TechBrief

The Federal Highway Administration's (FHWA) Hydraulic Program seeks to improve safety and resilience of the nation's transportation system within the following areas: Hydrology & Floodplains, Roadway Drainage, Scour, and Culvert, Bridge, and Coastal Hydraulics.

FHWA supports the Every Day Counts (EDC) initiatives as part of enhancing safety, improving infrastructure, deploying innovation and serving America efficiently and effectively. The Hydraulics Program leads one such EDC initiative "CHANGE."

CHANGE promotes application of advanced hydraulic models to improve both the science and understanding of complex interactions between river or coastal environments and transportation assets.

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Overview of Practices for Adopting 2D Hydraulic Modeling

This Technical Brief provides an overview of various State Department of Transportation (DOT) and other approaches for incorporating use of two-dimensional (2D) hydraulic models into their procedures, practices, and standards.

1. INTRODUCTION

The Federal Highway Administration (FHWA) "Every Day Counts" (EDC), "Collaborative Hydraulics: Advancing to the Next Generation of Engineering" (CHANGE) initiative promotes application of two-dimensional (2D) hydraulic models into State and local Department of Transportation (DOT) practice. CHANGE seeks to improve the science, tools, and understanding of complex interactions between river or coastal environments and transportation assets, enabling better design, enhanced communication, and more efficient project delivery.

The CHANGE initiative has revealed that, for most State DOTs, one of the primary barriers to more widespread and effective use of 2D hydraulic modeling is the lack of examples of processes and approaches a State DOT may wish to add to its standards, guidance, and technical manuals.

This Technical Brief (TechBrief) provides a background and overview of hydraulic models and modeling. This includes distinctions between one-dimensional (1D) and 2D models. The TechBrief also provides a synthesis of various State DOT and other approaches for incorporating use of 2D hydraulic models into practice and project delivery. This overview and synthesis provides examples of associated State DOT specific language, standards and guidance.

The TechBrief accomplished this by reviewing a selection of State DOT manuals to determine how they considered 2D hydraulic modeling application in both policy and technical aspects. The review focused on the scope and depth of coverage, including descriptions and language currently in the manuals. The TechBrief also includes a review of American Association of State Highway and Transportation Official (AASHTO) and National Cooperative Highway Research Program (NCHRP) materials, as well as various FHWA regulations, materials and manuals for any additional available insights and information.

Finally, while the FHWA does not have any requirements or guidance for such additions, the TechBrief synthesizes State DOT and other language to provide a possible template for those entities who may desire to incorporate such language into their own materials.

This TechBrief does not constitute a FHWA Policy, Directive, Guidance, or Standard. This TechBrief does not supersede any other FHWA materials.

1.1 REGULATORY BASIS

This TechBrief will help State DOTs with compliance of the FHWA's regulations found within the Code of Federal Regulations (CFR), Title 23, Highways (23 CFR). The FHWA requires compliance with 23 CFR and other regulations for a project to be eligible for Federal-aid or other FHWA participation or assistance [23 CFR 1.36].

The following FHWA regulations apply to highway projects and actions interacting with and within waterways and floodplains (paraphrased for brevity):

23 CFR part 625 – Design Standards

a. National Highway System (NHS) projects must follow hydrologic, hydraulic, and scour related sections of the AASHTO LRFD Bridge Design Specifications [23 CFR 625.3(a)(1) and 23 CFR 625.4(b)(5)].
b. Non-NHS projects must follow State DOT drainage and/or bridge standard(s) and specifications [23 CFR 625.3(a)(2)].

23 CFR 650 subpart A – Location and Hydraulic Design of Encroachments on Flood Plains

a. Hydraulic Design Standards [23 CFR 650.115]. This regulation applies to all Federal-aid projects, whether on the NHS or Non-NHS. Neither Federal, State, local, nor AASHTO standards may change nor override these 23 CFR 650.115 design standards. The design standard requires development of a "Design Study" for each action in an encroachment (23 CFR 650.115(a)).
b. Content of Design Studies [§650.117]. This regulation requires studies to contain the hydrologic and hydraulic data and design computations [23 CFR 650.117(b)]. As both hydrologic and hydraulic factors and characteristics lead to scour formation, such data and computations apply to scour as well. Project plans must show the water surface elevations of the base flood (i.e., 100-year flood) and overtopping flood [23 CFR 650.117(c)]. Having a formal process and language for describing how a design study applies 2D models assists a State DOT in meeting compliance with these regulations.

1.2 BACKGROUND ON HYDRAULIC MODELS

This section briefly describes hydraulic models and modeling, describes the evolution of practices and advanced modeling tools, and identifies some of the models used in transportation hydraulic modeling practice. This practice typically uses only those hydraulic models certified by the Federal Emergency Management Agency (FEMA).

1.2.1 What is a Hydraulic Model?

Hydraulic models typically use physics-based approaches (and assumptions) to predict the characteristics of water in a riverine or coastal environment. They may consist of physical or numerical (computer) forms. For the purposes of this TechBrief, we are interested in the set of numerical (computer) models used in simulating water surface elevations, depths, velocities, loads, and other variables associated with selected discharge or flow condition at specific locations along and within the waterway.

