Guidance for Flood Risk Analysis and Mapping

Determination of Wave Characteristics

February 2019

FEMA

Requirements for the Federal Emergency Management Agency (FEMA) Risk Mapping, Assessment, and Planning (Risk MAP) Program are specified separately by statute, regulation, or FEMA policy (primarily the Standards for Flood Risk Analysis and Mapping). This document provides guidance to support the requirements and recommends approaches for effective and efficient implementation. Alternate approaches that comply with all requirements are acceptable.

For more information, please visit the FEMA Guidelines and Standards for Flood Risk Analysis and Mapping webpage (https://www.fema.gov/guidelines-and-standards-flood-risk-analysis-and-mapping). Copies of the Standards for Flood Risk Analysis and Mapping policy, related guidance, technical references, and other information about the guidelines and standards development process are all available here. You can also search directly by document title at https://www.fema.gov/library.

Document History

Affected Section or Subsection	Date	Description
First Publication	February 2019	Initial version of new transformed guidance. The content was derived from the Guidelines and Specifications for Flood Hazard Mapping Partners, Procedure Memoranda, and/or Operating Guidance documents. It has been reorganized and is being published separately from the standards.

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1.0 Overview and Purpose

Wind generated waves create a significant flood hazard as they dissipate their energy at or near the coastline. This type of flood hazard can result in direct impacts such as beach erosion, high-velocity currents, wave runup, wave setup and overtopping, all of which put buildings and infrastructure along developed shorelines at risk.

This document provides guidance on determining the wave characteristics that are required for a coastal hazard analysis. In this case, the coastal hazard analysis is part of a FEMA Flood Insurance Study (FIS) performed to help communities understand their coastal flood risks. The FIS applies engineering judgement and analysis to calculate the coastal hazards and create a Flood Insurance Rate Map (FIRM). It is part of the document series “Guidance for Flood Risk Analyses and Mapping,” which supports the Federal Emergency Management Agency’s (FEMA’s) Risk Mapping, Assessment, and Planning (Risk MAP) program. This guidance focuses on wave determination associated to a FIS but the same should be applicable to any other type of project that relates to FEMA mapping.

The primary goal of an FIS in a coastal area is to determine flood elevations and wave hazards. The flood elevations are determined for the 10-, 4-, 2-, 1-, and 0.2-percent-annual-chance occurrences. The wave hazards are defined as areas with significant wave energy, more specifically, as areas with a wave height greater than 3 feet. Waves directly impact the flood elevations via runup and overtopping and can cause inland wave hazards via overland propagation. The waves considered in an FIS are typically generated offshore during storms events. Wind-generated waves propagate shoreward to the nearshore zone, are subject to various transformations, and ultimately impact the coastline. In typical coastal engineering studies, this process is known as the transformation of deep water waves to shallow water waves. The extent of the impact of these waves on the coast depends on many factors including the level of surge, beach geometry, and the presence of structures. For instance, the waves may break and runup on dunes, overtop bluffs and structures, or if the surge is high, continue propagating overland and dissipate, runup, or overtop structures farther inland.

Because the physical processes governing wind-wave generation, propagation, transformation, erosion, runup, and overtopping are complex and diverse, specialized methods have been developed to analyze individual wave processes. The guidance in this document addresses wind-wave generation, propagation, and transformation from the offshore zone to the nearshore zone. The wave characteristics that are developed according to this guidance are not the end product but serve as input in overland wave propagation, erosion, wave runup, and overtopping analyses.

Figure 1 is a schematic of wave propagation and shows the zones in the coastal area, which are differentiated by the dominant wave processes (see Section 2.0).

This document is not intended to be prescriptive or procedural because there is sufficient guidance in coastal engineering literature on wave calculation protocols. Instead, this guidance is intended to provide the logic of and a framework for calculating wave characteristics that can be used as input in the analysis of erosion, runup, overtopping, and overland wave propagation. While coastal engineering literature provides guidance on the specifics of methods, calculations, models, and similar issues, this guidance aims to describe the general considerations and typical approaches used in FISs for determining wave characteristics.

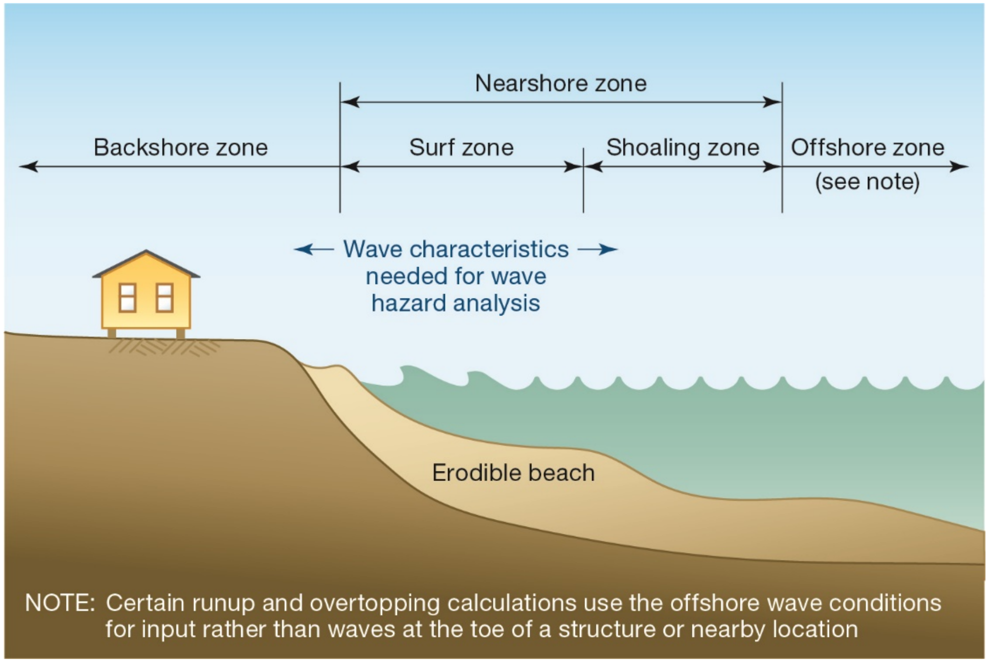

Figure 1. Wave Zones in Coastal Areas

Determining wave characteristics in the nearshore zone for an FIS requires knowledge of the input requirements for erosion, runup, overtopping, or overland propagation analyses. There are many methods of calculating erosion, runup, overtopping, or overland propagation, and it is important to consider the required wave characteristics and input location when developing a wave determination approach. For instance, an overtopping method may require the significant wave height and mean period at the toe of the structure, whereas the input for an overland propagation method is the significant wave height and peak period outside the surf zone.

The methods used to determine overland wave propagation, erosion, wave runup, and overtopping are one-dimensional (1D) and are applied along 1D transects that are typically perpendicular to the coastline. Thus, the wave determination guidance in this document focuses on providing wave characteristic inputs at the beginning of the 1D transects.

