D.2.4 Water Levels

This subsection provides guidance for the determination of water levels, including tide and wind setup. New guidance on special considerations in sheltered waters is provided. This subsection also includes guidance on 1-percent stillwater levels (SWELs), combined effects of surge and riverine runoff, and consideration of nonstationary processes.

D.2.4.1 Overview and Definitions

The two fundamental components of the BFE are *water levels*, discussed in this subsection, and waves, discussed in a subsequent subsection. The stillwater level (SWL), also known as the stillwater elevation (SWEL), is the base elevation upon which the waves ride. It consists of several parts including mean sea level (MSL), the astronomic tide that fluctuates around MSL, and storm surge. All storm wave contributions are excluded; static and dynamic wave setup (Subsection D.2.6) is included in the *mean water level* (MWL), which is somewhat higher than the SWEL (which does not include wave setup).

The Mapping Partner performing the flood analysis shall adopt previously documented SWEL analyses (by others) or determine the SWELs in a rational, defensible manner, and shall not include contributions from wave action either as a result of the assumptions of the predictive model or of the data used to calibrate the model. Only the 1-percent-annual-chance SWEL is currently required for determination of coastal BFEs, although 10-, 2-, and 0.2-percent-annual-chance elevations are tabulated in the FIS report, and the 0.2-percent-annual-chance floodplain boundary is mapped on the FIRM as the limit of the shaded X Zone.

SWELs may be defined by statistical analysis of available tide gage records or by calculation using a storm surge computer model. A minimum of 30 years of recorded tide data is needed if the SWEL is to be based on tide gage records alone. Measured tide levels are preferred over models, provided they have an adequate period of continuous record and can accurately represent the geographic area of the study. FEMA previously prescribed the use of its hurricane storm-surge model (FEMA, August 1988) and a northeaster model that simulates the wind and pressure fields of an extratropical storm (Stone & Webster Engineering Corporation, 1978). The FEMA storm-surge model as well as other FEMA-accepted hydrodynamic models that meet the NFIP regulatory requirements can be used for storm surge studies, including the Advanced Circulation Model (ADCIRC) and the DHI MIKE-21 model. For the northeast Atlantic coasts from Long Island Sound to the Maine border with Canada, FEMA Regional offices have adopted the USACE New England District tide profile analysis of the 1-percent-annual-chance elevations (based on long-term tide gage data throughout the region), which has superseded use of the Stone & Webster northeaster model.

The Mapping Partner shall use these or other approved computer models for complex shorelines where gage records are limited, nonexistent, non-representative, or which otherwise indicate appreciable variations in flood elevations from point to point within a community. FEMA also

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has specified procedures required for intermediate reviews and documentation of coastal flood studies using a storm-surge model, as discussed separately in section D.2.9.

The following subsections discuss each of the stillwater components in turn, including an outline of methods to determine water-level statistics. Also included is a discussion of nonstationarity in the processes that control relative water levels.

D.2.4.2 Astronomic Tide

The astronomic tide is the regular rise and fall of the ocean surface in response to the gravitational influence of the moon, the sun, and the Earth. Because the astronomic processes are entirely regular, the tides, too, behave in an entirely regular, though complex, manner. A useful overview of tidal physics is presented in a small booklet published by the National Ocean Service (NOS), *Our Restless Tides*, now out of print, but available in electronic form from the NOAA website (<http://tidesandcurrents.noaa.gov/pub.html>) where many other documents of related interest can be found.

D.2.4.2.1 Tides and Tidal Datums

The tides along the Atlantic are semidaily or semidiurnal, meaning that there are two highs and two lows each day, while in the Gulf of Mexico the tides are mix of diurnal, meaning that there is only one high and low each day, and semidiurnal. The average of all the highs is denoted as mean high water, MHW, while the average of all the lows is mean low water (MLW). Averages are taken over the entire tidal datum *epoch*, which is a particular 19-year period explicitly specified for the definition of the datums; a full astronomic tidal cycle covers a period of 18.6 years. The average of all hourly tides over the epoch is the MSL.

The daily highs are generally unequal, as are the lows, and are identified as Higher High, Lower High, and so forth. At a given coastal location, each of these has a mean value identified as mean higher high water (MHHW), mean lower high water (MLHW), mean higher low water (MHLW), and mean lower low water (MLLW). In addition to these, one speaks of the mean tide level, MTL, which is the average of MHW and MLW, and which is also called the half-tide level.

These several levels are important because they constitute the datums to which tide data have traditionally been referred. Local charts and recorded tide gage data are generally referenced to local MLLW or MLW. This introduces some ambiguity because MLLW and MLW vary from place to place and from epoch to epoch. For use in FEMA Flood Map Projects, then, these tidal datums are insufficient in themselves, and must be related to a standard vertical datum such as the North American Vertical Datum of 1988 (NAVD88) or the National Geodetic Vertical Datum of 1929 (NGVD29); it is not always straightforward to make this connection. However, NOAA maintains tidal benchmarks for many stations that are now tied to a standard vertical datum. Benchmark sheets for active and historic stations are available at the NOAA Website, <http://tidesandcurrents.noaa.gov/station_retrieve.shtml>. The following example is extracted directly from the Galveston, Texas benchmark sheet for Galveston Pleasure Pier:

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Tidal datums at GALVESTON PLEASURE PIER, GULF OF MEXICO based on:

LENGTH OF SERIES: 5 Years
TIME PERIOD: January 1997 - December 2001
TIDAL EPOCH: 1983-2001
CONTROL TIDE STATION:

Elevations of tidal datums referred to Mean Lower Low Water (MLLW), in METERS:

HIGHEST OBSERVED WATER LEVEL (09/11/1961)	= 2.805
MEAN HIGHER HIGH WATER (MHHW)	= 0.622
MEAN HIGH WATER (MHW)	= 0.563
MEAN TIDE LEVEL (MTL)	= 0.341
MEAN SEA LEVEL (MSL)	= 0.338
NORTH AMERICAN VERTICAL DATUM-1988 (NAVD)	= 0.186
MEAN LOW WATER (MLW)	= 0.119
MEAN LOWER LOW WATER (MLLW)	= 0.000
LOWEST OBSERVED WATER LEVEL (02/12/1985)	= -1.487

National Geodetic Vertical Datum (NGVD 29)

Bench Mark Elevation Information In METERS above:

Stamping or Designation	MLLW	MHW
NO 43 1957	7.539	6.976
WALL 1933 ELEV 15.279 FT	4.536	3.973
E 168 1936 ELEV 15.502 FT	4.586	4.023
WALL NO 1 1942	4.508	3.945
NO 44 1957	4.565	4.002
NO 10 1973	4.555	3.992
NO 45 1975	4.573	4.010
NO 46 1975	4.560	3.997
NO 47 1975	4.525	3.962
S 449 5	4.574	4.011

In this example, NAVD88 is shown to be at 0.186 meters above MLLW for the specified 1983-2001 epoch, fixing the tidal datums. Not all NOAA benchmark sheets include NAVD88 (or NGVD29) as this example does, but most include surveyor's benchmark information as shown above, through which the tidal datums can usually be tied to a standard vertical datum as needed in FEMA Flood Map Projects; these benchmark sheets include full descriptions of the benchmarks and exact locations. If other tide gages without surveyed bench marks are used as part of the FIS, these need to be surveyed and tied into other established bench marks to determine the NGVD29 or NAVD88 elevation reference levels.

D.2.4.2.2 Tide Observations

The tide is recorded at a large number of gages maintained by NOAA, with records dating back over 100 years in many cases. Much of this data is available at NOAA's website for the National Water Level Observation Network, <http://tidesandcurrents.noaa.gov/nwlon.html>, as either six-minute or hourly time series over the particular site's entire period of record. Additional data may be available from other sources.

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The tide observations include the total water level at the gage, suitably filtered to suppress high frequency wave components, leaving the long period components associated not only with astronomic tide, but also with sea-level variations caused by atmospheric pressure fluctuations, wind setup (storm surge), riverine rainfall runoff into a relatively confined region, low frequency tsunami elevation, and wave setup to the degree that it occurs at the gage site. In general, little wave setup is reflected in tide gage data because gages are often located in protected areas not subject to much setup, or in open areas outside the surf zone, and so seaward of the largest setup values (see subsection D.2.5.1 for discussion of the physics of wave setup).

