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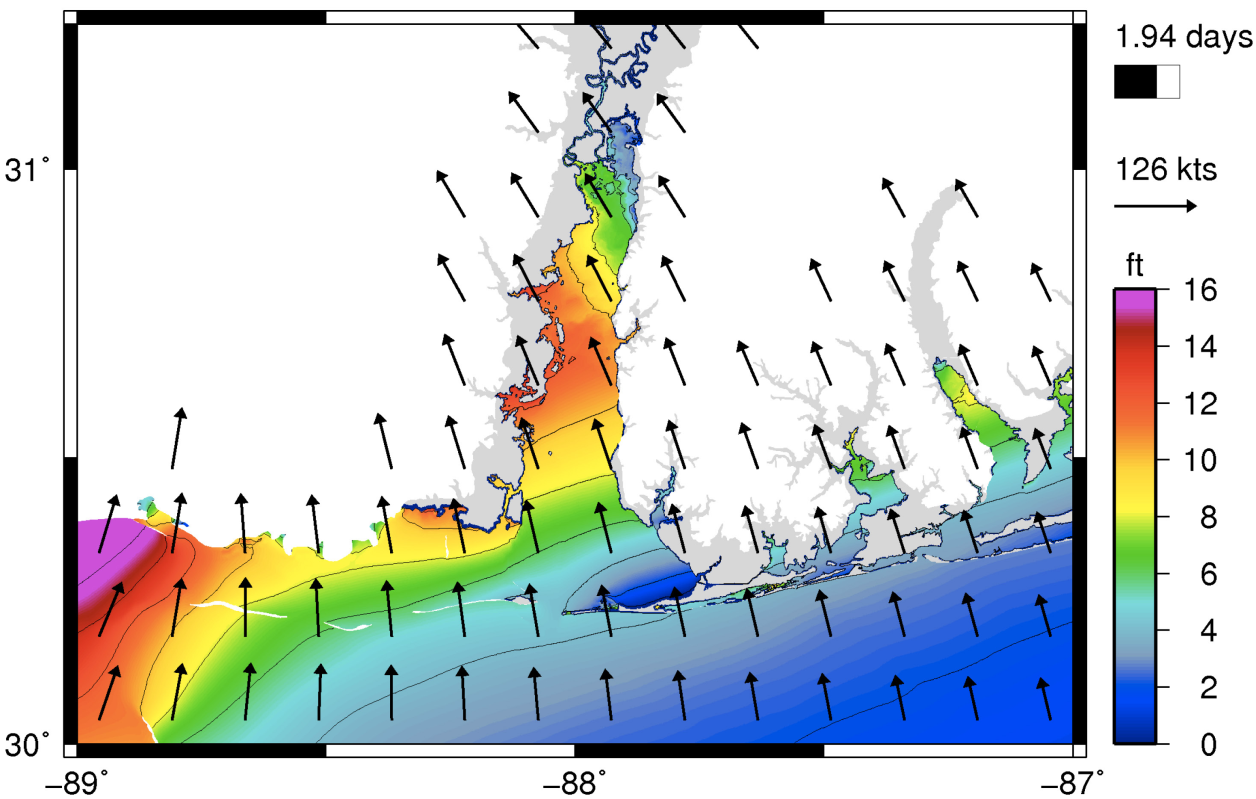

A Primer on Modeling in the Coastal Environment

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16. Abstract
This manual provides an introduction to coastal hydrodynamic modeling for transportation engineering professionals. The information presented in this manual can be applied to better understand the use of numerical models in the planning and design of coastal highways.

Here, the term "coastal highways" is meant to generally capture the roads, bridges, and other transportation infrastructure that is exposed to, or occasionally exposed to, tides, storm surge, waves, erosion, and sea level rise near the coast. The hydrodynamic models that serve as the focus of this manual are used to describe these processes and their impacts on coastal highways through flooding, wave damage, and scour.

The primary audience for this manual is transportation professionals ranging across the spectrum of project delivery (e.g., planners, scientists, engineers, etc.). After reading this manual the audience will understand when, why, and at what level coastal models should be used in the planning and design of coastal highways and bridges; and when to solicit the expertise of a coastal engineer. This manual provides transportation professionals with the information needed to determine scopes of work, prepare requests for professional services, communicate with consultants, and evaluate modeling approaches and results.

The manual also provides guidance on when and where hydraulic and hydrodynamic models are used, and how they are used to determine the dependence of bridge hydraulics on the riverine or coastal design flood event.

The manual also gives recommendations for the use of models in coastal vulnerability assessments.

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Notice

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Notes on Terminology and Nomenclature

As an overview of coastal modeling, this manual uses and applies many terms, concepts, and nomenclature not in typical use within the transportation or hydraulic community.

To assist the audience, this manual signifies when text uses terms found in the glossary by combining *italics* and font color. Examples include *hydrodynamic modeling* or *waves* or *skill*.

Providing such a distinction and usage is important to allow the audience to properly recognize and understand context. To illustrate, there could be a critical difference between describing the "skill of a modeler" versus the "*skill* of the model."

This usage includes instances when the term or nomenclature requires a plural (e.g., *wave* into *waves*), or denotes an action or change in tense (e.g., *coupling* into *coupled*), or other grammatical usage or construct.

Sometimes, terminology might reflect the combination of several defined terms. For example, "*storm surge hydrograph*" describes and uses the terms *storm surge* and *hydrograph*.

The manual may combine multiple defined terms to assist in contrasting them. For example, "*hydraulic* and *hydrodynamic models*" consists of two separate defined terms; *hydraulic model* and *hydrodynamic model*.

Finally, no effort is perfect, so the audience should recognize this manual might miss or otherwise inadvertently or inconsistently apply these approaches. If encountering such situations, remember Voltaire wrote "*Dit que le mieux est l'ennemi du bien"* (i.e., *"The perfect is the enemy of the good …"*) (Voltaire, 1772).

Glossary

ACCELERATION: The change in fluid velocity with respect to time.

ANIMATE: The process of animating model output for presentation in the form of a video or other multimedia.

ASTRONOMICAL TIDE: The tidal levels that would result from gravitational effects, e.g. of the Earth, Sun, and Moon, without any atmospheric influences.

BAROMETRIC: Having to do with air pressure, as measured by a barometer.

BEACH PROFILE: A ground surface elevation cross-section taken perpendicular to a given beach; the profile may include the face of a dune or sea wall; extend over the backshore, across the foreshore, and seaward underwater into the nearshore zone.

BOUNDARY CONDITION: Environmental conditions, e.g. water levels, *waves*, currents, etc. used to describe conditions along the boundaries or edges of numerical models.

CALIBRATION: The direct comparison of model results with a standard or reference in a manner that allows parameter values to be modified with the goal of improving the comparison outcomes.

COMPUTATIONAL COST: The level of effort and computer time associated with the use of a model.

COMPUTATIONAL FLUID DYNAMICS (CFD): The use of applied mathematics and physics to develop computational software for the purpose of describing or visualizing fluid behavior or movement.

CORIOLIS EFFECT: Force due to Earth's rotation, capable of generating currents. It causes moving bodies, including oceanic currents, to be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The "force" is proportional to the speed and latitude of the moving object. It is zero at the equator and maximum at the poles.

CORIOLIS SETUP: An increase in the mean water level along a shoreline due to the deflection of currents by the Coriolis force.

COUPLING: Combining two or more models, numerically, in order to simulate the interactions of one model on another, or of all models on one other.

COURANT NUMBER: A dimensionless number that describes a relationship between fluid velocity, model time step, and computational *grid* spacing or *mesh* size which limits numerical stability in some explicit models.

CROSS-SHORE: Perpendicular to the shoreline.

DEPTH-AVERAGED: The process of averaging/integrating an equation or solution over the vertical coordinate of depth in order to yield a two-dimensional result. Also known as depth-integrated.

DETERMINISTIC MODEL: A model in which all variables are determined by given parameters, such that the model will produce the same results every time from one set of parameters.

DIURNAL TIDE: A *tide* with one high water and one low water in a day.

EDDY VISCOSITY: An artificial viscosity, sometimes specified by a model user, to simulate the effects of momentum dissipation through turbulence.

ENERGY SPECTRUM: In ocean wave studies, a graph, table, or mathematical equation showing the distribution of wave energy as a function of wave frequency and/or direction. The spectrum may be based on observations or theoretical considerations.

EXTREME EVENTS: Severe, rarely occurring event that usually causes damage, destruction or severe economic losses. Such events may include unseasonable weather, heavy precipitation, a *storm surge*, flooding, drought, windstorms (including hurricanes, tornadoes, and associated *storm surges*), extreme heat, extreme cold, earthquakes and *tsunamis*.

FETCH: The distance or area in which wind blows across the water forming *waves*. Sometimes used synonymously with fetch length and generating area.

FIDELITY: The degree to which a numerical model reproduces its actual prototype condition or state.

FLOOD INSURANCE RATE MAP (FIRM): Map produced by the Federal Emergency Management Agency (FEMA) portraying special flood hazard areas, including the estimated 100-year *return period* flood inundation area.

FLUID-STRUCTURE INTERACTION: The one-way or two-way interactions between a flowing fluid and a structure of any kind.

FORCING: *Boundary conditions* that "force" the model, describing phenomena that cause the movement of water in the model domain.

FORECASTING: Application of a numerical model to simulate a potential future event (also forecast).

FRICTION FACTOR: A parameter used to represent the *roughness* of land or water bottoms.

GRID: Network of points covering the space or time-space domain of a numerical model, specifically when the points are organized in a structured format.

HIGH WATER MARK (HWM): A wet-dry line or debris line reference mark on a structure or natural object indicating the maximum high water level in a flood. Often these are noted inside flooded buildings which are protected from wave action.

HINDCASTING: Application of a numerical model to simulate a past event. Often used in model *validation* to see how well the output matches known events.

HORIZONTAL PROJECTION: A system of geographic coordinates.

HOT START: To begin a simulation run based on existing, simulated data from the same model, usually to reduce computer time for repeated or aborted runs.

HYDRAULIC MODEL: A computer program that simulates the engineering properties and behavior of a fluid, specifically in closed pipes, open channels, rivers, and streams.

HYDRODYNAMIC MODEL: A computer program that simulates the movement of water, particularly in coastal settings, based on the fundamental equations of motion.

HYDROGRAPH: A depiction (usually graphical) of: 1) the variation of *still water level* over time; or 2) discharge over time.

INITIAL CONDITION: The values of water levels, velocities, concentrations, etc., that are specified everywhere in the computational domain at the beginning of a model run.

MEAN SEA LEVEL: The average height of the surface of the sea for all stages of the *tide* over a 19-year period, usually determined from hourly height readings. Not necessarily equal to mean tide level.

MESH: The unstructured network of computational points (nodes) linked together by finite element connection tables to form a digital representation of the modeled area’s geometry.

MORPHOLOGIC MODEL: A computer program that simulates the results of differential *sediment transport* in space and time for the purpose of modifying the seabed elevation.

NAUTICAL MILE: A unit often used to measure distance at sea, equal to the length of a minute of arc; approximately 6,076 feet; 2,025 yards (1,852 meters) or 1.15 times as long as the U.S. statute mile of 5,280 feet.

NAVIER-STOKES: The equations governing fluid motion that account for fluid *acceleration*, pressure, gravitational effects, and fluid viscosity as derived from Newton's 2nd Law of Motion.

NESTING: A method of running models consecutively, usually to translate between spatial scales or between models.

NON-LINEAR: Occurring as a result of a mathematical operation that is not linear.

OVERTOPPING: Passing of water over the top of a structure or facility as a result of *wave runup* or surge action.

OVERWASH: The landward transport of sediment, from the beach or dune, when water levels exceed the elevation of the dune.

PARAMETRIC EQUATION: An equation yielding a quantity that is an explicit function of one or more independent variables or parameters.

PARTIAL DIFFERENTIAL EQUATION: An equation containing one or more partial derivatives.

QUASI-STEADY: A variable or condition that stays constant for a finite period of time, then changes predictably.

RESIDUAL ERROR: The difference between the computed and observed value of a variable at a specific time and location.

RETURN PERIOD: The average length of time between occurrences in which the value of a random variable (e.g. flood magnitude) is equaled or exceeded. Actual times between occurrences may be longer or shorter, but the return period represents the average interval. The return period is the inverse of the Annual Exceedance Probability (AEP). For example, if the AEP equals 0.01 (or one percent) the return period is 100 years.

RISK: Chance or probability of failure due to all possible environmental inputs and all possible mechanisms. The concept of flood risk often captures both the probability of the flood event and the consequences of the flood event. Also interpreted as the likelihood of a certain event being equaled or exceeded in a given period of time.

ROOT MEAN SQUARE ERROR: The square root of the average of the squared residuals, used to measure model error.

ROUGHNESS: The characteristic describing the land or seabed surface, usually by a dimensionless value or coefficient (e.g., Manning's roughness coefficient).

SAINT-VENANT EQUATIONS: Also known as the shallow water equations, a set of *partial differential equations* that describe fluid motion below a pressure surface.

SEA LEVEL RISE: The long-term trend in *mean sea level*.

SEDIMENT TRANSPORT: The movement of sedimentary materials by gravity (gravity transport); flowing water (rivers and streams); ice (glaciers); wind; or the sea (currents and longshore drift).

SETUP: A sustained increase in mean water level along a shoreline owing to the effects of wind, *waves*, or currents.

SHALLOW-WATER EQUATIONS: Derived from the *Navier-Stokes* equations for cases where the horizontal length scale is much greater than the vertical length scale (also known as the *Saint-Venant equations*).

SHORELINE CHANGE: A net change (either landward or seaward) in the *cross-shore* position of the shoreline.

SIGNIFICANT *WAVE HEIGHT*: The primary measure of energy in a sea state that is calculated either as the average height of the one-third highest *waves* or via energy density spectral analysis methods.

SKILL: Quantifies how well a model reproduces expected values or patterns as functions of time and/or space. Skill is often used to describe the potential usefulness of various climate models.

SPECTRAL *WAVE PROPAGATION* MODEL: A numerical wave model that describes the propagation and transformation of a *wave spectrum* over variable bathymetry and/or terrain.

SPINUP: A period of simulation in a *hydrodynamic model* that allows the effects of certain initial *forcing* conditions to propagate throughout the model domain or to reach their assigned values.

STEADY: A variable or condition that does not change with respect to time.

STILL WATER LEVEL (SWL): The surface of the water if all wave and wind action were to cease.

STOCHASTIC: A process characterized by random probability.

STOCHASTIC MODEL: Also called statistical or probabilistic model. A model in which variable states are described by probability distributions to introduce randomness to the model.

STORM SURGE: A rise in average (typically over several minutes or hours) water level above the normal *astronomical tide* level due to the effects of a storm. Storm surge results from wind stress, atmospheric pressure reduction, and *wave setup*.

STORM TIDE: The total observed seawater level during a storm, which is the combination of normal high tide, *storm surge*, and any other meteorological anomaly.

STRATIFICATION: The formation of layers or "strata" with different properties (i.e. salinity, temperature) over the *water column*.

SURVEY DATUM: Also called a fixed, orthometric, or map datum, a consistent reference to which heights are measured for the purpose of direct comparison.

TAILWATER: Water conditions downstream of some reference point, usually a hydraulic structure or a receiving waterbody.

TIDAL EPOCH: The 18.6-year period of time corresponding to the longest tidal period on Earth that is used to evaluate *tidal datums* such as *Mean Sea Level*.

TIDAL DATUM: A *vertical datum* based on some elevation of the *tide* at one location in a tidal water body, such as *mean sea level* or mean high water.

TIDE: The periodic rising and falling of the water that results from gravitational attraction of the moon and sun and other astronomical bodies acting upon the rotating Earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the tide, it is preferable to designate the latter as tidal current, reserving the name tide for the vertical movement.

TOTAL WATER LEVEL: The elevation of water along the coast including *astronomical tides*, *storm surge*, and *wave runup*.

TSUNAMI: A long-period wave, or series of *waves*, caused by an underwater disturbance such as a volcanic eruption or earthquake. Commonly referred to incorrectly as a "tidal wave."

UNSTEADY: A variable or condition that changes with respect to time.

VALIDATION: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

VERIFICATION: The process of confirming that a model is correctly implemented and free of developmental or mathematical errors.

VERTICAL DATUM: Any permanent line, plane, or surface used as a reference datum to which heights are consistently measured.

WATER COLUMN: A conceptual column in a water body extending from the water surface to the water bottom.

WATER QUALITY: A term that describes the condition of the water, including chemical, physical, and biological characteristics.

WATER SURFACE ELEVATION: A measure of the free water surface with respect to a given datum.

WAVE: A disturbance, deformation, or undulation of the surface of a liquid caused by a displacement of the free surface due to winds, boats, or other physical effects.

WAVE BREAKING: Reduction in *wave height* due to changes in water depth or *wave* steepness (height divided by length).

WAVE FIELD: A spatial distribution of individual *waves* characterized by height, period, and direction.

WAVE GENERATION: (1) The creation of *waves* by natural or mechanical means. (2) The creation and growth of *waves* caused by a wind blowing over a water surface for a certain period of time.

WAVE HEIGHT: The vertical distance between a *wave* crest and the preceding trough.

WAVE KINEMATICS: The velocity and *acceleration* of individual water particles in a *wave*.

WAVE LOADS: The force imparted, usually to a structure or embankment, by a *wave*.

WAVE PROPAGATION: The transmission, or movement, of *waves* through water.

WAVE RADIATION STRESS: The excess flux of momentum owing to the existence of a *wave*.

WAVE RUNUP: The vertical extent of *wave* action on a slope or a wall as measured from the *still water level*.

WAVE SETUP: Super-elevation of the water surface over normal surge elevation due to onshore mass transport of the water by *wave* action alone.

WAVE SHOALING: A change in *wave height* due to changes in water depth or interactions with currents as governed by the conservation of energy.

WAVE SPECTRUM: See ENERGY SPECTRUM.

WAVE TRANSFORMATION: Change in *wave* energy due to the action of physical processes including shoaling, refraction, diffraction, reflection, and breaking.

WIND FIELD: A spatial distribution of wind speeds and directions.

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1 Introduction

A "Primer" is an elementary work that serves as an introduction to a subject of study. As such, this manual provides an introduction to coastal *hydrodynamic modeling* for transportation engineering professionals. The information presented in this manual can be applied to better understand the use of these numerical models in the planning and design of coastal highways. Here, the term "coastal highways" is meant to generally capture the roads, bridges, and other transportation infrastructure that is exposed to, or occasionally exposed to, *tides*, *storm surge*, *waves*, erosion, and *sea level rise* near the coast. The *hydrodynamic models* that serve as the focus of this manual are used to describe these processes and their impacts on coastal highways through flooding, *wave* damage, and scour.