For details on input wave requirements for erosion, runup, overtopping and overland propagation analyses, see FEMA's Guidance for Flood Risk Analysis and Mapping: Coastal Erosion, FEMA's Guidance for Flood Risk Analysis and Mapping: Overland Wave Propagation, and FEMA's Guidance for Flood Risk Analysis and Mapping: Coastal Wave Runup and Overtopping.

As noted previously, determination of wave characteristics in the nearshore is just one part of the FIS, and approach for determining waves will likely be coupled to other processes and methods. Specifically, particular is the statistical framework of the analysis and the coupling with surge analysis.

The primary goal of an FIS is to determine the frequency of occurrence of coastal hazards such as the 1- or 0.2-percent-annual-chance event. The guidance in this document does not address the statistical component of a wave analysis. Guidance on statistical approaches can be found in FEMA's Guidance for Flood Risk Analysis and Mapping: Statistical Simulation Methods.

In the nearshore zone (see Figure 1), waves and water depth can be highly coupled due to wave setup processes. The coupling of wave setup and surge is not explicitly covered in this guidance, but many of the wave determination approaches naturally provide estimates of the setup processes, and coupling could be included in the approach. For information on coupling wave setup and surge, see FEMA's Guidance for Flood Risk Analysis and Mapping: Coastal Water Levels and FEMA's Guidance for Flood Risk Analysis and Mapping: Coastal Wave Setup.

This guidance is organized as follows: Section 2 presents an overview of wave processes, Section 3 presents wave models and analysis methods, Section 4 discusses general data types and their sources, and then Section 5 present a general wave transformation approach. The document ends with several recent examples of wave transformations methods in FEMA coastal studies.

FEMA and communities (e.g., Cooperating Technical Partners) often contract flood insurance studies (e.g., community-initiated Physical Map Revisions) to qualified consultants, referred to as Mapping Partners. The Mapping Partners have a high level of experience and expertise with coastal processes and are the intended audience of this guidance. Refer to FEMA's Guidance for Flood Risk Analysis and Mapping: Coastal Notations, Acronyms and Glossary of Terms for the definition of terms that are used in this document.

2.0 Wave Processes and Characterization

Waves in the nearshore zone are the result of numerous complex processes that typically start with offshore wind-driven wave generation and proceed to propagation to the shoreline. The propagation of waves to the shoreline is an area of study in coastal engineering that is generally called transformation of deep water waves (where waves are not affected by the ocean bottom) to shallow water waves (where waves are affected by the bottom).

This section provides an overview of wave processes and the need for Mapping Partners to determine wave characteristics in the nearshore zone for use in erosion, runup, overtopping, and overland wave analysis.

When an approach to determining wave characteristics in the nearshore zone is developed and implemented, it is important for the dominant wave processes to be represented. These processes may include:

- *Wind generation* – Wind generation is the transfer of wind energy to wave energy. The generation is typically considered in the offshore region and is dominated by wind speed and duration. Wind generation in inner bays and lakes may also be limited by the fetch length.
- *Propagation* – Wind-generated waves propagate without change in deep water. However, during wave generation, waves of different wave lengths occur and disperse as they propagate. Dispersion is the sorting of waves by wave speed due to the fact that waves with different wavelengths travel at different speeds.
- *Transformation* – When waves encounter shallow water or structures, they begin to transform. Shallow-water transformations start to occur when the water depth is approximately one-half the wave length. The transformations that may occur are:
    - *Refraction* – Turning of the waves so the propagation direction is perpendicular to bathymetric contours (2D process).
    - *Shoaling* – Shortening of the wavelength, slowing of wave speed, and increase in wave height as the water depth decreases. Shoaling is most notable just before wave breaking (1D or 2D process).
    - *Dissipation* – Loss of wave energy to bottom friction. Bottom dissipation effects can be enhanced in muddy or sea grass bottoms that deform due to the wave bottom stresses.
    - *Diffraction* – Turning of waves as they encounter structures (2D process).
    - *Breaking* – Steeping of the wave until it becomes unstable (1D or 2D process).
    - *Reflection* – Reflection of energy when a wave encounters an obstruction, causing increased wave energy in the adjacent areas (1D or 2D process).
- *Wave setup* – In the shoaling and surf zones, waves create a radiation stress gradient. Stress gradients impart a body force on the water column in the direction of wave propagation. The net result is that the water levels in the nearshore zone are increased by the wave process in addition to what would occur from only wind drag. Ocean waves are

not uniform and are typically considered randomly distributed around mean values. Ocean waves are therefore characterized by their energy distribution in the frequency and direction domains, which are referred to as wave spectrum. While many methods of wave analysis involve the wave spectrum, sometimes the methods use a parameterization that simplifies the spectrum to a characteristic height, period, and direction. Also, when the methods use the frequency and direction distribution (wave spectrum), the data are often reduced to a simpler parametrization for convenience.

Some of the common parametrizations are as follows:

- For wave height
  - *Significant wave height (H_s)* – Average of the highest one third of the waves during a specified period (20 minutes to 1 hour)
  - *Root mean square wave height (H_{rms})* – Square root of the average of the wave height squared
- For wave period
  - *Peak period (T_p)* – Wave period associated with the most energetic waves in the total wave spectrum
  - *Mean period (T_m)* – Mean of all wave periods in a wave spectrum or time series
- For wave direction
  - *Mean direction (θ_m)* – Mean of all the individual wave directions in a time series
  - *Peak direction (θ_p)* – Direction of the waves with the highest energy

These processes and conventions described above should be considered when developing an approach for wave determination and selecting analysis tools. Some of these tools are presented in the following section on wave modeling and analysis.

3.0 Wave Models and Analysis Methods

Many tools are available for simulating waves in coastal areas. Advances in computer technology and numerical methods have yielded powerful wave models capable of simulating all wave processes. The most common modeling and analysis approaches are reviewed in this section. The methods can be divided into the following three categories:

- Models based on the energy balance equation
- Models based on the Boussinesq approximation
- Methods based on semi-empirical and empirical approaches

Within each category, there is a large variety of capabilities, sophistication, and applicability. This section provides a general description of wave models and analysis methods that will help guide the Mapping Partner in selecting the appropriate model or method. As always, engineering judgement is required to ensure that the appropriate tools (model or method) are used.

3.1 Energy Balance Models

Models based on the energy balance equation (also referred to as the wave balance equation) are the most common, and many are available. Although the models vary in the details of the formulations and numerical solution techniques, they all use a discrete spectral representation of the wave energy and direction, are grid based, and are typically 2D.