The fact that the tide gage record includes all of these non-astronomic low frequency components makes it possible to extract stillwater statistics from gage data, subject to the setup limitation noted. A general method to do this is discussed below.

D.2.4.2.3 Tide Predictions

The Mapping Partner should obtain NOAA's tide prediction computer program, NTP4, or an equivalent, and generate tide predictions as needed. The advantages include not only convenience, but more importantly, the ability to use other constituent values than those currently adopted. This is important because the local tide depends not only on the astronomic forcing, but also on the response of the local basins. The response can, and does, change with time owing to deposition and dredging, construction of coastal structures such as breakwaters, changes in inlet geometry, and so forth. Consequently, the astronomic tide observed at a fixed location may not be stationary, but may have changed over the period of record. NOAA can provide prior estimates of the tidal constituents for a site, and these should be used with the NOAA computer program to produce more realistic estimates of historical tides than would be achieved using the current data for a prior period. In order to verify tide prediction validity, a set of observed tide data for a period without any significant influence from local or regional weather conditions (periods of prolonged droughts are preferred) is required. Once determined, the data can be used to compare measured/observed tide levels to the predicted tidal fluctuations. Any differences in predicted versus observed can then be accounted for in model adjustments if necessary.

NOAA's tide prediction program, NTP4, is not available online, but can be purchased from NOAA at nominal cost, including both source code, an executable file (a DOS console program), and two manuals that thoroughly document the theory and practice of tide prediction: U.S. Department of Commerce Special Publication 98, *Manual of Harmonic Analysis and Prediction of Tides* (1940, 1958), and a 1982 supplement updating certain numerical factors to 21st century values.

D.2.4.2.4 Tidal Constituents

The astronomic component of the observed tide gage record is considered to be well-known in principle, consisting of the summation of 37 tidal constituents that are simply sinusoidal components with established periods, and with site-dependent amplitudes and phases. These constituents are available for most gage locations from the NOAA site, <http://tidesandcurrents.noaa.gov/products.html>.

The NOAA website also provides tide predictions for any date in the past or future, limited however to download of one year of predictions at a time. Note that these predictions are

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computed using the currently adopted values of the 37 tidal constituents for the site, not prior values.

D.2.4.2.5 Tide Gage Analysis (Surge Anomaly) and Extraction of Non-astronomic Stillwater from Gage Records

As discussed above, both observed data and a method to predict the purely astronomic component of those observations are available. By subtracting the predictions from the observations, one arrives at a time series of the non-astronomic contribution to the measured stillwater (the tide residual or tide anomaly), including surge and meteorological effects, rainfall runoff, and tsunamis – in fact, all non-astronomic components termed stillwater. As a practical matter, the static setup will not usually be present in the record to a significant degree, for reasons already mentioned. Figure D.2.4-1 shows observed, predicted, and residual tides (observed minus predicted) at Panama City, Florida for a five-day period in August 2005 during Hurricane Katrina's approach and landfall to the west in Louisiana and Mississippi. As shown, a slowly varying residual component approximately 2.5 feet in amplitude is superimposed on the fluctuating astronomic tide.

The recommended procedure to extract the residual stillwater as the difference between the observed and predicted data is extremely simple in concept, assuming that the period of record is adequate (30 years or more) and that the older predictions were made using the appropriate set of tidal constituents, not necessarily those in current use. It would also be assumed that the observed and predicted data has been adjusted to the same vertical datum prior to extraction. One first determines the differences between the observed and predicted elevations (either for all points or only for the highs and lows, as appropriate), and then scans these to locate the annual peaks. These annual peaks are used to fit an extreme value distribution from which the 1-percent-annual-chance elevation can be found.

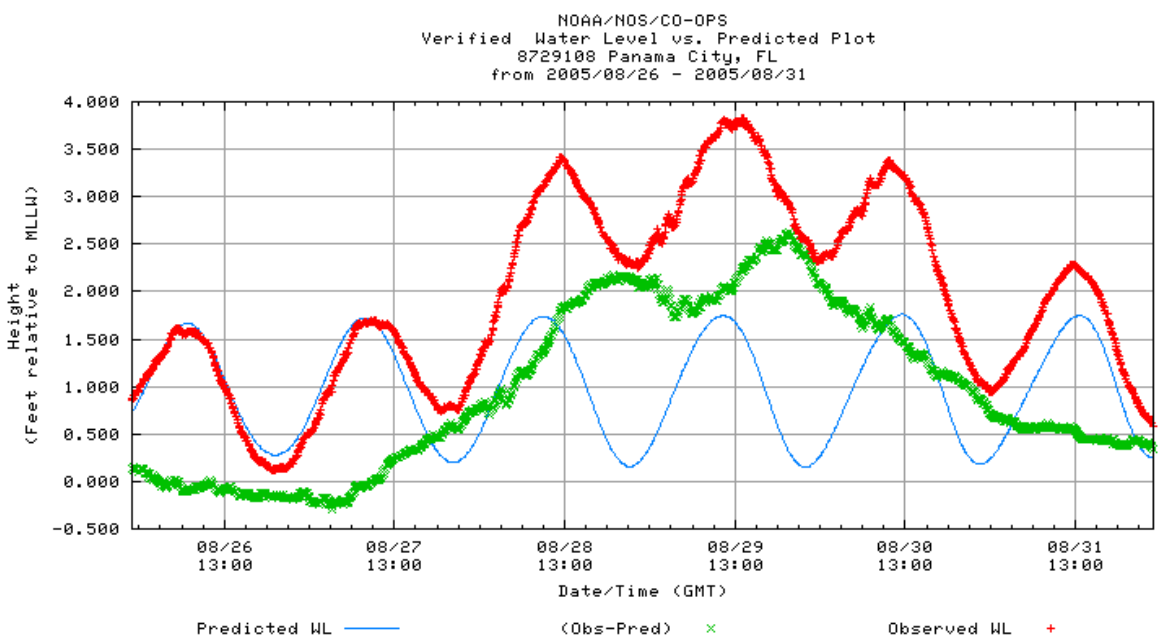

Figure D.2.4-1 Predicted, Observed, and Residual Tides at Panama City, Florida

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As discussed in Subsection D.2.3.3, an acceptable approach for the extreme value analysis is to adopt the GEV Distribution, and to determine the distribution parameters by the method of maximum likelihood. The Mapping Partner may consider other distributions and other fitting techniques as may be necessary to adequately fit the observations, although the particular result with the greatest likelihood value among all of the considered distribution types should be adopted, unless otherwise approved by the FEMA Study Representative.

This recommended procedure is based upon the annual maxima of the residual rather than the annual maxima of the raw data because the underlying astronomic tide is not a random variable, but is deterministic and is limited to a known maximum (less than or equal to the sum of the 37 tidal constituent amplitudes). For these reasons, it may not be appropriate to extrapolate the bounded and deterministic portion of the record out to the upper tail of an unbounded distribution. Subsequent determination of the combined effects of the separated tide and the residual stillwater can be made as discussed in the following Storm Surge section.

Finally, it is emphasized that although this procedure is straightforward in concept, it can be complicated in practice. One complicating factor – changes in the tidal constituents over time – has already been mentioned. Another is the fact that tidal predictions are made with respect to tidal datums, and these may have changed over time, even when referenced to a fixed standard such as NAVD88. Changes in the constituents are one source of datum shift, while changes in relative sea level (including sea-level rise and land subsidence) are another. The Mapping Partner should carefully review the history of the tide gage, the history of the tidal datums, the history of the published constituents, and the local history of relative sea level to ensure that at each step, the residual is properly defined.

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D.2.4.3 Storm Surge

D.2.4.3.1 General Considerations

Storm surge is the rise of the ocean surface that occurs in response to barometric pressure variations (the inverse barometer effect) and to the stress of the wind acting over the water surface (the wind setup component). Wave setup is excluded by this definition. Setup is not incorporated in the common procedures for storm-surge modeling, nor is it present to a significant degree in tide gage data owing to the typical configuration of gages with respect to the zone of large setup; consequently, it must be taken into account separately as discussed in Subsection D.2.5.1.

Storm simulation models must be capable of adequately prescribing and implementing wind, pressure, and tidal conditions into the physics represented by the model if the model-generated spatial and temporal distribution of surge and circulation are to be physically realistic. Models of differing complexity are in wide use, including both 1-D and 2-D models. The Mapping Partner should consult FEMA's list of accepted models to select an appropriate model for a given study. Should a model that is not on the list appear advantageous, the Mapping Partner shall discuss the possibility of its use with the FEMA Study Representative.

