Guidance for Coastal Flood Hazard Analyses and Mapping in Sheltered Waters

Technical Memorandum

February 2008

FEMA

All policy and standards in this document have been superseded by the FEMA Policy for Flood Risk Analysis and Mapping.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.

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1. Introduction

This memorandum provides supplemental guidance[1] to Mapping Partners for coastal flood hazard analyses (primarily the 1-percent-annual-chance event) in sheltered water areas. It updates and extends guidance contained in the existing guidelines for the Atlantic, Gulf of Mexico, and Pacific Coasts (FEMA, 2003; FEMA, 2004; FEMA, 2007).

This supplemental sheltered water guidance addresses two categories of studies, as appropriate:

1. Studies for which prior Flood Insurance Study (FIS) results are not available and, therefore, for which new water level and wave analyses are required - the "New Studies" approach.
2. Studies for which prior water level (and sometimes wave) analyses from a FIS are available and, therefore, can serve as input to new sheltered water analyses - the "Existing FIS" approach.

Sheltered waters in this document refers to bays, sounds, estuaries, fjords, and other water bodies that are hydraulically connected to open coast waters during flood conditions. Sheltered water shorelines can be exposed to the same types of flood-producing processes as open coastlines (i.e., high winds, storm surge, wave generation and overland propagation, wave runup, and wave overtopping). However, sheltering implies the inland propagation of open coast flooding and a modification of these processes by land masses or other obstructions. In many cases, sheltered water shorelines are subject only to locally generated waves. For some geometries, the distinction between open coast and sheltered waters may not be evident. In such cases, the Mapping Partner should discuss the most appropriate classification with the FEMA Study Representative.

There are four technical considerations that may complicate the analyses of sheltered waters beyond typical open-coast analyses. These may require a substantially greater computational effort on the part of the Mapping Partner and should be considered carefully prior to the initiation of a new study or the modification of an existing study:

- Coincidence (Phasing) Between the Highest Water Levels and the Highest Waves: The highest water levels and the highest waves coincide along many open coast areas due largely to the fact that the same event (such as a hurricane or extratropical storm) controls both. This may or may not be the case in a sheltered water body, and if such coincidence occurs it will likely not occur everywhere within the sheltered water body. Thus, even within the same sheltered water body, flood analyses must deal with a wide range of phasing possibilities - from full coincidence (e.g., hurricane flooding and wave penetration at a segment of a sheltered water shoreline area) to no coincidence (areas with only locally generated waves, astronomical tides, and small surge). If there is no significant coincidence at a sheltered water shoreline, it may be possible to decouple the hydrodynamic and wave analyses, address each independently, and combine the results statistically.

[1] Guidance is provided on seven main issues: Water Levels, Offshore Waves, Wave Setup, Event-Based Erosion, Coastal Structures, Wave Runup and Overtopping, and Overland Waves.

- Number of Events Modeled: It may be necessary to model more coastal flood-producing events in sheltered waters than on the open coast. While a given event may cause a similar flood response everywhere along an open coast, the same event may cause greatly different responses in a sheltered water body (e.g., the event may cause high surge and waves along one shoreline segment, but may concurrently cause a negative surge, a set–down, and no onshore waves along another shoreline segment).
- Complexity of the Sheltered Water Shoreline and Bathymetry: The complexity of the sheltered water body shoreline and bathymetry will dictate the sophistication of the hydrodynamic and wave models required. Simple water body shapes and relatively uniform depths may allow simplified storm surge and wave analyses. More typical complex water body shapes and variable depths will likely require 2-D hydrodynamic and wave models unless otherwise dictated by study constraints (e.g., available data, study schedule, and study budget).
- Number of Analysis Transects Required: Many sheltered water bodies have irregular shorelines, changing profile characteristics (e.g., wetland, beach/dune, bluff, and various armored profiles), and variable upland development patterns. These factors may dictate a reduced transect spacing (down to a few hundred feet in places) and may require many more transects than might be used along an open coast shoreline of the same overall length. It is not possible in most sheltered water flood studies to place transects close enough to capture all of the alongshore variability. However, an experienced Mapping Partner should be able to interpolate between transects using topographic, shoreline structure, land cover, and backshore development information, thereby significantly reducing the number of transects required.