When describing hydraulic models, modeling practice uses the spatial extent (dimensionality) to describe the character of the input and output information. For example, as depicted in Figure 1, a one-dimension (1D) hydraulic model assumes that a series of cross-sections, representing the channel geometry, athwart (i.e., from one bank to the other) a waterway. For each cross-section, 1D models compute hydraulic parameters (e.g., velocity, depth, etc.) and uses conservation of energy and additional assumptions to link these parameters from cross-section to cross-section. The 1D model normally does not consider important directional (or vector) parameters such as momentum. The parameters are normally scalar or, at best, for velocity vectors, acting in perpendicular to the cross-section. To illustrate, in a 1D model each specific cross-section has a single velocity assumed to act orthogonal to that cross-section. Likewise, a 1D model often assumes a constant water surface elevation over the entire cross-section. In reality, velocities and water surface elevations vary across a cross-section.

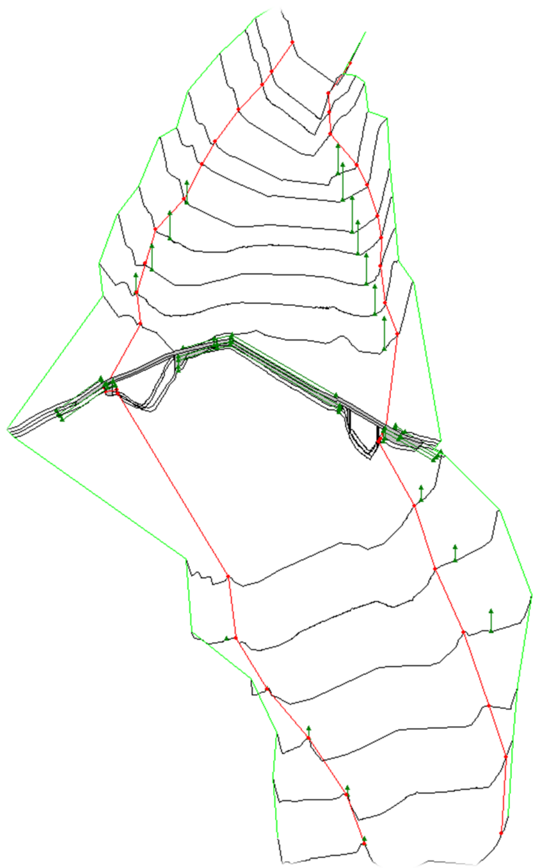

Figure 1. Depiction of a conceptual 1D model cross-sectional layout (image provided by NHDOT, 2018).

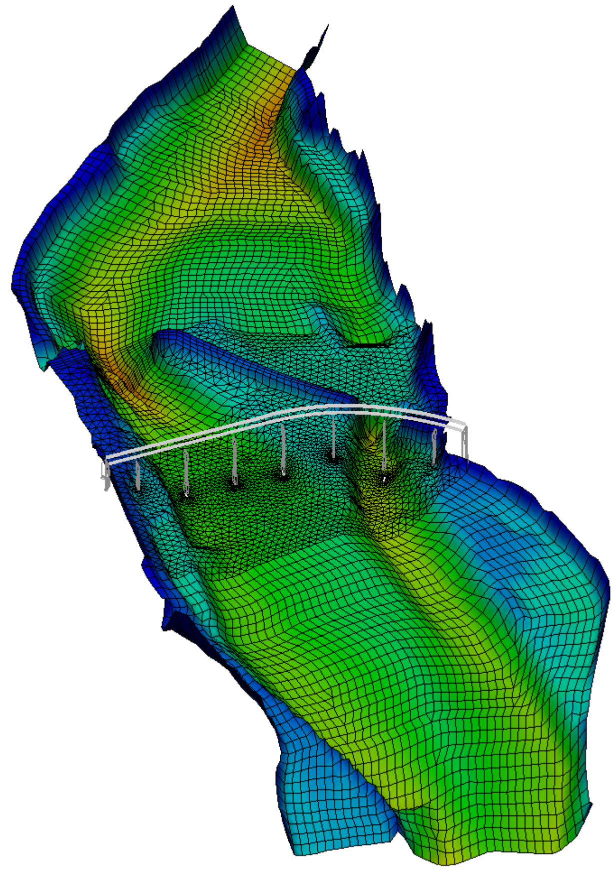

Figure 2. Depiction of a conceptual 2D model mesh (image provided by NHDOT, 2018).

A 2D model replaces cross-sections with a series of connected points (or nodes) that form a grid or mesh. The 2D model may use many thousands of these nodes to define waterway geometry, with the entire mesh spanning the waterway of interest (Figure 2). An advantage is that the mesh configuration allows the 2D model to determine velocities, depths, momentum, loads, and other hydraulic parameters at each specific node. The node also contains the vector quantities of velocities, momentum, and loads. Additionally, the size of the mesh can vary, allowing higher fidelity (denser portions of the mesh) at areas of specific interest (e.g., near a bridge pier). Overall, the use of the 2D mesh avoids the need to make the many assumptions inherent in 1D modeling, thereby allowing a better representation of the actual physics of the site.