Some of the factors that must be considered in selection and application of a model are enumerated below. Specific guidance regarding each factor is not given here. Instead, guidance for complex 2-D modeling is best obtained from the user's manual for a particular model, and from review of prior studies which have successfully used that model. A good general overview of surge modeling for flood insurance studies can also be found in the 3-volume documentation of the FEMA Surge Model (1988), although specifics of application will differ for other models.

Modeling factors that shall be considered in any full storm surge study include:

- The *governing equations* of the model, typically the nonlinear long wave equations accounting for conservation of mass and momentum, with surface wind and barometric pressure terms representing the influence of the storm

- The *numerical scheme* used by the model, whether finite differences computed on a grid of rectangular cells (commonly of fixed size) or in curvilinear coordinates, or finite elements represented by triangular or quadrilateral cells (of varying sizes). The numerical scheme may also be explicit or implicit, affecting time step constraints, and so affecting study cost

- The *flooding / drying* treatment of cells as the surge and tides advance onto land and then recedes

- The *storm representation*, such as a planetary boundary layer model for a hurricane, or a simpler empirical/parametric description, including both wind and pressure; the storm representation will be quite different for hurricanes and northeasters although the modeling principles remain the same in each case; on-land filling will be significant for sheltered waters; winds and pressure representations must be appropriate 10 meter elevation, averaged winds

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- The *wind stress coefficient* which relates the windspeed at the surface to the stress felt by the fluid; consideration must be given to the possibility that the wind stress is capped under the most extreme conditions

- The *sheltering* treatment, adjusting the effective wind stress to account for partial reduction by tall vegetation, terrain, and structures (especially significant for sheltered waters)

- The offshore *bottom friction* treatment over the relatively smooth ocean or bay bottom, which retards the flow

- The onshore *flow resistance* treatment accounting for bottom friction and resistance offered by tall vegetation and structures; critical for sheltered waters

- The source and quality of *bathymetric* data, defining the varying depths at the site

- The source and quality of *topographic* data, such as traditional quad sheets or newer LIDAR data

- The manner in which *normal storm erosion* alters the topography used in the model

- The manner in which *catastrophic erosion* might affect the modeling assumptions, in the event of loss of a major barrier to inland flooding

- The representation of the bathymetry and topography in the model *grid* system, which depends upon the numerical scheme

- The *faithfulness* of the grid to the irregular bathymetry and terrain, including conformance to boundary shapes and inclusion of small sub-grid barriers which may control the local variation of overland flow

- The *resolution* of the grid, whether fixed or varying through the study area

- The *boundary conditions* which impose approximate rules along the edges of the model area, both offshore and onshore, permitting termination of the calculations at the expense of accuracy

- The treatment of *astronomic tide* which might be handled as part of the simulation through the boundary conditions and tidal potentials, or which might be treated as an added effect separate from the surge simulations

- The types and limits of *calibration* which might be done, including small amplitude astronomic tide reproduction for which calibration data is reliable

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- The role of *verification hindcasts* to confirm the apparent reasonableness of the final model when compared with historical surge records

- The role of *wave setup* (a separate topic in these guidelines), especially in the interpretation of high-water marks used for hindcast verification

These factors have been listed here to alert the Mapping Partner to the numerous and complex issues which must be addressed during the course of a full storm surge study. For each, the Mapping Partner must review model documentation and user's manuals, as well as recent studies accepted by FEMA using the selected model, to discern the appropriate level of effort for a new study.

D.2.4.3.2 Simplified One-Dimensional Surge Modeling

While specific guidance for large-scale 2-D surge modeling is beyond the scope of these guidelines, a simplified one dimensional tool has been specially developed for restricted use in flood insurance studies.

There are several reasons a Mapping Partner might wish to make simplified estimates where detailed 2-D modeling is either not needed or is inappropriate: the Mapping Partner may wish to determine SWEL in regions of sheltered waters where an absence of tide gage data makes it impractical to extract stillwater data from the tide residual; the Mapping Partner might wish to compare the surge level from a wind of a certain magnitude with the 1-percent-annual-chance wave event; the 1-percent-annual-chance wave event might be accompanied by strong onshore winds and the Mapping Partner might wish to include this contribution or to evaluate the significance of neglecting it; or the Mapping Partner may wish to explore the sensitivity of locally generated surge levels to windspeed or direction, or to variations in bathymetry and topography.

For such approximate and/or diagnostic purposes, a computer program (BATHYS) has been developed based on the so-called Bathystrophic Storm Tide (BST) theory formulated originally by Freeman, Baer, and Jung (1954). The BST theory accounts for the onshore component of wind stress and the Coriolis force associated with the Earth's rotation. The assumptions of the model are that the onshore forces are in static balance; however, the longshore component includes inertia and requires some time to achieve a balance. A user's manual describing the program and its use in much greater detail is available separately from FEMA.

D.2.4.3.2.1 The System of Interest and Governing Equations

The system of interest is shown in Figure D.2.4-2. A wind with speed W is directed at an angle, θ, to the x-axis that is parallel to the shoreline. The surge distribution is $\eta\,(y)$, where y is the cross-shore direction. The wind obliquity induces a mean current, $U(y,t)$, which varies with time, t.

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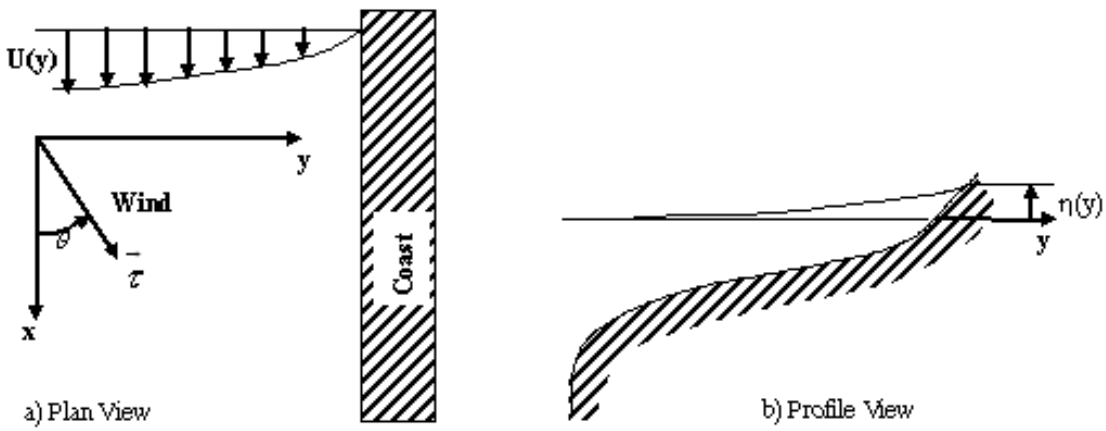

Figure D.2.4-2 Definition Sketch for the BST Formulation

The governing equations are:

y Direction

$$\frac{\partial \eta}{\partial y} = \frac{1}{g}\left(\frac{n\tau_y}{\rho(h+\eta)} - f_c U\right) \tag{D.2.4-1}$$

x Direction

$$\frac{\partial U}{\partial t} = \frac{1}{h+\eta}\left(\frac{\tau_x}{\rho} - \frac{fU^2}{8}\right) \tag{D.2.4-2}$$

In these equations, n ($\approx$1.05 to 1.1) is a factor that augments the onshore component of the wind stress, τ_y, to account for the bottom frictional effect because of return flow; τ_x is the longshore component of wind stress; ρ is the mass density of water ($\approx$1.99 slugs/ft^3); and f_c is the Coriolis coefficient (= $2\Omega \sin\varphi$) where Ω and φ are the rotational speed of the Earth in radians per second and latitude, respectively. The quantity f is the Darcy-Weisbach friction factor ($\approx$0.08 to 0.16).