These models are phase averaging and therefore do not resolve individual waves. The implications are that grid spacing and time steps are not limited by the individual wave period and length. Grid spacing is dictated by the coastal geometry and bathymetry. Also, if the model is applied in the nearshore zone, particularly in the surf zone, the required grid resolution may be dictated more by the rapid change in wave heights than the bathymetry. For unsteady applications, the time steps for these models are dictated by the time scales of the forcing, namely the wind fields, and are typically on the order of 10 to 20 minutes.

The discrete representation of the frequency range and direction is often referred to as bins. There is a trade-off between computational speed and resolution of the frequency range. For higher resolution, more bins are required and the computational burden increases. It is important to ensure that the frequency range covered by the bins covers the tails of the energy spectrum sufficiently. Furthermore, in applying these models to complex study areas, it is likely that waves will be generated with a larger range of wave periods. Periods for the offshore wave approaching an open coast may be 12 to 15 seconds, and periods generated in bays and other sheltered waters may be 4 to 6 seconds. Thus, the full frequency range in a model application can span a larger range than when only shelter areas or only open coasts are considered. The larger range yields additional computational burdens since for the same bin size; more bins are needed to cover the larger frequency range.

The energy balance class of models can represent all of the processes described in Section 2.0 except for wave reflection and diffraction. Algorithms have been developed that include wave reflection and diffraction in the energy balance models, but they are highly parameterized, and the algorithms for diffraction are considered experimental.

Some capabilities and potential limitations of these models are described below.

3.1.1 Half-Plane vs. Full-Plane Models

Full-plane models allow wave generation and transformation in all directions. Thus, they are ideal for simulations of cyclonic storms in which the wind field may change 180 degrees as it passes the coastline.

Half-plane models allow wave energy to propagate in one general direction, typically applied to simulate propagation from the offshore toward the nearshore. All waves traveling in the offshore, such as those reflected from the shoreline, steep bottom features, and structures, as well as those generated by offshore-blowing winds, are neglected in half-plane simulations. The half-plane version has considerably lower computational requirements, and executes faster than half-plane models and is generally appropriate for most nearshore coastal applications except for semi-enclosed bays and lakes where there is no obvious offshore direction. In these cases, a full-plane model should be used since it allows wave transformation and generation in all directions.

3.1.2 Unsteady vs. Steady-State Models

Unsteady models can represent wave generation and transformation in general settings and are ideal for simulating waves during storm events since the wind forcing is time dependent. However, there are times when a steady-state approach is valid and can reduce the computational burden significantly. A steady-state model is appropriate for wave conditions that vary more slowly than the time it takes for waves to transit the domain. For wave generation, the steady-state assumption means that the winds have remained steady sufficiently long for the waves to attain fetch-limited or full-developed conditions (i.e., waves are not limited by the duration of the winds).

3.1.3 All Encompassing vs. Coupled Approaches

Some energy balance models can be considered “all encompassing” in that they are unsteady and represent both the wave-generation and wave-transformations processes (with the notable exclusion of reflection and diffraction). These models have the advantage of seamlessly representing all required processes and the disadvantage of being computationally intensive.

Other models may be coupled to harness the focused benefits of individual models. The individual models may focus on one or more of the wave processes and may therefore be limited in their applications. Examples are deepwater wave generation models that focus on unsteady wind generation and dispersion but do not represent other wave transformation processes. Other models are steady state and focus on shallow water wave transformations. These models have the advantage of computational efficiency. Applying the strengths of these individual models and coupling them allows their combined efforts to represent the required wave processes. However, this approach requires a transfer of data between the models, which may reduce the computational efficiency.

3.1.4 Wind Averaging Periods

Wind data are used to simulate wave generation and are characterized by speed and direction. An important consideration when using wind data as input to models is the wind averaging time. Wind data and outputs from wind models typically represent a defined averaging period (e.g., 1- or 10-minute winds). Similarly, the wind-wave generating algorithms in the models are designed to use wind inputs with a designated averaging period. Thus, it is important to consider the averaging period of both the wind data used to force the model and the averaging period required by the model. The transformation from different averaging periods is not unique, but there is guidance available in the general literature if wind data need to be adjusted from one averaging period to another.

The standard height for reporting land-based wind data is 10 meters above ground, and it may be necessary to adjust the wind speed for height above ground to be consistent with the expected height in the model.

3.1.5 Publicly Available Grids

Beginning in the mid-2000s, FEMA has been developing a library of model meshes (typically for ADCIRC [ADvanced CIRCulation] and SWAN [Simulating WAves Nearshore]) for coastal areas. These large-scale, pre-computed model domains are typically made available at the completion of an FIS. As such, Mapping Partners interested in restudying flood hazards where wave transformation is necessary should consider using FEMA's collection of model domains as a starting point. For example, a new coastal development that modifies the coastline significantly may require a review of water levels, including wave setup. In this case, the Mapping Partner may use the larger model domain as a boundary condition for a more refined, nested grid developed specifically for said coastal development. In all cases, model grids should be constructed with the appropriate resolution to simulate irregular bottom contours and any special bathymetric features.

3.2 Boussinesq Models

As with energy balance models, there are many variations in Boussinesq models in both mathematical formulations and numerical solutions. However, Boussinesq models all share the important characteristics of being phase-resolving and time dependent (unsteady). The phase-resolving characteristic yields the benefit of representing reflection and diffraction directly but at the expense of higher computational requirements when compared to wave balance models. Boussinesq models require relatively high resolution, typically with more than 10 grid cells per wavelength. In addition, the time step must resolve the wave period, thus requiring time steps on the order of 1 second or less.

Therefore, due to their significantly higher computational burden Boussinesq models are typically applied in smaller domains than those used with the energy balance models. Boussinesq models are commonly used near the coastline, with most applications in harbors or similar enclosures where diffraction and reflection are important. In these applications, waves needed at the entrance of the harbor or offshore of the structure as input to Boussinesq models are obtained from measured data or from an energy balance model.

3.3 Overview of Empirical Methods of Wave Generation

Prior to the advent of the high-speed computing and the application of comprehensive wave models, simpler approaches for wave generation and transformation were applied. The empirical and semi-empirical methods provide a simplified approach for wave determination in comparison to applications of the energy balance and Boussinesq models presented in Sections 3.1 and 3.2. These methods can be useful to estimate wave characteristics prior to employing sophisticated models, and can also be applied in cases where the coastal geometry, bathymetry and forcing conditions meet the simplifying assumptions of each method. Smoothly varying coastlines and bathymetry and small sheltered waters are examples of potential applications of the empirical and semi-empirical methods.

The empirical, semi-empirical and theoretical wave methods consist of both equations and nomograms and are documented in the Shore Protection Manual (USACE, 1984) and the Coastal Engineering Manual (USACE, 2003). A number of the wind-generation and wave transformation methods have been coded in the Automated Coastal Engineering System (ACES) software package (USACE, 1992). Mapping Partners should consult these manuals for details on these and other empirical, semi-empirical and theoretical methods.

