative guidance on terrain requirements to ensure all hydraulic controls relevant to a project’s goal are captured in the final terrain. As a general rule of thumb, it is recommended that topographic data be acquired along the channel that extends roughly two times the floodplain width upstream and two times the floodplain width downstream. Other controls or features in the reach can also play an important role in this determination. A traditional practice of collecting cross sections a fixed distance upstream and downstream of a bridge for every project is not acceptable.

* The horizontal coordinate system and projection, along with the vertical datum, are known and can be re-projected, if necessary, to the model’s system and datums.
* The terrain data are in a digital format, or can readily be converted into a digital format, that can be read and used by the selected modeling software (for example, usable as SMS scatter data).
* Within the areas of key interest (e.g. in the vicinity of the project site and at significant hydraulic controls throughout the model domain), the terrain data meets the accuracy standard of NDDDA RMS 0.3 feet in Chapter 4 of the FHWA reference document *“Two-Dimensional Hydraulic Modeling for Highways in the River Environment”*
* Throughout the remainder of the model domain (outside the areas of key interest), the terrain data meets the accuracy standard of NDDDA RMS 0.6 feet in Chapter 4 of the FHWA reference document *“Two-Dimensional Hydraulic Modeling for Highways in the River Environment.”*

## Site Assessment

A thorough site assessment is essential to developing a successful hydraulic model study. The requirements below focus on the observations needed for modeling. Depending on the purpose of the study, it may also be important to include a geomorphic and stream stability assessment.

The Consultant shall conduct a site reconnaissance visit for the purpose of documenting conditions on the ground. The Consultant shall prepare and submit, within one month of completing the field reconnaissance, a Site Assessment Memorandum. The memorandum will document the observations from the reconnaissance and will include:

* Copies of field notes.
* An organized documentation of potential roughness value assignments for various ground cover type (for example worksheets facilitating the use of Cowan’s method).
* Descriptions and photographs of debris blockages.
* Descriptions and photographs of major hydraulic control features (crossings, diversions, critical depth sections, levees or other longitudinal floodplain encroachments, major obstructions, scour-resistant rock or other vertical grade controls, downstream water bodies, etc.).
* Document apparent high-water marks (e.g. marks on structures, seed lines, debris in trees, etc.) through GPS, descriptions, and photographs.
* Description and photographs of any indicators of lateral channel instability (e.g. recent bank retreat, cut banks, fresh point bars, channel braids, etc.).
* Description and photographs of any indicators of vertical channel instability (e.g. depositional areas, head cutting, incision terraces, exposed foundations of structures or bridge piers, etc.).
* Dimensional measurements of bridge and culvert openings within the study reach.
* Description of the likelihood of pressure flow and/or roadway and bridge deck overtopping at existing bridge (For bridge replacements or bridge scour evaluations).
* Description and photographs of any visible scour holes (For bridge replacements or bridge scour evaluations).
* Documented and photographed end inspections at both ends (For culvert replacement or rehabilitation projects).
* Description and photographs of any scour holes at either end but especially the downstream end (For culvert replacement or rehabilitation projects).
* Photographs at locations of established FEMA model cross sections (For projects requiring FEMA documentation).

## Hydrology

The following is a generic recommendation: The Agency’s standard requirements for, and approaches to, hydrologic analysis should be followed and inserted into this section. In addition to the Agency’s documented standards and requirements for hydrology, the FHWA document HDS 2 “Highway Hydrology” is a useful and thorough reference. The approach to hydrology and the discharge values adopted for analysis should be approved by the Agency before proceeding with hydraulic analysis. A wide range of approaches is possible, including the list provided in this section of the SOW. The list of hydrology approaches appearing after the next paragraph below may be re-ordered and numbered, to reflect the preferences of the state.

The [Agency Name] may specify a particular approach to obtaining or developing the discharge rates to be used in the hydraulic analysis. The Consultant shall submit a proposal to the [Agency Name] for a either that approach or an alternative proposed approach to hydrologic analysis. The [Agency Name] must approve the approach and resulting discharge values before the Consultant proceeds with the hydraulic analysis. Absent specific instruction from the [Agency Name] or its documented standards, good resources may include flood frequency studies obtained from the U.S. Geological Survey (USGS), FEMA, US Army Corps of Engineers (USACE) or analyses conducted by state or local agencies. The following list reflects a general preference, in descending order.