Study Considerations

Given the potential complications discussed above, the type, extent, and complexity of sheltered water coastal flood analyses should be clearly identified and discussed thoroughly by the Mapping Partner and the FEMA Study Representative prior to and during project scoping. Study considerations include the following:

- Evaluating an Existing FIS: A variety of issues may affect the adequacy of an existing FIS and may affect the scope of work (i.e., revising the existing FIS or conducting a new study). For example, have sheltered water body depths, channels, islands, shoals, etc., changed significantly? Has the shoreline been altered? Is more and/or better data (climatologic, bathymetric, topographic, water level, wave, other) available today? Has freshwater discharge into the sheltered water body changed? Have new openings or storm surge pathways been made (either naturally or artificially) between the sheltered water body and the open coast water body? Have previous openings or pathways been closed or modified? Have upland development patterns changed? Are the previous analyses defensible?
- Combining New Wave Analysis with Existing FIS Water Levels: This is likely to be one of the most common updates to an existing FIS, and is often carried out using new topographic data. This type of update also involves many of the topics addressed in this memorandum such as the propagation of ocean waves into the sheltered water body, the generation and

transformation of local waves, methods to combine water levels and wave heights, erosion, and coastal structure considerations.

- Replacing Approximate V Zones with Detailed Wave Analysis: In some portions of existing studies, approximate V zones have been delineated. These approximate V zones indicate areas where the stillwater depth exceeds 4 feet (the water depth that is necessary to support a 3-foot breaking wave height associated with a V Zone), but for which the earlier study was not sufficiently detailed to determine the degree of coincidence between surge and waves. Consequently, the existing Base Flood Elevation (BFE) includes only the 1-percent-annual-chance stillwater contribution. The Mapping Partner and the FEMA Study Representative must agree upon the method by which available information can be used to estimate the combined elevation of water level and wave height, or upon the new information that must be developed in order to do so.
- Response Analyses and Statistical Simulation Analyses: There are two general approaches for specifying hydrodynamic model input[2]: 1) the response method which is based on the observed characteristics of actual historical events; and 2) statistical simulation methods which develop synthetic conditions abstracted from historical events (Monte Carlo, EST, JPM). The response method is more applicable to the Pacific open coast and the statistical simulation method is more applicable to the Atlantic/Gulf open coasts. The response method is generally more applicable to sheltered waters.

  The response method usually involves an extreme value analysis of the annual flood maxima at each site. In this approach, the responses (i.e. total water levels[3]) for the largest forcing conditions occurring each year must be determined. This requires examining a number of events each year to ensure that the largest response is captured, because the largest response may not correspond to the largest value of any single parameter, such as surge or wind speed. Annual events corresponding to high water levels, high winds, and possibly other physical parameters, must be examined. In sheltered waters, the annual maxima at different transects may not correspond to the same event because the surge and waves are functions of the wind direction. Consequently, more annual events may have to be simulated to ensure that the maximum conditions at each transect are captured. The computed annual maxima at each transect are then examined using an extreme value statistical analysis to determine the 1-percent-annual-chance response.

  To minimize the necessary number of cases that are examined, the candidate events can be filtered based on simple estimates of the response. For example, to filter the candidate events based on total water level, use very simple surge, wave hindcast, and runup models with typical, simple conditions (constant fetch, one structure slope, etc). Then examine the wind and water level data for times when the sum of the tide, surge, and runup (or wave crest) is largest and only analyze several specific cases.

[2] Sections D.4.2.4 and D.4.3.2 of the Pacific Guidelines (FEMA, 2004) also discuss the Event Method which considers the response to one or more idealized events, such as design storms. The Event Method is not generally recommended.
[3] Total water level is the sum of all components which influence the water level including tide, surge, wave setup, and wave runup.

The statistical simulation methods may also require an increase in the number of cases examined to ensure that significant conditions are captured at each transect. Since each synthetic storm has a prescribed annual rate of occurrence, the 1-percent-annual chance response can be determined by summing the rates of all events that produce floods above specified levels.

To reduce the number of events simulated using statistical methods, it may be possible to band the parameter space examined (e.g., only consider winds from several important directions rather than all directions, or, for hurricanes, band according to wind speed ranges and neglect storms incapable of producing 1-percent-annual-chance flood levels). The recently developed optimum sampling techniques (JPM-OS) significantly reduce the number of events that must be simulated (see, for example, Resio, 2007, or Toro, 2007).

- Freshwater Contributions: Should the Mapping Partner have reason to believe that unusual local conditions (e.g., upstream dams or freshwater discharge controls) require a detailed evaluation of the combined effects of rainfall runoff, riverine flow, storm surge, and tide in a sheltered water body, a technical justification and work plan should be developed and discussed with the FEMA Study Representative.
- Inclusion of Event-Based Erosion[4]: The potential effects of including event-based erosion in a sheltered water study must be considered carefully by the Mapping Partner and the FEMA Study Representative during the scoping phase. That said, detailed guidance for estimating event-based erosion in sheltered water studies has yet to be developed, and this memorandum does not provide complete guidance.