3.4 Parameterizations and Representations of Wave Processes

The models and methods described above all use various parameterizations and representations of wave processes. The Mapping Partner should carefully review the wave parameterizations for each model or tool used in the selected approach to ensure that the appropriate definitions are used and that the definitions are consistent throughout the approach.

4.0 Data Types and Sources

As in all technical analyses of coastal processes, the available data support many elements. While it is not possible to identify and define all of the data that may be available or the data that may be needed for a particular study in a particular area, this section can help Mapping Partners think through the data needs of their study.

Elements of a study for which data may be used are:

- Site characterization
- Model configuration
- Model forcing
- Model calibration or validation

Types of data that may be used for these elements include:

- Bathymetric and topographic elevation data
- Sediment grain size and distribution
- Time and spatially varying winds
- Time varying waves
- Water levels
- Ice formations (where applicable)

4.1 Study Elements

4.1.1 Site Characterization

Site characterization is the process of reviewing data in the context of the study goals. The characterization will determine the available data, key wave processes, the required extent of the study area as well as other considerations. The results of the site characterization will guide the development of an approach for determining waves in the nearshore region. Site characterization can range from high-level considerations to site conditions that may require special consideration.

An example of a high-level consideration is the length of coastline covered in the study and its geometric complexity, which could determine whether a 1D or 2D analysis is required. An example of a site condition that may require special consideration is bottom sediments. The muddy bottoms near the Mississippi River Delta will be deformed by wave action. Deformed muddy bottoms will increase the dissipation and attenuation of waves as they propagate and reduce the wave energy approaching the shoreline. Thus, if a wave transformation model or method is being applied in the Mississippi River Delta region of the coast, it is important that the dissipation due to bottom friction be accounted for in the model.

4.1.2 Model Configuration

The data for model configuration are primarily bathymetric, topographic, and land use. Topographic data may be necessary because the surges that occur in large wave events often inundate land, and the nearshore zones may be over what is land under normal water level conditions. Land-use data can be used to identify appropriate friction factors and model boundaries.

Of course, in some regions, ice cover is also significant. A unique aspect of the Great Lakes and other ice-covered areas, such as Alaska, is that during part of the year, ice develops from the shoreline (i.e., shore-fast ice) toward offshore, which leads to partially or completed ice-covered water bodies. When present, shore-fast ice becomes a natural impediment for storm-generated waves to reach the shoreline. If ice cover is omitted from the wave model, there is a potential for introducing biases into the flooding analysis. Neglecting ice cover could result in overstating the frequency and severity of wave conditions at the shoreline in the winter. Mapping Partners should consider any unique aspects of the geographic areas that are being modeled.

4.1.3 Model Forcing

Forcing data can consist of wind, tide, and wave data depending on the details of the wave determination approach. Wind data are used to force wave models that include wave generation. Water-level data, when combined with bathymetric data, can be used to set the water depths in a wave analysis or as input to a surge model when the wave and surge determination are coupled. Wave data either from observations or generated by larger scale models (see section 4.3) can be used as an offshore boundary condition.

4.1.4 Model Calibration and Validation

Model calibration and validation data require measured wave data. Model calibration and validation are essential in evaluating model performance. During model calibration, model parameter values are adjusted to improve the match with a specific dataset. This process is sometimes referred to as “tuning” the model for a best match with the data.

Model validation is the process of applying the calibrated model to simulate another set of measured data that are not used in the original model calibration and making comparisons. The results of the validation are often used to characterize the uncertainty in the model predictions to make predictions beyond the periods and/or scenarios used for calibration.

4.2 Bathymetric and Topographic Data

Bathymetric and topographic data are one of the most important aspects of any study. It is critical to use the best available data at the time of the study. Elevation data sources include Light Detection and Ranging (LiDAR) data (where visible in shoaling zones or for use as topographic input), U.S. Army Corps of Engineers (USACE) and U.S. Navy hydrographic surveys, and National Oceanic and Atmospheric Administration (NOAA) navigation charts and surveys, as detailed in FEMA’s Guidance for Flood Risk Analysis and Mapping: Coastal General Study Considerations. Some state and local beach surveys can be used to characterize the surf zone in regional-scale modeling.

4.3 Wind Data

Because most of FEMA coastal FISs use wind-driven waves as the dominant cause of flooding, many wave studies require wind data for a variety of inputs. For example, a surge modeling study requires wind fields that simulate a hurricane as input into an ADCIRC model. The Mapping Partner should rely on meteorological experts when appropriate.

The needs of every study are unique, and the Mapping Partner is encouraged to conduct a thorough search of available wind data when necessary. Sources include:

- NOAA weather stations
- Airport and similar wind gages
- Offshore gages and data buoys
- Hindcasts (WAVEWATCH III)
- Private meteorological datasets and forecasts

4.4 Wave Data

FISs can often use existing wave data to enhance or validate a wave analysis or model result. Wave data are also often used to set boundary conditions for analytic solutions or wave models. The Mapping Partner should rely on engineering judgment for the appropriate use of wave data in an FIS.

Wave gages collect measurements of wave characteristics. The gages typically report the wave data as height, period, and direction, or they report the wave spectra. Wave gages are expensive to install and maintain and are sometimes taken out of service for maintenance or repair or as in the Great Lakes, removed to prevent ice damage during the winter. Wave gages with wave height, period, and direction data are critical for the calibration or verification of hindcast modeling, for the validation of other wave models, and for the development of offshore wave conditions for input to wave transformation models.

When measured data are used in offshore boundary conditions in a wave transformation model, the period of record is relevant to the calculation of wave statistics. In general, for a low frequency statistic, the period of record must be relatively long. Typically, 30 years of gage data are considered appropriate to calculate a 1-percent-annual-chance event, based on current practices. However, the Mapping Partner must evaluate on a case-by-case basis whether the period of record is sufficient to calculate a particular return period. The evaluation can be most readily accomplished by comparing how well the data fit the assumed probabilistic distribution. For a full discussion of coastal statistics, refer to FEMA's Guidance for Flood Risk Analysis and Mapping: Statistical Simulation Methods.

4.4.1 Measured Offshore Wave Data

As discussed previously, offshore wave data are often the source of the deep water wave information that can be transformed by the Mapping Partner for use in the nearshore input for a variety of coastal processes such as erosion, runup, overtopping, or overland wave analysis. This section discusses the most common publicly available sources of measured offshore wave data and hindcast wave data. One-off collections of wave data may be available from oil company platforms, ships, local agencies, satellites, and engineering studies performed along the coast and may also provide valuable wave data information for an FIS.