* Adopt and use the flood-frequency relationship presented in previous studies by the [Agency Name] for the same reach.
* Adopt and use the flood-frequency relationship (peak discharge rate for various flood recurrence intervals) from the FEMA FIS for the reach of interest.
* Adopt and use the flood-frequency relationship provided for the reach by the USACE or other federal or state entities.
* Perform Flood-Frequency Analysis using annual peak flood values from streamflow gauges on the same stream reasonably near the study site.
* Perform detailed rainfall-runoff analysis to develop flood hydrographs for a range of recurrence intervals.
* Use USGS regional regression equations (possibly implemented in the USGS Streamstats website).

# HYDRAULIC MODEL REQUIREMENTS

This section of the SOW sets out the expectations for an acceptable model under the contract. These requirements are important because there is a broad spectrum of quality and detail in hydraulic modeling. Failure to understand and agree on the modeling expectations will likely result in an outcome that doesn’t meet the needs of the project or that requires excessive financial and schedule resources. Brief descriptions of the various elements of a suitable model are provided in this section. The FHWA Reference Document “Two-Dimensional Hydraulic Modeling for Highways in the River Environment” provides detailed guidance relevant to this section of the SOW.

## General

The requirements in this section establish the expectations for the quality of the hydraulic model. The precise specifications for quality depend upon the purposes of the modeling study, and how the model results will be used. Certain main components are common to all two-dimensional modeling studies:

* An efficient, accurate geometric mesh of sufficient extent and appropriate detail.
* Correct boundary condition assignments.
* Appropriate Manning’s n assignments.
* Correct handling of hydraulic structures and controls within the model domain.
* Appropriate model control parameters.

## Extents of Model Domain

In establishing the model domain extents, the Consultant shall, at a minimum:

* Encompass at least the full inundation width of the largest flood recurrence interval to be simulated, typically the 500-year flood.
* Extend the domain far enough downstream of the locations of interest (e.g. the project site) that the uncertainty associated with any user-imposed water surface boundary conditions does not affect the model results at the location of interest.
* Extend the domain far enough upstream to fully depict any impacts caused by the project on the water surface and velocity magnitude (both increases and decreases).
* Where feasible, extend the domain upstream to a location where the flow is consolidated, without any need to distribute the flow among multiple inflow boundary condition assignments.
* If the inflow must be distributed among multiple inflow boundary conditions, extend the domain upstream far enough that the user-estimated flow distributions do not affect the accuracy of model results at the locations of interest.
* Demonstrate through sensitivity analysis that the model results at the locations of interest are not sensitive within a reasonable variation of the downstream water surface assignment or upstream flow boundary condition distribution.

Chapter 5 of the FHWA reference document *“Two-Dimensional Hydraulic Modeling for Highways in the River Environment”* provides detailed guidance for establishing the appropriate model domain limits, and the Consultant shall follow those recommendations to the extent practicable and must provide justification where certain recommendations cannot be followed.

## Mesh Configuration, Density, Level of Detail

The appropriate configuration of the model mesh is project specific and dependent on the objective of the model study, on the topographic and geometric complexity of the study reach, and on the size and scale of hydraulically important features within the model domain. Note that with modern mesh development software, it is tempting and easy to develop an extremely detailed mesh that provides a high level of accuracy throughout the domain. The Agency should guard against this tendency, however, because even though the development of such a model is easy for the Consultant, the end product can be extremely difficult to use later because of excessive model run times. A model delivered to the Agency that requires many hours to run a single simulation is not acceptable because of its impact on project design costs and schedule.

The SOW should require adherence to the recommendations of the FHWA reference document “Two-Dimensional Hydraulic Modeling for Highways in the River Environment.” To incorporate the level of detail and judgment required directly into a SOW would require an unreasonable amount of contractual volume. Therefore, the SOW text provided below is very general and mostly calls attention to the reference document.

The Consultant shall:

* Develop a sufficiently detailed mesh with small enough element sizes in the vicinity of the project and at significant hydraulic controls to achieve sufficient accuracy for the study purposes.
* Demonstrate that the mesh represents the terrain to a sufficient level of accuracy for the study purposes.
* For design projects, develop separate meshes for proposed conditions versus existing conditions.
* Check the mesh quality criteria (e.g. element area changes, aspect ratio, interior angle, etc.) and mitigate serious and/or widespread mesh quality issues.
* Provide appropriate variation in model density based on proximity to the project area and to significant hydraulic controls.
* Exercise due diligence in the tradeoff between small element sizes for more detail and accuracy versus larger elements sizes for greater speed of computation.
* Keep the total number of elements within a single model to less than 100,000 if feasible
* Consult with the Agency prior to submittal if the final model is to have considerably more than 100,000 elements.
* Obtain prior approval from the Agency if the model run time for a single simulation is to be more than 2 hours when run on a standard grade business personal computer.