  In the case of a new study, the same profile may erode to different extents depending on the water levels and wave conditions affecting the shoreline. This variable profile response, in turn, affects the nature of the flood conditions that must be modeled at the shoreline and inland of the shoreline (i.e., overland wave propagation vs. wave runup and overtopping) for each modeled event. Inclusion of large-scale morphologic changes (such as barrier island lowering or breaching) can also complicate sheltered water analyses.

  For existing studies, after-the-fact addition of event-based erosion may complicate the subsequent mapping of wave effects and inland flooding. For example, erosion of a particular geomorphic feature may expose a large area (that was previously "dry" during the base flood) to storm surge flooding and wave effects. This, in turn, may alter or invalidate the previous storm surge and wave analyses, and could require extensive analyses not anticipated by the Mapping Partner.

- 1-D versus 2-D Wave Height Analysis: The traditional FEMA coastal flood analysis of overland waves uses WHAFIS and compatible 1-D models to determine wave crest elevations along each study transect. The Mapping Partner must first estimate the incident wave conditions at the start of each transect, utilize the 1-D models, and then interpolate between transects to identify flood hazard zones and BFEs. Currently, 2-D wave models are

[4] Event-based erosion is also referred to as storm-induced erosion or episodic erosion. It does not include long-term or chronic erosion.

increasingly used for coastal studies. However, while 2-D wave models have advantages over the traditional approach (e.g., providing a two-dimensional description of the wave field over flooded water and land areas, avoiding problems introduced by crossing transects, and accounting for surge-wave phasing), these models do not yet incorporate bottom friction and obstruction effects of the sort considered by WHAFIS, and (at this time) work only with pre-flood uneroded terrain. Furthermore, FEMA has not developed guidance for 2-D overland wave modeling. Nevertheless, the results of 2-D wave models can be used by Mapping Partners to help develop estimates of the incident wave conditions for transect analysis. For scoping purposes, the Mapping Partner and the FEMA Study Representative must agree on where and how 2-D wave models will be used, and where and how the "handoff" from the 2-D wave model to the 1-D models will be made.

- Historical Flood Conditions: Data from previous flood events along sheltered water shorelines (including water levels, flood paths and velocities, incident and overland wave conditions, erosion and overwash, wave overtopping and ponding, flood-borne debris, building damage, etc.) can help to supplement and refine sheltered water flood studies. There may be opportunities to gather historical flood data in sheltered water areas that do not exist on open coast shorelines, either because of reduced wave energy (and destruction of upland development) in sheltered waters, the number of buildings situated along sheltered waters, or other reasons.

  Historical flood conditions may be estimated through a post-storm flood hazard verification process and through a historic flood hazard reconstruction process:

  - Verification involves the documentation of flood conditions immediately following a flood event using field reconnaissance and surveys[5],
  - Reconstruction involves research and interviews to reconstruct the characteristics of a past significant flood event.

  The Mapping Partner and the FEMA Study Representative should discuss the appropriateness and feasibility of conducting flood hazard verification and reconstruction activities.

2. Water Levels

The stillwater elevation on the open coast includes the contributions of astronomic tide, storm surge and freshwater inputs. The sum of stillwater and wave setup (discussed in a later section) is termed the mean water level. Within sheltered waters, the stillwater level may depend in part upon the adjacent open coast flood levels (owing to inland penetration), and may further depend upon local processes including wind setup[6] and rainfall. While wave setup is excluded from the definition of

[5] Note that time is of the essence should a significant flood event occur during the study period, high water marks are perishable and may be quickly obliterated by rainfall and cleanup efforts; eroded beach profiles may be altered by post-event tidal and wave action or by human activities.
[6] The CEM (USACE, 2006) defines Wind Setup as follows: On reservoirs and smaller bodies of water (1) the vertical rise in the still-water level on the leeward side of a body of water caused by wind stresses on the surface of the water; (2) the difference in still-water levels on the windward and the leeward sides of a body of water caused by wind stresses on the surface of the water.

stillwater, the inland penetration of the coastal storm surge will include some portion of the open coast wave setup, which will then be counted as part of the sheltered stillwater. Locally generated setup, however, remains excluded, contributing instead to the sheltered mean water level. Each component of the sheltered stillwater level must be accounted for in a study, in accordance with the procedures recommended below.

Recommended Procedures

New Studies: If a sheltered basin is included within the domain of a new detailed coastal study, all processes contributing to the stillwater level will be explicitly accounted for, and special sheltered water considerations should not be required. An exception might be the need to consider the direct contribution of rainfall if special site characteristics require. In such a case, the guidance given for storm surge studies can still be followed, with the time and space-varying rainfall intensity chosen according to storm characteristics, and included as an additional term in the surge model continuity equation.