Two commonly available wave data sources in the United States are:

- **National Data Buoy Center (NDBC)** – The NDBC (https://www.ndbc.noaa.gov/) is a branch of NOAA. The NDBC has installed and maintained offshore meteorological and oceanographic buoys since the late 1960s. Each NDBC buoy records data for different time periods.
- **Coastal Data Information Program (CDIP)** – Since 1975, the CDIP (https://cdip.ucsd.edu/) has operated buoys that record directional wave spectra. Part of the Scripps Institute of Oceanography (SIO), the CDIP analyzes buoy data to provide wave height and wave direction estimates. CDIP wave buoy measurements are available along the Pacific Ocean, Gulf of Mexico, and Atlantic Ocean.

In addition to these common wave data sources, the Mapping Partner should investigate other local data sources that may be useful.

4.4.2 Hindcast Waves

Hindcast wave data are developed using wave generation models (hindcast models) that estimate wave parameters from weather data such as wind and pressure fields. Two common hindcast datasets are the Wave Information Studies (WIS), developed by the USACE Coastal and Hydraulics Laboratory Engineer Research and Development Center, and hindcasts based on NOAA's Wave Watch III model.

Significant improvements have been made in the analysis of historical meteorology in recent years. Wind fields have been re-analyzed and used in so-called third- and fourth-generation wave hindcast models, yielding improvements in wave hindcasts. The advent of economical high-speed computing capabilities has enabled directional wave spectral modeling to be performed globally. The newer models have been calibrated and verified by comparing them with measured data at offshore buoys and with satellite scatterometer measurements.

Hindcast wave data are valuable as boundary data in wave modeling and could be used in some cases for additional model calibration. However, given that hindcast waves are derived from modeling, their use as a source of calibration data should be approached cautiously. Preferably, the data is used as a basis for comparison for evaluating the accuracy or consistency of other models.

Currently, two commonly available wave hindcast databases and third-party datasets are as follows:

- **WAVEWATCH III** – NOAA's Marine Modeling and Analysis Branch prepares weather and wave forecasting for all of the world's oceans by executing the WAVEWATCH III model, which computes directional wave spectra (https://polar.ncep.noaa.gov/waves/). Products include sea wave heights, periods, and directions; swell wave heights, periods, and directions; and several other meteorological parameters. The emphasis of the available data is forecasting. WAVEWATCH III is a third-generation deepwater wave prediction model (Tolman, 1997; 1999; 2009).

- **Wave Information Studies** – The WIS was created by the USACE's Waterways Experiment Station (http://wis.usace.army.mil/). WIS reports cover the Pacific, Atlantic, Gulf of Mexico, and Great Lakes shorelines. Wave hindcast data include separate values for sea and swell wave heights, periods, and directions. Many stations are close to shore and include some portion of shallow water transformations but not directly at the shoreline. Currently, the available time periods for the WIS hindcasts vary by region and gage location (wis.usace.army.mil). Datasets begin as early as 1979. The regions of data and the approximate number of stations are as follows:
  - Western Alaska: 469 stations
  - Pacific Ocean: 374 stations
  - Atlantic Ocean: 565 stations
  - Gulf of Mexico: 365 stations
  - Great Lakes: Total of 1,950 stations in Lakes Ontario, Erie, Huron, Michigan, and Superior
- **Third-Party Datasets** – Some third-party vendors provide commercially available hindcast wave datasets. The datasets include the results of hindcast modeling systems that cover the Pacific Ocean, Atlantic Ocean, and Gulf of Mexico but not the Great Lakes. The datasets are continually updated after comparisons with buoy measurements and scatterometer satellite observations. The Mapping Partner should consult with vendors about the available data in the study area.

4.5 Water Level Data

Water level data are used for a variety of applications in a coastal FIS and in particular for the wave transformation from offshore to nearshore. The data are often used to verify model results and provide critical information on how a model is performing. The Mapping Partner should include model comparisons to water-level data as appropriate. A recent example of the critical nature of applying water level data to model results is a comparison of ADCIRC + SWAN surge model results to historical events. A good agreement between model results and measured water-level data can greatly increase the public's confidence in model results and therefore increase their confidence in the final mapped flood hazards.

The tide is recorded at a large number of gages throughout the Atlantic, Gulf of Mexico, and Pacific coastlines, with some records dating back more than 100 years. Most of the data are available at NOAA's website for the National Water Level Observation Network (https://tidesandcurrents.noaa.gov/) as a 6-minute or 1-hour series over a particular site's entire period of record.

Additional data may be available from other sources including the U.S. Geological Survey and USACE. Data information is also available in FEMA's Guidance for Flood Risk Analysis and Mapping: Coastal Water Levels.

4.6 Ice Formations

As previously mentioned, local conditions must be considered in every study. In several FEMA Regions, ice cover is a significant factor affecting wave determination. The Mapping Partner should understand and apply ice data as appropriate. Ice data are available from the following data sources, which cover distinct time series:

- NOAA Great Lakes Environmental Research Laboratory (GLERL) Ice Concentration Data Base (1960 to 1979), https://nsidc.org/data/g00804.html
- NOAA GLERL Digital Ice Atlas (1973 to 2002), https://www.glerl.noaa.gov/data/ice/atlas/
- NOAA GLERL ice thickness data (1966 to 1979), https://nsidc.org/data/g00803.html
- NOAA GLERL digital ice cover data (2003 to 2009); obtain from GLERL

5.0 General Wave Transformation Approach

Section 4.0 discusses data types and sources, information that is critical to the approach and methods used to perform the wave transformation from deep water to shallow water waves. The Mapping Partner must decide what an appropriate transformation approach is, based on available data, the physics of wave transformation in the particular area, the physical characteristics of the site, and the end use of the transformed wave characteristics.

Section 5.0 presents a general approach to wave transformation from offshore to nearshore for the purpose of determining wave characteristics that can be in subsequent analysis, in particular they can be used in erosion, overland wave propagation, runup, and overtopping analysis. While this section presents the wave transformations in a general sense, Section 6.0 presents examples from recent FISs.

Wave transformations in a FIS vary significantly across the United States. The Mapping Partner should be aware of the primary driving forces for waves and their transformation in the area of study. As a simple example, deepwater waves in the Pacific have completely different characteristics and transformational properties as they impact the coast of California than deepwater waves have in the Atlantic as they impact the coast of North Carolina. The Mapping Partner should be aware of the current practices and commonly applied methodologies in the study area.

Figure 2 presents a flowchart of a wave transformation study that can guide the Mapping Partner to establish the wave transformation processes typically used in a study.

Collecting data and identifying the site characteristics are the first step in an FIS (Step 1). The available data often drive the selection of the transformation approach. For instance, a lack of wave data may require the use of an offshore wave generation model. Conversely, an abundance of offshore wave data may mean the study only needs to transform the data to the nearshore for use in erosion, setup, runup, overtopping and overland wave analysis. In Step 2, the Mapping Partner uses existing deep water wave data or develops his or her own data with a model and then transforms the data to the nearshore. Section 3 of this document discusses various wave models used in this transformation. Again, a wave determination is a site-specific analysis that depends on an understanding of the local wave physics.