Coastal regions are complex design environments. The use of *hydrodynamic models* to address this complexity is commonplace in the practice of coastal engineering. However, it is likely foreign to many transportation professionals. This manual seeks to narrow that gap by addressing frequently asked questions such as:

- What are the costs of modeling and can they be justified? (Section 1.3)
- What type of model should I use and when? (Chapter 2)
- What are one-dimensional, two-dimensional, and three-dimensional models? (Section 2.3)
- What are *hydrodynamic models* and what can they do? (Section 2.6)
- What are differences between *hydraulic* and *hydrodynamic models*? (Sections 2.5, 2.6)
- How can models be used to determine whether coastal or riverine processes will govern hydraulic conditions at a road or bridge? (Section 2.8)
- What type of information do I need to run a model? (Chapter 3)
- What are my options for modeling design-specific scenarios? (Section 3.6)
- How are model results interpreted and what should I look for? (Chapter 4)
- What type of performance should I expect? (Chapter 5)
- What are acceptable levels of model error? (Section 5.6)
- What is model *coupling* and why/when is it important? (Chapter 6)
- How can models be incorporated into vulnerability analyses? (Chapter 7)

The primary audience for this manual is transportation professionals ranging across the spectrum of project delivery (e.g., planners, scientists, engineers, etc.). Given their diverse educational backgrounds and discipline focus, this document only serves as an introduction to coastal modeling.

The Federal Highway Administration (FHWA) does not intend that this document serve as a "step-by-step" or "how-to" manual, where transportation professionals will learn enough to become proficient at the practice of modeling. Obtaining such proficiency typically includes several semesters of graduate level education equivalent to an advanced degree and many years of experience. However, FHWA anticipates the audience will be able to understand when, why, and at what level coastal models should be used in the planning and design of coastal highways and bridges; and when to solicit the expertise of a coastal engineer. Furthermore, FHWA also anticipates this manual will provide transportation professionals with the information needed to determine scopes of work, prepare requests for professional services, communicate with consultants, and evaluate modeling approaches and results.

1.1 Need for Modeling

Coastal hydrodynamic processes are rarely described by simple, mathematical equations. *Waves*, tidal currents, water levels, and *sediment transport* are complex, *unsteady* (i.e., changing in time) processes that vary substantially in space due to changes in bathymetry (terrain), *roughness*, shoreline geometry, and meteorology (e.g., wind, pressure, precipitation, etc.). These processes are also dependent on one another. For example, consider a completely still water body, having some average (mean) water level position. The introduction of *waves* impart momentum to the *water column*. This in turn causes a change in the mean water level, along with associated changes in the movement of water and sediment. Those subsequent changes also then directly affect the *wave* characteristics. So, it is apparent that a dynamic feedback exists between these processes, making it difficult to describe them all simultaneously using simple mathematical expressions. These types of interactions can be recreated, however, through physical or numerical modeling.

Hydrodynamic models allow users to simulate complex coastal processes. Traditionally, riverine and coastal models used scaled (i.e., smaller) physical representations of the desired study area in a laboratory setting. This type of representation is called a “physical model.” The need to represent scale of both the area (e.g., bathymetry, topography, *roughness*, etc.) as well as the various *forcing* functions (e.g., *tides*, *waves*, etc.)—the forces that create the water levels, *waves*, velocities, and so forth—often necessitated creation of expensive facilities and model representations. Even still, some of the physical scale disparities are so great that they cannot be overcome. An appropriate example is the inability to drastically alter the sediment grain size without changing its composition and behavior.

Advances in computer science and hardware make it possible to develop numerical representations of study areas ranging from small to very large. Today, such “numerical models” represent the state of practice for simulating riverine and coastal processes for the purpose of planning, design, and analysis. Numerical models account for the site specific details and processes that give rise to complex interactions between water and the surrounding natural and built environments. Once developed, and with little additional effort, experienced practitioners can repeatedly apply such models to evaluate a range of possible projects and/or conditions. The conditions applied to a numerical model are commonly referred to as “model *forcing*” and may constitute *tides*, winds, precipitation, or streamflow.

The application of *hydrodynamic models* also improves the confidence in the description of design conditions. While it may still be appropriate to use simple, mathematical tools for the design of some minor projects or repairs, results from such tools are typically characterized by a high degree of uncertainty. The use of numerical models reduces the uncertainty associated with the prediction of the relevant coastal processes often needed for the design of roads and bridges. In other words, as the complexity of a project or process increases, so too should the ability of the methods to accurately simulate the design event characteristics. For example, engineering practice would not apply a sophisticated *hydrodynamic model* to design a small stormwater drainage channel along a roadway; similarly, practice would not use a simple mathematical expression to determine the potential elevation of a coastal bridge to avoid *wave loads*.

1.2 Typical Model Applications

Coastal *hydrodynamic models* can be used separately, or in combinations, to simulate a wide range of coastal processes relevant to the transportation professional (see Figure 1). Examples include the simulation of *storm surge* and coastal flooding; *waves* and *wave transformations* including *wave breaking*; erosion, transport, and deposition of sediments; *shoreline change*; dune erosion; scour; and even *water quality*.

Figure 1 makes a distinction between three general categories of models, with each category defined by the types of equations that are solved, numerically, to predict a certain process. The categories are defined as general circulation models, *wave* models, and *sediment transport* models. The items listed in each category represent (some of) the processes that are simulated in each model type. Note that some numerical models may possess the ability to represent all of these processes interdependently by sharing the results of one model type with another. This is called model *coupling* and is described in Chapter 6.

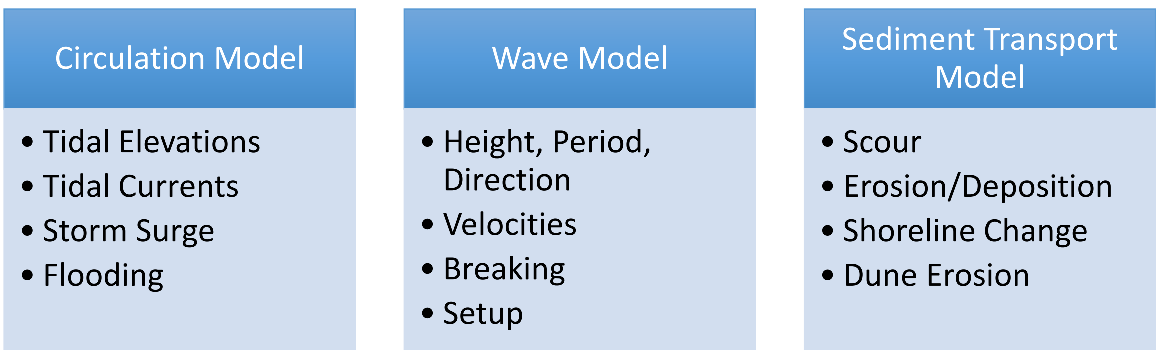

Figure 1. Overview of general model types and their applications.

Coastal *hydrodynamic models* have numerous possible applications, but some are of less relevance for the planning, design, or assessment of coastal roads and bridges. This manual presumes that the most relevant coastal *hydrodynamic model* applications are those that are used to model *storm surge*, *waves*, and the subsequent *sediment transport* processes leading to erosion, deposition, and scour. Therefore, this manual does not address models that describe topics such as *stratification* and mixing, constituent transport, or *water quality* (though many of those numerical models do exist).

1.3 Justification for Modeling

The cost of developing a numerical model is typically small relative to the overall project cost. However, application of a complex numerical model is not necessary in some cases. Some smaller projects may not warrant model development, particularly those that are designed to lower *return period* storm events or where the consequences of failure are relatively innocuous. For example, consider the design of a revetment to protect a small, two-lane residential road in a tidal setting. Unless that roadway is directly exposed to ocean *waves* or the consequences of failure are very high (e.g., roadway serves as a school bus or evacuation route), a complex *hydrodynamic model* is probably not needed to estimate an appropriate armor unit weight for the revetment stone. To contrast that example, imagine designing a major highway bridge over a tidal estuary. Regardless of the setting or conditions found there, the consequences of failure are very high (i.e., cost of failure, service disruptions, etc.), and the need to limit the uncertainty in the design is similarly high. The use of *hydrodynamic models* in this case is appropriate and justifiable.

Given the examples above, a simple way to justify when and where modeling is needed is to consider its cost relative to that of the project or the consequences of project failure. In other words, make a decision based on *risk*, which accounts for the probability, costs, and consequences of failure. If the *risk* is high relative to the cost of model development, then the costs associated with that development are justifiable. If the *risk* is low relative to the cost of model development, then simpler methods of analysis are likely appropriate. More information about when, where, and how to use appropriate methods for simulating coastal hydrodynamics is provided in Chapter 7. This guidance is presented in terms of the three-level vulnerability analysis framework outlined in HEC-25 Volume 2 (FHWA, 2014).

1.4 EDC-4: CHANGE Initiative

The Every Day Counts[1] (EDC) initiative, launched by FHWA in cooperation with American Association of State Highway and Transportation Officials (AASHTO), is a program that identifies and deploys new but rarely-used innovations that improve efficiencies at the state and local levels. A purpose of EDC is to identify new methods that save time and resources with the goal of delivering more projects for the same amount of money. The two-year EDC programs are not just focused on economic efficiencies; they also seek to reduce project timeframes, improve safety, and increase environmental sustainability. Throughout these two-year programmatic cycles, information about these new innovations is developed and disseminated broadly in order to speed their implementation and deployment across the nation.

One of the priority areas identified in the fourth round of EDC programs (EDC-4) is broadening the use of more sophisticated numerical modeling tools. The *Collaborative Hydraulics: Advancing to the Next Generation of Engineering*[2] (CHANGE) program focuses on advancing state-of-the-practice modeling of the complex interactions between river or coastal environments and transportation infrastructure with the goals of improved project design and delivery. Although most *hydraulic modeling* to date has been performed using one-dimensional (1D) models, the FHWA recognizes the benefits of two-dimensional (2D) *hydraulic modeling* and has developed guidance and training opportunities to support its use (e.g., HDS 7, HEC-18,

[1] https://www.fhwa.dot.gov/innovation/everydaycounts/about-edc.cfm

[2] https://www.fhwa.dot.gov/innovation/everydaycounts/edc_4/change.cfm

FHWA-NHI-135095). This manual makes and describes the distinction between 1D and 2D models in Section 2.3.

Within the context of this EDC-4 CHANGE initiative, the purpose of this manual is to provide transportation professionals with an introductory overview of coastal *hydrodynamic modeling,* as it differs from *hydraulic modeling* in a number of ways that are relevant to the transportation sector.

1.5 Primer Contents

This manual provides the reader with a very general overview of coastal modeling. To accomplish this goal, the document is divided into short chapters, the order of which attempts to mimic the process of developing and applying a numerical model to simulate coastal processes.

Chapter 2 provides some basic information about modeling in general including how models work, the types of models that exist, and some of the nuances of coastal *hydrodynamic modeling*. Of particular interest to transportation engineers and *hydraulic modelers*, Chapter 2 also describes when and how hydrodynamic and *hydraulic models* can be combined, substituted, or used to determine if and where coastal or riverine processes dominate design conditions at a road or bridge.

Chapter 3 describes the most common types of inputs required by numerical models and how coastal modeling practice develops such inputs to satisfy these requirements.

Assuming then that the audience has used a model to simulate a scenario of some type, Chapter 4 describes how to interpret and/or use those results.

Next, Chapter 5 introduces the audience to the separate steps of model *calibration* and model *validation*, as well as how to evaluate model error or *skill*, and what *skill* levels are appropriate.

Chapter 6 presents information on when, where, and how to combine (or couple) models to achieve a desired outcome.

Chapter 7 describes how modeling is incorporated into vulnerability assessments using the three-level methodology outlined in HEC-25 Volume 2.

Chapter 8 at the end of the manual provides references; listed in alphabetical order.

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2 Modeling Basics

Chapter 1 described distinctions between physical and numeric models. Both types of models reduce uncertainty associated with simpler mathematical approaches. However, modeling practice recognizes that numerical models better represent and provide the ability for considering greater complexity, accuracy, and rapid consideration of various scenarios and alternatives. Furthermore, numerical models can incorporate some degree of statistical uncertainty to better represent the *stochastic* (characterized by random probability) nature of coastal processes that are rarely *deterministic* (pre-determined outcome).

The first thing to understand about numerical models is that they are all wrong to some extent. But they can be very helpful if you know how to use them correctly! They are "wrong" in the sense that the numerical estimate of the complex physical processes provided by the model is not going to match that of the prototype precisely. But they can, and do, match the prototype well enough for engineering design decisions when used correctly. This chapter serves as an introduction to and overview of numerical modeling basics. It provides an introduction to modeling for those who are not familiar with it and a refresher for those who are. The chapter describes numerical models in general terms and how their governing equations are solved in one, two, or even three physical dimensions, as well as in time. This chapter also describes general characteristics of numerical models. Also, this chapter gives recommendations regarding when and where to use *hydraulic* and/or *hydrodynamic models*, and when to consult a coastal engineer. Finally, the chapter describes application of *hydraulic* and *hydrodynamic models* to determine whether riverine or coastal conditions govern design conditions.

2.1 What are Numerical Models?

Simply put, numerical models are specialized computer programs that solve governing (usually physics-based) equations using numerical simulation techniques. A model could be as simple as a spreadsheet solution or as complex as a multi-routine program containing thousands of lines of code that represent the many different physical processes being simulated. In many cases relevant to the topics covered in this manual, the related field of study is commonly referred to as *computational fluid dynamics* (CFD). The terminology CFD is also used to describe a subset of numerical models that are extremely complex and typically only applied to very specific scenarios, but the reader should understand that all numerical models, by definition, are CFD models.

The purpose of a numerical model is to solve an equation, or system of equations, repetitively in time and/or space in a highly efficient manner. Efficiency is truly the distinguishing factor when compared to the alternative of solving a set of equations by hand or using a calculator. However, there is a tradeoff. With efficiency comes error. Almost all numerical models introduce some amount of error due to inadequacies of the numerical simulation technique used to solve them (which is one reason why they are all wrong). These techniques, and their errors, are discussed in the subsequent section.

2.2 How are Equations Solved?

Mathematical equations are solved using numerical simulation techniques. These techniques range from relatively simple to extremely complex. You may have used a numerical simulation technique in a spreadsheet analysis without even knowing it! For instance, linear interpolation provides an estimated value relative to two or more known values. Or, you may have estimated the area under a curve using the "trapezoidal rule." Believe it or not, these are examples of numerical simulation techniques that many of us master and use regularly. However, for most of the coastal *hydrodynamic models* encountered in practice, the techniques used to solve the governing equations are more sophisticated, and that's because the equations are much more difficult to solve.

Generally speaking, the models that serve as the focus of this manual rely on the solution of three or four *partial differential equations* consisting of numerous terms, in multiple dimensions; spatial and temporal no less! There are a number of different techniques for solving these equations; Figure 2 summarizes some examples. In that figure, the name of the technique used to relate the mathematical expressions to the physical system, in both time and space, is given on the left. Some comments about each technique are provided on the right. In many cases, the technique used depends upon the nature of the problem and the equations being solved. The technique used by a model is invisible to the user and of little significance. For more information on how these techniques are applied, please refer to a source such as Fletcher (1998).

Finite Difference Method (FDM)	• Uses values of adjacent, discrete points in time and space • Mostly limited to models using regular, structured grids • Difficult to represent complex domains or features
Finite Element Method (FEM)	• More challenging to implement • Well suited to modeling complex domains • Neighboring points used to define an elemental area for computations
Finite Volume Method (FVM)	• Robust and applicable for stuctured and unstructured domains • Solutions are explicitly conservative (in terms of mass) • Fluxes into/out of small volumes around each physical point are evalauted
Spectral Element Method (SEM)	• Similar to the finite element method, with less computational error • Typically requires smaller elements, more computational time • Functions represented by series of approximating polynomial equations
Boundary Element Method (BEM)	• Very high accuracy • Often less efficient than volume methods (FDM, FEM, FVM) • Exact boundary values used to solve for interior point values using integrals

Figure 2. Common types of numerical methods for solving mathematical equations.

2.3 1D, 2D, and 3D Models

Four basic dimensions could be resolved by a numerical model: one is time (*t*), the other three are spatial (*x, y, z*). Here, we will focus primarily on describing the differences between one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) models in terms of the spatial dimension. Note that 1D and 2D models could involve any one or two of the three spatial dimensions, respectively, in addition to simulating the *unsteady* processes as a function of time.

The three spatial dimensions are commonly referred to as *x, y,* and *z*. These spatial coordinates are (in most cases) analogous to east-west (easting), north-south (northing), and up-down (vertical). In other words, the spatial dimensions, *x* and *y*, generally refer to the horizontal plane while *z* refers to the vertical plane. Exceptions do exist and the user of a numerical model is cautioned to first understand the coordinate system and sign convention used in their model (i.e., are depths specified as positive or negative values?). This is typically described in the model user manual or development documentation.

Most of the coastal *hydrodynamic models* used for the planning and design of coastal transportation infrastructure are 2D models (in the *x*-*y* horizontal plane). These models are the focus of this manual. Notable exceptions do exist, and there are certain scenarios where a 2D model is not needed, and potentially others where it may not work well. The text that follows attempts to summarize and briefly describe limitations of the most common applications of 1D, 2D, and 3D models.

Some notable 1D models are still routinely used in coastal engineering. These are mainly *cross-shore* (perpendicular to the shoreline) models that simulate *beach profile* change, dune erosion, *wave shoaling* and breaking, *wave setup*, and currents (see Figure 3). Figure 3 depicts modeling the erosion of a sand dune using a 1D model. It shows the Initial Bed Elevation (between *cross-shore* location 50 m and 100 m) being reduced to the Final Bed Elevation. With the Final Water Level at or near the crest of the sand dune, its material is eroded and moved landward (to the right) in a process known as *overwash*. Also shown are the *wave setup* effect (increase) on the Final Water Level and the *wave height* decay (Final Wave Height) due to breaking. The Federal Emergency Management Agency (FEMA) uses similar models in the development of modern coastal *flood insurance rate maps* (FIRMs)[3].

[3] https://www.fema.gov/wave-height-analysis-flood-insurance-studies-version-40

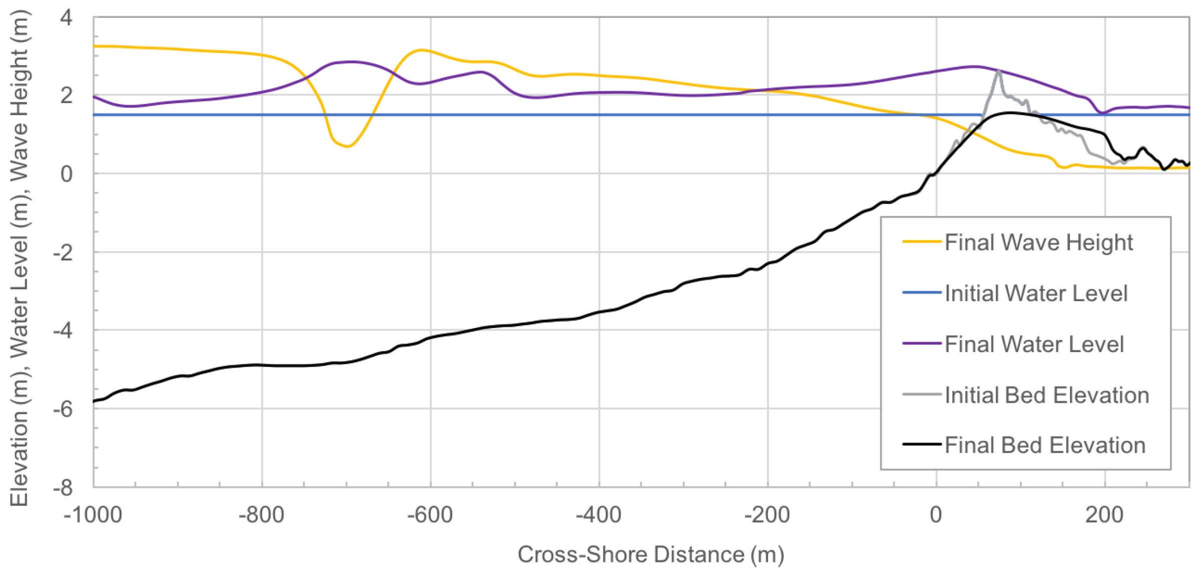

Figure 3. Representative results from a 1D cross-shore hydrodynamic model showing wave transformation and profile change following a hurricane.