Existing FIS: Unlike a new detailed coastal study in a sheltered water area, previous modeling for an existing FIS may not account explicitly for all stillwater parameters. Thus, the following issues should be considered when updating an existing study:

Inland Penetration of the Coastal Flood – If a sheltered basin is included within the domain of a detailed coastal study, the coastal influence will be explicitly included. However, if a basin falls outside the detailed study region, but is hydraulically connected to the coast during flooding, then the coastal influence must be routed to the site. Although the 1-percent-annual-chance stillwater elevation is a statistical entity and not associated with any particular storm, the Mapping Partner may be able to approximate the coastal influence by use of an equivalent-event hydrograph routed to the sheltered site using simplified modeling such as standard 1-D unsteady flow models. Guidance for the selection of an equivalent hydrograph can be found in the documentation of bridge scour procedures for tidal sites published by State and Federal highway agencies (e.g., see Federal Highway Administration Hydraulic Engineering [2004] Circular 25 [HEC 25] or Sheppard and Miller, 2003). The hydrograph shape should be chosen to mimic the hydrograph of a typical storm, and should have an amplitude equal to the coastal elevation at the recurrence interval of interest. The effective hydrograph duration should approximate the duration of a storm of median size and forward speed, the two parameters that govern duration. A simple analytical form of an equivalent hydrograph suggested by Cialone et al. (1993), and discussed in HEC 25 is:

$$S(t) = S_{peak}\left(1 - e^{-\left|\frac{D}{t-t_0}\right|}\right)$$

in which D = R/V = half storm duration (hr); R = radius to maximum winds (n-mile or km)[7]; V = forward speed of storm (knots, kph); S_{peak} = peak surge elevation for selected return period (ft or m); t = time (hr); and t_0 = time of the hydrograph peak (hr). HEC 25 also gives a slightly more

[7] Note that all dimensions must be in consistent units.

complicated form which better represents the falling limb of a typical surge hydrograph, and which may be preferred in practice. The Mapping Partner should review HEC 25 for additional information.

If the sheltered geometry is extremely complex or large, or if there is not a natural conveyance channel between the site and the coast, then this simplified approach may not be acceptable, and a full study may be necessary.

Local Wind Setup - In addition to the inland penetration (if any) of the open coast storm surge, local winds may produce a variation of the stillwater level if the sheltered basin is of sufficient size. A strong wind blowing across a bay, for example, will elevate the water level on the downwind shoreline, and depress the level on the upwind shoreline. The method used to compute this effect will depend upon the size and complexity of the sheltered water body. In the simplest case, a fixed wind speed and direction might be chosen based upon the local climatology and with consideration of the associated open coast flood event. The surface tilt can then be estimated using a simplification of the long wave equations, in which time variation and flow are excluded and a balance is assumed between the surface slope and the wind stress terms. How this is implemented depends on the nature of the local storms (hurricanes vs. northeasters, for example) and the characteristics of the site (such as forest and other land cover that may provide wind sheltering). General guidance regarding the appropriate governing equations, the wind stress coefficients, wind speed dependence upon hurricane parameters, and wind sheltering coefficients, can be found in the User's Manual for the FEMA storm surge model (FEMA, 1988). At the next level of complexity, a 1-D model such as BATHYS (Dean, 2004) could be adopted. If 1-D estimates are not deemed adequate, then more complex modeling should be undertaken using a 2-D hydrodynamic model, restricted to the vicinity of the sheltered site.

Particular consideration must be given to wind direction and phasing with the open coast flood. For northeasters, a single dominant direction can be assumed, with coincidence between the inland surge penetration and the locally generated components. The situation is more complex in a hurricane region because the circular wind pattern and rapid storm translation allow winds of any direction and phasing. In this case, the Mapping Partner should be guided by the fact that the 1-percent-annual-chance coastal flooding is dominated by storms passing to the left of the region (by a distance of about one median storm radius), and traveling at median speed in the median direction. Given these assumptions and knowledge of the inland propagation time, a reasonable inference can be made regarding wind speeds and directions at the sheltered site.

Rainfall Contributions - Open coast flood levels are primarily controlled by surge and tide, neglecting any rainfall contribution. However, the relative significance of rain may increase in sheltered waters where the surge/tide magnitude declines and where the rain volume is concentrated and confined within the local watershed. In order to account for rainfall effects, the Mapping Partner may adopt a rainfall representative of the local storm characteristics (e.g., hurricane or northeaster), and estimate the runoff within the sheltered watershed as an addition to the surge prism. Owing to a lack of hurricane rainfall data and the complexity of the combined processes, a simple approach to rainfall selection is recommended. For hurricanes, an empirical estimate of rainfall intensity vs. central pressure and radius was developed for the Interagency Performance Evaluation Task Force (IPET) study (USACE, 2007) based on the NASA Tropical Rainfall Measuring Mission. The suggested intensity in millimeters per hour for radial distances *r* (n-mile) from the eye is given by[8]:

$$m(r) = \begin{cases} k(1.14 + 0.12\Delta P)\ ;\ r \le R_{\max} \\ k(1.14 + 0.12\Delta P)e^{-0.3(r - R_{\max})/R_{\max}}\ ;\ r > R_{\max} \end{cases}$$

in which R_{max} is the radius to maximum winds (n-mile), ΔP is the central pressure deficit in millibars, and k is a dimensionless coefficient accounting for azimuthal variation. Following the IPET study, it is suggested that k be taken as 1.0 to the left of the eye, and 1.5 to the right.