On any part of a study that includes modeling it is important for the Mapping Partner to consider and to document the calibration or validation data. The Mapping Partner should present calibration/validation data for any applied models. This step (Step 3) greatly increases the public trust in the modeling effort and ensures that the model is performing reasonably well. Of course, a lack of wave data greatly increases the challenge of this step.

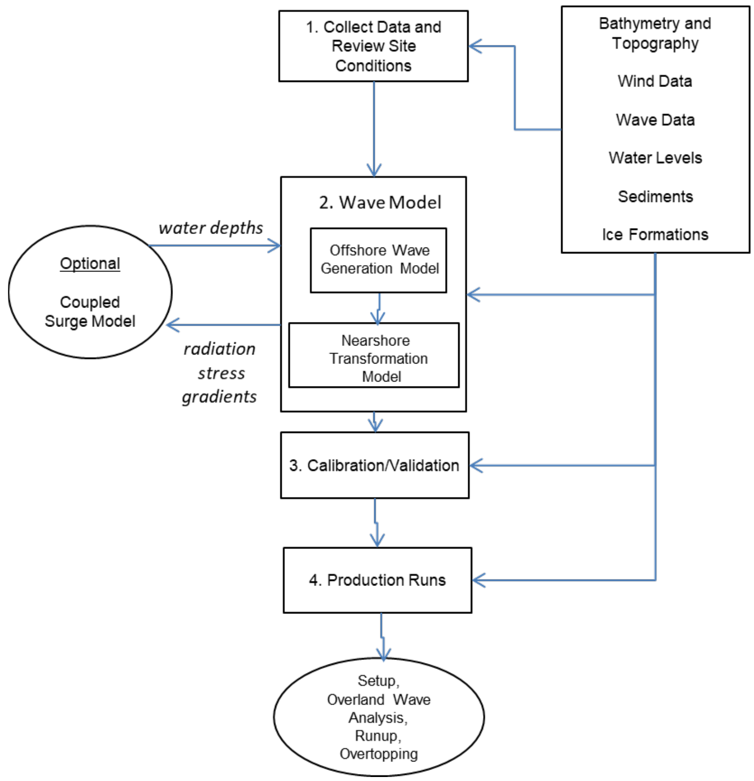

Figure 2. Wave Transformation Study Process

The final step in the flowchart is the input of the transformed data into various coastal processes such as erosion, setup, overland wave analysis, runup, and overtopping analyses. The Mapping Partner will have reviewed these processes and the tools they will use to analyze them and will have determined the input requirements to ensure that the output of the wave transformation from Step 2, after calibration and/or validation, is consistent with the input required for the next analysis in the study.

There are numerous approaches to determining waves for the subsequent analysis of erosion, overland propagation, runup, and overtopping. The Mapping Partner must consider the study objectives, study area characteristics, and available data when developing an approach and selecting the models or tools (methods) for the analysis. The two key components of wave determination are wave generation and wave transformation. If sufficient offshore wave data are available from measurements or a wave hindcast, then offshore wave generation might not be necessary.

Engineering judgement is required at every step of an FIS. A key consideration is the processes that control wave generation and transformation (see Section 2.0). The Mapping Partner should review the site conditions and available data to determine which processes need to be represented in the analysis.

As discussed in Section 3.0, there are many modeling and analyses tools available for wave determination and transformation. Therefore, another key consideration is the variety of modeling parameters that are applied in various numerical models. Restrictions and minimum requirements in 1D and 2D models affect the specification of numerical parameters. For instance, the spatial grid cell size in the surf zone must be sufficiently small if the wave setup will be simulated. For models simulating the wave spectrum, the range of the discrete frequency bins need to span the range of expected wave periods. The Mapping Partner needs to ensure that the selected numerical parameters are appropriate for each application.

The Mapping Partner should also consider data and model units and conventions. Conventions refer to the standards used for the data, such as wind data being collected at a 10-meter height. Is that the same assumption used for wind input in a wave model? Consistent application will reduce the potential for introducing errors into the analysis. Both winds and waves can be characterized using different conventions (e.g., the use of 1-minute, 10-minute, and 20-minute winds). Waves can be characterized by the significant wave height, root-mean-square height, or others, and wave period and direction can be characterized by the peak and mean direction. The Mapping Partner should identify the required conventions to make sure the appropriate conventions are used throughout the analysis.

Section 6.0 presents examples of how the wave transformation process shown in Figure 2 was applied in recent studies.

6.0 Recent Examples of Offshore-to-Nearshore Wave Transformations in Flood Insurance Studies

While it is not the intent of this document to dictate how to analyze wave transformations from offshore to nearshore, examples of wave transformations in recent FISs (as of 2017) may be useful. Some models are applied in both the offshore and nearshore zones and are able to calculate the physical processes in each zone. Details on why the studies used particular methods can be found in the Intermediate Data Submittal (IDS) reports provided for each study and are available on FEMA's Mapping Information Platform (https://hazards.fema.gov/femaportal/wps/portal). This list is a representative example of the analysis/model used in each region but is not exhaustive. Many combinations of models and analysis can and have been used in each Region. For example, Region IV has had more than 10 coastal FISs, each applying some variation of the models.

Table 1 is a list of the wave models used in some of the offshore and nearshore analyses in the FEMA Regions. There are many ways the Mapping Partner can approach these analyses. Table 1 is only an example of the modeling and analyses that could be used. For a further analysis of why each approach was selected, the Mapping Partner is encouraged to read the FISs that accompany each county-wide study or the IDS provided for each study. In these documents, the Mapping Partner will find the key reasons the methods were selected and how and when they were applied.

A summary of four recent studies is provided below as examples of wave determination approaches. They were selected to span a range of approaches and serve as examples that can be used to guide future studies. For the first three examples, listed below, the discussion focuses on the open coastlines. The final study example provides wave analyses applied in a sheltered water. Sheltered water areas are exposed to the same hazard-causing processes as are open coastlines (high winds, wave setup, runup, and overtopping), but sheltering effects reduce the wave energy and flood potential. Examples are bays, estuaries, and harbors.

- FEMA Region IX: Southern California Coastal Analysis
- FEMA Region V: St. Clair County, MI
- FEMA Region IV: Big Bend Study
- FEMA Region IX: Morro Bay, San Luis Obispo County, CA

Sections 6.1 through 6.4 present summaries of the studies to provide context for how the wave determination fits into the FIS, followed by the details of the wave determination approach, the role of measured data in the approach, and the procedures for handing off the wave inputs at the beginning of the runup, overtopping, and overland propagation transects.