The longshore and onshore components of the wind stress are specified in terms of a wind stress coefficient, k, and the wind direction, θ, relative to a shore normal

$$\begin{Bmatrix} \tau_x \\ \tau_y \end{Bmatrix} = \begin{Bmatrix} \cos\theta \\ \sin\theta \end{Bmatrix} k|W|W \tag{D.2.4-3}$$

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where the wind stress coefficient, k, is that developed by Van Dorn (1953):

$$k = \begin{cases} 1.2x10^{-6}, & |W| \le W_c \\ 1.2x10^{-6} + 2.25x10^{-6}\left(1 - \dfrac{W_c}{|W|}\right)^2 & |W| > W_c \end{cases} \qquad \text{(D.2.4-4)}$$

D.2.4.3.2.2 BATHYS Program Input and Output

The input quantities to the program are the bathymetry along the shore normal transect, $h(y)$, and the windspeed and direction , $W(t)$ and $\theta(t)$, which can be specified so as to vary linearly with time between specified pairs of windspeeds and directions at selected times. The output of the program is the wind surge at the shore, η_s, as a function of time. To incorporate the effects of astronomic tide, the program permits specification of a time-dependent condition at the seaward boundary of the transect.

Because the longshore current varies as a function of time, the surge, η_s, also varies with time. This reflects the contribution of the Coriolis force; for fixed wind conditions, the surge approaches a constant value as the longshore current approaches its constant equilibrium value for a given windspeed and direction.

The program is extremely efficient and easy to use, with minimal input requirements. The necessary bathymetric data can be obtained from available charts, and wind data can usually be extracted from common sources or from parametric storm descriptions. Users need to be certain that model output is for 1-percent-annual-chance surge elevations, and make any necessary data or input changes to obtain the desired results.

A second simplified tool, the DIM program discussed in Subsection D.2.5, is also available. It was developed especially for the computation of setup over a shore-normal transect similar to that used here by BATHYS. DIM requires additional input, however, because its primary purpose is wave setup simulation. The user's manuals for these programs should be consulted for additional details and examples of use.

D.2.4.3.3 Surge Estimation from Tide Data

A procedure was outlined in Subsection D.2.4.2.5 to extract the total stillwater, exclusive of astronomic tide, from a tide gage record. It is in general difficult or impossible to distinguish among the several components of the residual, which include surge, and there is usually no need to do so. Consequently, the tide residual methodology can be considered equivalent to the estimation of surge from tide data, for all practical purposes. What one generally wants is the 1-percent-annual-chance level of the total flood, irrespective of mechanism.

D.2.4.3.4 Aspects of 2-D Surge Modeling

As noted before, a detailed exposition of 2-D surge modeling is beyond the scope and intent of these guidelines; model documentation and user's manuals as well as detailed documentation of prior studies must be consulted by the Mapping Partner. However, some general guidance is offered in this subsection. The goal of this guidance summary is to identify and discuss important

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model features and capabilities that should be part of any numerical model that is to be used to simulate tropical or extratropical storms, and the general procedures to be followed.

Grid Considerations:

A primary consideration in numerical modeling is that the modeled domain is adequately represented by the computational grid. This includes not only the shoreline and island land boundaries in the area of interest, but also the offshore boundary. For example, the grid should extend far enough offshore of the project area to allow the storm to generate a fully developed surge as a function of tides and wind/pressure. If the grid is too small, the surge will not develop completely, resulting in an under prediction of the surge. Additionally, if the model boundaries are too close to the project area and located in shallow water, i.e., on the continental shelf, nonlinearities and numerical instabilities may develop, or the boundary computations may be otherwise inaccurate. In general, outer boundary conditions should be prescribed as far from the study area and in as deep water as possible.

A second grid consideration concerns irregular boundaries along open coasts and within estuaries or embayments. Although curvilinear coordinate structured grids can be made to adequately represent irregular boundaries, it may be difficult and time consuming to develop an acceptable structured grid, especially if currents as well as surface elevations are a concern. There is also a computational burden associated with structured grids because the high resolution in the area of interest must be extended to the grid boundary. Therefore, unstructured grids are often preferable to structured grids in large domain modeling applications. Unstructured grids are usually easier to generate and provide the necessary flexibility to define offshore boundaries that are well removed from the project area. Simple structured grids are acceptable, however, and may consist of a succession of nested grids of increasing resolution, rather than a single grid.

A third consideration in the development of any computational grid is the compatibility with the maps used to generate the grid. Many grids are referenced to Latitude and Longitude; however, some are referenced to X- and Y-coordinate systems that may in turn be referenced to one or more state-plane coordinate systems. If the grid overlaps multiple systems, the modeler needs to ensure that all data is compatible. Compatibility includes not only the numerical values of common but translated or rotated nodes at a specific topographic/bathymetric feature, but also the projection used to determine horizontal distances. If different projection methods are used in adjacent regions, the derived model grid may be correspondingly skewed.

Finally, the selected grid must be populated with the most up to date and accurate bathymetric and topographic data available. Even the best numerical model will give erroneous results if depths and land elevations are in error. It is very important to ensure that all data are referenced to the same vertical datum, so that the geometry of the basin is faithfully reflected in the model. Depths are often referred to Mean Lower Low Water (MLLW) on navigational charts, not to some mean level; in many locations, the difference between MSL and MLLW is significant, perhaps as much as a few meters. Topography will generally be referenced to either NAVD88 or NGVD29. These potential differences must be resolved to ensure consistency among bathymetry, topography, ocean surface elevation, and tidal forcing.

Boundary forcing:

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Tropical storms require both pressure and windfields in order to simulate the storm surge; northeasters and extratropical events may only require wind. However, both applications may require the storm to be simulated with the influence of tides. In this case, tidal boundary conditions on the open-coast boundaries as well as tidal potential terms over the entire computational grid must be specified. The model selected for the storm surge computations may have these capabilities as part of the model package. If a model does not contain these features, the user will have to provide the necessary boundary conditions. Global tidal boundary conditions and extratropical windfields are available from a variety of sources. Tropical storm input for a model may be based on a separate wind and pressure model.

Tidal elevation boundary conditions can be obtained from the global tidal constituent data bases of Schwiderski (1979) or LeProvost (1995, 1998) or from domestic data bases such as the tidal constituent data base of Mukai, et al (2002). For small domain applications, it is possible specify a single tidal time series along the open water boundary of the grid and neglect tidal potential terms. For applications in which the surge is not large with respect to the tide or there is not a significant amount of overland wetting and drying or barrier island overtopping, it may also be acceptable to model the surge without tides and then to linearly add a reconstructed tidal time series to the surge time series.

Tropical storm models are available from both the public domain and commercial sources. These models range from simple empirical/parametric representations of a hypothetical storm, to more complex planetary boundary layer models that incorporate some of the essential physics of an actual storm event. Regardless of the model selected, output is in the form of windspeed and atmospheric pressure over the computational grid.

Extratropical windfields can be obtained from a variety of sources, including commercial sources. The U.S. Navy Fleet Numerical Meteorological and Oceanographic Center provides hindcast, nowcast, and forecast wind over the world on a fixed delta-Latitude/Longitude basis at fixed time intervals. Wind and weather archives are also available from the National Weather Service (NWS) at specific station locations. For large domain modeling (regional scale), a spatially and temporally variable wind is required. However, for small domain (local scale) projects, a time varying single point windspeed over the full grid may be sufficient. Such data might be obtained from a local airport or from the NWS database.

Regardless of the type of storm event (tropical or extratropical) and the origin of the data used to drive the hydrodynamic model, the data *must be compatible* with the wind drag formulation used in the hydrodynamic model (see below). For example, windfield databases may specify winds at 20-m heights while the selected model formulation may assume 10-m heights. Database units of windspeed can be in ft/sec, m/s, or possibly knots. Care must be taken to assure compatibility in units and in the particular convention chosen for windspeed definition.

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Model-Specific Capabilities:

The following list of model capabilities repeats some features of the grid and boundary forcing items mentioned above. They are reiterated below because some aspects of the grid and boundary forcing are also model specific, and are treated differently by different models.

- Governing equations: All two-dimensional (2-D) numerical long wave storm-surge models should solve essentially the same governing equations – the nonlinear equations representing the conservation of mass and linear momentum. For large domain applications, the governing equations must also include the coriolis parameter. For storm surge, it is generally acceptable to assume hydrostatic conditions and constant density in the governing equations.

- The surface stress distribution resulting from storm induced wind is computed through application of some specified wind drag formulation that includes empirical coefficients. Selection of an appropriate formula and coefficients is extremely important because the shear stress is proportional to the square of the windspeed. A formulation/coefficient that is appropriate for extratropical events may not be appropriate for tropical storms. A versatile numerical model should provide the user with capability to specify parameters for a given formulation, including reductions in the presence of vegetation. Based on current research progress, it may soon be a standard procedure to consider allowing the wind stress to be capped at the highest windspeeds, owing to reduction in sea surface roughness during extreme events.