With very few exceptions, a 2D coastal *hydrodynamic model* simulates some process of interest in the *x-y* (easting and northing) horizontal plane. Therefore, 2D models are commonly referred to as *depth-averaged* or depth-integrated models and are often signified as 2DH, meaning two-dimensional in the horizontal plane.

Relevant examples include *wave propagation* and transformation models (e.g., STWAVE, CMS-WAVE, SWAN, XBEACH), tidal circulation models (e.g., ADCIRC, CMS-FLOW, FVCOM), *storm surge* models (e.g., ADCIRC, CMS-FLOW, FVCOM), and some *sediment transport* models (e.g., XBEACH, CMS). Most of the 2D models used for such purposes are both state-of-the-art and state-of-the-practice. For demonstration purposes, Figure 4 shows representative results from a 2D *storm surge* model. That figure shows the spatially varying water levels (contours) and *wind fields* (vectors) predicted at a specific time from a simulation of Hurricane Katrina's track and *wind fields*.

The major assumptions common to all 2D models are that the fluid is homogeneous and the vertical dimension of the problem (i.e., the depth of the water body) is small compared to the horizontal length scales. While these assumptions are not overly limiting for modeling *waves* or *storm surge*, they certainly can be if the goal is to predict the distribution of velocity over the *water column*, particularly if the water body is stratified. Velocity is a quantity that can vary in all three spatial dimensions as well as time. Since quantities like *wave heights* and water levels are single-valued functions that only depend on their position in the horizontal (2D) plane, they do not require three-dimensional equations. Hence, 2D models are capable of predicting their values. So, while a 2D model cannot tell you that water near the surface is moving faster than water near the bottom, or possibly moving in different directions, it can certainly calculate a *wave height*, water level, or even a change in the ground surface elevation due to erosion or accretion. This point is often confusing to people and they may incorrectly assume that only 3D models can simulate such processes.

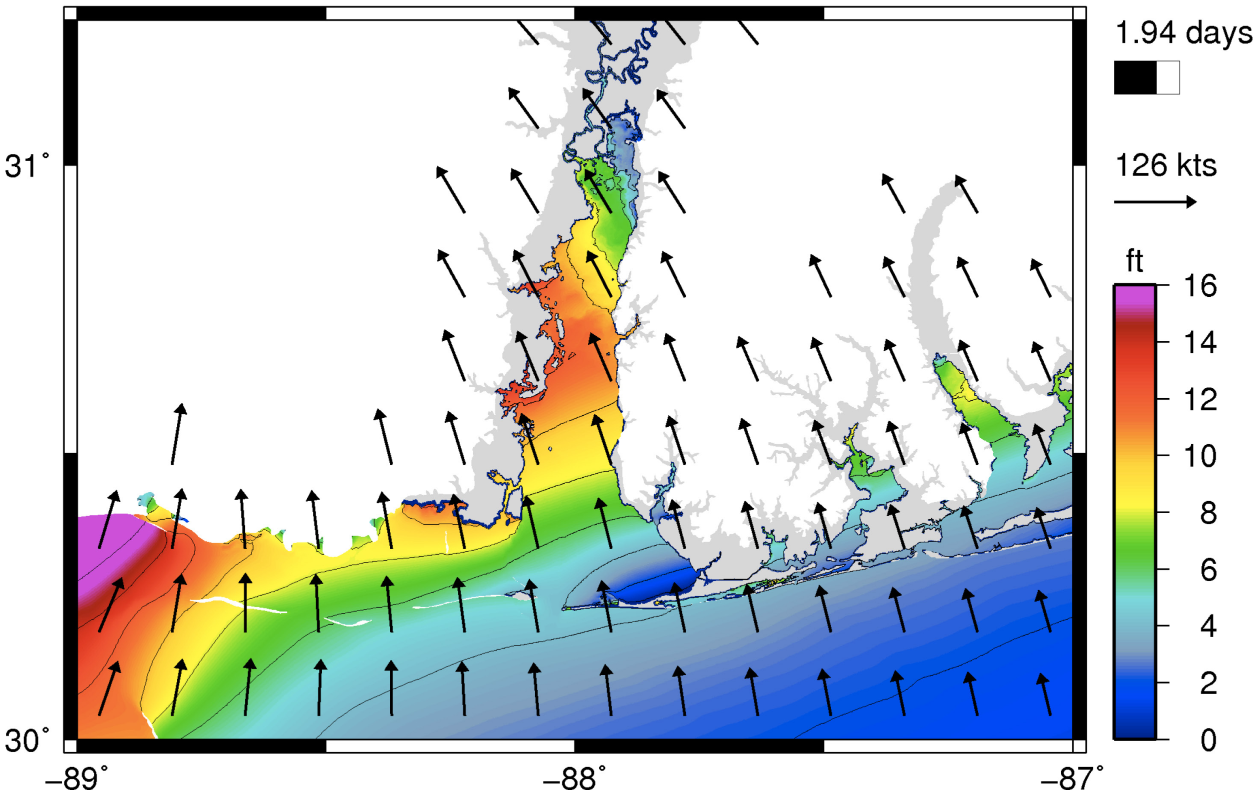

Figure 4. Representative 2D hydrodynamic model results showing spatially variable water surface elevations (ft, MSL) and wind fields (vectors) from a simulation of Hurricane Katrina.

A 3D *hydrodynamic model* is one where the governing equations for momentum, specifically velocity, are solved in all three dimensions. This is the most sophisticated group of coastal *hydrodynamic models* and, as such, is infrequently used in coastal engineering design. This is because 3D models (e.g., DELFT3D, or the 3D version of ADCIRC) often require a substantial amount of input (i.e., *initial conditions*) that is not readily available to the engineer, and also due to the *computational cost* of running such models. These models require a considerable amount of time to run on conventional desktop computing systems. In some cases, the quality of our input, like bathymetry, is poor enough that any additional accuracy provided by a 3D model could certainly be canceled out. Also, 3D models are not needed in every situation. For example, 2D *storm surge* and *wave* models have been shown to give very good results when used appropriately. When modeling circulation in a highly stratified estuary, in a waterbody having considerable depth contrasts, or for the purpose of investigating *fluid-structure interactions* (FSI), 3D models are likely more appropriate. Widespread use of 3D coastal *hydrodynamic models* is becoming more commonplace as the quality of our input improves and our low-cost computing power increases.

2.4 Steady and Unsteady Models

The previous section was devoted to the three basic dimensions of space, but the time dimension is also important. Coastal *hydrodynamic models* may be *steady* or *unsteady*, but the processes that they seek to resolve are best described as *quasi-steady* or completely *unsteady*

(Figure 5). A *steady* process is one where a specific variable (e.g., depth, velocity, *wave height*, etc.) does not change with respect to time (Figure 5a). An *unsteady* process is one where a specific variable does change with respect to time (Figure 5c). A *quasi-steady* process is one where the variable may remain constant for some finite period of time (i.e., *steady*) but then change in some predictable manner (Figure 5b). A simple example of a *quasi-steady* process would be the tidal velocity in a long, narrow, and shallow channel. For one-half of the tidal period, that velocity is going in the same direction at a relatively constant speed. For the other one-half of the tidal period, the velocity is going in the opposite direction at a relatively constant speed.

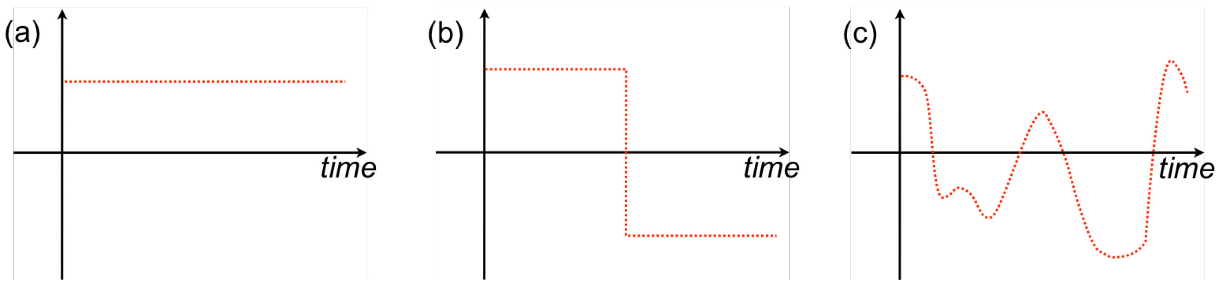

Figure 5. Examples of (a) steady, (b) quasi-steady, and (c) unsteady processes. The value or the process is represented by the vertical axis while time is shown on the horizontal axis.

Most coastal *hydrodynamic models* are *unsteady* models that integrate the equations of motion over time to provide predictions of the relevant variables at successive time intervals over a period of interest. Note that any steady-state model can be used to give answers over a period of time assuming the user is able to provide that model with the requisite inputs (e.g., wind, *waves*, currents, etc.) as a function of time. This is how coastal modeling practice applies many 2D *wave propagation*/transformation models. For example, the *water surface elevations* and currents from a 2D *storm surge* model are extracted at some interval, say hourly, and used as input to a steady-state *wave* model that is run at each one of those unique times. What results are discrete "snapshots" of the 2D *wave* characteristics over the storm duration and they can be represented graphically to show how the values change over time.

2.5 Hydraulic Model Characteristics

Hydraulic models describe the basic mechanical properties of a fluid, particularly the behavior of fluid in closed conduits and open channels. Accordingly, models of open channel flow, streamflow, and riverine systems have often been referred to as *hydraulic models*. These models tend to describe the basic engineering properties or behavior of a fluid, such as average velocity, depth, water surface slope, and channel friction. There are numerous examples of 1D (e.g., HEC-RAS) and 2D (e.g., SRH-2D) *hydraulic models* used in practice today, with the 2D models becoming increasingly more common in transportation planning and design. Some of these are very robust 2D *hydraulic models* being used to simulate stream and river flows with complex geometries. Such models are overcoming previous limitations of assuming *steady* and/or uniform flow and limited ability to specify variable channel *roughness* and flow obstructions. While it is not strictly the case, *hydraulic models* are generalized in this document as describing open channel, riverine, or stream flows. We assume that the *hydraulic models* most commonly used by transportation professionals neglect the influence of wind on water levels as well as its ability to generate *waves*.

2.6 Hydrodynamic Model Characteristics

Hydrodynamic models focus on the detailed motions and behavior of fluids. *Hydrodynamic models* are in many ways similar to *hydraulic models* commonly used in transportation engineering and design. Briefly, both types of models:

- solve equations of fluid motion in space and time,
- provide some method for the treatment of turbulence,
- simulate wetting and drying, and
- have some limitations or restrictions on numerical stability.

Most hydrodynamic and *hydraulic models*, particularly 2D models, solve some simplified form of the *Navier-Stokes* equations, also known as the *Saint-Venant* or *shallow-water equations*. These equations describe the *accelerations* within the fluid, as well as pressure, viscous, and friction forces acting within or on the fluid. With increasing frequency, these models also allow for some treatment of turbulence, often through specification of an *eddy viscosity* or application of a particular turbulence closure method. The wetting and drying functionality allows computational points within the model domain to be either instantaneously wet or dry depending on changes in the local water level relative to the underlying terrain.

Numerical models also have some restrictions that limit numerical stability. These requirements may restrict the size of computational *grid* cells or the duration of the time step, or both. One example of a stability requirement is the *Courant number*. It serves as a practical limitation on *grid* size, time step, and fluid speed for explicit models. Explicit models are those that predict values at the next time step using only the values at the current time step. Comparatively, implicit models predict values at a successive time step using values at the current <u>and</u> future time steps. Implicit models are not restricted by the Courant stability limit, but do possess other stability restrictions.

This manual has already established a characterization of a *hydraulic model*. Contrastingly, modeling practice categorizes *hydrodynamic models* as those that simulate coastal processes such as water levels, currents, *waves*, and *sediment transport*. A few key items make *hydrodynamic models* different than *hydraulic models*, and they include:

- influence of the *Coriolis* force,
- wind,
- *tides*, and
- *wave generation* and propagation.

Most *hydraulic models* do not account for the *Coriolis* force, or the *acceleration* on a fluid imparted by Earth's rotation. Most *hydraulic models* also neglect the effect of wind on fluid motion. These limitations prevent *hydraulic models* from accurately describing the behavior of water levels along the coast as *Coriolis* and wind (and atmospheric pressure) affect water levels, currents, and *waves* in shallow coastal seas. *Hydraulic models* also often neglect tidal *forcing*, further limiting their ability to accurately describe water levels in coastal areas. Tidal *forcing* is common in coastal *hydrodynamic modeling*.

A defining characteristic of coastal *hydrodynamic models*, or at least a subset of them, is their ability to model *waves*. More specifically, their ability to model:

- *wave generation* (growth), propagation (travel), and transformation (change),
- *wave setup*,
- current generation,
- interactions with currents, and
- *wave loads* on structures and facilities.

Given that *waves* are often the largest contributors to *sediment transport*, erosion, and structural damage, modeling them is particularly important to transportation engineering design. *Wave* models may either be *steady* or *unsteady*. Steady state *wave* models tend to be called *spectral wave propagation models*. A *wave spectrum* is a distribution of *wave* energy as a function of *wave* period and/or *wave* direction. This type of model describes the entire distribution of energy in an irregular sea state, usually in the 2D horizontal plane, instead of trying to resolve each individual *wave*. In contrast, *unsteady wave* models solve for the *wave kinematics* in the time domain, thus resolving the generation, propagation, and transformation of each individual *wave* in both space and time.

Both types of *wave* models are useful in transportation engineering design. For example, a steady-state spectral *wave* model may be used to transform *waves* from a distant, offshore location (i.e., an offshore *wave* buoy) to a point near a bridge. An *unsteady wave* model can then use that information to generate *waves* in the time domain over a much smaller *grid* of the bridge/area for the purpose of estimating scour, hydrodynamic loads, or *wave loads* on the bridge sub/superstructure.

2.7 Combining Hydraulic and Hydrodynamic Models

Because *hydraulic* and *hydrodynamic models* generally solve the same types of equations describing fluid motion, there are opportunities for combining or using the results from one model to constrain or force another. Such opportunities are described in other sections of this manual, but a few examples include:

- using discharge from a *hydraulic model* to simulate river input in a *hydrodynamic model*,
- using the stage from a *hydraulic model* to simulate a variable upstream water level in a *hydrodynamic model*,
- using tidal or storm water levels from a *hydrodynamic model* as *tailwater* conditions in a *hydraulic model*, and
- using water levels or velocities from a *hydrodynamic model* as input to a *hydraulic model* when coastal flows drive water upstream.

Some of these concepts may be foreign to those unfamiliar with modeling, but they will be made clear in subsequent sections of this document. It is important to recognize that combining *hydraulic* and *hydrodynamic models*, or using them interchangeably, may not always yield appropriate results. An example of a potentially inappropriate use of a *hydraulic model* is when the effects of wind on water levels are important (i.e., large study areas). Another example is when a *hydraulic model* is applied in an area, or scenario, where *waves* are present. Similarly, *hydrodynamic models* are often not well suited to simulating flows in channels, streams, or culverts (unless specifically developed to do so).

Quantitative advice on when to use a *hydraulic* or *hydrodynamic model* is not available due to the site-specific nature of such problems. Instead, Figure 6 provides general guidance on selecting the most appropriate model, and when to potentially consult a coastal engineer. Figure 6 is conceptual and qualitative and (as related above) by no means quantitative in nature. In Figure 6, the decision regarding which model to select is shown as a function of distance from the coast and how critical the infrastructure is. Additional clarifying statements regarding the conditions where a hydrodynamic or *hydraulic model* might be applied are given on the right, since "distance from the coast" is a somewhat subjective measure. Similarly, examples of infrastructure are provided in terms of their use, type, and service to suggest a hierarchy of importance across the top. Note that items listed in the left and center columns may slide to the right depending on the setting.

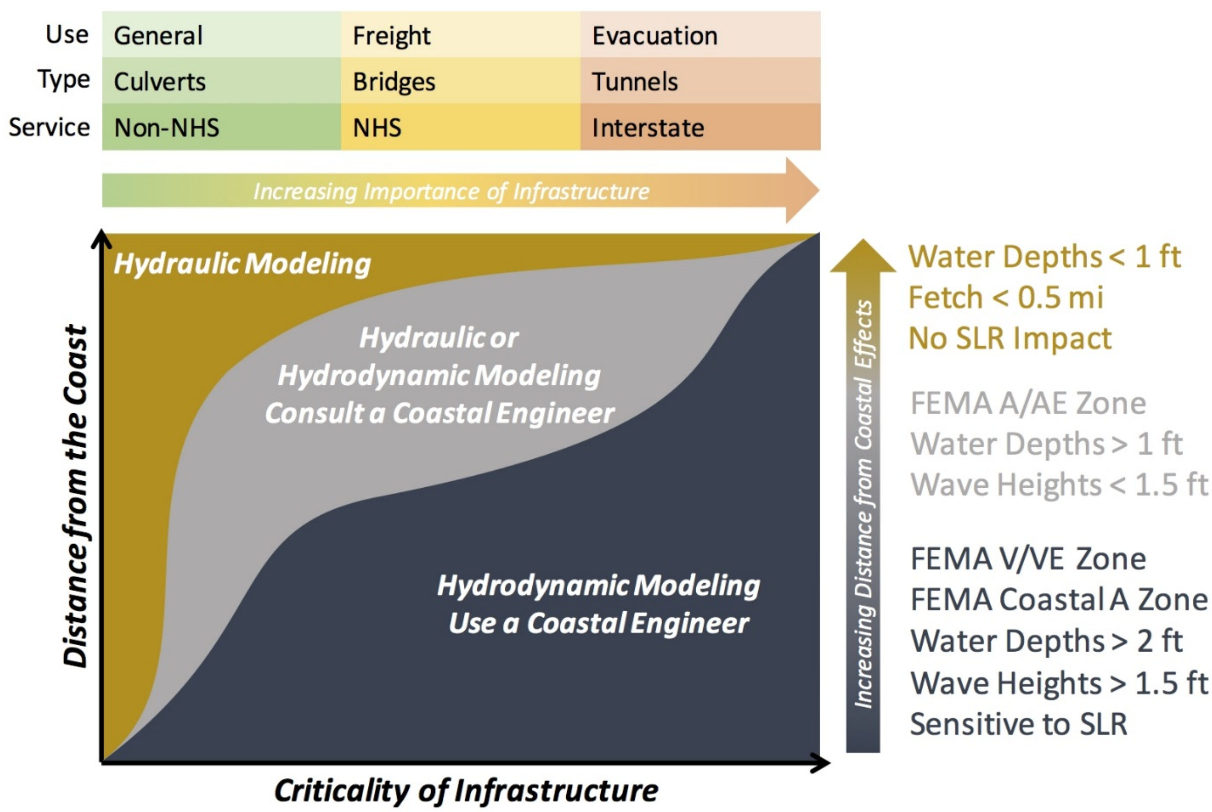

Figure 6. When and where to apply hydraulic and hydrodynamic models as a function of distance from the coast and importance of infrastructure.