6.1 Example 1: FEMA Region IX: Southern California Coastal Analysis

The FEMA Region IX Southern California Coastal Analysis (FEMA, 2015) includes the five California coastal counties of Santa Barbara, Ventura, Los Angeles, Orange, and San Diego. Figure 3 is a map of the study area. The study area includes 300 miles of coastline with variable characteristics including sandy beaches and non-erodible bluffs. Sections of the coastlines are backed by dunes and may also include seawalls, revetments, breakwaters, or combinations of these structures. The Channel Islands protect portions of the coastline.

Table 1: Wave Models Used in Offshore and Nearshore Analyses in the FEMA Regions

FEMA Region	Offshore Analysis / Model	Nearshore Analysis / Model
I	Gage analysis	Gage analysis
II	ADCIRC + SWAN	ADCIRC + SWAN
III	ADCIRC + SWAN	ADCIRC + SWAN
IV	ADCIRC + SWAN / STWAVE	ADCIRC + SWAN / STWAVE
V	ADCIRC + SWAN, WAM	ADCIRC + SWAN, STWAVE
VI	STWAVE	ADCIRC + STWAVE
IX	OWI GROW For the Hawaiian Islands – ADCIRC + STWAVE / WISWAVE / SPM	MIKE 21, Scripps' MOP model For the Hawaiian Islands – WAVETRAN, ADCIRC SPM
X	OWI GROW	SWAN

- ADCIRC (Advanced Circulation Model). https://adcirc.org.
- MIKE21 – MIKE series models. www.mikepwoeredbydhi.com.
- MOP (Monitoring and Prediction). MOP systems provide wave research products as part of the Scripps's Coastal Data Information Program (CDIP). https://cdip.ucsd.edu/documents/index/product_docs/mops/mop_intro.htm.
- OWI GROW (Ocean Weather Inc. Global Reanalysis of Offshore Waves). https://www.oceanweather.com/metocean/grow/.
- SPM – *Shore Protection Manual* (USACE, 1984).
- STWAVE (Steady-State Spectral Wave model). Developed by the USACE. https://www.erdc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/476716/steady-state-spectral-wave/
- SWAN (Simulating WAves Nearshore). Wave model developed at Delft University of Technology. www.swan.tudelft.nl.
- WAM (Wave Model). Third-generation wave model.
- WAVETRAN – Performs a wave information study (WIS) transformation. No website currently available.
- WISWAVE (Wave Information Studies Wave Model) – USACE-supplied wave information studies for wave hindcast model estimates, wave analyses products, and decisions tools. http://wis.usace.army.mil.

Figure 4 is an example of 1D erosion, runup, overtopping, and overland propagation transect layout. Transects were originally set at 200-meter intervals along the coast and then filtered to remove transects in areas where the wave climate was uniform and the coastal conditions were similar. Due to the range of coastal settings along the Southern California coastline, a variety of erosion, runup, overtopping, and overland propagation tools were used, each with different requirements for starting conditions. Therefore, the end of the offshore transects was located at the 15-meter water depth, typically just outside the breaker zone for the larger events. If wave conditions at a different location along the transect were required for a specific erosion, runup, overtopping, or overland propagation analysis, additional wave transformations were applied to provide the wave inputs.

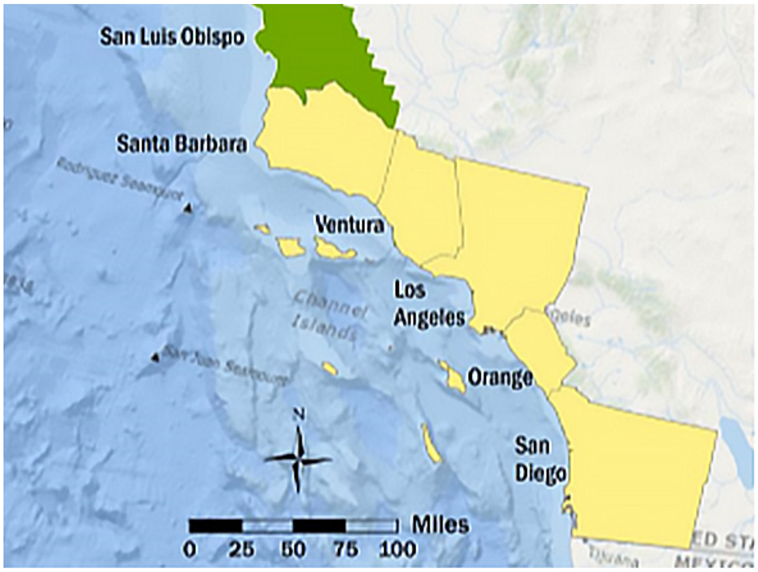

Figure 3. Southern California FIS Area

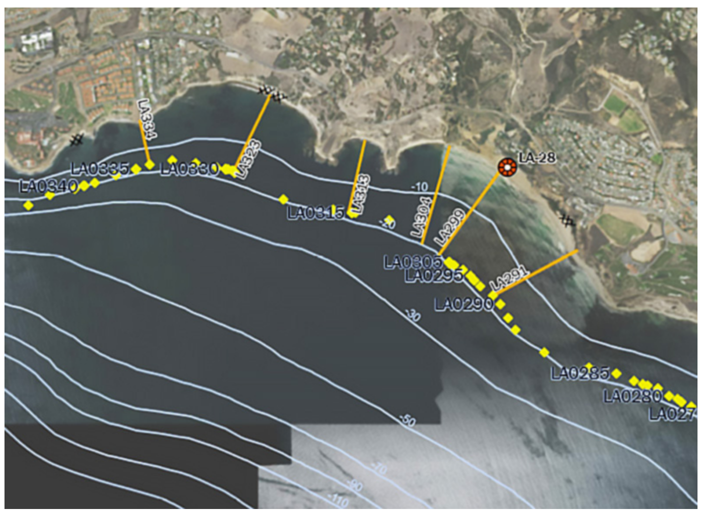

Figure 4. Example Transect Layout for the Southern California FIS

The basis of the FIS approach was to develop a 50-year (1960 to 2009) hourly wave and water level hindcast at the offshore end of the transect and then predict the total water levels and wave characteristics onshore. The results were analyzed statistically to determine the values of the water levels and waves for a range of occurrence frequencies.

The wave determination task in this FIS and the focus of the guidance in this example is to develop the 50-year hourly wave hindcast at the offshore end of each transect (i.e., at the 15-meter water depth). To meet this objective, a deepwater and a nearshore shelf model were combined to provide the required hindcast. The purpose of the deepwater wave modeling was to provide boundary condition wave spectra to drive the nearshore shelf-scale wave transformation modeling.

The deepwater hindcast was developed using a series of four models, each applied on one of four nested grids, starting with a global scale grid and each subsequent grid providing a smaller extent grid with spatial refinement and converging on the Southern California region.