When implemented as an equivalent single storm, suitable values for the storm parameters are the median local radius and the pressure corresponding to a storm producing a peak coastal surge approximating the 1-percent-annual-chance value. An analogous approach could be followed for northeasters, with the additional option of basing the rainfall estimate directly on historical rainfall observations (averaged over multiple gages) for storms that produced coastal levels approximating the 1-percent-annual-chance value.

The only other rainfall-related topic suggested for inclusion at this time is the statistical combination of riverine flood elevations with coastal elevations where the processes are assumed to be independent. The computation follows methods given in the Atlantic/Gulf and Pacific guidelines[9] (e.g., see Atlantic/Gulf guidelines Section D.2.4.5.4 *Combined Effects: Surge plus Riverine Runoff*).

3. Offshore Waves

Long-term wave information necessary to develop flood hazard estimates is often not available in sheltered waters[10]. In these cases, wave estimation is required. Wave estimation in sheltered waters may be more complex than for offshore conditions as a result of interactions with the seabed, complex geometry of the water body, wave transformations, and topographic/land cover influences on the wind. However, many sheltered waters are small and have fetch-limited conditions, which simplify wave estimation.

[8] Note that r and $R_{\max}$ must have the the same units (e.g., miles, nautical miles, etc.).
[9] A more detailed treatment of correlated coastal storm tide and rainfall effects would be extremely complex and is not justified in most sheltered water studies. However, this is a topic that should be evaluated during project scoping.
[10] To obtain estimates at the 1-percent-annual-chance level, at least 30 years of data is commonly recommended.

Two general approaches for estimating waves are parametric and numerical. The parametric models are 1-D and only include the most rudimentary physics. The numerical models are 1-D or 2-D and include more physics, but may also be data intensive and computationally demanding.

The parametric models used in the United States are based on the Sverdrup-Munk-Bretschneider equations. Several adjustments have been developed for wind speeds, temperature, fetch width, etc., and these are summarized in the Shore Protection Manual (SPM) (USACE, 1984) and the Coastal Engineering Manual (CEM) (USACE, 2006). The shallow water form of the hindcast equations given in the SPM includes an adjustment for bottom friction. The SPM shallow water equations do not reduce to the deep water equations in deep water, but Hurdle and Stive (1989) have provided an alternative formulation that addresses this issue. This approach is recommended for sheltered waters[11].

Three common numerical wave models are SWAN (acronym for Simulating Waves Nearshore), MIKE 21 NSW & FM SW (acronyms for Nearshore Waves and Flexible Mesh Spectral Waves, respectively), and STWAVE (acronym for Steady State Spectral Wave).

- SWAN is a public domain code developed at the Delft University of Technology. A commercial version, which can couple SWAN with Delft3D (a nearshore hydrodynamic model), is marketed by Delft Hydraulics. SWAN includes wave generation, dissipation, non-linear interactions, and transformations. It also includes bottom friction, currents, shoaling, refraction, diffraction, depth induced breaking, and wave setup.
- MIKE 21 is a proprietary code developed and marketed by the Danish Hydraulic Institute and is a family of 2-D models for simulating free surface flows. The MIKE 21 NSW module is for nearshore spectral wind-wave estimation. MIKE 21 includes wave generation, dissipation, interactions, and transformations. The domain may be gridded using rectilinear, curvilinear, or flexible meshes. Interactions between long wave flows (tides, surge) and waves can be fully coupled.
- STWAVE is a code developed by the U.S. Army Corps of Engineers, one version of which is available from USACE[12], and another version of which is available from the Corps' private, technology transfer partner, Veri-Tech. STWAVE is a steady state model that includes wave refraction and shoaling, depth and steepness induced wave breaking, diffraction, parametric wave growth, wave-wave interaction, and white capping.

Recommended Procedures

New Studies: The draft guidelines for both the Pacific and the Atlantic/Gulf coasts (FEMA, 2004; FEMA, 2007) recommend the use of 2-D models. Given that the effort to develop the primary

[11] The CEM recommends using the deep water hindcast equations in all depths and imposing a limit on the maximum wave period.
[12] http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=Software;9

input data (gridded bathy/topo, wind fields, and friction coefficients) is similar for the models, it is recommended that only "third generation" models be used. MIKE 21 is a third generation model and is on the approved list of FEMA models. SWAN is also a third generation model and has been used for post-Hurricane Katrina FEMA flood studies in Mississippi. Note that the current version of STWAVE is not a third generation model; however, use of this model by USACE or other experienced STWAVE users may be acceptable in some instances. Model selection should be discussed with the FEMA Study Representative in the scoping phase.