1.2.2 Evolution of Modeling Practice

Engineers and designers have routinely used 1D hydraulic modeling tools for nearly 60 years. Although user interfaces have greatly improved during this time, the underlying computational techniques have remained the same. These modeling techniques apply several simplifying assumptions that can lead to conservative, inadequate, or inaccurate results, which are insufficient to meet many of today's project requirements.

For example, in recent years, resource agencies have increased their focus on the assessment of environmental impacts associated with river crossings. As a result, hydraulic engineers have become responsible for demonstrating that impacts have been avoided or minimized to the extent possible. Traditional hydraulic tools do not effectively support these levels of inquiry and analysis.

1.2.3 Advanced Hydraulic Modeling

Modeling practice can apply currently available 2D hydraulic modeling software, graphical interfaces, and supporting resources to infrastructure design to improve understanding of the complex interactions between river or coastal environments and transportation assets. Recent advances in computer hardware, modeling software, Geographic Information Systems (GIS), and survey practices have made 2D modeling very efficient, effective, and accessible to engineers and designers.

Because 2D models avoid many of the limiting assumptions required by 1D models, the results can significantly improve the ability of highway agencies to design safer, more cost-effective, and resilient structures on waterways.

In addition, three-dimension (3D) visualization capabilities of these modeling tools aid in communicating design results and implications to a variety of stakeholders through intuitive and visually rich graphical output. These tools also allow effective visualization of time variable simulations, such as those driven by astronomical tides or runoff hydrographs.

Fully spatial 3D hydraulic models have been used for some transportation projects. These models use computational fluid dynamics (CFD) to allow consideration and calculation of hydraulic information within the full spatial domain (i.e., x-y-z planes). In other words, these models do not just develop the velocity at each node, but the velocity distribution at each depth associated with that node. However, applying such models currently requires supercomputers to complete the enormous number of calculations.

1.2.4 Hydraulic Models

Table 1 provides a partial listing of models used (or having been used) in transportation hydraulic modeling practice. Modeling practice typically refers to a hydraulic model by some acronym, so the table provides both that acronym and the actual name. Table 1 also characterizes each model as being 1D, 2D, or some combination of these approaches.

Not all of the models listed in Table 1 are still in common use (or even available). However, as will be seen in later sections, State DOT drainage and design manuals may still refer to them. Therefore, providing them in Table 1 provides some context for those reviews.

Table 1. Selected Hydraulic Models.

Acronym	*Name (commentary)*	*Type*
BRI-STAR	***BRI**dge **S**tream **T**ube Model for **A**lluvial **R**iver **S**imulation*	*1D*
FLO-2D	*FLO-2D (Developed for FEMA).*	*2D*
FESWM	***F**inite **E**lement **S**urface **W**ater **M**odel*	*2D*
FST2DH	***F**low and **S**ediment **T**ransport model – 2D*	*2D*
HEC-RAS	***H**ydrologic **E**ngineering **C**enter (HEC), **R**iver **A**nalysis **S**ystem (Developed by the U.S. Army Corps of Engineers (Corps). Most commonly used hydraulic model within the United States)*	*1D* *2D*
HEC-2	***H**ydrologic **E**ngineering **C**enter, program number **2**, Water Surface Profiles (Precursor to HEC-RAS, developed by the Corps)*	*1D*
RMA-2	***R**esource **M**anagement **A**ssociates (Developed for the Corps, Waterways Experiment Station)*	*2D*
SRH-2D	***S**edimentation and **R**iver **H**ydraulics – **2D** (Developed by U.S. Bureau of Reclamation)*	*2D*
WSPRO	***W**ater **S**urface **PRO**files (Developed by the U.S. Geological Survey (USGS)).*	*1D*

2. REVIEWS & FINDINGS

The TechBrief reviewed four different types of sources for information related to hydraulic modeling and, in particular, advanced and/or 2D modeling. These sources included:

- State DOT manuals
- AASHTO materials
- NCHRP materials
- FHWA materials

The State DOT manuals consist of materials based on authorities including those listed under 23 CFR 625.3(a)(2) (i.e., State laws, regulations, directives, safety standards, design standards, and construction standards). Typically these materials include State DOT drainage and/or bridge standard(s) and specifications. A State DOT may have several manuals that apply to hydraulic modeling.

The AASHTO materials include those cited either directly under 23 CFR 625.3(a)(1) and 23 CFR 625.4(b)(5), or cited from within those materials (i.e., indirectly). For example, several AASHTO materials cite the AASHTO "Hydraulic Drainage Guidelines" (2007) and "AASHTO Drainage Manual" (2014).