Chapter 5 of the FHWA reference document *“Two-Dimensional Hydraulic Modeling for Highways in the River Environment”* provides detailed guidance on appropriate configuration and density of the mesh. It also defines the appropriate level of accuracy for studies of various purposes. The Consultant shall follow those recommendations to the extent practicable and must provide justification where certain recommendations cannot be followed.

## Manning’s n Assignments

The Consultant should be expected to exercise diligence in assigning Manning’s n values to the various regions of the model. This includes considering the authoritative references on the topic (identified in the FHWA reference document “Two-Dimensional Hydraulic Modeling for Highways in the River Environment”), and discerning the appropriate references for the stream setting (e.g. high-gradient, wide and broad flat floodplains, etc.). The model domain must be completely covered by Manning’s n assignments.

The reference document explains depth variable Manning’s n values available in some modeling programs and these may be appropriate where the effective roughness for a certain ground cover type is sensitive to the flow depth. Additionally, the Consultant should be expected to make a good faith effort to identify calibration data and to perform calibration or verification to the extent feasible. Ideally, the calibration event corresponds to the highest flow event with available data.

In assigning Manning’s n values throughout the model domain, the Consultant shall:

* Assign Manning’s n values that reflect the ground cover and resistance characteristics in each location.
* Define regions (e.g. polygons), not overlapping and together covering the entire model domain, each having a Manning n value that will be assigned to the mesh elements within that polygon.
* Assign Manning’s n values that are defendable considering standard authoritative references on Manning’s n assignment.
* Make use of depth-variable Manning’s n values as appropriate.
* Make a good faith effort to obtain data for use in calibration or verification of the model’s Manning’s n assignments.
* Perform calibration or verification as allowed by the data obtained.
* Account for any differences in Manning’s n values that are appropriate for the proposed versus existing condition.

Chapter 5 of the FHWA reference document *“Two-Dimensional Hydraulic Modeling for Highways in the River Environment”* provides detailed guidance and cites many authoritative references on assigning Manning’s n values. Chapter 6 describes the processes of calibration and verification. The Consultant shall follow the recommendations of Chapter 5 to the extent practicable and must provide justification where certain recommendations are not followed. Additionally, the Consultant is expected to seek out and make use of calibration/verification data for use in developing and validating Manning’s n values.

## Structures

The Consultant should be expected to follow sound practices in representing structures of different types in a 2D model. The FHWA 2D reference document provides extensive descriptions of best practices for modeling highway bridge and culvert crossings, along with many other types of structures. The SOW text below is a partial summary of the recommendations of the reference document.

The Consultant is expected to develop model simulations that accurately represent the hydraulic effects of various manmade structures that exert a significant hydraulic control. The Consultant shall represent the effects of various types of structures as described below.

### Weirs or Overtopped Embankments

* Accurately represent the horizontal alignment of the side slopes and the top with element edges forming break lines.
* Accurately represent the embankment cross section with at least two rows of elements on each side slope and two rows of elements on top and with accurate elevation assignments on all nodes.

### Bridges and/or Culverts

* Accurately represent the bridge waterway opening shape and elevations.
* Accurately represent the locations, alignment, orientations and shapes of the abutments.
* Represent piers eithers as voids in the mesh or using drag forces applied at the pier locations.
* If the bridge low chord is expected to be partly or fully submerged, incorporate the effects of pressure flow (for instance, using the pressure flow feature in SRH-2D) and align element edges along the upstream and downstream faces of the bridge deck.
* Represent the waterways of large box culverts using the same approach as required for bridge waterways.
* Represent smaller or non-rectangular culverts, or large box culverts that are located well outside the area of interest, using 1D culvert modeling routines.

### Spurs, Guide Banks, or Bendway Weirs

* Represent spurs, guide banks or bendway weirs by aligning elements for an accurate depiction of their horizontal layout, crest profile and cross section geometry.
* If spurs or guide banks are not to be overtopped in the simulation, they may be modeled as voids in the mesh.

### Grade Control and Drop Structures

* Align element edges at the crest and at the toe of the grade control for accurate depiction the channel bed profile.
* If the actual step in the grade control is vertical, depict it with a steep, non-vertical slope.