Unless sheltered water flood studies are conducted in simple settings, with very limited data, or with very limited budgets/schedules, a 2-D wave generation model should be used and coupled with a numerical hydrodynamic model (long-wave flow models that account for tides and surge). Full physical coupling provides the best results because tides and surge determine the water depth upon which waves are generated and transformed, and wave setup resulting from wave breaking influences the water depth. However, full coupling has a high computational overhead. In sheltered waters, the waves are usually small and the wave setup is small. As a result, it may not be necessary to implement full coupling between the models. Rather, solving the hydrodynamic model for tides and surge and then solving the wave model may lead to sufficiently accurate results. The model coupling decision, and its impacts on project effort, budget, and schedule should be examined during the scoping phase.

For flood studies in simple settings or with very limited wind information or limited budgets/schedules, it may not be necessary (or possible) to conduct a full 2-D model simulation. For these cases, the parametric methods of SPM, CEM, or Hurdle and Stive (1989) should be used. For small basin cases, the wind may be considered steady and uniform and the waves may be fetch limited, further simplifying the analyses. The SPM/CEM equations are for a uniform depth; if variations in bathymetry are significant, these methods may be generalized to a transect form (Dean, 2005).

Offshore waves may propagate into the sheltered water bodies and may complicate the analyses. However, long-term open coast wave information is often available from measurements or hindcasts, and this information may sometimes be specified as a boundary condition for 2-D wave models employed within the sheltered water body. The 2-D wave generation models employed should include appropriate wave transformations. If a parametric method is used to estimate the waves generated within the sheltered water body, the offshore waves must be transformed and added to the locally generated waves. A 2-D wave transformation model or methods described in the SPM and CEM may be used.

The spectral wave height and spectral wave period are used in the runup and overtopping analyses. In regions where both offshore and local waves exist and are propagating in the same direction, the combined wave height and combined wave period can be estimated as

$$H \approx (H_1^{\,2} + H_2^{\,2})^{1/2}$$

and

$$T \approx \frac{T_1 H_1^{\ 2} + T_2 H_2^{\ 2}}{H_1^{\ 2} + H_2^{\ 2}}$$

in which (H_1, T_1) and (H_2, T_2) are associated with the offshore and local waves, respectively.

On the Pacific coast, offshore waves propagating into a sheltered water body may induce dynamic setup[13], an effect that may be determined using the DIM model (FEMA 2004).

Existing FIS: In order to update an existing FIS, the Mapping Partner should evaluate available information and make new calculations that indicate how water levels and wave heights should be combined. The Mapping Partner should then select a water level-wave height combination having maximal local flood impact, whether controlled by runup and overtopping, or by overland wave propagation, depending upon the nature of the terrain. A conservative default procedure for use in updating existing studies is to combine the 1-percent-annual-chance SWEL with the 1-percent-annual-chance wave height that controls the upland flood conditions.

Available information that should be considered includes the nature of the controlling storms, data describing those storms, including parameter distributions from prior simulation studies, and direct observations from historical storms. In a hurricane environment, for example, it may usually be assumed that 1-percent-annual-chance flooding is dominated by storms passing to the left of the site, represented by median values of storm radius, forward speed, and track angle, with intensities sufficient to produce the 1-percent-annual-chance stillwater. Given this and the geometric storm representation, an inferred wind speed and direction history can be obtained at any point. From these, simple wave estimates can be obtained using the methods discussed above. It is recognized that any such construction of an equivalent event is inherently approximate, and so must be performed with care so as to ensure an acceptable result. If this cannot be done, the only recourse may be to conduct a new detailed study.

4. Wave Setup

Existing guidance, given in the Pacific and Atlantic/Gulf guidelines is appropriate for use in sheltered waters and hence remains unchanged. Note that locally generated wave periods are short in sheltered waters and associated dynamic setup is not likely to be important, and can therefore be neglected for locally generated waves. However, dynamic wave setup associated with ocean waves that penetrate into a sheltered water body should be considered in the analyses, as described in Section 3 of this memorandum.

[13] Dynamic setup is the modulation of the wave setup associated with the interactions among different wave frequencies in the incident wave spectrum. Dynamic setup is generally more important for longer period waves, such as experienced on the open coast of the Pacific. Dynamic setup is not included in water level estimates on the Atlantic and Gulf coasts, or in sheltered waters where the locally generated waves have shorter wave periods.