The TechBrief sought out NCHRP materials that described modern hydraulic modeling practices. As many NCHRP research projects might have used models during their investigations, the review particularly sought out those projects describing any contrasts between 1D and 2D modeling.

FHWA materials include various technical materials and references, which include Hydraulic Engineering Circulars (HECs) or Hydraulic Design Series (HDS), as well as various EDC CHANGE materials.

From each source, the review provides a synopsis of relevant information, including findings and any synthesis.

2.1 STATE DOT

The TechBrief reviewed 11 State DOT drainage and/or design manuals. The review selected these States to represent geographic diversity and to reflect a range of uses of 2D modeling within the State.

The review found that references to 2D modeling in state drainage or hydraulics manuals is highly variable and to a large degree is reflective of when a State most recently updated their manual (although this is not always the case). Table 2 lists the manuals reviewed, including the title and date of most recent version or revision.

Table 2. Reviewed State DOT manuals.

State	**Manual**	**Year**
Arizona	Highway Drainage Design Manual: Hydraulics	2007 (January)
Arizona	Highway Drainage Design Manual: Volume 2 - Hydrology	2014 (January)
Arizona	Roadway Design Guidelines	2012 (2014 revisions)
California	Highway Design Manual	2006 (September) (revised 2015)
Colorado	CDOT Drainage Design Manual	2009 (September)
Georgia	Drainage Design for Highways	2018 (February)
Illinois	Illinois DOT Drainage Manual	2011 (July)
Mississippi	Roadway Design Manual	2001
Montana	Hydraulics Manual	1997
North Carolina	Guidelines for Drainage Studies and Hydraulic Design	2016 (November)
Pennsylvania	PennDOT Drainage Manual	2010
Texas	Hydraulic Design Manual	2016 (July)
Wisconsin	Wisconsin DOT Bridge Manual	2017 (January)

Several manuals mention specific 2D hydraulic models (including Arizona, California, and Georgia). Several manuals also specify no longer readily available or used 1D models.

The review found that some manuals provide limited discussion of 1D versus 2D modeling, but make statements that 2D modeling is more involved and/or more complicated. In a few situations, some manuals specifically stated that the designers are required to seek approval for use of 2D hydraulic modeling.

The following paragraphs (2.1.1 through 2.1.11) briefly summarize the observations from the review of each state manual. When the discussion in those paragraphs refers to "guidance" or "policy," it refers to those from the particular State DOT (i.e., not from FHWA).

2.1.1 Arizona

Arizona DOT (ADOT) has three manuals that reference 2D hydraulic modeling:

- Highway Drainage Design Manual: Hydraulics (2007). This document mentions 2D modeling including stating that the use of 2D modeling must be approved.
- Highway Drainage Design Manual: Volume 2 – Hydrology (2014). This document includes a Chapter (9) "Modeling Guidance for FLO-2D."
- Roadway Design Guidelines (Section 610 – Bridges) (2012 with 2014 revisions). This document states "The USACE HEC-RAS program shall be used to analyze the hydraulic conditions at bridges." The section also references HEC-18 for scour.

Arizona DOT has been piloting 2D modeling studies in some of its projects and is in the process of developing its own 2D hydraulic guidance. ADOT intends this to be a brief (one-page) "how to get started" guidance, possibly including a flow diagram.

2.1.2 California

California's Highway Design Manual (2006 with revisions in 2015) includes a few references to 2D modeling:

- Chapter 800 "General Topics" lists HEC-RAS and FESWMS as acceptable models for water surface profile computations (Table 808.1)
- Topic 821.5 "Effects of Tide, Storm Surge and Wind" states "detailed statistical analysis and use of unsteady flow models, including two-dimensional models, provide the most accurate approach to describing the combined effects of tidal and meteorological events."

2.1.3 Colorado

The Colorado DOT Drainage Design Manual (2009) references 2D modeling as follows:

- Chapter 10 "Bridges" includes a section on hydraulic design computer programs (section 10.3.4) that mentions HEC-RAS, WSPRO, "2-dimensional modeling," and BRI-STARS. The text states that 2D modeling is more complex than 1D modeling. This chapter also contains other isolated mentions of 2D hydraulic modeling.

2.1.4 Georgia

The Georgia DOT (GDOT) Drainage Design for Highways manual (2018) references 2D modeling as follows:

- Chapter 5 "Channels" includes a section (5.3.4.7) on "Special Analysis Techniques." One subsection (5.3.4.7.1) "Two-Dimensional Analysis" recommends 2D modeling for complex flows and specifically mentions FESWMS and RMA-2. (The other special analysis technique is unsteady flow analysis.)
- Chapter 12 "Requirements for Hydraulic Design Studies – Contents" Section 12.2.6 "GDOT Acceptable Computer Models" includes SRH-2D in a list of acceptable models.
- Chapter 12 Section 12.3.1 "Methods/Procedures – All Riverine Bridge Projects" states that the use of 2D hydraulic models must be approved.