### Buildings in the Floodplain and Enclosures with Solid Fences

* Individual buildings or enclosed areas with solid fences expected to have a significant effect on the hydraulics in the area of interest should be represented by creating a void in the mesh within the building or enclosure footprint.
* Represent widely scattered smaller buildings (such as a residential subdivision without solid fences, outside the area of interest) by using a higher Manning n value to represent the aggregate effects of the buildings, rather than creating many voids in the mesh.

Note that small elements are typically needed to meet the requirements described above for the various structure types, while maintaining mesh quality. The FHWA reference document *“Two-Dimensional Hydraulic Modeling for Highways in the River Environment”* provides detailed guidance on properly modeling the structures of various types.

## Boundary Conditions

The Consultant is responsible for assigning correct boundary conditions to the model. The essential boundary conditions are external: inflow and exit boundary conditions. Inflow boundary conditions put flow into the model, either a constant, steady discharge value or a time-varying discharge hydrograph. The inflow boundary conditions must reflect the hydrology that has previously been established or performed for the study.

Exit boundary conditions usually set the water surface elevations at the locations where flow exits the model domain. The water surface elevation at an exit location can be specified as a certain known value, a value that will be calculated based on normal depth, or as a time-varying stage hydrograph (such as in a tidal zone). The exit conditions must be based on the best available information for the specific reach being modeled. Such information may include previous studies or known values of the water surface elevation for certain flowrates.

The Consultant shall assign appropriate boundary conditions as needed. Such boundary conditions will include, but are not necessarily limited to:

* One or more inflow boundary conditions specifying a discharge value associated with the event being modeled (as developed or obtained in the earlier hydrology work).
* One or more outflow (exit) boundary conditions specifying starting water surface at the model’s downstream external boundary(ies) based on the best available information, which could be:
  + Assumed normal depth (if the flow conditions just downstream of the exit location are generally uniform), or
  + A known value, taking information from another resource such as a previous hydraulic study, or
  + A time-dependent water surface hydrograph (such as in a tidal waterway).
* Flow monitoring or continuity lines to track the discharge across the model at different locations.

The FHWA reference document *“Two-Dimensional Hydraulic Modeling for Highways in the River Environment”* provides detailed guidance on properly developing and assigning boundary conditions.

# MODEL OUTPUT AND RESULTS

The output and results from a 2D model are primarily in the form of graphical plots and tables of values. The Consultant should be expected to prepare a variety of plots and tables to communicate the results to reviewers and the design team.

FHWA regulation 23 Code of Federal Regulations (CFR) Content of Design Studies [§650.117] requires project plans to show the water surface elevations of the base flood (i.e., 100-year flood) and overtopping flood [§650.117(c)].

## Model Development Information

The Consultant shall prepare and submit the following, at a minimum, to clarify details of the model development:

* Plan view elevation contour plot of the terrain surface.
* Summary table of mesh statistics: number of elements, minimum and maximum elements size, etc.
* Plan view plots of the mesh elements for existing and proposed conditions.
* Plan view plots of mesh quality for existing and proposed conditions.
* Plan view plots of the Manning’s n (material type) zones for existing and proposed conditions.
* Tables of the Manning’s n values used for each zone.
* Plan view plots of mesh elevation contours for existing and proposed conditions, for comparison to the terrain surface.
* Cross section plots showing mesh elevations versus terrain.
* Plan view plot showing the locations of monitoring points and monitoring lines.

## Sensitivity Analysis and Calibration/Verification

Sensitivity analysis reveals the degree to which the results of a specific model can be influenced by inaccuracies of certain input variables. The assigned water surface elevations at outflow boundaries usually incorporate an unknown amount of error, and if the project site is too close to the location of the outflow boundary this error might affect the model results where they matter the most. The Consultant shall, after running the model with the most likely outflow water surface elevation using the best available information (as determined under Section 3.6 above), perform sensitivity simulations with the assigned water surface values set higher and lower than the most likely value, covering a reasonable range of uncertainty. The Consultant shall prepare and submit water surface profile plots showing the longitudinal water surface profile along the main channel, left overbank and right overbank for different settings of the outflow boundary water surface elevations.

Assuming that adequate data were available to perform calibration or verification of Manning’s n values (see Section 3.4 above), the Consultant shall prepare plan view plots showing the locations of observed high water marks or velocity measurements along with the model’s computed water surface elevation contours or velocity magnitude contours. If calibration or verification was not feasible, the Consultant shall perform simulations with uniformly higher Manning’s n values and uniformly lower Manning’s n values, covering a reasonable range of uncertainty. The Consultant shall examine the results of the models and document the differences between the models in and around the project site location.