5. Event-Based Erosion

Topographic changes during a storm are dependent on a number of factors, most notably:

- Stillwater flood levels (tide, storm surge, wave setup, seiching, freshwater input, etc.)
- Incident wave conditions (wave height, period, and direction) associated with each water level analyzed
- Storm duration
- Sediment type(s) subject to erosive forces during flood conditions
- Pre-storm profile
- Failure of a coastal structure[14]

In extreme cases, event-based erosion (EBE) may result in large-scale topographic changes (i.e., barrier island lowering/breaching or coastal structure failure) that alter the pathways by which open coast surge and waves penetrate into sheltered water bodies. This issue can have significant effects on the complexity of a flood study and must be considered carefully during project scoping.

Section D.2.9.3.4 of the Atlantic Ocean and Gulf of Mexico Coastal Guidelines Update (FEMA, 2007) states, "For the purposes of assessing storm-induced erosion, the classification of an area as "sheltered" suggests that shoreline or wetland response to the storm surge and wave action is expected to be minimal." There may be some sites where this assumption may not be appropriate -- historical evidence and geologic data should be reviewed by the Mapping Partner since they will be of greatest use in evaluating whether and to what extent EBE should be included in a study.

While the current FEMA suggestion to ignore EBE generally holds true for tidal flats and wetland shorelines that are inundated during the entire flood, further guidance is needed for sheltered water sandy beaches (with or without dunes) and erodible banks and bluffs that are attacked by waves during flood conditions.

Recommended Procedures

New Studies: In general terms, the Mapping Partner should first consider the physical setting at the site (including the presence of underlying rock, previous inlet formation, etc.) as a guide to whether EBE will be significant. If the local sediments are consolidated and resistant to erosion, the Mapping Partner need not proceed further with an EBE analysis. If historical evidence suggests a site has not been subject to erosion during past severe flood events, then it is reasonable for the Mapping Partner to assume future EBE will not be significant during a base flood.

If the initial review shows that a sheltered water shoreline is not resistant to erosion (or has eroded in past severe flood events), the next step is to evaluate how the analyzed stillwater, wave, and storm conditions will affect the site. One possible approach is to follow the general EBE approach contained in the Atlantic and Gulf guidelines, but to "calibrate" for local conditions based on historical evidence. Mapping Partners are advised, however, that outright adoption of open coast

[14] Failure of coastal structures is considered in the next section of this memorandum.

cross-sectional erosion rules is not recommended for sheltered waters[15]. The preferred alternative is the use of geometric methods based on observed eroded profile geometries. At this time, there are insufficient historical erosion datasets and existing flood hazard studies in low-energy environments available to prescribe a single geometric approach to assess EBE of beaches, banks, or erodible bluffs in sheltered water areas. The Mapping Partner may develop a geometric approach based on an analysis of local pre- and post-storm profile data, if available, for the study reach or another area with similar geomorphic, geologic, and physical characteristics. The proposed approach and all relevant supporting data should be submitted to the FEMA Study Representative for approval.

Process-based erosion models, such as those discussed in Section 4.6 of the Pacific guidelines, may be suitable for application in sheltered water areas. With the consent of the FEMA Study Representative, the Mapping Partner may investigate the applicability of process-based models, but must ensure that model assumptions and limitations are consistent with their use in the study area. Because process-based models generally require more sophisticated input data and more computational effort than the geometric models, the Mapping Partner should select a model that is consistent with the level of effort to be applied in the overall study. Model selection must be made in close coordination with the FEMA Study Representative. Where used, results from process-based models should be evaluated against historical data to ensure that the results are reasonable.

<u>Existing FIS</u>: The procedures described above for evaluating the potential for sheltered water EBE in new studies will also apply to existing studies. However, after-the-fact addition of EBE to existing studies may complicate or invalidate prior flooding and wave analyses. If EBE methods cannot be implemented for an existing study, then either EBE considerations must be simplified (or ignored in some cases), or a new detailed flood study incorporating EBE must be undertaken.

[15] For open-coast settings, prescribed cross-sectional erosion volumes have been established (e.g., the 540 square foot criterion for retreat/removal of dunes on the Atlantic and Gulf; 270 and 190 square foot bluff retreat profiles applied along the Great Lakes).

6. Coastal Structures

Current guidance for evaluating coastal structures during 1-percent-annual-chance flood analyses is provided in Section D.2.10 of the Atlantic/Gulf Coast guidelines and Section D.4.7 of the Pacific guidelines and is applicable to studies in sheltered waters areas. Supplemental guidance has evolved from recommendations made in the aftermath of recent FISs.

Recommended Procedures

For both new and existing studies in sheltered waters, the Mapping Partner should use the recommended guidance below as supplements to existing guidance.