2.1.5 Illinois

The Illinois DOT Drainage Manual (2011) briefly references 2D modeling in the following chapters:

- Chapter 5 “Open Channel Flow” mentions HEC-RAS,
- Chapter 6 “Culvert Hydraulics” discusses HEC-RAS,
- Chapter 7 “Bridge Hydraulics” describes WSPRO and HEC-RAS as “accepted” methods,
- Chapter 10 “Scour” discusses HEC-RAS,
- Chapter 11 “Scour Countermeasures” mentions 2D modeling, and
- Chapter 14 “Computer Software” lists HEC-RAS and WSPRO.

2.1.6 Mississippi

The Mississippi Roadway Design Manual (2001) does not mention channel modeling or 1-D or 2D models or modeling. It notes that the Bridge Design Division is responsible for hydraulic design of bridges, but a design manual covering hydraulic design of bridges was not found as part of the work preparing this TechBrief. The Roadway Design Division performs hydraulic design of some bridges, but only when the drainage area is less than 1000 acres.

2.1.7 Montana

The Montana Hydraulics Manual (1997) is a series of chapters edited from the AASHTO Drainage Manual. Chapter 10 “Bridges” includes a brief discussion on 2D modeling in section 10.4.4 “Methodologies.” It notes that 2D modeling is more complicated than 1-D modeling. Chapter 10 also includes a brief discussion of “WSPRO Modeling” (Section 10.4.5).

2.1.8 North Carolina

The North Carolina DOT Guidelines for Drainage Studies and Hydraulic Design (2016), Chapter 8 “Bridges,” Section 8.5 “Hydraulic Analysis” mentions 2D models and states that approval from the State Hydraulics Engineer is needed to use 2D models. The section also states that HEC-RAS is the preferred 1-D software. HEC-RAS is mentioned throughout the document.

2.1.9 Pennsylvania

The PennDOT Drainage Manual (2010), Chapter 10 “Bridge Hydraulics” mentions 2D models and concludes they are not justified in most situations.

2.1.10 Texas

The Texas DOT Hydraulic Design Manual (2016), Chapter 9 “Bridges” defines 2D models as requiring high-level expertise and time. Section 4 “Hydraulics of Bridge Openings” includes a brief section on “Two-Dimensional Techniques.”

2.1.11 Wisconsin

The Wisconsin DOT Bridge Manual (2017) recommends HEC-RAS and WSPRO in Section “8.3.2.5 “Select Hydraulic Model Methodology.” Specific references to these models are made in various other places in the manual. The manual does not mention 2D modeling.

2.2 AASHTO MATERIALS

The AASHTO Drainage Manual (ADM) (2014) provides material on hydrologic and hydraulic models, particularly within Volume 2, Chapter 5 "Software:"

Section 5.2.2.3, "Complex Floodplains (Two-Dimensional Flow)" reads:

> *Natural channels or streams cannot be adequately represented by a series of cross sections that are taken perpendicular to the assumed direction of flow:*
>
> - *if uniform velocity cannot be assumed in the direction of flow, or*
> - *if depths and velocities vary rapidly with time.*
>
> *For these cases, the floodplain should be analyzed with a computer model that utilizes a higher order solution.*

Additionally, the ADM provides some conditions for use of 2D hydraulic models with bridges:

> *5.2.7.2 Analyzing 2D Flow with Bridges*
>
> *The 2D models simulate flow in two directions, longitudinal and transverse, at a series of user-defined node points. Flow in the vertical direction is assumed to be negligible. These models can account for transverse flow due to lateral velocities and water surface gradients that cannot be accounted for with 1D models. Examples of such conditions include:*
>
> - *skewed bridges,*
> - *floodplain crossings with multiple openings,*
> - *channel bifurcation,*
> - *flow around channel bends, and*
> - *flow around islands.*
>
> *Advanced 2D hydraulic models (as outlined in Table 5-10 and discussed in this section) should be considered for major projects with complex flow patterns that 1D models cannot adequately analyze. … Examples of situations where 2D models should be considered are as follows:*
>
> - *wide floodplains with multiple openings, particularly on skewed embankments;*
> - *floodplains with significant variations in roughness or complex geometry (e.g., ineffective flow areas, flow around islands, multiple channels);*
> - *sites where more accurate flow patterns and velocities are needed to design better and cost-effective countermeasures (e.g., riprap along embankments, abutments); and*
> - *high-risk or sensitive locations where losses and liability costs are high.*

The ADM also provides a synopsis of various hydrologic and hydraulic models used in practice.

The AASHTO "Hydraulic Drainage Guidelines" (HDG) (2007) provides the following material within Chapter 7 (Hydraulic Analysis for the Location and Design of Bridges):

> *One-dimensional methods (step backwater) are inadequate to provide a quantitative analysis of water surface elevations up- and downstream of a skewed highway crossing of a stream. Finite element and finite difference models are two-dimensional methods that can be applied in some complex situations.*
>
> *These models enable designers to study the water surface elevations in cross sections rather than in profile only and can identify locations where undesirable*

head differentials could occur. These are more complex models that require more site information and a greater length of time to use.