Another limiting factor on the application of *hydraulic models* in coastal settings is the availability of comprehensive hydrodynamic data that can be used as input to them. As stated previously, no *hydraulic model* will be able to simulate the effects of *waves*. Therefore, when *waves* are present, or when they are expected to be present (water depths > 1 foot, *fetch* lengths > 0.5 mi), a *wave* model should be used. In some specific situations, a *hydraulic model* may be able to describe water levels and flows associated with *tides* or *storm surge*, but only across small areas where winds are no longer substantially contributing to their behavior. Some large scale *hydrodynamic modeling* results exist and are provided as part of the US Army Corps of Engineers' Coastal Hazards System (see Section 3.6). However, a majority of those data are found across the coastal floodplain where wind and *wave* effects may still be substantial. A coastal engineer should be consulted on the potential applicability of those data in a *hydraulic model* simulation.

Some illustrative (and hypothetical) scenarios: a project may have a small culvert under a non-NHS road at some distance "X" from the coast. Using Figure 6, the project might conclude that using a *hydraulic model* for that culvert is likely appropriate. However, if evaluating a culvert under an Interstate for that same distance "X" from the coast, then the project may want to consult/use a coastal engineer. Another hypothetical scenario; if disruption (or failure) of a non-NHS culvert might result in an adverse impact on an evacuation route (or reflect some other increased consequence of failure), then a prudent step would be to elicit the services of a coastal engineer. The advice also works the other way; designing a small 12-inch culvert very close to the coast likely does not call for the services provided by a coastal engineer. Finally, while these examples use culverts, such advice lends itself to all manner of hydraulic transportation appurtenances.

2.8 Using Models to Evaluate Riverine vs. Coastal Influence

There are more than 36,000 bridges within 15 *nautical miles* of the US coast (FHWA, 2008). While approximately 1,000 of these bridges may be vulnerable to *storm surge* and *wave* damage, including foundation scour and deck displacement, many more may be affected by coastal processes to some degree during storm events (Webb & Matthews, 2014). When a bridge or roadway is not clearly dominated by riverine or coastal processes, some quantitative assessment must be made to evaluate the asset's vulnerability to scour, hydrodynamic forces, and possibly *wave loads*. This type of analysis is most commonly performed as part of bridge hydraulic studies, the results of which are communicated in a bridge hydraulics report (BHR).

Hydrodynamic and *hydraulic models* can be used to evaluate a bridge or roadway's vulnerability to coastal and riverine processes, respectively. For example, a *hydraulic model* may be used to estimate water levels and flow velocities for a given *return period* discharge event at a bridge crossing near the coast. *Hydrodynamic models* of *storm surge* and *waves* can be applied for an appropriate *return period* coastal storm event at that location, and the results compared to those of the *hydraulic model*. The model and scenario yielding the higher velocity will most likely indicate the conditions that govern scour at the bridge foundation. The model and scenario yielding the higher water level will more than likely indicate the conditions that govern vulnerability of the bridge superstructure to *wave* attack. For some locations, the maximum velocities may be controlled by riverine floods but the water levels may be controlled by coastal storms. *Wave* modeling on the peak surge/flood levels can be used to estimate *wave loads* on bridge components. Figure 7 provides a suggested workflow. This is an area of transportation engineering design that would benefit from more objective guidance, determined through additional research.

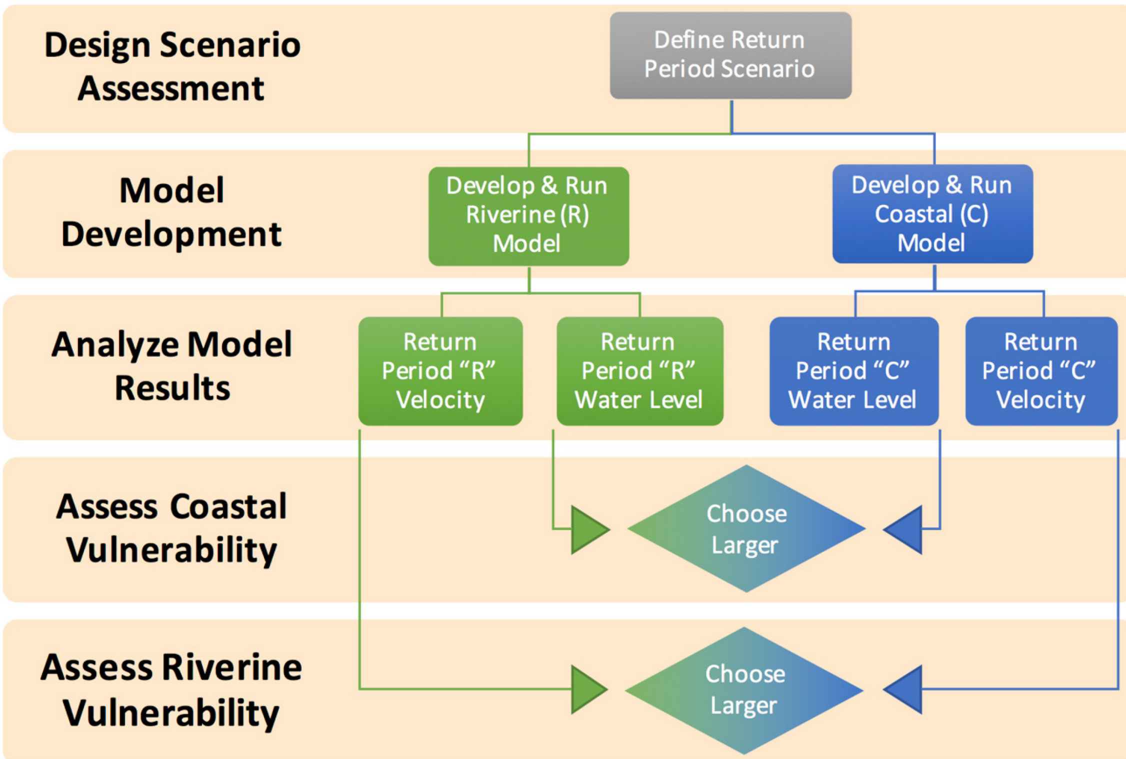

Figure 7. Suggested workflow for using hydraulic and hydrodynamic models to determine whether an asset is dominated by riverine or coastal flood processes.

2.9 Coupled Morphologic Modeling

Models are often linked, combined, or "*coupled*" together to exchange information such that the dependency between different processes can be simulated. For example, *storm surge* and *wave* models are *coupled* together to account for their interactions with one another. These models can also be used to estimate *sediment transport* rates and fluxes, which can in turn be used to update the bed level over time to simulate erosion and deposition. This is generally referred to as *morphologic modeling*, which represents a different subset of numerical models altogether. Chapter 6 describes *coupled* models and provides much more information on the subject.

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3 Preparing Model Input

Every numerical model requires some form of input. This input is generally some type of *boundary condition* or *initial condition* that tells the model what to do, when to do it, and how to do it. A *grid* or *mesh* is also needed to provide spatial structure and coordinates for the computations, or in other words where to do it. This chapter describes how a model is developed and identifies the most common input parameters required by the user during that process. Topics include model *grids* and *meshes*; data requirements, particularly elevation data; *boundary* and *initial conditions*; model *forcing*; and how model scenarios are developed, selected, and implemented.

3.1 Grids, Meshes, and Nesting

The most basic requirement of any numerical model is its computational domain. The computational domain is a collection of points at which the governing equations are solved. Each point is defined by at least three attributes: its two coordinates, or position, in the horizontal plane (*x*-*y*), and its vertical coordinate or position (*z*). In this manner, each point knows its position relative to all others in the computational domain.

The organization of points in a computational domain can be structured (i.e., a *grid*) or unstructured (i.e., a *mesh*) depending on the numerical simulation technique used to solve the governing equations. Structured *grids* consist of rectangular cells, the corners of which are defined by computational points. These *grids* are either rectilinear or curvilinear. Rectilinear *grids* consist of points connected by straight and parallel lines everywhere. Figure 8 depicts an example of a rectilinear *grid* with variable *grid* spacing. Variable *grid* spacing allows resolution to increase or decrease throughout the model domain. Curvilinear *grids* are a special type of structured *grid* that allows a computational domain to better fit complex geometries or areas. Figure 9 shows an example of a curvilinear *grid*.

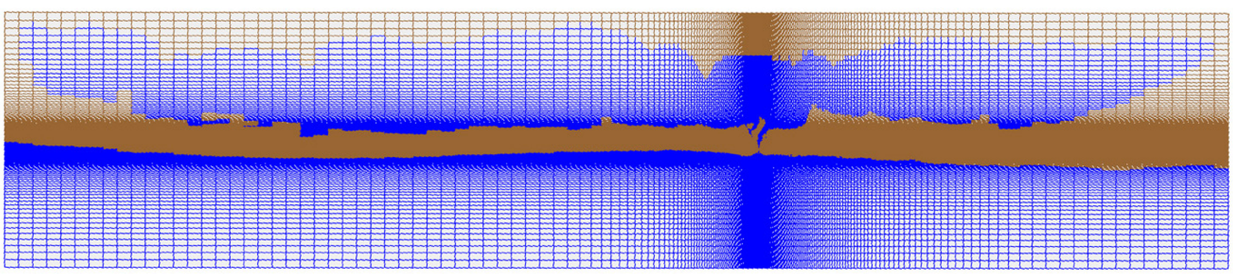


Figure 8. A rectilinear grid with variable grid spacing showing increased resolution at the tidal inlet, Lagoon Pass, in Gulf Shores, Alabama. The blue cells are "water" cells and the brown cells represent land.

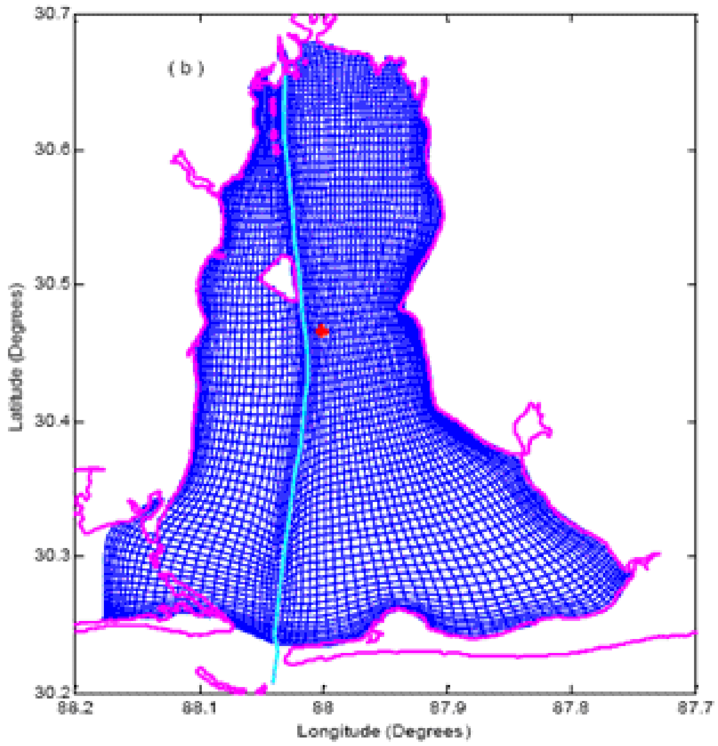


Figure 9. Curvilinear grid of Mobile Bay, Alabama taken from (Chen & Douglass, 2003). The blue lines represent the grid cells and the purple line is the approximate shoreline position. Note how the grid cells stretch, compress, and conform in areas where higher resolution is needed, such as along the shoreline or the ship channel, shown in the figure as the linear feature vertically bisecting the grid.

Unstructured *meshes* do not necessarily have any pre-determined structure or organization of the computational points. Instead, the points are placed with the specific intention to better define complex features or boundaries within the computational domain. These points are often connected by triangular elements, though elements having six or more sides are also possible. These multi-sided elements can be compressed or expanded to provide very good resolution (i.e., computational points spaced closely together) in places with complex features, or expanded to lower resolution (i.e., computational points spaced further apart) in other places. These concepts are demonstrated in the sample *mesh* of a complex ocean-inlet-bay system shown in Figure 10.

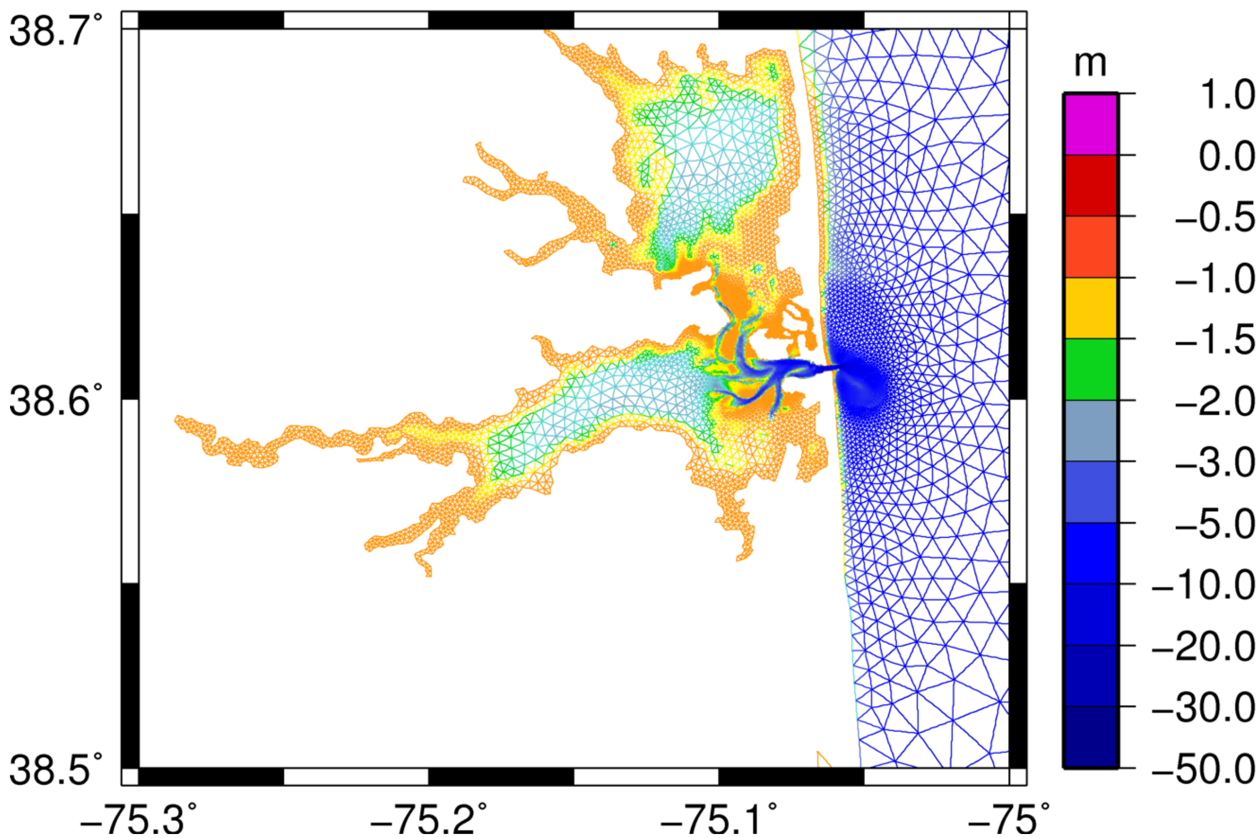


Figure 10. Unstructured mesh of Indian River Inlet, Delaware. The figure shows the distribution of mesh nodes and variable size of the mesh elements. The colors of the mesh elements represent the bed elevations (m, MSL). Areas shown in solid white are land or small features not resolved in the model mesh.

When modeling is required across a wide range of spatial scales, *grids* and/or *meshes* can be "*nested*" within one another. A simple example of *nesting grids* would be simulating *waves* on a large but low resolution *grid* of the Chesapeake Bay, but then passing that information to a much smaller, higher resolution *grid* of Baltimore Harbor. These models are run consecutively, not concurrently. The results obtained on the larger *grid* are extracted and passed on as input to the *nested grid*, a topic covered in the next chapter (Section 4.3). *Grids* can also be *nested* within *meshes*, or *meshes nested* within *grids*, when sharing information between different types of models is desired. A graphical example of both a *nested grid* and model is provided in Figure 11, which shows a 2D structured *grid* and *hydrodynamic model* (XBeach) *nested* within a much larger basin-scale finite element *storm surge* model (ADCIRC+SWAN) *mesh*. In that case, the resolution of the *nested grid* had to be much better (on the order of meters) than that of the unstructured *mesh* (on the order of tens to hundreds of meters) for the purpose of resolving flow around a bridge abutment. A different color scheme is used to represent the elevations of the *nested grid* for ease of viewing. Also shown in Figure 11 is the point (white circle) where data were extracted from the basin scale model and used as input to drive the much smaller (2 km by 2 km in area) 2D *hydrodynamic model*.

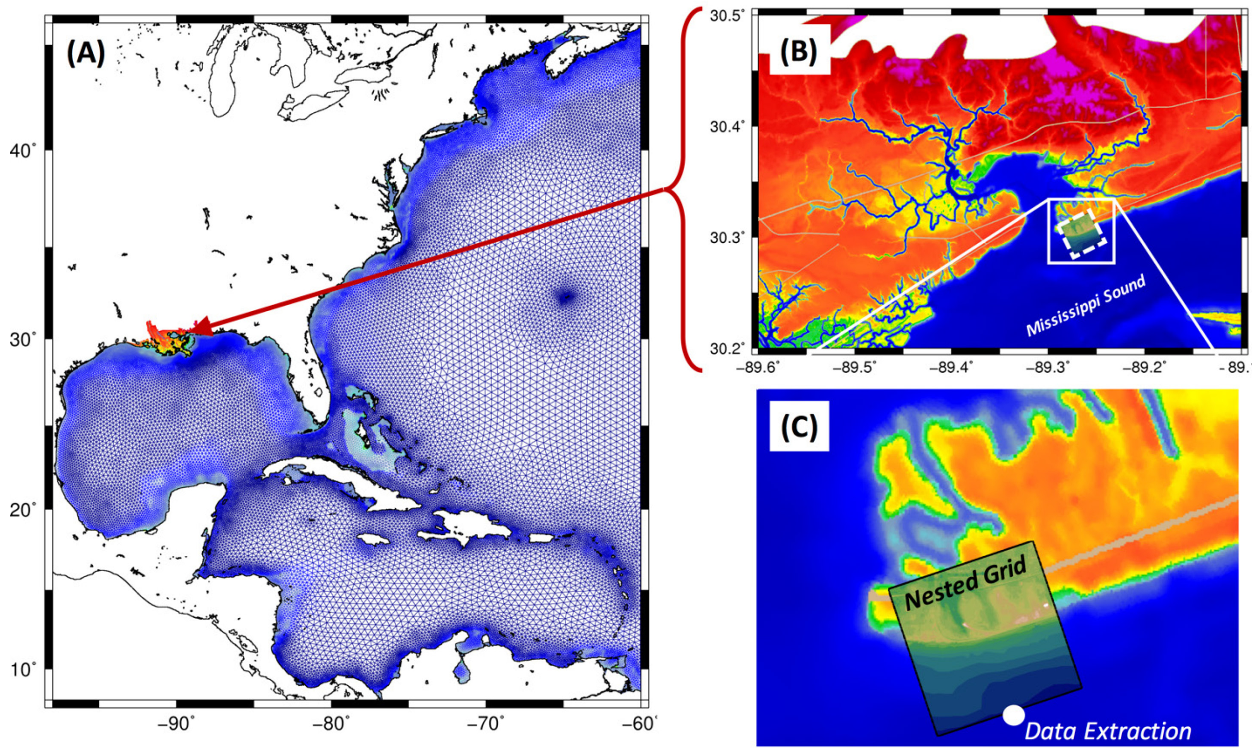


Figure 11. Example of a nested grid (and model) showing the (A) mesh extents and characteristics for the larger basin scale finite element mesh model, (B) a detailed view of a smaller region of the basin scale mesh, and (C) an image of the nested model grid overlaying the finite element mesh below.