- Levee accredited to provide flood protection for 1-percent-annual-chance flood on existing FIRM: FEMA accredited levees should be modeled as barriers to flow in setting up the storm surge model, and should also be treated as such in all other subsequent flood hazard analyses pertinent to the 1-percent-annual-chance flood. Levee certification should be revisited/verified based on the results of the new analyses. The Mapping Partner should follow established guidance for evaluating interior flood hazards due to levee overtopping and freshwater input/drainage/ponding in areas behind the levee, where applicable.
- Non-certified Levees, Salt Pond Levees (single or multiple): Non-certified levees should generally be removed from toe to heel at ground level in the storm surge model setup and in other subsequent flood hazard analysis pertinent to the 1-percent-annual-chance flood. In instances where the Mapping Partner has reason to believe that the removal of non-certified levees would result in the underestimation of the peak storm surge elevation windward of the levees and hence should not be removed, an evaluation and proposal should be made to the FEMA Study Representative for concurrence. The proposal to FEMA should address the extension of storm surge and wave effects to non-levee protected areas.
- Coastal Armoring Structures, Navigation Structures, and Beach Stabilization Structures (e.g. revetments, seawalls, jetties, quay walls, groins, breakwaters etc.): These structures should generally be left intact in the storm surge model setup, unless the Mapping Partner has reason to believe that the failure or removal of such structures will best represent hydro-morphologic conditions during storms; in such cases, the Mapping Partner should consult with the FEMA Study Representative prior to making final decisions regarding failure or removal of these structures. These structures should be evaluated for stability per existing guidance (for coastal armoring structures, miscellaneous or beach stabilization structures), as appropriate, during the analysis of overland wave propagation, wave runup, wave overtopping, etc. In instances where TWLs are to be computed for several storm simulations, an initial evaluation should be made to determine which structural configuration (intact or failed structure), on average, best represents the most hazardous condition; this configuration should be used in computing the TWLs.
- Causeways, Roads, and Railroads: These obstacles should not be evaluated according to FEMA guidance on levees or coastal armoring structures even though they may act as such in certain instances. During storm surge modeling and the analysis of wave-related effects,

these obstacles should generally be left in place as captured in the topographic data and no additional effort should be made to either remove or represent these structures in the modeling setup. If the Mapping Partner has reason to believe that the removal or the explicit representation of such obstacles might best represent hydro-morphologic conditions during storms, the Mapping Partner should consult with the FEMA Study Representative regarding possible removal or representation of these structures.

- Industrial Facilities, Tank Farms, Containment Berms, Perimeter Roads, and Related Structures: These structures should remain in place if captured in the topographic data and no additional effort should be made to represent these structures in the modeling setup unless the Mapping Partner has reason to believe that their explicit representation will best reproduce the hydraulic conditions during storms. If these structures are captured in the topographic data, engineering judgment should be used to ascertain whether their presence unreasonably results in the under-estimation or over-estimation of flood effects, and if the Mapping Partner believes this to be the case, should consult with the FEMA Study Representative regarding possible failure or removal of these structures.

7. Wave Runup and Overtopping

Existing guidance, contained in Section 2.8 of the Atlantic/Gulf Coast guidelines and Section D.4.5 of the Pacific guidelines is appropriate for use in sheltered waters and hence remains unchanged.

8. Overland Waves

The propagation of waves overland is modeled to determine the additional flood elevation contributed by wind waves riding atop the underlying stillwater.

Recommended Procedures

New Studies: The methods to be used in new sheltered water studies should be based on WHAFIS (1-D transect approach) as specified in the Atlantic and Gulf guidelines, or on a combination of 2-D wave modeling and a WHAFIS analysis. Any WHAFIS analyses should use the most recent version of the program (V4.0 at the time this memorandum was prepared – see Divoky, 2007) which allows specification of variable wind speeds for both over-water and inland fetches. In a sheltered water study, the Mapping Partner should determine characteristic wind speeds for these fetch categories[16].

Existing FIS: Methods to be used for updating overland wave propagation in an existing study will be similar to those used for a new study. A 2-D wave model may or may not be employed to specify incident wave conditions for the WHAFIS modeling. It must be kept in mind that the locally-onshore waves may not occur in coincidence with the onshore winds, and that the maximum

[16] Mapping Partners should select sheltered water wind speeds that are consistent with present guidance for open coast mapping procedures (80 mph for OF, 60 mph for IF).

crest elevation may not occur precisely at the time of peak stillwater level. The Mapping Partner should perform a review of computed combinations of water levels and wave heights to find the condition approximating maximum crest elevation. Unless this review indicates coincidence of the highest water level and highest wave height is unlikely to occur, it is recommended that the Mapping Partner assume that it does occur.

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