However, the HDG notes that, at the time of publication (2007), 2D models were more difficult to use. The EDC CHANGE initiative has demonstrated that 2D modeling tools have improved to the extent that, in many cases, practitioners can use 2D models and tools as readily as 1D models.

2.3 NCHRP MATERIALS

As described earlier, many NCHRP projects and studies regularly apply 2D or 3D models as part of their specific investigations or research. For example, in 2006, NCHRP published the results of Project 24-24 “Criteria for Selecting Hydraulic Models (2006) that provided the most up-to-date, independent description and assessment of such hydraulic model use. As described in the abstract of the report:

This report documents and presents the results of a research effort to develop a decision tool for selecting either a one- or two-dimensional hydraulic model when examining flow through bridge crossings. The research began with a literature search and survey of the state of the practice to identify and characterize the site conditions and design requirements that may affect model selection. From this list of factors that influence model selection, a series of “desktop” experiments were constructed that compared one- and two-dimensional model results over a wide range of possible configurations. This research also examined several design criteria to discern their sensitivity to possible inaccuracy in numerical modeling results. From these results, a decision tool in the form of a decision matrix was developed as well as guidelines for its application. This tool provides a formal procedure for selecting the most appropriate model for a particular application incorporating site conditions, design elements, available resources and project constraints.

The report demonstrated the utility of using 2D models in a variety of situations where practitioners consider transportation assets and hydraulic conditions. For example, the project (and report) also developed an extensive appendix (576 pages) demonstrating sensitivity tests of 1D and 2D models to various hydraulic/transportation situations, including baseline models, multiple openings, bridges located on river bends, bridges near confluences, bridges with significant constrictions, overtopping flows, embankment skew, bridges over meandering rivers, asymmetric floodplains, and tidal hydraulics.

The results of NCHRP 24-24 demonstrated the potential of 2D hydraulic models in all aspects of overall transportation practice and informed many (including FHWA) on suitability of use, including when and where.

2.4 FHWA MATERIALS

The FHWA has a long history of providing technical materials and references for the hydraulic analysis and design of waterways and bridges (typically in the form of the HECs and HDSs publications).[1]

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[1] Some State DOT choose to incorporate these FHWA materials into their standards and materials.

The FHWA promoted research into 2D modeling as early as 1977 by supporting a workshop and publishing a "Summary Report from Workshop on Two-Dimensional Mathematical Models for Use in Hydraulic Problems" (1977). Findings of the workshop included:

> *Existing methods for backwater analysis at bridges are one-dimensional and the determination of discharge distributions and bridge opening design are highly empirical. Only longitudinal flow transmission and variations in water surface elevations are considered in backwater computations. Methods for selecting the distribution of flow through multiple openings in highway embankment and processes for bridge backwater determination are based on extrapolations of laboratory studies and practical experience. Improved methods of analysis and design are clearly indicated. They are needed not only for the daily routine design problems but also to deal more effectively with the secondary and potentially more far-reaching implications of legislative programs and public awareness of the environment.*
>
> *There exist two-dimensional mathematical models which appear to offer considerable potential for solving multi-dimension hydraulic problems at bridge waterways. Even a cursory investigation reveals that several existing models have been used successfully in a variety of other problems and may have immediate and important applications in the hydraulic problems facing the modern highway engineer.*

Clearly, even 40 years ago, practitioners recognized the caveats and limitations of 1D models and the improvements 2D modeling brought to hydraulic engineering.

The following sections provide an overview of the contents of some FHWA reports and manuals as they relate to 2D hydraulic modeling.

2.4.1 "Highway Hydraulics State of Practices"

In January 2012 FHWA published a report entitled "Highway Hydraulics State of Practices" (2012a) that covered all 50 State DOTs, the District of Columbia DOT and the Puerto Rico DOT. The report compiled results from an Office of Management and Budget (OMB)-approved survey of the hydrologic and hydraulic related approaches covering all aspects of drainage, culvert, bridge, scour, and other aspects of DOT practices. The data collection period that formed the basis of this report ranged from October 2009 to January 2010.

The information collected included DOT software and modelling practices, including use of 1D and 2D hydraulic modeling. As of those dates, the report found that each of the DOTs used 1D models in their practices. However, approximately 35 percent of the DOTs also reported using some form of 2D modeling.

The extremely rapid evolution in 2D hydraulic modeling between that 2012 report to today made any other useful inferences problematic, except to establish a baseline. To illustrate, in 2019, EDC CHANGE has 45 State DOTs actively participating in the initiative.

2.4.2 Hydraulic Design of Safe Bridges

The Hydraulic Design Series (HDS) No. 7 "Hydraulic Design of Safe Bridges" (HDS 7) (2012b) provides one of the most detailed discussions of 2D hydraulic modeling among the FHWA references. Section 4.2.1 *1D versus 2D Modeling* describes that 2D modeling is likely more appropriate than 1D modeling for the following applications:

- Multiple openings
- Wide floodplains
- Skewed roadway alignment
- Road overtopping
- Upstream controls
- Bends, confluences, angle of attack
- Multiple channels
- Tidal conditions and wind simulation
- Flow distribution at bridges
- Countermeasure design

Table 3 reproduces material from HDS-7, providing a 4-tiered rating system for selecting a type of model based on the situation. A major theme from this rating is that 2D models are either "well suited" or a "possible application" in all situations. By contrast, there are some situations where 1D models are "unsuitable or rarely used."