3.2 Elevation Data

When making a *grid* or *mesh*, the elevation or vertical coordinate of each computational point must be specified. This value will either be a positive or negative number depending on whether the point is located above or below a specified *vertical datum*, respectively. A *vertical datum* is a surface, typically corresponding to an elevation of zero, to which heights are referenced to maintain consistency in their values. Examples of *vertical datum*s include the North American Vertical Datum of 1988 (NAVD88) and the *Mean Sea Level* (MSL) *tidal datum*. The NAVD88 is often referred to as a survey or map datum. Land surveyors and engineers typically use it to reference heights. In addition to other *tidal datums*, like Mean Low Water (MLW) and Mean High Water (MHW), the MSL datum is a *tidal datum* that changes over time. The MSL and other *tidal datums* are reassessed every 19 years, which is the period of time corresponding to one *tidal epoch* (18.6 years actually): the longest tidal period. The MSL and other *tidal datums* also change with *sea level rise*. Relationships between NAVD88 and *tidal datums* are often given at *tide* gages. Software packages, like NOAA's VDATUM program, are also available that perform datum conversions based on a project's geographic location. More information about the relationship between tidal and *survey datums* is provided in FHWA (2008).

Model results will be referenced to the *horizontal projection* (coordinate reference system) and *vertical datum* used to specify the three-dimensional position of each computational point. *Horizontal projections* are either flat or spherical depending on the model being used, or the size of the modeling domain. Examples of flat projections include local coordinate systems (e.g., *x-y* systems in feet or meters), state plane coordinates, and Universe Transverse Mercator (UTM) coordinates. Spherical coordinate systems use latitude and longitude referenced to some common system like the North American Datum of 1983 (NAD83) or the World Geodetic System of 1984 (WGS84). Smaller modeling domains (on the order of meters or kilometers) are best described by a flat *horizontal projection* system. Larger modeling domains (on the order of hundreds of kilometers) typically use spherical projections and geographic coordinates due to the distortion in lengths over larger distances as a result of the Earth's curvature.

Elevations in numerical models are specified relative to a *vertical datum*. Generally speaking, points on land (i.e., above zero elevation) have positive values while points in the water (i.e., below zero elevation) have negative values. While this is the traditional sign convention for elevations, it is not always the sign convention used by *hydrodynamic models*. The user must exercise caution by reading the model documentation to understand how point elevations are specified. Many models require an opposite sign convention where points below the water are specified with their depth, which is always a positive number, and points on land are given negative elevations. Regardless of the convention, whatever *vertical datum* is used to reference the ground surface elevations used in the model will be the same *vertical datum* to which all model results are referenced. For example, if the elevation data used to represent the terrain is measured relative to NAVD88, then model predictions of *water surface elevations* are also relative to NAVD88.

3.3 Boundary Conditions

Boundary conditions are a requirement of all numerical models and serve two important purposes. First, they represent an essential component for solving the *partial differential equations* that govern the problem. Such conditions are used to constrain the solution by describing how the fluid behaves when reaching an edge of the computational domain. Models use these *boundary conditions* to define the outer edge of the computational domain as well as interior features like islands, levees, culverts, weirs, roads, etc.

Boundary conditions also represent the external *forcing* applied to a model. The most common types of hydrodynamic *boundary conditions* include the specification of oscillatory (e.g., *tides*, *waves*) or non-oscillatory (e.g., river discharge) flows; water levels (e.g., *tides*, *storm surge*); *wave* conditions (e.g., time series, *energy spectrum*); and/or atmospheric *forcing* like wind and pressure. Common types and methods of model *forcing* are further described in Section 3.5.

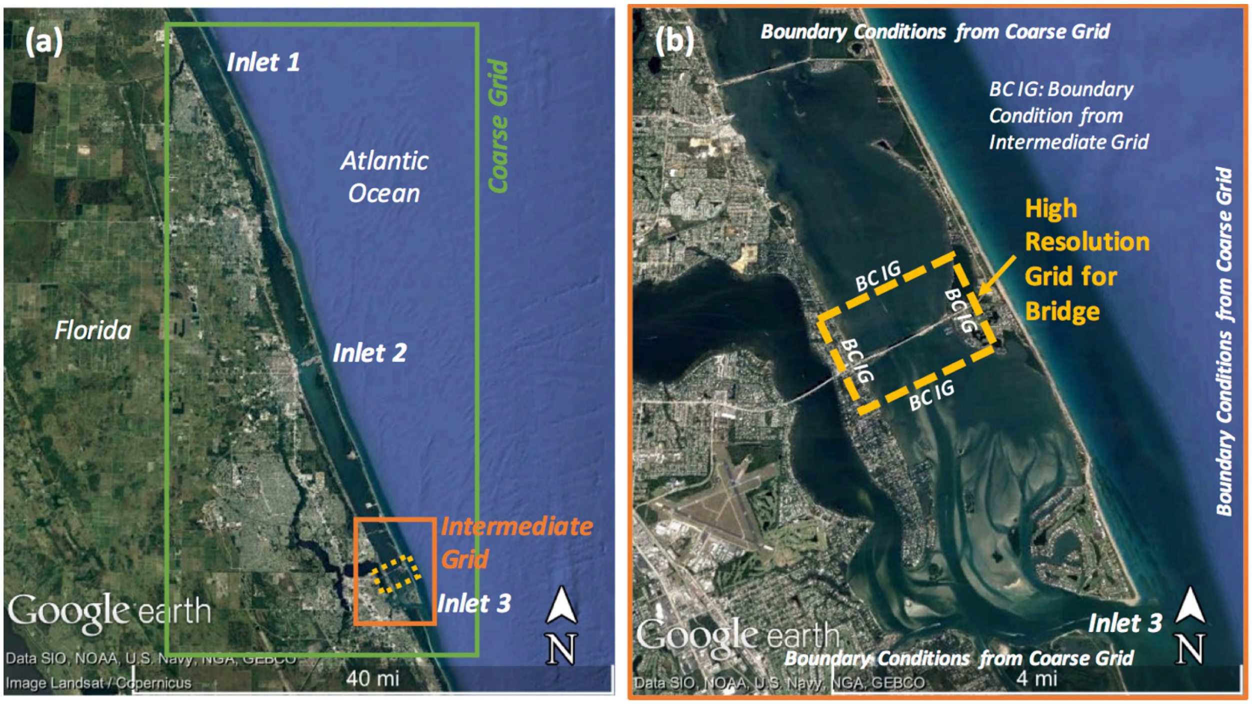
An important step in developing a numerical model is deciding how large the model domain needs to be. The size of the domain will determine how far to apply the *boundaries conditions* from the object being studied. The objective is to place the model boundaries far enough from the study area to ensure that numerical errors associated with them are reduced or practically eliminated within that study area. But how far away is far enough? The answer to that question depends on two things: (i) the event being modeled and (ii) the process being modeled.

Sometimes the event that is being simulated will somewhat dictate the extents of the model domain. Consider the simulation of a hurricane that forms in the Atlantic, travels to the Caribbean, and then enters the Gulf of Mexico. If the study area is along the Texas coast, modeling the storm when it is in the Atlantic Ocean is probably not necessary. As that storm moves closer to the study area, it will start to change the water levels and/or *wave* conditions within the Gulf of Mexico. So at the very least, the modeling domain would include the Caribbean Sea and the Gulf of Mexico. Now if the project location were in the Florida Keys instead, then modeling the Atlantic Ocean is probably extremely important. Understanding the track and characteristics of the storm event of interest is an important part of knowing how large of an area to model.

In other cases, what is being modeled will determine the size of the domain needed to accurately simulate the coastal processes of interest. For example, consider the development of a model to evaluate scour at a bridge foundation in an estuary with multiple inlets, as in Figure 12. Developing a *grid* that captures the effects of only one tidal inlet is probably inadequate. Developing a model *grid* that initially captures all the tidal inlets, but perhaps at a reduced resolution, is a better place to start. From there, subsequent models with increasing resolution can be developed and the results from one passed to the next as *boundary conditions*. In this manner, the effects of all tidal inlets on velocity and scour are evaluated at a resolution necessary to resolve the bridge foundation.

3.4 Initial Conditions

Initial conditions represent another essential component for solving *partial differential equations*. *Hydrodynamic models* may be started from rest (i.e., *waves*, velocities, water levels are all zero) or "*hot started*" from some other pre-determined condition. A *hot start* is when a model is essentially restarted using the complete results of a prior simulation. This procedure is most commonly used to restart a failed simulation or to restart a model with a new set of conditions. The latter is commonly used in modeling *storm surge* in the presence of *tides* and/or river discharge. In such cases, the approach runs the *hydrodynamic model* for a period of time (i.e., *spinup*) to allow the proper simulation of *tides* and/or river inputs within the computational domain. Once the *tides* and river discharge have been initialized, this approach stops that first simulation, and uses its results to "*hot start*" a new simulation, starting from the time when the last one left off, that now includes the hurricane wind and pressure fields.



Original Photos: © 2017 Google® (see Acknowledgements section)

Figure 12. Examples of identifying appropriate model domain sizes for simulating tidal flows in a multiple inlet system on Florida's east coast. Panel (a) shows the overall area containing three tidal inlets and the general sizes and locations of multiple grids. Panel (b) shows an enlarged image of the Intermediate Grid and how boundary conditions might be passed from one grid to the other.

Models that integrate the governing equations over time generally require some initial period of *spinup* for the purpose of model equilibration. This *spinup* time allows *forcing* that is applied along boundaries to propagate throughout the entire computational domain. The required *spinup* time is a function of what is being modeled and how large the model domain is. *Spinup* times can range from hours to weeks. Larger computational domains typically require more *spinup* time. Steady-state models, like *spectral wave propagation models*, do not require *spinup* because their equations are not solved in the time domain. The results from this period of time associated with *spinup* are discarded as they contain errors due to initial transients that develop when the model is forced from an at rest position. As an example, consider a swimming pool with still waters (no kids). When the pool opens, the first child gleefully runs and performs a "cannonball" into the pool with a resultant large *wave*. Soon the pool is full of children, each making small *waves*, but limiting the space for additional cannonballs. You would not want to use that initial cannonball *wave* as describing the *waves* produced by the larger group of children. Simply put, your *spinup* time is the time required to fill the pool with kids.

3.5 Forcing

Hydrodynamic models accept different types of *forcing* as *boundary conditions* for or on the governing equations. For general circulation (flow) models, *forcing* of the fluid body is applied either through specification of a velocity or a water level time series or by surface *forcing* in the case of winds. Such *forcing* can be oscillatory, as is the case with tidal *forcing*, or non-oscillatory as in the case of specifying discharge from a river or stream. Alternatively, a 2D flow model could be forced along a boundary by a measured or predicted *storm tide hydrograph*, which represents the distribution of water levels over time at a given location. Surface *forcing* in 2D flow models are specified based on meteorological parameters like wind speed and direction, as well as atmospheric pressure. Meteorological *forcing* results in the generation of currents and changes in the mean water level due to wind-induced *setup*, *Coriolis setup*, and *barometric* effects that either depress (high pressure) or lift (low pressure) the mean water level.

The type of *forcing* applied in *wave* models depends on the nature of the model and how it is being used. As mentioned previously, *wave* models may be *steady* or *unsteady*. Steady-state models are typically forced with a distribution of *wave* energy over different *wave* periods and directions (i.e., a *wave energy spectrum*). Offshore *wave* buoys are a source of information for *wave* energy spectra. *Unsteady wave* models are usually forced by a water velocity and water level time series, and perhaps by wind velocity as well. Furthermore, *wave* models may be used to simulate *wave propagation*, *wave generation* (by wind) or even both simultaneously. *Wave propagation* models transform some *wave* condition specified along the offshore boundary over variable bathymetry and/or currents. *Wave generation* models simulate the growth and propagation of wind *waves* due to meteorological *forcing*. It is common practice to simulate both propagation and generation, unless the study area is in an enclosed, or semi-enclosed, body of water (e.g., lake, bayou, estuary, sound) of short *fetch*, or anywhere wind-*wave generation* may be negligible.

Forcing from *wave* and circulation models may be passed back and forth as input when necessary. If the transformation of *waves* over nearshore currents is important (e.g., Columbia River Estuary), then the results of a general circulation model can be supplied to the *wave* model as additional *forcing*. Alternatively, if the effects of *waves* on mean water levels is important (i.e., *wave setup*), then the results of a *wave* model can be passed to a circulation model as additional *forcing*. This topic, model *coupling*, is described at length in Chapter 6.

3.6 Developing Design Scenarios

One of the more challenging aspects of numerical modeling is developing appropriate design scenarios. This is especially true since any single model simulation tends to be less helpful than comparing the results of a number of different model scenarios. For the purpose of engineering design, *hydrodynamic models* are best applied in a comparative, or relative, sense as opposed to a purely predictive sense. Besides the fact that error is inherent in all model scenarios, most numerical models are deterministic instead of *stochastic*. A *deterministic model* gives the same result for a specific set of parameter values. *Stochastic models* introduce and account for some degree of randomness in the simulation. One ill-formed *deterministic model* run will likely give ill-suited answers that are of little value.

The easiest way to characterize model scenarios is to assign them to one of two categories: scenario-based or probabilistic (sometimes also referred to as *risk-based*). A scenario-based simulation describes a specific event that has previously occurred or that may occur in the future. The former is termed model *hindcasting*, while the latter is known as model *forecasting*. Here, *forecasting* is described as the process of modeling an event based on a weather forecast prediction. For example, modeling the predicted track and intensity of a hurricane, or the predicted characteristics of a nor'easter. The term *forecasting* can, however, be used in a slightly different manner that lends itself to simulating some known event at a future date. An example of this type of *forecasting*—perhaps better described as projecting—is simulating a historical hurricane on a higher future sea level.

Hindcasting, or recreating, the effects of prior storms is often a useful tool in engineering design; whereas *forecasting* is not. *Hindcasting* is a very useful tool when applied correctly. An example of model *hindcasting* is using a *storm surge* and/or *wave* model to recreate the conditions from a historical storm event, like a tropical cyclone (i.e., hurricane) or extratropical cyclone (i.e., nor'easter). Alternatively, scenario-based simulations can be based upon input parameters derived from statistical analysis. Examples may include a maximum offshore *wave height*, seasonal wind speed and direction, etc. The reader is directed to Choate et al. (2012) and Webb & Marr (2016) for examples of scenario-based modeling.

Probabilistic, or *risk-based*, model simulations are developed in a way that allows the user to assign and communicate the probability of an event, or perhaps even the joint probability of two or more independent events happening together. When the probability (P) of an event or its outcome is known, *risk* (i.e., likelihood) and reliability can be quantified as a function of service life duration (N) using the equations below.

$$Risk = 1 - (1 - P)^N$$

$$Reliability = 1 - Risk = (1 - P)^N$$

There are many ways to develop and run a *risk-based* simulation, and the possibilities range from fairly simple to very complex. Some simple examples might include:

- specifying a set of *wave* conditions along an offshore model boundary for which the *return period*, or probability of occurrence, is known,
- applying a *storm surge hydrograph*, having a known *return period*, as a *boundary condition*,
- applying a discharge *boundary condition* for which the probability is known or can be determined, and/or
- specifying a *wind field* having a known probability.

Existing data sets can be used to develop the *forcing* characteristics (e.g., wind, water level, *waves*) needed in these simple examples. For example, the US Army Corps of Engineers (USACE) Coastal Hazards System[4] and Wave Information Studies[5] contain frequency-based estimates of water levels, winds, and *waves* at thousands of locations around the United States coastline. These databases have been developed using coastal modeling techniques described in this

[4] https://chs.erdc.dren.mil

[5] http://wis.usace.army.mil

manual. A model can apply other resources, such as the USGS StreamStats[6] tool, if needing to obtain discharge *boundary conditions* or determining a streamflow *return period*. Independent studies and sources of data may also prove useful for deriving the simulation *forcing* conditions, and the reader is directed to the reports of Sheppard & Miller (2003), Wang et al. (2007), and Wang (2015) for a state-specific example that shows the type of information needed to do so.

Much more complex methods are used to perform *risk-based*, or probabilistic, modeling. Without describing each one in detail, they generally seek to simulate a number of possible storm scenarios, each having its own assigned probability. The results of those independent simulations are combined using statistical analyses to describe the probability of an event, like *storm surge* or *wave height*, at a particular location. Older techniques like the Empirical Simulation Technique (Scheffner et al., 1996) have largely been replaced by more sophisticated methods, many of which are used in the development of new coastal flood hazard maps by FEMA. Along the Gulf and Atlantic coasts, coastal flood probabilities are estimated using the Joint Probability Method with Optimal Sampling, or JPM-OS for short (see for example Niedoroda et al., 2008 and Toro et al., 2010). The JPM-OS method is used in these areas because the higher *return period* (lower probability) water levels are dominated by tropical cyclones, for which many storm parameters (e.g., wind speed, pressure, forward speed, landfall angle, etc.) can be assigned individual probabilities. Other statistical methods, like extremal analysis, are used in the Great Lakes and along the Pacific Coast because their water levels are dominated by extratropical cyclones and frontal systems. The probabilities of specific storm parameters are difficult to determine in those areas, so the probability analysis is performed using measured *total water levels* instead. *Total water levels* account for all contributions to water levels along the coast including *astronomical tides*; meteorological *forcing* (i.e., winds); *waves*, *wave setup*, *wave runup*; and watershed contributions to the coast.

Monte Carlo simulation techniques are often used to represent the *stochastic* nature of natural processes. This technique is also commonly applied in a *risk-based* framework to randomly sample the probability space of a process of interest. In many cases, however, application of Monte Carlo techniques is incompatible with the amount of time required to run high resolution coastal hydrodynamic simulations. Instead, a technique like JPM-OS is used whereby a number (perhaps thousands) of low resolution simulations are performed in order to define the most probable values that may occur, and then a subset (perhaps hundreds) of those scenarios (e.g., events that describe 99.9 percent of the 100-year floodplain) are simulated with a high resolution model. Furthermore, because of the nature of tropical storms and hurricanes, their characteristics (i.e., wind speed, central pressure, forward speed, etc.) are not completely random with some having known dependencies, such as the relationship between central pressure, wind speed, and radius to maximum winds. Accordingly, Monte Carlo simulation techniques are not needed to describe something like hurricane *storm surge* probabilities. It may be useful in describing the variability in *total water levels* in the Great Lakes or along the Pacific Coast where storm characteristics, water levels, and *wave runup* exhibit more independent behavior.