## Results from Study Simulations

The Consultant shall prepare and submit the following, at a minimum, to explain the results of the simulations for each recurrence interval of interest:

* Summary tables of discharge across lines in various locations for existing and proposed conditions.
* Summary tables of water surface elevation, depth and velocity magnitude at various points throughout the model for existing and proposed conditions. In SMS, summary tables can be generated to document the minimum, maximum and average values for depth, water surface elevation, velocity and other variables along a line.
* Plan view contour plots of resulting water surface elevations for existing and proposed conditions.
* Plan view contour plots of resulting velocity magnitudes (including velocity vectors) for existing and proposed conditions.
* Plan view contour plots of the differences (differential plots) in results for proposed versus existing (possibly including multiple alternatives for proposed conditions).
* Water surface profile plots (along river channel, left overbank and right overbank) showing the terrain, existing conditions water surface, and proposed conditions water surface.

## Additional Analysis for Bridge Waterway Capacity Design

For bridge design projects, the Consultant shall provide the following, in addition to the output and results described above:

* Determination of freeboard above the design-flood water surface for the low chord of a proposed bridge.
* Determination of freeboard above the design-flood water surface for the approach road profile.
* Determination of the distribution of flow through multiple bridge/culvert openings.
* Determination of overtopping event, if applicable.

## Additional Analysis for Bridge Scour Evaluation

For bridge scour evaluation, the Consultant shall provide the following, in addition to the output and results described above:

* Contour plots of shear stress in the vicinity of the bridge waterway and in the main channel upstream and downstream of the bridge.
* Contour plots of velocity magnitude and vectors showing flow direction in the vicinity of the bridge opening.
* Calculation of clear-water or live-bed contraction scour at proposed or existing bridge.
* Calculation of local scour at bridge piers and abutments.
* Calculation of required riprap size for abutment, channel bank, or road embankment protection.
* Tables summarizing hydraulic variables used for scour analyses.

## Additional Analysis for Culvert Design

For culvert design, the Consultant shall provide the following, in addition to the output and results described above:

* Determination of culvert headwater elevation.
* Determination of culvert outlet velocity.
* Calculation of expected outlet scour hole for the design event.

## Additional Analysis for River Rehabilitation Design

For river rehabilitation design, the Consultant shall provide the following, in addition to the output and results described above:

* Contour plots of shear stress for lower discharge rates (bank-full flow and lower).
* Contour plots of stream power for lower discharge rates (bank-full flow and lower).

## Additional Analysis for FHWA and FEMA Floodplain Regulatory Compliance

For bridge evaluations within a designated floodplain, the Consultant shall provide the following, in addition to the output and results described above:

* Tables of average water surface elevation along established FEMA model cross section lines for the 100-year flood, comparing proposed to existing conditions. In SMS, summary tables can be generated to document the minimum, maximum and average values for depth, water surface elevation, velocity and other variables along a line.
* Table of average water surface elevation along established FEMA model cross section lines for the 100- year flood with the regulatory floodway encroachments in place, comparing proposed and existing conditions.
* Table of the floodway widths at established FEMA model cross section lines for the 100-year flood, comparing proposed and existing conditions.
* Water surface elevations of the base flood (i.e., 100-year flood) and overtopping flood.

# MODEL REVIEW

A two-dimensional hydraulic model can be developed through a rather mechanical process without much attention to accuracy or to hydraulically important features and controls. The model results can be misleading or unusable unless a thorough process is in place to ensure the quality of the modeling. Quality starts with assigning conscientious engineers, well-trained in hydraulics and two-dimensional modeling, to the model development effort. Quality is controlled and assured, however, by consistently applying best practices in model review.

The Consultant is responsible for delivering a model with reliable, accurate results that are useable for the model study’s defined purposes. The Consultant shall perform and document the review processes described below. The documentation shall be provided in the form of a Review Memorandum.

## Top-Down Review

The Agency’s technical staff may choose to perform some elements of a top-down review as described below. The Consultant, however, must be responsible for conducting such a review before submitting deliverables to the Agency or the design team.

The Consultant’s engineer in responsible charge, or a designated senior hydraulic engineer, shall perform a top-down review of the model prior to submitting it as final. The review shall be documented in the Review Memorandum, stamped by a registered professional engineer, which provides a narrative of the review, findings and conclusions.