HDS 7 also provides substantial information on use of 2D models in other chapters or sections, including materials on "2D Bridge Hydraulic Analysis" (Chapter 6), "2D Unsteady Flow Models" (Section 7.9), and "Computing Scour: 2D Models" (Section 8.4.2). Many of these sections draw upon State DOT or NCHRP information.

2.4.3 Coastal Modeling Primer

The FHWA manual "A Primer on Modeling in the Coastal Environment" (2017) introduces concepts of coastal hydrodynamic modeling to transportation professionals. These professionals range across the spectrum of project delivery (e.g., planners, scientists, engineers, etc.). The information presented in the Primer can be applied to better understand the use of numerical models in the planning and design of coastal highways.

Drawing from experiences of State DOTs, the Primer assists its audience in understanding when, why, and at what level coastal models should be used in the planning and design of coastal highways and bridges.

To facilitate this, the Primer provides recommendations on when and where to use hydraulic and hydrodynamic models, and how they are used to determine the dependence of bridge hydraulics on the riverine or coastal design flood event.

Using experiences of State DOTs, AASHTO, and others, the Primer offers insights of when to solicit the expertise of a coastal engineer. While not explicitly providing sample scoping materials, the Primer provides transportation professionals with an overview of information needed to prepare such scopes of work and requests for professional services; communicate with consultants; and evaluate modeling approaches and results.

2.4.4 EDC CHANGE Initiatives

The EDC CHANGE initiatives have been a part of both the EDC-4 cycle (2017-2018) and the current EDC-5 (2019-2020) efforts. Implementation plans (2017, 2019) and reports yield useful information and insights based on the interactions with the State DOTs. Initially, in 2017, the baseline assessment revealed that 17 States possessed demonstration, assessment, or institutionalized stages of CHANGE implementation. By December 2018, this had increased to 43 States having reached demonstration, assessment, or institutionalized stages.

Table 3. Bridge Hydraulic Modeling Selection.

Bridge Hydraulic Condition	Hydraulic Analysis Method	
	1-D	2D
Small streams	●	○
In-channel flows	●	○
Narrow to moderate-width floodplains	●	○
Wide floodplains	○	●
Minor floodplain constriction	●	○
Highly variable floodplain roughness	○	●
Highly sinuous channels	○	●
Multiple embankment openings	◉	●
Unmatched multiple openings in series	◉	●
Low skew roadway alignment (<20°)	●	○
Moderately skewed roadway alignment (>20° and <30°)	○	●
Highly skewed roadway alignment (>30°)	⊗	●
Detailed analysis of bends, confluences and angle of attack	⊗	●
Multiple channels	○	●
Small tidal streams and rivers	●	○
Large tidal waterways and wind-influenced conditions	⊗	●
Detailed flow distribution at bridges	○	●
Significant roadway overtopping	○	●
Upstream controls	⊗	●
Countermeasure design	○	●

KEY to symbols	
●	well suited or primary use
○	possible application or secondary use
◉	possibly unsuitable depending on application
⊗	unsuitable or rarely used

An impediment described by the State DOTs has been a lack of template language to aid in institutionalizing their 2D hydraulic model use. An important goal of this TechBrief is to provide template language for consideration.

2.4.4 Other FHWA Materials

FHWA regulation 23 CFR 650 subpart C "National Bridge Inspection Standards" (NBIS) requires evaluations of scour at bridges. Hydraulic Engineering Circular No. 18 "Evaluating Scour at Bridges," (HEC-18) (2012c) provides FHWA's technical reference for doing so in compliance with NBIS. HEC-18 recognizes and discusses use of both 1D and 2D models. HEC-18 recommends 2D models for complex flow situations and, citing improved accuracy and potential reduction of project costs, using 2D models on all but the simplest bridge crossings.

3. SUMMARY AND SYNTHESIS OF FINDINGS

State DOT manuals, AASHTO, NCHRP, FHWA, and other materials that address hydraulic modeling of waterways and bridges vary widely. However, common elements included addressing:

- The need for approval for the use of 2D modeling;
- The technical applicability of such 2D modeling use;
- References to AASHTO standards, FHWA regulation and technical references, and other common documents.

The level of detail given to 2D hydraulic modeling ranges from a brief mention to having a section covering the topic. Generally, the types of manuals having this information ranges from roadway design manuals to hydraulic design manuals.

Additionally, as documented in the CHANGE initiative Implementation Plans (2017, 2019), there is a wide range in expertise in 2D modeling within each State DOT. Therefore, proposed language should be sufficiently broad to encompass a wide range of State DOT experience while facilitating progress in expanding the use of 2D hydraulic modeling.