[6] https://water.usgs.gov/osw/streamstats/

3.7 Selecting Design Scenarios

The prior section identified three possible strategies for developing model scenarios: *hindcast*, future projection, and *risk-based* simulations. Knowing which scenario to select, and when to use it, is often a challenge. Figure 13 provides some general guidance about when, where, and how to use each of these scenarios appropriately. Additional comments about each of these scenarios, and how they might be developed, are summarized below.

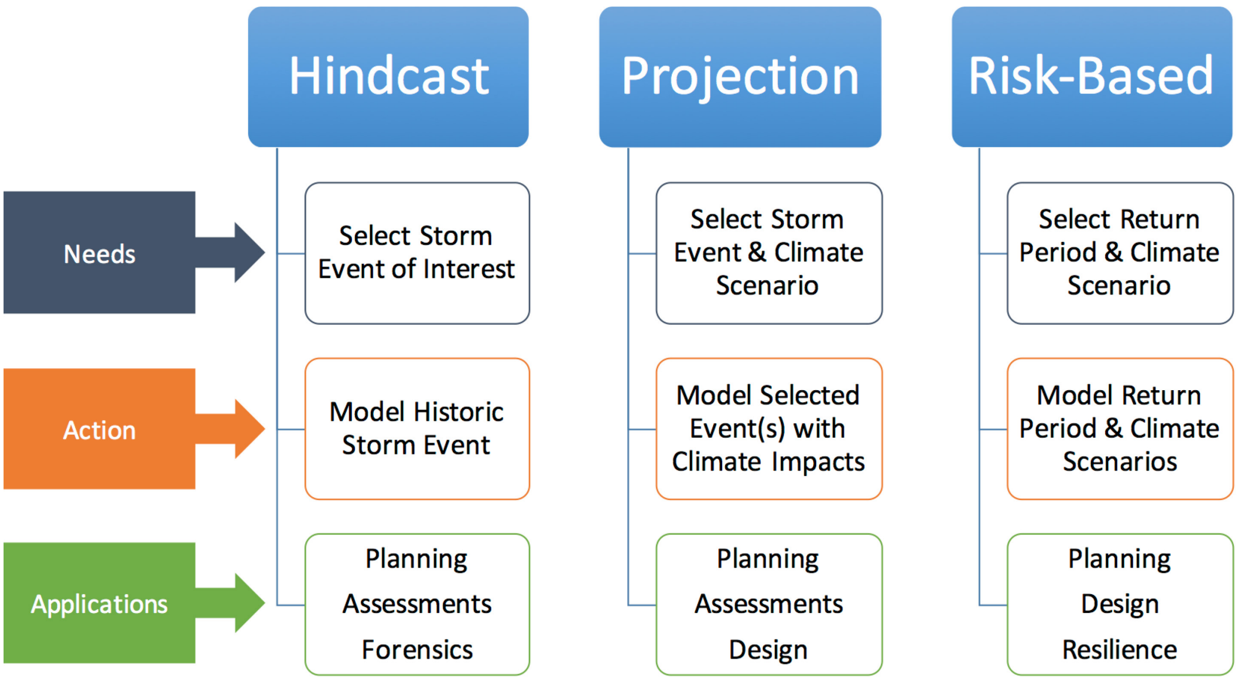


Figure 13. Needs, actions, and applications associated with model hindcasts, model projections, and risk-based simulations.

3.7.1 Hindcast Simulations

As previously described, *hindcast* simulations are those that recreate a historical storm event, or some event that occurred in the past. Examples include modeling the *storm surge* and *waves* from a historical hurricane, nor'easter, or other storm event (see Figure 14). These are events for which the *forcing* (i.e., storm characteristics) are well known and where measurements of relevant parameters, such as water levels, *wave heights*, velocity, scour, or discharge, are available.

Performing *hindcast* simulations is typically an important step in model *validation* (*validation* is covered in Chapter 5), but they can be used for other purposes (Chapters 4 and 5 cover *hindcasting* in more detail). *Hindcast* simulations can also be used for planning purposes, performing assessments and feasibility studies, and in forensic analysis. The FHWA does not recommend the use of model *hindcasting* for design purposes. Designing for a specific storm event that has already occurred ignores the probability that a similar event may or may not happen again, as well as any potential change in those hazards over time. Model *hindcasts* might best be characterized as being both low in complexity and confidence (Figure 14), where confidence relates to the project's ability to describe appropriate design conditions.

3.7.2 Future Projections

Describing the impacts that a historical storm may have under a set of alternative future climate conditions can be a worthwhile exercise. Since this type of simulation is not truly a forecast of a future storm, this manual refers to it as a future projection. This type of modeling is best described as having moderate complexity and confidence (see Figure 14). A future projection performed with a historical storm is best applied to planning and assessment studies. If the projection is performed with an event having a known *return period*, it may be appropriate for design purposes. Examples of future projections include:

- simulating a known or historical event on a higher future sea level,
- simulating a known or historical event with changes in storm intensity,
- simulating a known or historical event with modified storm tracks, and
- simulating a synthetic, or made-up, storm event using any of the modifications listed above.

For the purpose of transportation planning and assessment, the most common future projection might be simulating a known storm event on a higher future sea level, for which guidance does exist (e.g., FHWA, 2014). That storm is typically one that produced notable impacts or damage to the study area; it is a storm that locals remember and associate with damage. Demonstrating how those impacts might change under alternative *sea level rise* scenarios serves as an effective tool to communicate how hazards, and the damage they cause, might change over time in terms of magnitude or frequency. Alternatively, selecting a storm of lesser intensity can communicate another important consequence of future climate variability: a prior storm having minimal impacts may produce substantial impacts in the future due to *sea level rise* and/or storm intensification. The Gulf Coast 2 Study includes future projection modeling of major and minor historical hurricanes under future climate conditions and serves as an example of how those results are used in vulnerability assessments (Choate et al., 2012).

3.7.3 Risk-Based Simulations

Risk-based, or probabilistic, simulations are those where the *return period* of the event is known. These types of simulations are the most appropriate to use in engineering design. These simulations provide the information needed to design infrastructure to meet a stated *return period* threshold. They also provide an opportunity to describe the potential *risk* and reliability of the infrastructure relative to the *return period* scenario. These simulations are the most complex, but also provide the most confidence for design (see Figure 14). Similar to modeling future projections, *risk-based* simulations can include the effects of future climate change, such as *sea level rise*, storm intensification, or changes in topography and land use. Incorporating *sea level rise* into a *risk-based* model simulation, for example, can help inform how the vulnerability or performance of a road or bridge may change over time.

The data sources described in Section 3.6, specifically the Coastal Hazards System and Wave Information Studies, represent appropriate sources of information for developing *risk-based* simulation parameters. These data sources, collectively, provide *return period* estimates of water levels and *wave* characteristics, as well as other data like water velocities, and wind speed and direction. These are the essential data requirements that constitute the *forcing* for many coastal *hydrodynamic models*.

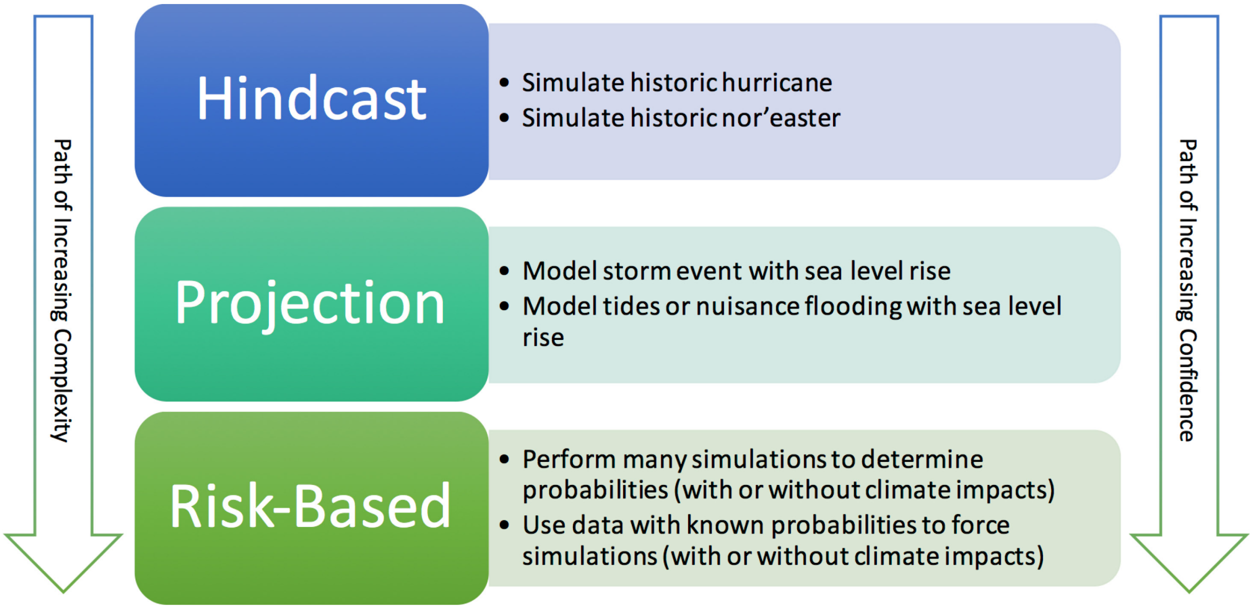


Figure 14. Descriptions of model hindcasts, projections, and risk-based simulations relative to complexity and confidence.

3.8 Sensitivity Testing

Whenever possible, it is best practice to perform some sensitivity testing of the numerical model to rule out, or at least quantify, computational bias (i.e., tendency to over or under estimate a value). Numerical solutions can be sensitive to choices in *grid*/*mesh* size and model time step, as well as other user specified constants like *friction factors* and *eddy viscosity* coefficients. A computational *grid* or *mesh* is first generated with the goal of resolving the smallest feature necessary. The remainder of the *grid* or *mesh* is then built around that constraint. The size of the smallest *grid* cell or *mesh* element, when combined with anticipated parameter values like flow velocity, then governs the model time step for explicit numerical models.

When a stable combination of *grid*/*mesh* size and time step are determined, it is helpful to explore the sensitivity of the project's model predictions to changes in one or both parameters. Running additional simulations with other reasonable values for constants and coefficients, if there are any, is also advisable. If the model consists of other "tunable" parameters, be they numerical or physical, sensitivity to changes in their values should at least be considered and addressed as part of model development.

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4 Interpreting Output

There are a number of different methods for interpreting and using model output. This chapter describes some of the most common forms of output analysis for coastal applications, identifies potential sources of error, and outlines the general process of using model output as input to another model.

4.1 Types of Analysis

Analyzing the results from a coastal *hydrodynamic model* involves some type of quantitative evaluation of the model predictions or output. Output analysis may be done for the purpose of model *calibration* (Section 5.2), model *validation* (Section 5.3), and/or scenario assessment in planning or engineering design (see Section 5.7). The type of analysis performed is a function of the model being used, how the results will inform subsequent design calculations, and the nature of any measurements to which the model results are compared.

While there are many potential ways to analyze model results, the approaches tend to fall into two basic categories: dynamic analysis and static analysis. A dynamic analysis is one where model results are evaluated as a function of time, typically at one or more specific geographic locations. A static analysis is one where some relevant parameter statistic (e.g., maximum water level, *significant wave height*) is evaluated at one or more geographic locations. Relevant examples of dynamic analysis include analyzing the behavior of water levels, currents, *wave* characteristics, or possibly *sediment transport* at a coastal bridge or roadway over the duration of the simulation (Figure 15). Figure 15 shows how modeled *storm surge* during the passage of Hurricane Ike compares with measured *tide* gage data. This figure shows that the peak surge values are in close agreement, but the tail of the surge *hydrograph* shows some discrepancies. Similar analyses of tidal or storm *hydrographs* allow the modeler or engineer to evaluate how parameter values change over time as well as relevant combinations that may lead to important design choices. This is particularly important because maximum parameter values may not occur simultaneously during a model simulation. When, or if, they do, then static analysis provides reasonable information.

Relevant examples of static analysis include evaluating maximum *storm surge* elevations (see Figure 16 and Figure 17), maximum *significant wave heights*, and maximum water velocity. Figure 16 shows how well all the modeled results agree with the measured data for peak surge and Figure 17 shows the spatial locations of the same information. Figure 17 shows the greater Galveston Bay (center) area including the Gulf of Mexico (lower right). Such analyses are helpful not only in engineering design but also in vulnerability assessments. They are also helpful in checking for persistent model bias, as described in Section 5.4.

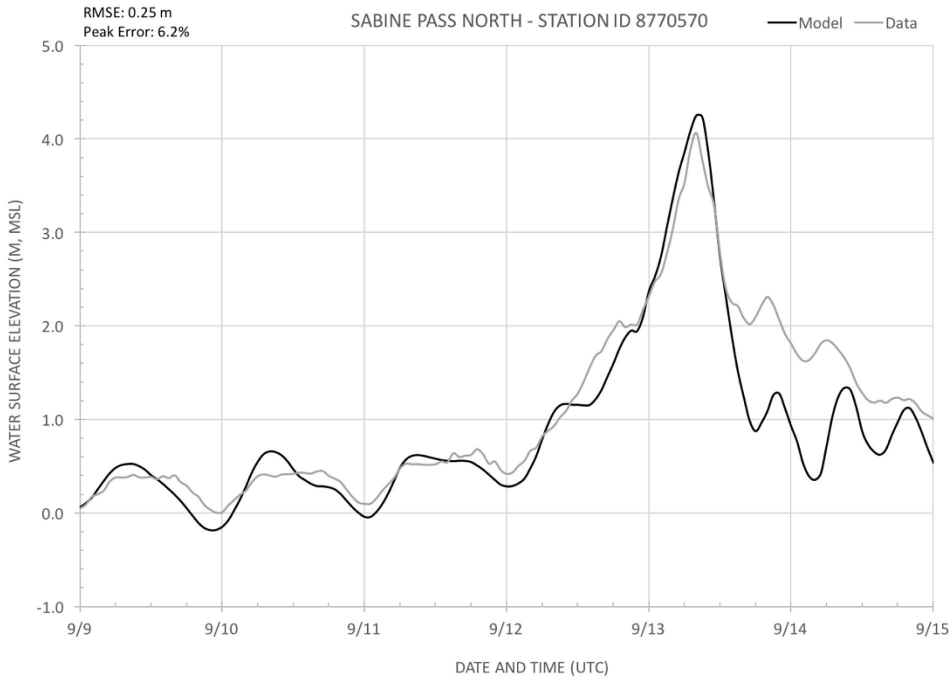

Figure 15. Example of dynamic analysis showing a comparison of modeled and measured (data) storm water levels (i.e., storm surge hydrograph).

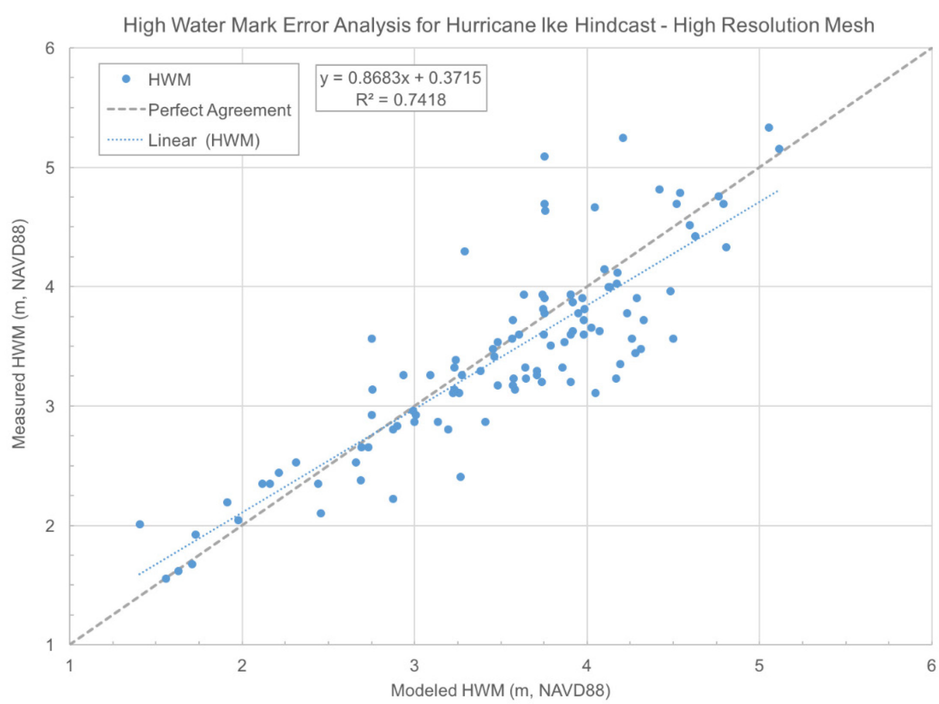

Figure 16. Example of static analysis showing a direct comparison of modeled and measured hurricane high water marks (HWMs). These same results are shown relative to their geographic location in Figure 17.

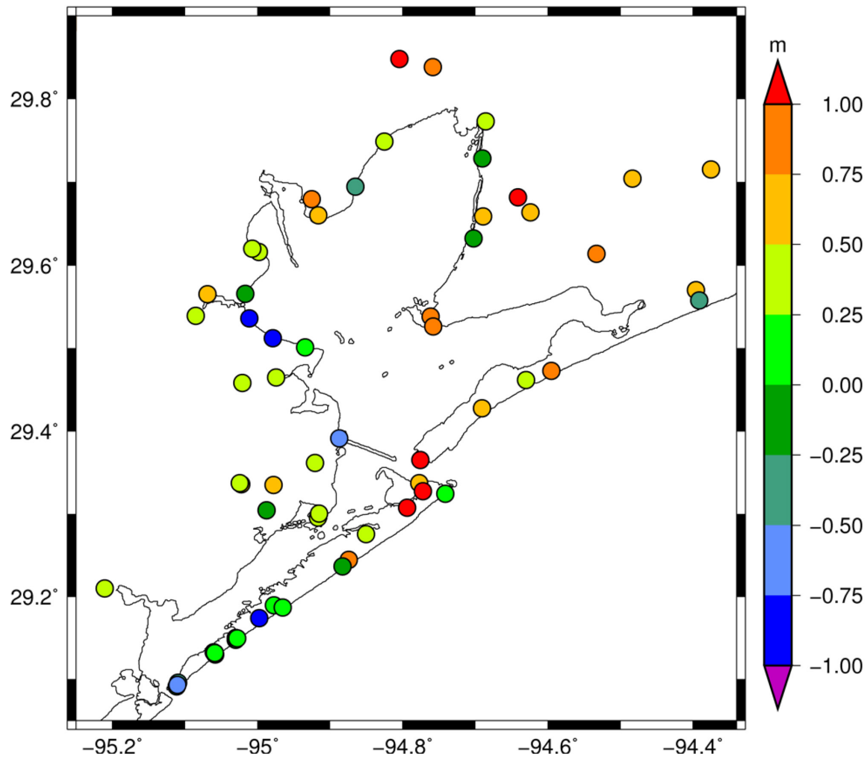

Figure 17. An alternative way of showing the results of a static analysis is to demonstrate the spatial variability of model error as in this HWM comparison.