The Consultant shall perform and document the review steps below, at a minimum:

* For steady-state model studies, verify that the simulation has run through enough time steps to achieve steady state (results no longer changing with time) at multiple monitoring line locations throughout the model domain.
* For steady-state model studies, verify that flow continuity is maintained at multiple monitoring line locations throughout the model domain for the final time step.
* For unsteady-flow models, plot flow hydrographs at multiple monitoring line locations throughout the model domain and verify that the hydrograph progression (shift in time, attenuation of peak discharge) appears reasonable.
* Verify that the water surface contours look reasonable.
* Explain differences between existing and proposed water surface contours.
* Verify that the resulting velocity magnitude contours and velocity vectors look reasonable.
* Explain differences between existing and proposed velocity magnitude contours and velocity vectors.
* Document whether the model results reveal a previously unknown problem with the design (for example, road overtopping where it was not expected).
* Verify that the ground surface as represented by the mesh elevations match the terrain closely, especially within the area of the project site.
* Verify that the computer time required to complete a simulation is reasonable, and not unduly burdensome.
* Follow up on adverse findings from the above review steps with further investigation of the modeling at specific locations where issues are found.
* Change the model to address issues or provide an explanation in the Review Memorandum as to why the issue is not a significant concern.

## Bottom-Up Detailed Review of Model Input

During the model development process, a peer-level review must be conducted by the Consultant team that examines each part of the model input in detail. The peer reviewer should be someone trained in two-dimensional modeling but not otherwise involved in the current study. The peer review is considered a bottom-up review. **The [Agency Name] should provide the Consultant with a review checklist.** The Consultant shall use this checklist or an equivalent. The review memorandum described in the previous subsection should make reference to this bottom-up review and include the completed checklist as an attachment.

The Consultant shall assign an engineer trained in 2D modeling, but not otherwise involved in the current study to perform the following:

* Conduct a peer-level review examining each part of the model input in detail.
* Document the review by completing the review checklist provided by [Agency Name].
* Submit the completed checklist as an attachment to the Review Memorandum.

# HYDRAULIC MODELING REPORT REQUIREMENTS

## General Outline

FHWA regulation 23 CFR §650.115 “Hydraulic Design Standards” applies to all Federal-aid projects. The design standard requires development of a “Design Study” for each action in an encroachment (§650.115(a)). Regulation 23 CFR §650.117 “Content of Design Studies” requires such studies to contain the hydrologic and hydraulic data and design computations [§650.117(b)]. As both hydrologic and hydraulic factors and characteristics lead to scour formation, such data and computations apply to scour as well. As described earlier, project plans must show the water surface elevations of the base flood (i.e., 100-year flood) and overtopping flood [§650.117(c)].

Your Agency may have a standard outline already in use for hydraulic modeling studies. If so, it would be appropriate to use the same outline with minor modifications to accommodate two-dimensional modeling instead of one-dimensional modeling. Exhibit B is provided as a standard report outline for inclusion in a Scope of Work if your Agency doesn’t already have a standard.

The Consultant shall thoroughly document the two-dimensional hydraulic modeling in a report following, in general, the outline presented in Exhibit A of this SOW or an outline provided by [Agency Name]. If the Consultant finds that the outline is not ideal or relevant for the study, minor deviations are acceptable; [Agency Name] staff must approve any significant deviations.

## Professional Certification

The Consultant must affix to the report the signed stamp of a registered professional engineer in the state in which the project is located, with a statement that the signing engineer was in responsible charge of the work.

# DELIVERABLES

The Consultant shall submit the following deliverables, at a minimum:

* The Hydraulic Modeling Report, as described in the previous section.
* The Site Assessment Memorandum.
* The Review Memorandum, complete with model review checklist as an attachment.
* If SRH-2D and SMS are used: SMS project files and SRH-2D model output files, with an index explaining what each file is (include only the files from simulations actually used and cited in the report) (Delete all case\_RST\*.dat files that are not used to support a simulation, as these unnecessarily increase the size of project archives.)
  + The ‘File: Save As Package’ option may be used in SMS to ensure that all project files are included in a zip file for transfer or archive.
  + The SMS ‘Edit: Project Metadata’ feature should be used to note important information, including:
    - Model developer
    - Location information
    - Project purpose
    - Source of terrain data
    - Source of material roughness information
    - Source of inflow data
    - Structure notes
    - Simulation summary (why specific simulations were performed)
    - Calibration data information
* Results plots (if not already included in the report) that depict significant findings of the modeling.
* Supporting data, in electronic form, including:
  + The digital terrain model files (LiDAR, TIN files, etc.).
  + Projection files that established the horizontal coordinate system.
  + As-built drawings of existing conditions and design drawings of proposed conditions (only the sheets that depict the hydraulically significant features).
* All floodplain related information relevant to the project including the governing regulations, correspondence or contact with floodplain administrators, and documentation of analysis that demonstrates compliance.