3.1 Synthesis of Approaches

Synthesizing these various State DOT materials and practices provides potential templates for inclusion of 2D modeling policies and technical language into an appropriate manual. Using State DOT approaches as an informed template, this TechBrief recommends that any proposed additions to State materials and practices be divided into two categories: policy and technical.

3.1.1 Potential Policy Template

A possible template for 2D hydraulic model policy language may be derived by synthesizing the various State DOT, AASHTO, NCHRP, and FHWA language and materials. Based on State DOT practices, the policy language may try to answer the following questions: What is a 2D tool? Can 2D tools be used for a project? Who can use them? The following language may represent an overall statement of intent to expand the use of 2D hydraulic modeling:

> *"To aid in compliance with 23 CFR 650.117 (Content of Design Studies), the [Insert State DOT name] recognizes that two-dimensional (2D) models produce computations and data to support design and risk analyses. 2D models achieve this by representing waterways and their interactions with bridges or other transportation infrastructure encroaching on a waterway in a more comprehensive manner than one-dimensional (1D) models. 2D models allow more realistic variation of key variables, including velocity and water surface elevation, across a river or other water body in addition to longitudinally. This improved representation results in better projects that allow improvement in the stewardship of project resources including time and budget. [Insert State DOT name] encourages the use of 2D hydraulic models in appropriate situations consistent with staff expertise and project resources."*

3.1.2 Potential Technical Template

A technical statement describes under which situations 2D hydraulic modeling is appropriate and how a design team should implement it. This statement should rely on authoritative resources such as those of AASHTO, NCHRP, or FHWA. Given the variety of potential 2D hydraulic models available for use, it should not direct a State DOT to specific tools, but allow the State DOTs to select those models. State DOTs also need the flexibility to capture potential situations where such use is more appropriate for their specific project needs. Possible template language is as follows:

All numerical hydraulic models (1D and 2D) incorporate simplifying assumptions, require certain types of input data, and operate under specific implementation limitations. It is the goal of any hydraulic model study to simulate anticipated flow conditions as accurately as possible within project constraints without violating the assumptions and ignoring the limitations of the model. Therefore, a modeling approach should be selected based primarily on its advantages and limitations, though also considering the importance of the structure, potential interactions with the waterway, cost, and schedule. For this reason, 2D hydraulic modeling is recommended for the following hydraulic modeling situations [State DOT to Select, Add, or Delete]:

- *Wide floodplains*
- *Highly variable floodplain roughness*
- *Highly sinuous channels*
- *Multiple embankment openings*
- *Unmatched multiple openings in series*
- *Moderately skewed roadway alignment (>20° and <30°)*
- *Highly skewed roadway alignment (>30°)*
- *Bends and confluences with significant momentum shifts*
- *Angle of attack analyses*
- *Multiple channels*
- *Large tidal waterways and wind-influenced conditions*
- *Detailed flow distribution and complex multiple openings at bridge crossings*
- *Significant roadway overtopping*
- *Upstream controls*
- *Countermeasure design*

The use of 2D hydraulic modeling in complex situations does not preclude use of these tools for simpler situations as project resources and context allow. [Insert State DOT name] allows the use of the following models [List of Models] or other models as approved by the State on a case-by-case basis.

4. CITED REFERENCES

AASHTO, 2007, "Model Drainage Guidelines," Fourth Edition, American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO, 2014, "AASHTO Drainage Manual," First Edition, American Association of State Highway and Transportation Officials, Washington, D.C.

FHWA, 2012a, "Highway Hydraulics State of Practices," FHWA Resource Center. January 2012.

FHWA, 2012b, "Hydraulic Design of Safe Bridges," FHWA-HIF-12-018, Hydraulic Design Series No. 7, First Edition, Washington, D.C. (Zevenbergen, L., L. Arneson, J. Hunt, and A. Miller). April 2012.

FHWA, 2012c, “Evaluating Scour at Bridges,” Hydraulic Engineering Circular No. 18, Fifth Edition, FHWA-HIF-12-003, FHWA, Washington, D.C. (Arneson, L., L. Zevenbergen, P. Lagasse, and P. Clopper). April 2012.

FHWA, 2017, “A Primer on Modeling in the Coastal Environment,” FHWA-HIF-18-002, FHWA, Washington, D.C. (Webb, Bret, et. al.). December 2017.

FHWA, 2017b, “EDC-4 CHANGE Implementation Plan” FHWA, Washington, D.C. (unpublished).

FHWA, 2019, “EDC-5 CHANGE Implementation Plan,” FHWA, Washington, D.C. (unpublished).

New Hampshire DOT, 2018, “Brattleboro Bridge Project,” internal project materials and communications (used with permission of NHDOT).

Office of the Federal Register, 2019, “Code of Federal Regulations, Title 23 – Highways,” U.S. Government Publishing Office, Washington D.C.

Overview of Practices for Adopting 2D Hydraulic Modeling

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