4.2 What to Look For

It is not uncommon for a numerical model to run to completion but give unreasonable results. While Chapter 5 covers evaluating model error and *skill*, some simple qualitative assessments should be performed as part of analyzing model output. First and foremost, evaluate the model output at the project location. This can be done using the dynamic and static analysis techniques described previously in Section 4.1. Another helpful technique is to *animate* the parameter values to see how they change in both space and time. In other words, make a movie of the relevant parameter values. This is a powerful tool for qualitative analysis that is commonly overlooked.

Regardless of the type of analysis performed—dynamic, static, or animation—it is important to look for inconsistencies or anomalies in the model results. These may be introduced through numerical error, or inappropriate input or parameter specifications. Such anomalies generally present themselves as sharp discontinuities in model results, either as a function of space or time (Figure 18). Figure 18 shows anomalies in output for a *wave* model applied along the Mississippi coast. The panel on the left shows the discontinuous *wave* directions in Mississippi Sound resulting from a numerical instability in the model. The panel on the right shows the correct solution, with *waves* coming from a direction of 280 degrees. The discontinuities often appear as stair steps or saw teeth in time series output and as linear features or random noise in spatial output. When animating results, pay particular attention to how the parameter values change near boundaries, as those are locations that often introduce numerical errors into the solution. Numerical errors typically appear in the form of inconsistencies or discontinuities, many times appearing as high frequency "noise" or spurious oscillations in water level or velocity.

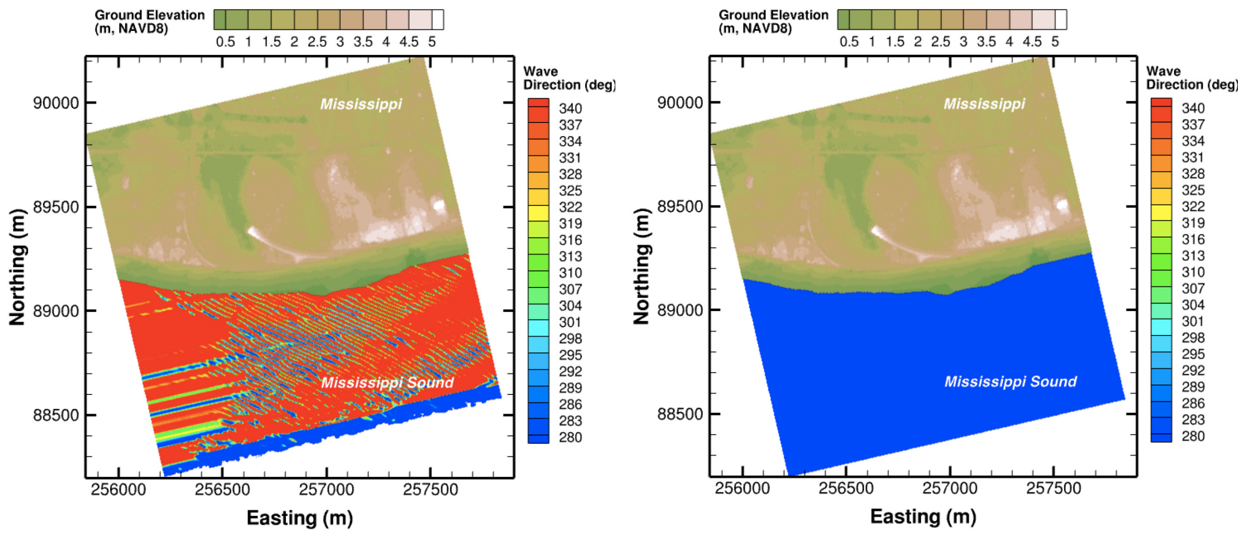

Figure 18. Example of numerical instability resulting in an incoherent solution for wave direction (left) and the correct solution (right) with waves coming from a direction of 280 degrees in Mississippi Sound as they approach the shoreline.

Some simple quantitative techniques can also be applied in the course of model output assessment. It is always good practice to perform a mass conservation check when using an *unsteady*, time-dependent numerical model. This is particularly true when flow/discharge or *sediment transport* is the focus of an analysis. Mass conservation can be evaluated by analyzing the volume of fluid, or volume of sediment, in the computational domain over the duration of the simulation. If the project's computational domain is very large, then the global conservation should be supplemented with an evaluation of local mass conservation over a smaller region that captures the project area.

Mass conservation checks can be performed as part of output analysis only if the global parameters are recorded and written to output at reasonable time intervals during the simulation. A reasonable time interval is somewhat subjective, but it should be frequent enough to capture substantial changes in a parameter value. For example, if simulating a *diurnal tide*, record the output at least once every three or four hours simply to resolve the tidal oscillation itself.

If sensitivity testing was performed as part of model development, it is important to evaluate the relative change in parameter values across the various simulations. In other words, how much does the velocity or water level change as a function of *grid* resolution or model time step? If the model predictions are insensitive to changes in model parameters, then the solutions should be free of computational bias and are said to have converged. That does not mean they are correct, but it does allow ruling out any numerical dependency of the model predictions.

4.3 Combining Modeling Outputs

Output from one *hydrodynamic model* can be used as input to, or a *boundary condition* for, another hydrodynamic or *hydraulic model*. This is not necessarily model *coupling*, which is described in Chapter 6. Instead, this is simply using output from one model to drive or constrain another in a manner where feedback between the models never occurs.

This procedure is most commonly used in cases where output from a larger, basin-scale model is used as input to a *nested grid* of the same or perhaps different numerical model (see Figure 12). This is an efficient way to accurately resolve the hydrodynamic processes at a reasonable scale within the project area. An example that is relevant to coastal transportation is extracting a time series of *storm surge* water levels and *wave* characteristics from a basin-scale model and using those data as input to a *nested*, time-dependent *wave* model. That *nested* model might resolve a bridge foundation or superstructure for evaluating scour potential or vulnerability of the bridge deck to *wave loads*.

The output from *hydrodynamic models* can also be used as *boundary conditions* for *hydraulic models* when they are applied in coastal watersheds. Streams and rivers that terminate in coastal waterbodies have dynamic *tailwater* conditions that are controlled by astronomical or *storm tides* instead of discharge and flow constrictions. As such, the output from a tidal or *storm surge* simulation, with or without the effects of *waves*, could be used to set the downstream *tailwater* elevation in *hydraulic models*. However, such an approach would only prove useful if the downstream water levels were unaffected by watershed contributions. In such cases, model *coupling* would need to simulate the dynamic feedback between the watershed contributions and the receiving coastal waterbody. Since it is unclear when or if a receiving water body is sensitive to such effects, some type of modeling must be performed to evaluate the potential impacts.

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5 Calibration and Validation

The terms *calibration* and *validation* are often confused or, unfortunately, used interchangeably. This chapter describes each of these independent processes, their differences, and how they are performed. Common methods of error analysis, the interpretation and evaluation of model errors, and some generally accepted standards for coastal model accuracy and/or allowable error are briefly discussed. Finally, some suggestions for incorporating model uncertainty into subsequent calculations are provided. Model *verification* is not described in this manual; it is related to the mathematical accuracy of the model itself. *Verification* is therefore something that is commonly performed by a model developer, not a model user.

5.1 What's the Difference?

Many people incorrectly use the terms model *validation* and model *calibration*, or assume they mean the same thing and use them interchangeably. The primary difference between the two is that a *calibration* describes the model's ability to accurately recreate one specific scenario, while *validation* reveals the model's ability to predict any other possible scenario. If the intended purpose of a *hydrodynamic model* is to recreate one specific historical event for which measured data are available, then the model can be calibrated to accurately reproduce those results. While models are often used for recreating a specific event, say for the purpose of forensic analysis, the *calibration* process alone is typically not enough to prepare a model for use in the engineering design process. The *validation* process must be carried out in order to assess potential model errors and how they may affect the engineering design. Other steps, like model sensitivity testing (see Section 3.8), are often performed in addition to the *calibration* and *validation* steps.

Here is a simple example of a potential modeling workflow, starting with *calibration* and ending with *validation*. First, a model is calibrated to some known condition, say Storm A. The *calibration* phase involves selecting or changing model parameters, or improving model input (e.g., terrain, *roughness*, etc.), until the known condition or preferred solution of Storm A is obtained. The user then validates the model using the same parameters, but under a different condition or scenario, say Storm B or Storm C. If the model produces acceptable agreement for the simulations of Storm B and Storm C, then the user has confidence that the model can simulate other events with similar success. As an intermediate step, the user may perform some type of sensitivity testing. The sensitivity testing can focus on numerical parameters or physical conditions. For example, the user may elect to simulate Storm A using lower or higher resolution, or smaller or large time steps, to evaluate the numerical sensitivity of the model (see Section 3.8). Alternatively, the user may elect to increase or decrease the model *forcing* (e.g., increase wind speeds, water levels, etc.) to ensure that the model produces reasonable changes in the expected results.

5.2 Calibrating a Model

Model *calibration* refers to the direct comparison of model results with a standard or reference in a manner that allows parameter values to be modified with the goal of improving the comparison outcomes. This process is sometimes referred to as *model estimation* due to the iterative nature of the *calibration* procedure whereby parameter values are modified and their effects on the standard comparison evaluated. A good example of model *calibration* is tuning the parameter values of a *hydrodynamic model* to obtain the best possible agreement between a model *hindcast* and observed data. In other words, forcing (or otherwise making) the model(s) to match the observations for a given event, at a given location.

5.3 Validating a Model

Model *validation* is a process to determine the accuracy of the model being used to simulate scenarios for which it was not specifically calibrated, or tuned, to match. In other words, model *validation* ensures that the model provides reasonable results for its intended use and allows the user to quantify model error. The model *validation* process will always follow model *calibration*. Furthermore, model *validation*s should never include the scenario used for model *calibration*, and model parameter values should remain fixed across all scenarios simulated in the *validation* step.

Validating a model usually involves simulating a number of relevant, historical scenarios through *hindcasting*. These scenarios are typically chosen based on relevance to the design project itself, the broader project area, or a specific design condition that is being evaluated. It is important to only select *validation* scenarios for which reasonable model inputs and historical measurements are available. Without reasonable model input (e.g., wind/pressure fields, *wave* conditions, etc.), the model scenario will be ill formed, leading to poor results. Without historical measurements (e.g., water levels, *waves*, currents), model error cannot be assessed.

5.4 Error Analysis

Error in *hydrodynamic model* simulations is determined through direct comparison between relevant model output and measured data. As previously described (see Section 4.1), these comparisons may be of time series at a discrete location, or static values at one or many geographic locations. True estimations of model error are only obtained at the locations where observations are available. Therefore, some interpolation and extrapolation of model error is needed in order to evaluate its magnitude at a project location if direct measurements are not obtained there. Figure 19 shows an example of interpolated model error. This map was generated by taking hundreds of discrete model-data error values, using both *tide* gages (as in Figure 15) and HWMs (as in Figure 17), and interpolating them in space over a defined geographic region. In this case, Figure 19 shows the potential errors from a *storm surge* model used to *hindcast* Hurricane Ike along the Texas coast.

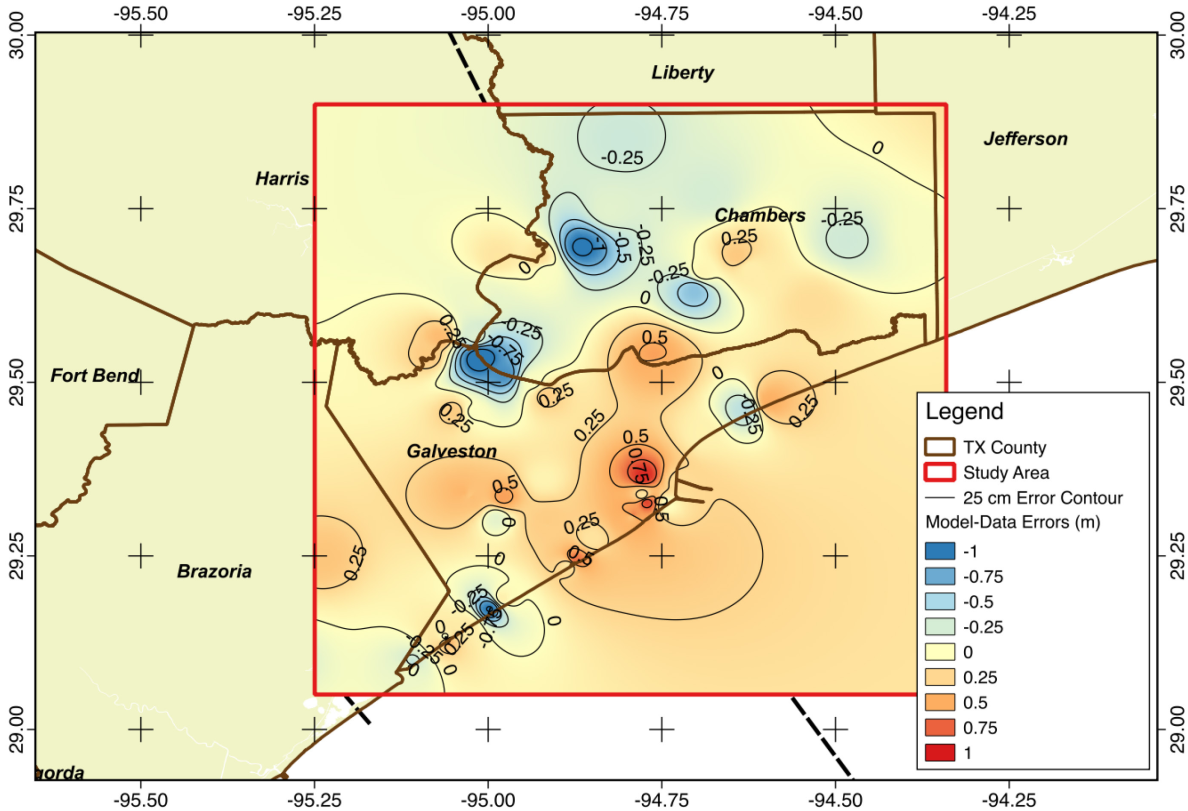

Figure 19. Example of interpolated model-data errors for simulated hurricane water levels.

For *hydrodynamic models*, the most common types of model-data comparisons are of predicted and measured water levels and/or *wave* characteristics as a function of time. Static *high water marks* (HWMs) are also used when they are surveyed after a storm event. Rarely are *hydrodynamic models* validated using measured currents as those are scarce in the coastal nearshore environment. Water level measurements are most commonly available from *tide* gages[7] along the coast operated by agencies like the National Oceanic and Atmospheric Administration (NOAA) and USACE. *Wave* measurements are usually obtained from offshore buoys or measurement platforms[8] operated by the NOAA National Data Buoy Center (NDBC), which are often very far from a project location. Static *high water mark* measurements are obtained over a much broader geographic area affected by a storm event and often represent the only sources for model-data comparison at points inland from the coast.

Regardless of the type of model-data comparison performed, a common way of quantifying model error is by assessing the average difference between predictions (model) and observations (data). This difference is also called the residual, or *residual error*. The *root mean*

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[7] http://tidesandcurrents.noaa.gov/

[8] http://www.ndbc.noaa.gov/

square error (RMSE) is often used to express model error either as a function of time or space (or both). In words, RMSE is the square root of the average of the residuals squared. Numerically, it is given by the following equation:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\hat{f}_i - f_i\right)^2}$$

where:

N is the number of values being compared (note: the number of predictions and observations must be the same),

$\hat{f}_i$ is the predicted value (model result), and

f_i is the observed value (measured data).

An RMSE value equal to zero indicates perfect agreement. Otherwise an RMSE value is always positive given the nature of the equation and that value represents the magnitude of the average error. The RMSE is described in many textbooks, including Emery & Thomson (2001).

The dimensions and units of RMSE are the same as those of the predictions and observations, making it a very helpful description of error. However, the magnitude of the error must be compared to that of the predictions and measurements in order to determine its significance. For example, consider a calculated RMSE of 1.5 feet. If the value of the observation is 15 feet then the calculated error is 10 percent of the expected value, which may or may not be significant. If on the other hand the value of the observation is 3 feet then the calculated error is 50 percent of the expected value, which is probably significant. For this reason, it is important to compare the magnitude of the RMSE to some metric of the expected values. The comparison could be to any relevant metric, such as the range of expected values, average expected value, maximum expected value, etc. Figure 15 demonstrates these concepts where the RMSE between the modeled and measured water levels is calculated (0.25 m) and compared to the peak surge elevation at that location, thereby resulting in a "peak error" value of 6.2 percent.

5.5 Model Skill

Another way to assess a model's accuracy is by evaluating its "*skill*." The *skill* of a model quantifies how well it reproduces expected values or patterns as functions of time and/or space. In other words, model *skill* assessment focuses on how well the model predictions match the observations as opposed to how much error exists between them. When used as a *forecasting* or predictive tool, a model's *skill* describes the accuracy or degree of association between the forecast, or some alternative scenario, and an established baseline condition or historical prediction.

Skill is presented in different ways depending on how the model is used and to what it is being compared. In the case of direct model-data comparison, where the results of a model simulation are directly compared to observations, a simple correlation coefficient (*R*) is described by:

$$R = \frac{\frac{1}{N}\sum_{i=1}^{N}(f_i - \bar{f})(r_i - \bar{r})}{\sigma_f \sigma_r}$$

where:

N is the number of points being compared;

f_i and $\bar{f}$ are the model result and the mean of all model results, respectively;

r_i and $\bar{r}$ are the observation and the mean of all observations, respectively; and

σ_f and σ_r are the standard deviations of the model result and observation, respectively.

When R is zero, there is no agreement, while a value of one suggests perfect agreement.

An alternative to the correlation coefficient is a *skill* score, which is often used to evaluate how well a model predicts an outcome relative to a reference condition, an expected condition, or an alternative model prediction. *Skill* scores are often used to describe the accuracy of climate models. The *skill* score is commonly presented as a number ranging from negative infinity to one. A *skill* score of one indicates perfect agreement between the model results and observations. A *skill* score of zero indicates that the model forecast is no better than the reference (observation) data. A *skill* score less than zero indicates that the model forecast is less *skillful* than the reference data or condition. The *skill* score is calculated as:

$$Skill\ Score = 1 - \frac{MSE_f}{MSE_r}$$

where:

MSE_f and MSE_r are the mean square error of the model forecast and reference condition, respectively.

The mean square error is the square of the RMSE as described by the equations below

$$MSE_f = \frac{1}{N}\sum_{i=1}^{N}\left(\hat{f}_i - f_i\right)^2$$

$$MSE_r = \frac{1}{N}\sum_{i=1}^{N}(\hat{r}_i - f_i)^2$$

where:

$\hat{r}_i$ is the reference value and all other terms are as previously described.