- The bottom drag must also be specified. As for the surface shear stress, a versatile numerical model should allow the user a variety of friction options. These options should include linear or quadratic options as well as provisions for variable resistance to account for the effects of all manner of vegetation and structures which might be encountered in overland flood propagation.

- Wave radiation stress forcing can be included in the numerical model if wave setup is of concern. At the time of this writing, appropriate methods for this are being developed and tested. Although wave setup is usually estimated separately and added to the computed stillwater surge, a coupled approach might be used. Primary drawbacks would be additional modeling complexity and cost; in practice, simpler approaches may be sufficiently accurate and considerably more efficient.

- The need for wetting and drying elements has been noted. Such a capability is mandatory for regions of low relief and large surge, although a model implementation with a fixed shoreline boundary would be acceptable if the terrain rises rapidly, limiting inland flood penetration.

Model Verification:

Verification of the hydrodynamic model is critical to ensure that grid resolution, bathymetry, topography, and boundary conditions are adequately defined. Verification includes elements commonly thought of as *calibration*, although, in general, surge models should not be calibrated in a traditional sense to reproduce observations. Fundamental model parameters such as wind

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stress coefficients, overland friction factors, and the like, should be based on published best-estimates, and are not free parameters for calibration.

For tides, verification can be achieved by comparing computed data to either measured prototype data collected for a specific time period at the location of interest, or to a multi-constituent (i.e., M2, S2, N2, N1, K1, O1, Q1, and P1) tidal time series reconstructed from published harmonic constituents. These constituents are available from the tidal data base sources such as the NOS or the International Hydrographic Center (IHC). Tidal verification should be achieved to better than 10 percent in both amplitude variation throughout the domain, and phase variation; generally, even better results should be possible. Failure to achieve tidal verification might indicate inadequate grid resolution, especially at inlets and other critical points. Any subsequent model calibration efforts to adjust bottom friction should be limited to values within published ranges for the local hydraulic conditions.

Verification for storm events is more complex. In order to achieve a meaningful result, both the storm conditions (winds and pressures) and the response conditions (such as high-water marks) must be known with accuracy. This is seldom achieved. Actual storm winds and pressures do not faithfully follow simple models, for example, and observed high-water marks may be contaminated by very local wave effects, and may include varying proportions of the local wave setup. Tide gage observations are more reliable, although, again, it is necessary to assess to what degree the record might incorporate setup; it also often happens that tide gages fail prior to the surge peaks of major storms.

In any case, the Mapping Partner shall undertake a thorough verification/hindcast effort for all significant storms that have affected the study area for which high quality data is available. Special hydrodynamic simulations using best wind and pressure estimates are required; such wind and pressure data may be available from Federal agencies, or may be obtained from commercial sources specializing in meteorological data. High-water marks and tide gage records must be evaluated to account for the possible contributions of setup and runup. It should not be expected that an exact comparison will be achieved for any storm. However, given several storms, the observed data should scatter around the model simulations, and not show any large, consistent bias. If certain areas of the grid produce consistently poor comparisons, this may suggest that the grid definition should be carefully reviewed to ensure that area-wide features, such as elongated road embankments, have been accounted for. Of course, it is also important to ensure that the grid represents conditions which prevailed at the time of the storm; barrier island erosion or inlet alterations from prior storms may produce sizeable alterations in a simulation. Consequently, it may be necessary to develop different grid versions for hindcasts, in order to obtain valid results.

No hard and fast rules regarding acceptable model verification are possible, although a careful verification study should permit a reasonable conclusion to be drawn. Should the verification effort be inconclusive, or should poor results be consistently obtained for the historical storm set, the Mapping Partner shall confer with the FEMA Study Representative and with FEMA's technical representatives in order to resolve the issue prior to proceeding with further modeling.

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D.2.4.3.5 Storm Climatology

The general topic of storm climatology includes issues of storm data sources and questions of statistical inference needed for storm surge studies. This is an area undergoing rapid development at the time of this writing. Consequently, it is inappropriate to offer firm guidelines at this time. Instead, only some general observations are collected below. The Mapping Partner shall consult the more recent literature at the time of a new study, and shall confer with the FEMA Study Representative and technical representatives for updated guidance.

The historical storm record is needed for two purposes: first, for definition of the characteristics of particular historical storms necessary for hindcast modeling and model verification as discussed above; second, for estimation of storm frequency and frequencies of such storm parameters as may be needed in the statistical simulation effort.

As already noted, extratropical data may be obtained from knowledgeable and experienced Federal agencies, as well as from commercial sources. Similar data for tropical storms and hurricanes is also available. The latter data is more problematic, however, owing to the sporadic quality of hurricanes and to their relatively large spatial gradients in winds and surge (compared with area-wide northeasters, for example). Important northeasters are of such dimension and duration as to affect large coastal areas, including numerous tide gages, and do not generally result in loss of gage data as is often the case for major hurricanes. Consequently, difficulties and limitations of storm climatology are more acute for tropical storms and hurricanes than for extratropical systems.

Critical data for historical storms and model verification studies should be prepared by experienced meteorologists. Such data may be available for significant storms within knowledgeable Federal agencies; new data for historical storms can also be obtained from commercial sources.

For synthetic storm definition as might be needed in a statistical simulation study, other data is needed. Common hurricane data sources include, especially, the HURDAT database of tropical storms in the north Atlantic. This data file purports to include all tropical storms since the mid-19th century, including eye position at six hour intervals, along with the corresponding peak winds and central pressures, as available.

It has become evident in recent studies, however, that the HURDAT data must be used with caution. In particular, the reported winds should not be used for FIS applications. In no event should they be used to back-estimate central pressures using standard empirical relationships between pressure and maximum windspeed. Central pressures given in HURDAT may be used, but are probably of highly variable quality. As a general rule, the highest quality track and pressure data extends back only to the 1970s, when satellite and other modern sensing technology became common.

A prior break in historical quality occurred during World War II, when aircraft and military reconnaissance began to contribute to improved data quality. Consequently, the period between about 1944 and 1970 might be regarded as a transitional period of good, but not best, data quality.

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The HURDAT data quality deteriorates as one continues to move back in time. Despite this, the entire record back to the 19th century may be useful for estimation of storm frequency and, more guardedly, for determination of track characteristics. It is the pressures and, especially, the winds which may not be appropriate for FEMA coastal flood insurance studies.

A secondary data source which contains information regarding both central pressure and radius to maximum winds is NOAA's NWS 38, prepared in 1987 especially for FEMA FIS applications. Although this document is now somewhat outdated, it includes a useful table of best estimates of storm pressures and radii for both the Gulf and Atlantic coasts for the period from 1900 to 1984. Data from this source can be used to supplement HURDAT. It is not recommended that the NWS 38 determinations of the probability distributions of storm parameters be used for new flood studies. This is due both to the accumulation of additional data over the last two decades, and to limitations in the analysis methods which were based on storm families defined by landfalling, exiting, and alongshore tracks as referenced to a curvilinear shoreline.

A recent update to tropical storm data since the 1940s has been developed by D. Levinson of the National Climatic Data Center, and has been made available in HURDAT format, although it is not part of HURDAT. This data is among the latest available and might still be considered preliminary; it is being used at the time of this writing in studies along the northern Gulf of Mexico by both FEMA and the USACE. This and other data sources and data compilations are currently in development, largely in response to post-Katrina needs.

In order to confirm storm climatology criteria, the Mapping Partner is advised to confer with the FEMA Study Representative and technical representatives to identify data sources and appropriate methodologies for review and consideration.

D.2.4.4 Water Levels in Sheltered Waters

Water levels in sheltered waters may be influenced by a variety of factors that can alter coastal flood characteristics. Incoming storm surge and the resulting extreme SWELs along the shorelines of sheltered waters may achieve higher elevations than at adjacent open-coast locations owing to channelization and tidal amplification controlled by the orientation, geometry, and bathymetry of the basin; lower elevations may occur if restrictive tidal inlets impede the incoming tide. Factors such as these should be implicitly accounted for in any detailed 2-D storm-surge modeling, and so would not need special attention. However, small basins may also experience higher water levels from the contributions of other mechanisms such as direct precipitation and runoff, or from resonant basin oscillations called *seiche*. These are non-standard factors in a FEMA coastal study, but should be considered by the Mapping Partner if the initial scoping effort suggests that there is reason to believe that the local conditions are such that a special problem or sensitivity might exist.