# EXHIBIT A

Sample Report Outline: Two-Dimensional Hydraulic Modeling

1. Table of Contents
2. List of Tables
3. List of Figures
4. INTRODUCTION
   1. Project Description
      1. Sponsor/authorization
      2. Purpose of Study
      3. Project location
      4. Previous relevant studies

**Figures required:** Project vicinity/location map

* 1. Site assessment/visit summary

1. HYDROLOGIC ANALYSIS
   1. Watershed Description
   2. Nature of Flood Risk
      1. Types of events
   3. Flood History
      1. Flood Event
      2. Historic Flood Data
      3. Noted maintenance concerns/issues
   4. Previous Hydrologic Studies in Watershed
      1. FEMA, USACE, USGS, DOT, or others
   5. Flood Frequency Relationship used and why

* per FEMA (if any previous study)
* Gage Data (if relevant gage data exists)
* Regional Regression Equations
* Rainfall-Runoff Analysis (if available or undertaken for study)

**Figures required:** Watershed Map; Flood-Frequency Curve from each method examined; Adopted Flood-Frequency Curve for this study, FEMA FIRM Panel

**Tables required:** Flood-Frequency Table showing values from each method examined; Adopted Flood-Frequency Table

1. MODEL DEVELOPMENT
   1. Topographic and Bathymetric Data
      1. Sources
      2. Vertical Datum (should be NAVD 88 except in special circumstances)
      3. Horizontal Coordinate System
      4. Key Topographic and Structural Hydraulic Controls

**Figures required:** Plot of terrain surface

* 1. Mesh Generation Existing Conditions
     1. Downstream and Upstream Limits (and why chosen)
     2. General Statistics (area covered, number of elements)
     3. Areas of High Density (and why)
     4. Mesh quality
     5. Representation of Terrain

**Figures required:** Plot of full mesh; plots of specific high-density areas; mesh quality plot; elevation contour plots demonstrating good representation of topography and bathymetry.

**Tables required:** Summary of mesh statistics and parameters (other summary tables referenced in the SOW).

* 1. Boundary Conditions Existing Conditions
     1. Inflow Boundaries Configuration
     2. Discharge Values (relate to Hydrologic Analysis)
     3. Exit Boundary Value Assignments
     4. Internal Boundary Conditions

**Figures required:** Annotated plot showing all boundary conditions

* 1. Roughness Assignments Existing Conditions
     1. Designation of Materials (how many and why)
     2. Assigned Manning’s n values
     3. Discussion of calibration approach and results

**Figures required:** Plot of the Manning’s n assignment polygons throughout the model domain, with a legend.

* 1. Run Control Parameters
     1. Explain time step selection and run duration
     2. Explain initial conditions settings
     3. Explain output format and frequency
     4. Other run control parameters
  2. Proposed Conditions
     1. Alternate 1 (modifications from existing conditions)
     2. Alternate 2 (etc.)

**Figures required:** Plots of mesh layout and elevations where different from existing (zoomed in on areas of interest); plot of materials coverage if different from existing.

1. HYDRAULIC ANALYSIS RESULTS FOR EXISTING CONDITIONS
   1. Water Surface Results

**Figures required:** WSEL contours; profile along river; profiles along overbanks or floodplain edges.

**Tables required:** Summary table of the minimum, maximum and average values of water surface elevation along various transects across the model width located strategically throughout the model domain (e.g. at FEMA model cross section locations if applicable).

* 1. Velocity Results

**Figures required:** Velocity magnitude contours and vectors, overall and zoomed in to areas of interest.

**Tables required:** Summary table of the minimum, maximum and average values of velocity magnitude along various transects across the model width located strategically throughout the model domain.

* 1. Depth Results

**Figures required:** Depth contour plots.

**Tables required:** Summary table of the minimum, maximum and average values of depth along various transects across the model width located strategically throughout the model domain.