Model *skill* assessment is typically performed in addition to error analysis. The two metrics are often used in combination to describe the *fidelity* of a model's results as opposed to simply relying on one or the other. The reader is directed to Taylor (2001), Hess et al. (2003), Plant et al. (2004), and Emery & Thomson (2001) for more specific information about *skill* assessment in *hydrodynamic modeling*. Table 1 gives a summary of the error analysis methods described previously.

Table 1. Summary of error analysis methods, their value ranges, and typical applications.

Name	Range of Values	Meaning of Values	Typical Applications
Root Mean Square Error (RMSE)	0 to ∞	= 0: no error > 0: error proportional to value	Water Levels High Water Marks Wave Heights Velocities
Correlation Coefficient (*R*)	0 to 1	= 0: No Agreement = 1: Perfect Agreement	High Water Marks Morphology Erosion/Scour
Skill Score	-∞ to 1	< 0: model results less skillful than reference condition = 0: model results no better than reference condition = 1: model results match observations	Morphology Erosion/Scour

5.6 Standards for Error and Skill

Determining an acceptable level of model error can be a subjective endeavor, and few standards are provided in the published literature. That is likely because acceptable accuracy varies from one application to the next. If model results are being used for the purpose of engineering planning, a high level of accuracy may not be necessary, particularly if a number of simulation results are being compared. If model results are instead being used in the context of engineering design, and the *risk* to human life is a consequence of failure, then a high level of accuracy is needed. For the design engineer, knowledge of the uncertainty inherent in engineering calculations is important as discussed in Section 5.7.

There are no codified standards for coastal *hydrodynamic model* accuracy or *skill* in general. Instead, written guidance tends to focus on assessing the level of (statistical) significance of model results and the importance of identifying any forms of persistent bias between model results and observations. Written standards for specific applications may be found in Hess et al. (2003) and FEMA (2007). In the latter, the use of 2D *hydrodynamic models* is described for the purpose of developing flood *risk* maps, and one objective standard is given: for the purpose of tidal *verification*, the variation in both tidal amplitude and phase should be achieved to within 10 percent or better throughout the model domain. While not written in any official report or manual, HWM model-data residuals should be 1 foot or less for a majority of the points evaluated in the context of modeling for flood map development. This is a benchmark that is commonly evaluated as part of the flood map technical review process.

5.7 Addressing Model Uncertainty in Design

As previously stated, all models possess inaccuracies that must be quantified and assessed. The need to minimize model error and eliminate persistent bias is imperative. The consideration of model error should not stop at the model *validation* phase. Instead, the user applying model results for the purpose of engineering design should consider, at least subjectively, how model uncertainty may affect the design calculations and ultimately the *risk* of failure. This is particularly true when *hydrodynamic models* are used to estimate forces on structures, foundation scour, and/or the potential for roadway *overtopping* and embankment erosion.

Consider a simple example where *storm surge* and *wave* models are used to determine the low chord elevation of a coastal bridge such that it avoids all *wave loads* during the 1 percent annual chance storm event (i.e., 100-year *return period* storm event). At the proposed bridge location, the model provides an estimated *storm surge* elevation of +11 feet above NAVD88, and the *wave* model predicts a maximum *wave height* of 8 feet. Assuming in this example that the model *validation* returned an error of ±5 percent for the *storm surge* model and ±10 percent for the *wave* model, the predicted values for *storm surge* and maximum *wave height* could potentially fall within the ranges of +10.45 feet to +11.55 feet NAVD88 and 7.2 feet to 8.8 feet, respectively.

So while the model suggests a low chord elevation above +17 feet NAVD88 (+11 feet + 0.75*(8 feet) = +17 feet), model uncertainty could lead to a range of +15.85 feet NAVD88 to +18.15 feet NAVD88.

Addressing model uncertainty in design is particularly important when the subsequent engineering design equations include *non-linear* sensitivities to the relevant variables. This is because the subsequent design equations can lead to considerable growth in uncertainty. For example, hydrodynamic forces and *wave* forces are proportional to the square of fluid velocity and *wave height*, respectively. If the uncertainty of the model results is high, then the subsequent squaring of the parameter value leads to a wider range of potential answers during the design phase.

As with evaluating model error or *skill*, there are no published standards or procedures for addressing model uncertainty in coastal engineering design. HEC-17 describes some guidance for dealing with model uncertainty (FHWA, 2016), albeit for highways in the riverine environment. However, a competent engineer who has experience using the output from numerical models in the process of design will apply engineering judgment to address the potential for model error to affect their design calculations and recommendations. But this is only possible when the modeler has effectively communicated the results of the model *validation* or *verification* to the design engineer. As such, well documented model *validation* is key to allowing such judgment to be made during subsequent project tasks.

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6 Model Coupling

While some *hydrodynamic models* are capable of simulating many physical parameters, separate models are commonly combined, or *coupled*, to simulate the interactions between different physical processes. This chapter briefly introduces the reader to the process of model *coupling*: when it should be done, and how it can be done. This chapter also provides some examples of commonly-used *coupled* models.

6.1 What is Model Coupling?

Model *coupling* is the process of combining two or more models, numerically, in order to simulate the interactions of one model on another, or of all models on each other. The goal of model *coupling* is to account for the potential physical interactions between relevant hydrodynamic processes/phenomena when they are of importance. Model *coupling* can be as simple as using the output from one model as input to another, or as complex as dynamically combining the results from two or more models at every time step.

A few key phrases are important to understanding model *coupling*: one-way *coupling*, two-way *coupling*, and dynamic *coupling*. One-way *coupling* is the simpler example of using the output from one model as input to another. Obviously, in the case of one-way *coupling* only one process is affecting the other, and the two models or processes do not interact (i.e., there is no feedback). The terms two-way *coupling* and dynamic *coupling* are effectively the same, but practice uses dynamic *coupling* more often as it does not imply that the *coupling* is limited to only two-way interaction (i.e., two models). The term “in-line steering” is also used, but it is a simulation procedure term and describes a process by which numerical models can communicate with one another as their solutions progress in time. It will not be described further in this document, but examples of one-way, two-way, and dynamic *coupling* are provided in Section 6.4.

6.2 When to Couple Models

Hydrodynamic models do not necessarily need to be *coupled* in every application. While *coupling* models will improve the prediction accuracy, it may not be needed in some cases. Models should be *coupled* if and when the user expects the interactions between different physical processes to be significant, particularly with respect to how the model results will be used for engineering design.

An illustrative example of the importance of model *coupling* is when a coastal bridge deck is exposed to *wave* action during coastal storms and *extreme events*. The dynamic *coupling* of *storm surge* and *wave* models is becoming more common, and it has direct implications for transportation design in the coastal environment. The dynamic interactions between storm water levels and *waves* can lift *wave* crests to higher elevations, thereby making bridge decks more vulnerable to damaging *wave* uplift loads. The defining characteristic that makes the dynamic *coupling* valuable in these cases is the ability to account for *wave setup* effects that raise the mean water level over time. However, in smaller water bodies that do not support substantial *wave* action during storm events (i.e., those with limited *fetches*), the *wave setup* effect may be minimal, and the dynamic *coupling* perhaps not be as important.

6.3 How to Couple Models

Hydrodynamic models can be *coupled* in two general ways. First, they can be *coupled* by using the output from one as an initial or *boundary condition* for another. Alternatively, they can be *coupled* by accounting for the physical interactions as additional terms in the conservation equations—typically in the momentum equations.

When using initial or *boundary conditions* for *coupling*, the output from one model is used to constrain or drive the other model simulation. The subsequent modeling results may or may not be exchanged with the initial model for further *coupling*. The *boundary condition* specified here may be a water level or *wave* time-series or static value, or the *initial condition* may be the spatially variable water levels or velocities from a circulation model.

If the physical interactions are modeled through terms in the momentum equation, then there is an inherent assumption that the dependence between the processes is known and can be accurately described within the conservation equation. A relevant example includes using the output from a *wave* model, specifically the *wave radiation stresses*, as an additional source term in the momentum equations of a circulation model.

6.4 Examples of Model Coupling

Examples of *coupling* models to improve model results are plentiful. This section provides some relevant examples to assist the reader in developing an understanding of the differences between one-way and dynamic *coupling*.

A simple example of one-way *coupling* is using the output from a *storm surge* model, specifically the increased water or inundation depths, as input to a *wave transformation* model. In this way, the *wave* model predicts *wave* growth, propagation, and transformation on higher water levels associated with the storm event. Since the behavior of *waves* is highly dependent on water depths, accounting for the elevated water level due to *storm surge* is important. Likewise, *wave transformations* in the nearshore region can lead to changes in the mean water level as well as mean currents and circulation. In one-way *coupling*, these effects are not simulated as the *wave* model results are never “passed back” to the *storm surge* model.

Two-way *coupling*, or dynamic *coupling*, is needed to simulate the dynamic feedback that exists between physically-dependent processes. In a similar example, water levels and currents from a *storm surge* model are passed to a *wave* model, whose subsequent results are then passed back to the *storm surge* model. The dynamic *coupling* process, therefore, implies that the models are being simulated over time and are not applied in a static or steady-state manner.

However, many *wave* models are stationary while *storm surge* models are time-dependent. In such cases, stationary *wave* models are executed at some time interval that is equal to or larger than the time step of the time-dependent model. Since *wave fields* generally change more slowly, they are typically run at much longer intervals than the hydrodynamic time step of the *storm surge* model. For example, a *storm surge* model may have a time step of 1 second, while the stationary *wave* model is run every 1800 seconds (30 minutes). Some sensitivity testing is required to determine appropriate *coupling* intervals for specific applications and needs.

Some newer models include *sediment transport* and morphology models in the dynamic *coupling* process (e.g., XBeach). This allows a user to simulate the dynamic feedback between water levels, currents, *waves*, and *sediment transport* on the bed elevation or morphology. These types of models are used to predict large-scale and small-scale bathymetric changes over a wide range of time scales, with some models capable of simulating decades to centuries worth of accretion and deposition. However, the uncertainties in the basic governing equations of *sediment transport* are much greater than those in the hydrodynamics. Thus, the uncertainties inherent in any *sediment transport* and morphology model dwarf those of any *hydrodynamic model*.

Model *coupling*, particularly dynamic *coupling*, is not limited to hydrodynamics. The interactions between hydrodynamic, ecological, biological, and geochemical processes could effectively be simulated if needed. Some modeling packages allow the user to simulate these types of diverse interactions (e.g., Delft3D).

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7 Levels of Analysis

This chapter describes how *hydrodynamic modeling* can be incorporated into vulnerability assessments. The discussion seeks to clarify when and why a user of HEC-25 Volume 2 might elect to perform a Level 1, Level 2, or Level 3 vulnerability analysis and how to integrate *hydrodynamic modeling* into those assessments.

Hydrodynamic modeling is an important component of engineering planning and design for transportation infrastructure in the coastal environment. This is particularly true when *hydrodynamic models* are used to simulate the outcomes of various design options whose results are directly compared to one another. Relative comparisons of model results highlight one of the most powerful uses of modern *hydrodynamic models* today. Such comparisons minimize the effect that uncertainty, either in the model itself or the simulation inputs, has on the final results.

Within the context of planning specifically, modeling is a critical component of performing vulnerability analyses to examine the sensitivity of a transportation asset to *sea level rise* and *extreme events*. Given that many of the levels of vulnerability analysis outlined in HEC-25 Volume 2 (FHWA, 2014) are scenario-based, the use of some type of coastal model is justified. However, applying sophisticated *hydrodynamic models* may not be necessary in every approach for every analysis.

Knowing when, where, and how to appropriately select and apply a coastal model are proficiencies that only come from experience and sound judgment. Those proficiencies typically reside with the modeler or coastal engineering consultant, but justifying the need for modeling typically resides with the client or funding agency. The cost and effort associated with modeling are sometimes clearly justifiable. For example, consider the design of a new coastal bridge or roadway exposed to *extreme events* either now or sometime in the near future. Such a project may cost tens or hundreds of millions of dollars (or more), making the cost of modeling likely less than 1 percent of the overall project budget. In some cases, much less than 1 percent of the budget.

On the other hand, there are probably many more examples of smaller coastal bridge or road analyses or projects where the need for, or justifiability of, coastal modeling are unclear. The remainder of this chapter aims to outline a decision-making process whereby an engineer, modeler, or planner can select an appropriate vulnerability analysis approach, and identify an appropriate modeling tool, or tools, to perform it. Figure 20 provides a brief graphical overview.

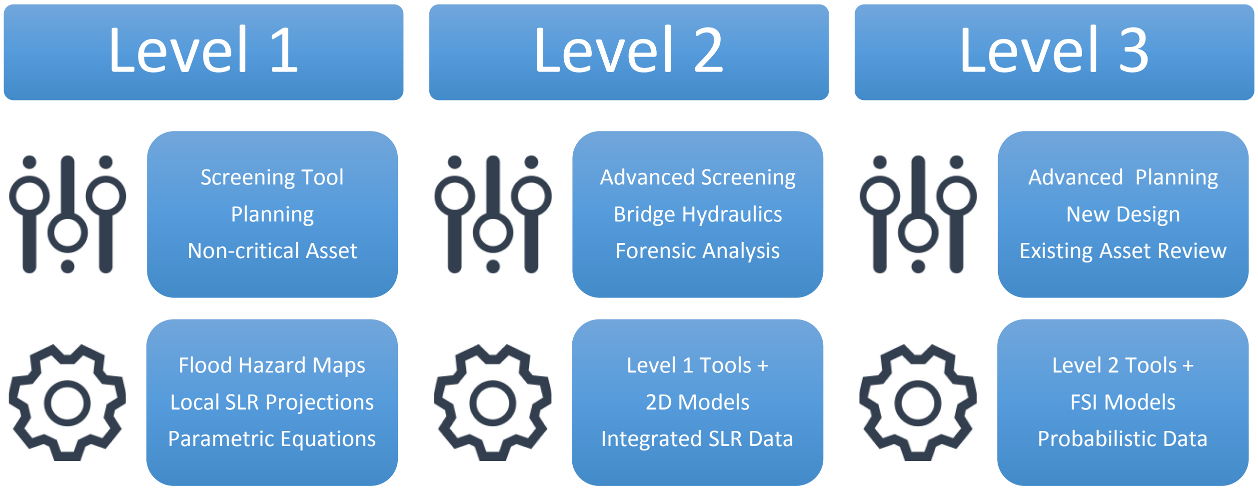

Figure 20. Summary of vulnerability analysis scenarios and tools.

7.1 Using a Level 1 Approach

The Level 1 vulnerability analysis is the lowest and simplest level of analysis described in HEC-25 Volume 2. A coastal engineer may not be required at this level of analysis. The intent of the Level 1 analysis is to provide a simple entry point for evaluating the vulnerability of coastal transportation infrastructure to *extreme events*, including *sea level rise*. Given the simplicity of this approach and the reliance on existing sources of data, this approach is best suited as an initial screening tool, for the purpose of planning and outreach, or perhaps for the review of a non-critical asset.

The use of numerical models is not expressly required in a Level 1 vulnerability analysis (but they certainly can be used). Instead, the Level 1 approach relies on the use of existing sources of data that describe probable flood elevations (e.g., flood hazard maps, *tsunami* inundation maps, etc.), and local projections of relative *sea level rise* to evaluate sensitivity of the asset over time. Simple *parametric equations* that describe water velocity and *wave* characteristics as functions of depth are suggested in this approach as alternatives to *hydrodynamic modeling*. Few simple models of erosion and deposition exist, so some 1D modeling of profile change or dune erosion could be used to enhance this level of analysis. When numerical models are used in a Level 1 analysis, performing storm *hindcasts* or potentially using a *hydraulic model* with hydrodynamic inputs may be appropriate strategies.

7.2 Using a Level 2 Approach

A Level 2 vulnerability analysis is more sophisticated than the Level 1 approach. It requires some form of coastal *hydrodynamic modeling*, or analysis of existing modeling results, specific to your asset and assessment scenarios. A coastal engineer should be consulted in this type of analysis. Given the additional complexity of this approach, the cost of implementation is likely higher but the confidence in the results is similarly higher (i.e., less uncertainty). The Level 2 assessment can therefore be used:

- as an advanced screening tool,
- for the purpose of performing bridge hydraulics studies,
- for determining the dominance of riverine or coastal hydraulics at a bridge,
- for the design of a small bridge or roadway, and
- as a forensic analysis tool.

That the Level 2 approach is scenario-based (i.e., *hindcasting* a specific storm event under current or future sea levels) perhaps lends itself better as a planning or forensic tool than it does a pure design tool.

The appropriate tools to use in a Level 2 assessment are primarily 2D circulation (i.e., *tides*, water levels, *storm surge*), *wave*, and *sediment transport* models, in addition to the tools outlined for a Level 1 approach. Some limited use of 1D *cross-shore* profile change or dune erosion modeling may also be appropriate given the circumstances. In a Level 2 approach, the effects of relative *sea level rise* are integrated into the *hydrodynamic modeling* to account for the potential *non-linear* effects of higher future water levels on flood elevations, *waves*, and morphology.

In cases where it is unclear whether bridge or road hydraulics are dominated by coastal surge and *waves* or riverine floods, the use of both *hydraulic* and *hydrodynamic models* may be warranted. How the models are *coupled*, or if they are *coupled* at all, is less important here than selecting appropriate models to simulate the different events. An appropriate 1D or 2D *hydraulic model* should be used to simulate the riverine flood condition. An appropriate 2D *hydrodynamic model(s)* should be used to simulate the coastal flood condition. While it is less likely for the design riverine and coastal floods to happen concurrently, the effects could be simulated in one or the other model if desired (see Section 2.8). For example, the design coastal flood elevation could be used as a *tailwater* condition for the riverine model, and the design discharge event could be used as a *boundary condition* for the coastal *hydrodynamic model*. Whether such scenarios are relevant or not would have to be determined through a joint probability analysis. The flooding that occurred in Houston as a result of Hurricane Harvey (2017) is a good example of compounding flood hazards where a persistently high *tailwater* along the coast exacerbated inland flooding.

7.3 Using a Level 3 Approach

The Level 3 vulnerability assessment is the most complex of the three approaches. This type of analysis should be performed by a coastal engineer. It requires original *hydrodynamic modeling* of coastal processes with assigned probabilities. Assuming all probabilities can be assigned and determined, the Level 3 approach provides the only means of communicating vulnerability in a *risk-based* framework. Because of its complexity, the Level 3 approach is better suited to advanced planning for major transportation projects, the design of new coastal bridges or roads, or potentially the analysis of existing assets that serve critical transportation functions (i.e., evacuation routes, major commerce networks, lack of redundancy, etc.).

The most appropriate tools for completing a Level 3 vulnerability assessment are the same as those listed for the Level 2 approach, with perhaps the addition of more complex 3D *fluid-structure interaction* modeling. While it requires the same types of modeling as outlined in the Level 2 approach, the level of effort required to define the simulation conditions and analyze the results can be considerable in the Level 3 approach. Developing a simulation matrix that robustly samples the probability space of potential *tides* and storm conditions is a significant task, but in some cases that work has already been completed. In such cases, the use of existing probabilistic data may be substituted for new modeling. Relevant examples of existing probabilistic data include the USACE Coastal Hazards System database, the USACE Wave Information Studies, FEMA flood insurance studies, and state-specific guidance as previously referenced. In such cases, significant savings may be realized as the effort associated with developing the probabilistic information is substantially reduced or eliminated.

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