For studies based not on a detailed 2-D model but on, for example, tide gage analysis, recorded tide elevations may require transposition from the tide gage to a nearby flood study site within the sheltered waters, to better represent the local stillwater elevation during the

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1-percent-annual-chance flood event. Some general guidance for evaluating and applying tide gage data to ungaged locations is provided in this subsection, although the Mapping Partner must carefully assess the likely magnitude of error inherent in such approximations, and determine whether a more detailed study might be necessary.

D.2.4.4.1 Variability of Tide and Surge in Sheltered Waters

As a very long wave such as surge or tide propagates though a varying geometry, its amplitude changes in response to reflection, frictional damping, variations in depth causing shoaling, and variations in channel width causing convergence or divergence of the wave energy. In general, these changes are best investigated through application of 2-D long wave models. However, it may be possible to adopt simpler procedures that can provide sufficient accuracy for much less time and cost.

In some cases, tide data may have to be transposed from a gaged site to an ungaged site. If a sheltered water study site is located in the immediate vicinity of a tide gage, the Mapping Partner can use data from the gage without adjustments, but if the study site is distant from the tide gage, the tide data may need to be adjusted so as to reasonably represent the site. It is emphasized that "Considerable care must be exercised in transposing the adjusted observed [tide] data to a nearby site since large discrepancies may result" (USACE, 1986). Although transposition of historic tide data from a nearshore tide gage out to an open-coast location is much simpler and so preferable to its transposition farther inland, there remains a need for reasonable methods to estimate the variation of inland tidal elevations in ungaged regions of sheltered waters.

Some simple empirical evidence may permit an approximate evaluation of these variations, adequate for a FIS:

- Established tidal datums from multiple gages in the sheltered area reflect the natural variation of tide elevations; interpolation between gages gives a first-order estimate of spatial variation patterns

- The normal vegetation line may provide additional information between gages, insofar as it mirrors the general variation of the normal tidal elevation.

- Similarly, observed debris lines and high-water marks from historical storms may illustrate the variation of storm surge within the sheltered geometry, outside the surge generation zone.

Tides and storm surges propagating into sheltered water areas undergo changes controlled by frictional effects and basin geometry. The Mapping Partner must evaluate the differences between the physical settings of the nearest tide gage(s) and the study site, and the distance and hydraulic characteristics of the intervening waterways between these locations to establish a qualitative understanding of the potential differences in tidal elevations between the gaged and ungaged locations. If flood high-water marks are available in the vicinity of the ungaged sheltered water study site, these elevations shall be compared to recorded tide elevations to correlate surge components of the tidal stillwater between locations. In general, surge data are of more limited availability than tide data. It may sometimes be reasonable to assume similarity

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between surge and tide, and so infer surge variation from known tide variation. The validity of such inference is limited, however, by differences in amplitude and duration of high water from the two processes, and by the fact that tide is cyclic and so may not vary in the same manner as a single surge wave.

Both empirical equations and numerical models can be used to describe the variation of tides and surges propagating into sheltered water areas. The Mapping Partner shall select the most appropriate approach for the study, with consideration of the location of the study site within the sheltered water body, the complexity of the physical processes, and the cost of a particular approach. Appropriate numerical models can range from simple 1-D models to complex 2-D models. The Mapping Partner shall thoroughly evaluate the limitations and capabilities of appropriate models in view of the site-specific issues that need to be resolved to obtain reliable estimates of tidal flood elevations.

For simple tidal inlet settings, or as a first approximation before detailed numerical modeling, Mapping Partners may use analytical methods provided in the CEM (Chapter II-6-2(b)) to estimate bay tide amplitudes. Guidance for estimating the associated inlet parameters is also provided in the CEM. Examples provided in the CEM are limited to estimating the predicted astronomical tide amplitude in a small bay based on an adjacent open-coast tide range obtained from tide tables. These CEM methods may also be applied in a two-step process to transpose recorded tide gage data (SWELs) from one bay to another nearby ungaged sheltered water body as follows:

1. Apply the CEM methods and nomograms in reverse to estimate the adjacent open-coast annual maximum SWELs (astronomical tide elevation plus storm surge height) based on recorded SWELs from a primary tide gage in the sheltered water body closest to the flood study site. The physical setting of a primary tide gage may be such that recorded tide elevations are representative of open-coast tide elevations; however, this condition should not be assumed.
2. Using the estimated open-coast tide elevation, reapply the CEM methods and nomograms (in forward mode) to estimate the associated annual maximum SWELs in the ungaged sheltered water body where the study site is located. Use of the same open-coast stillwater elevation between the gaged and ungaged sheltered water areas is acceptable if it can be assumed that the annual extreme SWELs are generated from regional storm systems large enough in spatial extent to encompass the two locations.

When tidal elevations are to be established in an ungaged sheltered water body, it is recommended that a limited tidal monitoring program be undertaken to estimate tidal datums near the study site. NOAA (2003) provides guidance on methods and computational techniques for establishing tidal datums from a short series of record. The accuracy of the resulting datums may vary insignificantly between a one-month series of data and a 12-month series (NOAA, 2003); a short-term effort will usually be entirely adequate for use in a FEMA FIS of a small sheltered region.

The complex shorelines and bathymetry of sheltered waters may lead to significant changes in tide characteristics. The objective of short-term monitoring should be to provide observed data

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from which tidal datums may be estimated to check the accuracy of subsequent higher elevation estimates of extremal SWELs in ungaged sheltered water areas and, in turn, to increase the level of confidence in the resulting flood hazard elevations.

Irrespective of the approach taken, the Mapping Partner shall evaluate the physical setting of the tide gage(s) from which data are used. Observation of the gage setting may provide insight into the relative degree of sheltering or other characteristics of a given tide gage. Information on NOAA tide gages can be obtained at <http://www.co-ops.nos.noaa.gov/usmap.html>. Mapping Partners shall also determine if a tidal benchmark has been established near the flood study site (<http://tidesandcurrents.noaa.gov/bench.html>). Tidal benchmarks are elevation reference points near a tide gage to which tidal datums are referenced. Some tidal benchmarks are now tied to the NAVD88, or to the earlier NGVD29, providing an appropriate vertical elevation reference. Benchmark elevations may become invalid over time if changes occur in local tide conditions because of dredging, erosion, or other factors; the Mapping Partner shall review the publication date of the data together with information concerning any recent changes in the vicinity of the tide gage setting to ensure the data are appropriate.

If the physical setting and tidal processes of a coastal flood study site are particularly complex and the application of the simple methods described in the CEM are questionable, the Mapping Partner must confer with the FEMA Study Representative and technical representatives for further guidance on estimating tidal and surge elevations at ungaged sites.

D.2.4.4.2 Tidal Inlets

Tidal inlets control the movement of water between the open coast and adjacent sheltered waters. Inlets may be broadly classified as unimproved (natural) or improved (maintained). The physical opening of a tidal inlet, whether natural or maintained, has a direct and often significant effect on the propagation of tides, surge, and waves into sheltered waters and on subsequent coastal flood conditions. The Mapping Partner shall review the CEM Section II-6-2 on inlet hydrodynamics for comprehensive guidance on data, methods, and example problems related to the behavior of currents and waves at tidal inlets, for possible application in simplified studies within sheltered waters.

D.2.4.4.3 Seiche

Seiche is a low frequency oscillation occurring in enclosed or semi-enclosed basins, which may be generated by incident waves or atmospheric pressure fluctuations; seiching may also be called harbor oscillation, harbor resonance, surging, sloshing, and resonant oscillation. It is usually characterized by wave periods ranging from 30 seconds to 10 minutes, controlled by the characteristic dimensions and depth of the basin (CEM, 2003).

The amplitude of seiche is usually small; the primary concern is often with the associated currents that can cause large excursions and damage to moored vessels if resonance occurs. However, surface elevations and boundary flooding in an enclosed basin may become pronounced if the incoming wave excitation contains significant energy at the basin's natural seiche periods. The Mapping Partner shall investigate the likelihood of seiche under extreme water-level and wave conditions if the pre-project scoping effort indicates that a sensitive site has been affected by seiche during past storms. Bathymetry, basin dimensions, and incoming wave characteristics should be reviewed to determine the potential for seiching; the CEM

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(Section II-5-6) provides background and guidance for estimating the natural periods of open and closed basins. Numerical models are most appropriate for evaluating the effects of long waves in enclosed basins and shall be considered for use in a sheltered water study if seiching is believed to have the potential to contribute significantly to boundary flooding during the 1-percent-annual-chance flood condition.