* 1. Discharge Distribution
     1. Check for model continuity
     2. Determine flow distribution at flow splits, multiple openings, etc.

**Figures required:** Plot showing discharge observation lines

**Tables required:** Summary table of the discharge across observation lines

* 1. Shear Stress Results if relevant

**Figures required:** shear stress contour plots

* 1. Other Project Specific Results Discussions

1. HYDRAULIC ANALYSIS RESULTS FOR PROPOSED CONDITIONS
   1. Water Surface Results

**Figures required:** WSEL contours; profile along river; profiles along overbanks or floodplain edges.

**Tables required:** Summary table of the minimum, maximum and average values of water surface elevation along various transects across the model width located strategically throughout the model domain (e.g. at FEMA model cross section locations if applicable).

* 1. Velocity Results

**Figures required:** Velocity magnitude contours and vectors, overall and zoomed in to areas of interest.

**Tables required:** Summary table of the minimum, maximum and average values of velocity magnitude along various transects across the model width located strategically throughout the model domain.

* 1. Depth Results

**Figures required:** Depth contour plots

**Tables required:** Summary table of the minimum, maximum and average values of depth along various transects across the model width located strategically throughout the model domain

* 1. Discharge Distribution
     1. Check for model continuity
     2. Determine flow distribution at flow splits, multiple openings, etc.

**Figures required:** Plot showing discharge observation lines.

**Tables required:** Table of discharges across observation lines.

* 1. Shear Stress Results if relevant

**Figures required:** Shear stress contour plots.

* 1. Relevant Differences from Existing Conditions

**Figures required:** Profile and contour plots showing impacts of proposed conditions.

1. HYDRAULIC DESIGN CONSIDERATIONS
   1. Bridge Freeboard and Hydraulic Capacity
   2. Backwater
   3. Freeboard for Bridges
   4. Freeboard for Road Surfaces
   5. Culvert Hydraulic Parameters
   6. Avoiding/Mitigating Unacceptable Water Surface Impacts
   7. Regulatory Requirements

**Figures required:** Unless as already described in the study, project plans shall show the magnitude, approximate probability of exceedance and, at appropriate locations, the water surface elevations of the base flood (100-year flood) and overtopping flood (or the greatest flood that must flow through the highway structure, if overtopping is not practicable) [23 CFR 650.117(c)].

1. STREAM STABILITY AND SCOUR EVALUATION
   1. Stream Stability Analysis:
      1. Stream Characteristics
      2. Land Use
      3. Stability
         1. Overall
         2. Lateral
         3. Vertical
      4. Debris Potential
      5. Stream Response
         1. Bed and Bank Material
         2. Watershed Sediment Yield
         3. Incipient Motion Analysis
         4. Armoring Potential
   2. Bridge Site Scour History
      1. Bridge Maintenance Inspections
      2. Previous Scour Studies
      3. Previous Bridge Scour Surveys
      4. Comparison of Design Survey with Historic Data
   3. Bridge Scour Study
      1. Justification for Selected Method
      2. Special Considerations
      3. Analysis for the 1% AEP Event
      4. Analysis for the 0.2% AEP Event
      5. Analysis for Other Events
      6. Geotechnical Adjusted Scour Depth (Only for Certain Situations)

**Figures required:** 1% and 0.2% AEP Event Scour Profiles Plots

**Tables required:** Scour analysis results

1. FEMA ANALYSIS
   1. Flood Zone Classification
   2. Models
      1. Effective Model
      2. Preconstruction/Existing Conditions
      3. Proposed Conditions
   3. Floodway/Floodplain Analysis
      1. Comparison of Models to Meet Floodplain Requirements and Guidelines
   4. Compliance for FEMA and Non-FEMA Floodplains
   5. Justification for Finding of “No Impact” or CLOMR/LOMR

**Figures required:** FEMA Existing and Proposed Conditions Profiles; FEMA Existing and Proposed Conditions Floodway Profiles

**Tables required:** 1% AEP Water Surface Elevations for the FEMA Existing and Proposed Conditions; 1% AEP Water Surface Elevations with Floodway for the FEMA Existing and Proposed Conditions; 1% AEP Floodway Widths the FEMA Existing and Proposed Conditions

1. DESIGN OF SCOUR AND STREAM INSTABILITY COUNTERMEASURES
2. OTHER PROJECT SPECIFIC TOPICS

* AOP Studies
* Flood Mitigation
* Sediment Transport

1. CONCLUSIONS
2. APPENDICES