D.2.4.4.4 Documentation

The Mapping Partner shall document the characteristics of all gages located within or near the sheltered water study area. Methods adopted to infer the variation of tidal datums between gages shall be documented, as shall procedures used to transpose data from one site to another. If a brief field effort is undertaken to determine the variation of tidal datums within ungaged regions, the Mapping Partner shall fully document that effort, including: locations of observations; observation methods and instrumentation; dates and times of all observations; meteorological and oceanographic conditions during and preceding the period of observation; and other factors that may have had an influence on water levels, or may affect interpretation of the results. If surge variation is inferred from tide variation, the Mapping Partner shall document the basis for similarity assumptions, and the manner in which the inferences were made. Inlet analyses should be documented including all procedures, methodological assumptions, field surveys (dates, times, procedures, instrumentation, and findings), and all inlet data adopted from other sources.

D.2.4.5 1-Percent-Annual-Chance Stillwater Levels

The 1-percent-annual-chance flood on the Atlantic and Gulf coasts is not often the result of stillwater alone; other processes such as wave setup, wave heights, and wave runup ride atop the stillwater, which serves as a base. The exception might be well-sheltered areas, protected from waves and affected only by the high SWELs associated with tide or surge. Even in such areas, however, the total 1-percent flood level may include a physically independent contribution from rainfall runoff.

Consequently, there are two aspects of stillwater statistics for a Mapping Partner to consider: What is the 1-percent-annual-chance SWEL at a site? How does stillwater contribute to the total 1-percent level? Even if it is known that the BFE at the study site is determined by wave runup, for example, the former question may not be irrelevant, and the Mapping Partner may need to estimate the 1-percent SWEL separately from the higher BFE.

Two distinct stillwater components can be identified: astronomic tide and storm surge (wind and pressure setup). A third stillwater component is important in sheltered waters, but is not the result of coastal processes as are the others. This is the superelevation of tidal waters associated with rainfall runoff. The riverine 1-percent flood profile along a tidal river typically begins near MHW or MHHW at the mouth, and rises as one proceeds upstream. Although the riverine flood level along the lower reaches of the tidal river may be physically unrelated to coastal flood processes, the final flood mapping must represent the contributions of both mechanisms. Consequently, the rainfall runoff excess elevation may be considered a third type of coastal stillwater elevation.

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The following subsections address methods by which the statistics of each stillwater type may be determined, and also give an overview of the ways in which the statistics of combined processes can be addressed.

D.2.4.5.1 Tide Statistics

The astronomic tide is a deterministic process. Consequently, tide statistics can be generated directly from the local tidal constituents. One simple way to do this is to sample the predicted tide at random times throughout the tidal epoch. Alternatively, predictions can be used to obtain highs and lows, from which corresponding statistics can be derived. It is noted that the maximum possible tide is given simply by the sum of the amplitudes of the 37 tidal constituents.

D.2.4.5.2 Surge Statistics

The development of surge statistics can be approached in two general ways. First, if sufficient data are available from tide gage records, then an extremal analysis of the residual after subtraction of the astronomic tide can be performed. As noted above, this requires determination of the annual peak residuals for the period of record, and a fit to a GEV or other appropriate distribution using the method of maximum likelihood (or an alternate acceptable method). The Mapping Partner should keep in mind that the 1-percent level determined in this way will include the contributions of all mean water components affecting the gage, including both static wave setup *to the degree it exists at the gage site*, and riverine rainfall runoff.

The second way in which 1-percent surge levels are determined is through numerical modeling of surge elevation using 1-D or 2-D models, as discussed above, combined with a statistical model relating the surge simulations to storm frequency and storm parameter distributions. Three ways of doing this have been used: the JPM, which has been used in many FEMA flood studies on the Atlantic and Gulf coasts in combination with the FEMA Storm-surge model; the more recent EST, which has been used in combination with the ADCIRC model for recent studies; and a Monte Carlo approach, which has been used for coastal setback determinations in the Florida Department of Environmental Protection, and which is particularly suited for use with the 1-D surge model, BATHYS, described previously. Because surge levels on the Atlantic Ocean and Gulf of Mexico are generally large, it is expected that JPM and EST studies with large 2-D surge models will most often be necessary. The 1-D BATHYS model with Monte Carlo simulation, or – more directly – with direct simulation of the wind record using, say, GROW data, may be adequate in some cases. Brief descriptions of the JPM, EST, and Monte Carlo methods are given in Subsection D.2.3.6.

D.2.4.5.3 Combined Effects: Surge Plus Tide

The simulation of storm surge is usually performed over water depths representing mean conditions, or some other fixed level. The 1-D Monte Carlo approach in which tide is incorporated as a time-dependent boundary condition is a notable exception.

Because tide is ubiquitous, the flood level associated with storm surge must be based on the combined surge-plus-tide levels. Four approaches of differing complexity are mentioned here.

First, if the surge and tide can be assumed to combine linearly (that is, neither is physically altered to an important degree by the presence of the other), then the simplest method is to simply add them in some manner. If a surge episode – such as a northeaster – is of relatively long

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duration compared with a tidal cycle, then high tide will be certain to occur at some time for which the surge is near its peak, and a simple sum of amplitudes may be sufficiently accurate.

However, if the surge duration is short – such as may be typical for hurricanes in northern latitudes – this approximation is inadequate. The next simplest assumption, still assuming linear superposition, is based on the fact that the PDF for a sinusoid is largest at its extrema – tide is generally near a local high water, or near a local low water, and spends more time near those values than in between. It may be reasonable, then, to assume that the peak surge occurs with equal probability near a high tide or near a low tide, taking mean high and mean low as representative values. Each of the corresponding elevation sums would be assigned 50 percent of the rate associated with the particular storm (as if each storm were to occur twice, once at high tide and once at low tide), and the frequency analysis would proceed with these divided rates.

A third, slightly more complex approach but still assuming physical independence, is based on the convolution method mentioned in Subsection D.2.3.3. In this method, the PDFs for both tide and surge without tide are used. Previous discussion has shown how both of these may be established. If the probability density of the tide level Z is denoted by $p_T(Z)$ and the probability density of the surge level is $p_S(Z)$, then the probability density of the sum of the two is given by:

$$p(Z) = \int_{-\infty}^{\infty} p_T(T) p_S(Z - T)\, dT = \int_{-\infty}^{\infty} p_T(Z - S) p_S(S)\, dS \qquad \text{(D.2.4-5)}$$

where the indicated integrations are over all tide and surge levels.

In some cases, however, the essential assumption that the tide and surge can be linearly added is not satisfied. In shallow water areas extending a large distance inland, the enhanced depth associated with tide (or surge) affects the propagation and transformation of the surge (or tide). That is, there is a nonlinear hydrodynamic interaction between the two. In such a case, more complex methods are required because the nonlinear interaction can only be accounted for by hydrodynamic considerations, not by any amount of purely statistical effort. Two approaches to this issue have been adopted in study methods already identified. The FEMA storm surge methodology adopts a procedure in which a small number of storms are simulated around a set of tide assumptions with differing amplitudes and phases. These additional simulations are used to provide guidance for simple adjustments that are made to the large set of computations performed on MSL. The EST approach treats astronomic tide (amplitude and phase) as additional input vector components, which are incorporated into the hydrodynamic model as part of the boundary conditions. The 1-D Monte Carlo approach includes tide as part of the surge simulation and so does not require a separate step to combine the two.

Should the Mapping Partner be required to perform 2-D surge modeling, it will be necessary to consult the user's manuals or other documentation of the adopted models to obtain additional guidance on this topic.

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D.2.4.5.4 Combined Effects: Surge Plus Riverine Runoff

The final instance of combined stillwater frequency to be described here, concerns the determination of the 1-percent SWEL in a tidal location subject to flooding by both coastal and riverine mechanisms. This is the case in the lower reaches of all tidal rivers.

The simplest assumption is that the extreme levels from coastal and riverine processes are independent, or at least widely separated in time. This assumption is generally acceptable because the storms that produce extreme rainfall and runoff may not be from the same set as the storms that produce the greatest storm surge. Furthermore, if a single storm produces both large surge and large runoff, the runoff may be significantly delayed by the time required for overland flow, causing the runoff elevation to peak after the storm surge. Clearly, there may be particular storms and locations for which these assumptions are not true, but even so they are not expected to be so common as to strongly influence the final statistics. If, for a steep terrain area of the east US coast, it is thought that peak runoff and peak surge may commonly coincide owing to local conditions, then the Mapping Partner must consider the likely correlation between the two, and discuss with the FEMA Study Representative whether a departure from the method given here should be used.

The simplified procedure is straightforward, beginning with development of curves or tables for rate of occurrence vs. flood level for each flood source (riverine and coastal). Rate of occurrence can be assumed equal to the reciprocal of the recurrence interval, so the 100-year flood has a rate of occurrence of 0.01 times per year. This is numerically equal to what is more loosely called the *flood elevation probability*. Then one proceeds as follows at each point of interest, P, within the mixed surge/runoff tidal reach.

1. Select a flood level Z within the elevation range of interest at point P.
2. Determine the rates of occurrence $R_{P,R}(Z)$ and $R_{P,S}(Z)$ of rainfall runoff and storm surge elevations exceeding Z at site P (number of events per year).
3. Find the total rate $R_{P,T}(Z) = R_{P,R}(Z) + R_{P,S}(Z)$ at which Z is exceeded at point P, irrespective of flood source.
4. Repeat steps (1) through (3) for the necessary range of flood elevations.
5. Plot the combined rates $R_{P,T}(Z)$ vs Z and find $Z_{P,100}$ by interpolation at $R_{P,T} \approx 0.01$.
6. Repeat steps (1) through (5) for a range of sites covering the length of the mixed tidal reach.
7. Construct the 100 year composite profile passing through the several combined 100-year elevation points, and blending smoothly into the pure-riverine and pure-surge 100-year profiles at the ends of the mixed reach.

The procedure is shown schematically in Figure D.2.4-3 in which the combined curve has been constructed by addition of the rates at elevations of 6, 8, 10, and 12 feet. The entire procedure can be implemented in a simple hand calculator program, with the input at point P being the 10-, 50-, 100-, and 500-year levels for both runoff and surge, as obtained from standard FIS report tables.

All policy and standards in this document have been superseded by the FEMA Policy for Flood Risk Analysis and Mapping.
However, the document contains useful guidance to support implementation of the new standards.

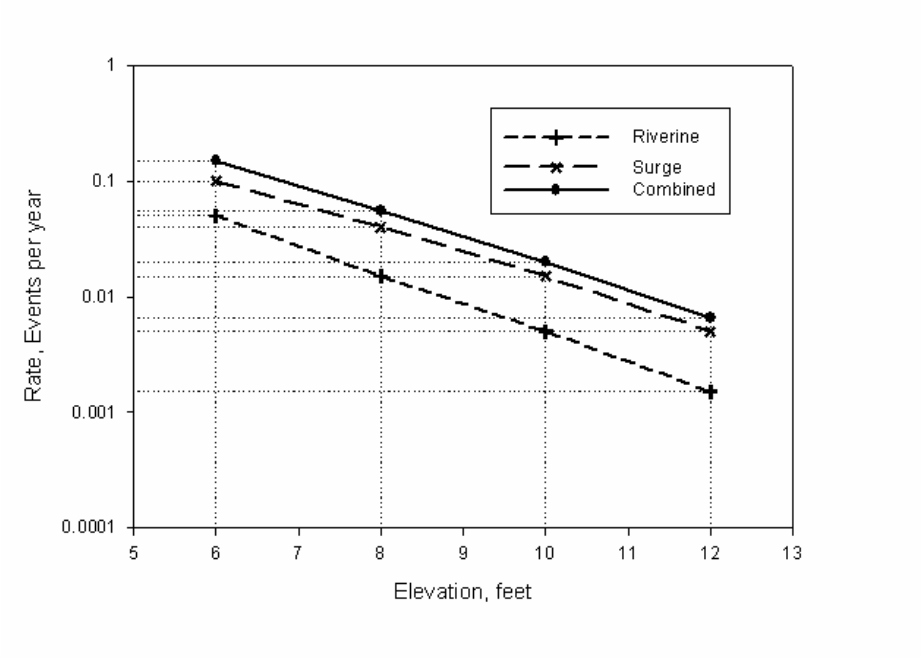

Figure D.2.4-3 Schematic Illustration of Riverine and Surge Rate Combination

D.2.4.6 Nonstationary Processes

Conceptually, a *stationary process* may be thought of as one that does not change in its essential characteristics over time; its descriptors are fixed or stationary. For example, a stationary random process would be one for which its mean, standard deviation, and other moments are unchanging over time. A nonstationary process is one for which these measures do change. Whether a fluctuating process is thought to be, or appears to be, nonstationary can depend upon the time window through which it is viewed. Processes that appear to display definite nonstationary trends when viewed at a short scale, may be seen to fluctuate around an unchanging mean when viewed from a more distant perspective. For example, the tide appears nonstationary when viewed over a period of one hour, but appears entirely stationary when viewed over an entire 19 year tidal epoch.

The appropriate time window for FEMA flood studies is established by the period of record covered by the available data on the one hand, and the probable lifetime of a particular study, on the other.

For practical FIS considerations, two sorts of nonstationarity seem significant. The first is the apparent change of sea level, which has been observed on all coasts. Because it is sea level relative to land that is most significant, an apparent change of sea level can be the result of either sea-level rise, or land subsidence.

The second type of nonstationarity that is important for coastal studies is the long-term change in tidal datums, which may occur as basins evolve through silting, dredging, migration and evolution of inlets, human construction including harbor improvements and breakwaters, and so forth. Both types are discussed below.

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D.2.4.6.1 Relative Sea Level – Sea-level Rise

Sea level rise appears to be a real, long-term effect observed all along the U.S. coastline. The Philadelphia District of the USACE maintains a useful collection of sea-level rise links at their website <http://www.nap.usace.army.mil/cenap-en/slr_links.htm>. There is also a very large set of sea-level trend data for individual stations along the Atlantic and Gulf coasts, which can be obtained from the referenced NOAA site.

The significance of such data is two-fold. First, the Mapping Partner must be aware of these changes to properly interpret historical data upon which new studies might be partly based. This has been discussed, for example, in a prior subsection on tides. Second, the likely continuation of these trends into the future will have some impact, although usually small, on the interpretation of today's FIRMs at a future date. In particular, the Mapping Partner should consider the likely impact of sea-level rise on floodplain boundary delineations, and document any unusual changes that might be anticipated.

D.2.4.6.2 Relative Sea Level – Land Subsidence

Land subsidence produces the same sort of effect as sea-level change – a rise in the apparent sea level – but subsidence might be much the more significant factor in a local area. Many areas along the coasts of Texas, Louisiana, and Mississippi have subsided by several feet as a result of gas, oil, or water extraction over the past few decades.

Such large displacements make it imperative that historical data be interpreted with caution. The Mapping Partner must ensure that gage datums have been properly adjusted over time so that water-level records, benchmarks, observed high-water marks, and all similar data are properly interpreted, and properly related to current conditions represented in the hydrodynamic model grid.

The USGS is a primary repository of land subsidence data for the United States, and should be consulted to obtain local site information covering the entire period of study data that might be compromised by unrecognized subsidence. The USGS web pages may be searched for local subsidence information at <http://search.usgs.gov/>.

Other data sources may be more helpful in some cases. The Mapping Partner should consult with local city and county engineering departments, and the professional surveying community, which may be aware of isolated subsidence issues not reflected in the national programs.

D.2.4.6.3 Astronomic Tide Variation

Tide datums and tidal constituents may change over time owing to changes in the geometry of a tidal basin, so that tide may also constitute a nonstationary process. This makes it imperative that tide predictions for prior years (hindcasts) be made using tidal constituents appropriate to that time, and that tidal data be adjusted as necessary for shifts in tidal datums with respect to a fixed datum such as NAVD88 or NGVD29. The NOAA website can provide predictions for past times, but all such predictions are made using the current default set of constituents, and so may inaccurately portray past tide levels and datums. Archived copies of tidal constituents can be obtained from NOAA by special request. Flexibility in applications such as these makes it wise to use a tide prediction program such as NOAA's own program, NTP4.

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