The four models and their grids were as follows:

- Global Reanalysis of Ocean Waves (GROW) model (0.625° latitude by 1.25° longitude grid)
- GROWFine:Northeast Pacific (NEPAC) (0.3125° latitude by 0.625° longitude grid)
- COASTAL model (0.0625° latitude by 0.0625° longitude grid)
- Southern California (SOCAL) model (0.0125° latitude by 0.0125° longitude grid)

Each nested model used wave spectra at the offshore boundary extracted from the parent grid.

The GROW model combines wind fields based on a National Center for Environmental Prediction / National Center for Atmospheric Research re-analysis and the UNIWAVE model, a proprietary model developed by Ocean Weather, Inc. (OWI) (Cardone and Ewans, 1992; Khandekar et al., 1994). UNIWAVE is a spectral wave model that incorporates shallow water processes (e.g., shoaling, refraction, dissipation). It can implement second- or third-generation wind wave source terms.

The GROWFine:NEPAC model is similar to the GROW model but applied on a more refined grid and smaller grid.

The COASTAL model uses the OWI3G high-resolution full spectral wave model. OWI3G is a proprietary model developed by OWI (Swail et al., 2006; Forristall and Greenwood, 1998; Khandekar et al., 1994). The wave model that was applied, OWI3G, is a third-generation spectral wave model that includes shallow water processes (e.g., shoaling, refraction, dissipation).

The SOCAL model hindcast also applies the OWI3G high-resolution full spectral wave model with shallow water processes. Bathymetry data were obtained from the National Geophysical Data Center. A SOCAL model validation was completed to ensure accurate representation of the deepwater wave climate throughout the study area and consisted of comparisons of buoy and model wave parameters at offshore buoy locations.

The results of the SOCAL hindcast were saved at discrete points along the coastline of the study area including the Channel Islands. The locations are shown in Figure 5. At each point, hourly full-plane wave spectra for the 50-year period from 1960 to 2009 were saved.

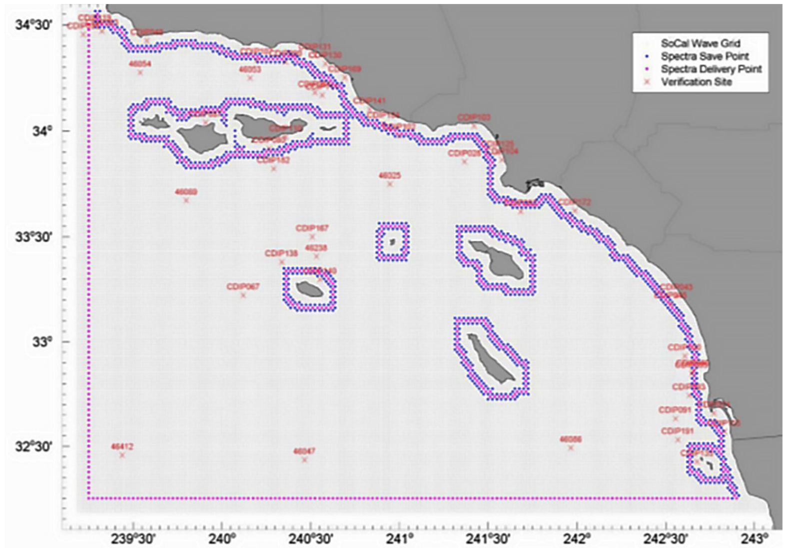

Figure 5. Output Locations for the SOCAL Model

The wave transformation from the SOCAL output to the nearshore was accomplished using the SIO SHELF wave model. The SIO SHELF wave model was developed by SIO as part of the Monitoring and Prediction (MOP) system (SIO, 2013). The MOP system traditionally uses observational wave buoy data as input to develop real-time nearshore wave forecasts. For this study, the SIO SHELF model was modified to accept the deepwater hindcast wave data as a boundary condition to construct a 50-year hindcast of nearshore wave conditions along the California coast.

The SIO SHELF model uses linear spectral refraction methods to transform deepwater wave spectra to shallow water. The spectral refraction is simulated using back-refracting wave rays from a shallow site to unsheltered deepwater over the entire range of possible wave frequencies and wave directions. The methods account for the impacts of island blocking, refraction, and shoaling. The model does not include diffraction, scattering, reflection, wind-wave generation on the shelf, bottom dissipation, nonlinear wave interactions, steepness-limited wave breaking, depth-limited wave breaking, wave reflection, tidal varying water level, or wave-current interactions.

The SHELF model requires two sets of boundary conditions: deepwater 2D frequency-directional wave spectra along the offshore boundary and the continental shelf bottom topography and bathymetry on the continental shelf. Deepwater 2D frequency-directional wave spectra were obtained from the SOCAL model output, and the bathymetric data were obtained from the National Geophysical Data Center U.S. Coastal Relief Model (CRM), NOAA's tsunami inundation digital elevation models, and NOAA's electronic navigational charts.

The SIO SHELF model was validated against nearshore wave data from historical nearshore observational data collected by SIO CDIP over the past several decades.

The SIO SHELF model output points were located at the 15-meter depth contour at approximately 100-meter spacing along the coastline. At some locations, SIO provided wave data at shallower depths (5 meters and 10 meters). The locations are typically regions protected by the Channel Islands. SIO provided wave data because waves are typically smaller in these locations and the transformation to a shallower depth captured any additional shoaling and refraction that may occur between the standard 15-meter SHELF model output depth and the breaker location. The SHELF model was then applied to each nearshore point to determine the nearshore wave conditions for each hour in the 50-year hindcast.

Each transect used the hindcast data at the nearest SIO SHELF model output point to provide input wave conditions for the 1D transect analysis. However, depending on the analysis applied along the 1D transect, additional wave transformations were applied. For instance, when setup and runup were calculated, the wave conditions at the 15-, 10-, or 5-meter depth were transformed farther inland using Snell's Law to refract and shoal the waves to breaking for input to the 1D transect calculations. Other transformations were applied to meet the needs of each 1D transect method. Additional details are available in the report (FEMA, 2015).

6.2 Example 2: FEMA Region V: St. Clair County, MI

The FEMA Region V: St. Chair County, MI, study includes a portion of Lake St. Clair shoreline (FEMA, 2017). A map view of Lake St. Clair is shown in Figure 6. The study is confined to the St. Clair county shoreline.

Figure 6. Lake St. Clair

The Lake St. Clair shoreline includes parkland, commercial areas, industrial and residential areas, and marshes.

The 1D erosion, runup, overtopping, and overland propagation transect layout is shown in Figure 7. Shore-perpendicular transects were placed with a consideration of the variations in topography, shoreline type, development density, land use, and incident wave conditions in order to provide information that was representative of every reach of the shoreline. Transects extend from offshore in an area with deepwater conditions to a point onshore that is inland of the limit of inundation.

Figure 7. Transect Layout for St. Clair County FIS

The basis of the FIS approach was to simulate 150 historical storms, apply the simulated storm peak surge and wave conditions at the 1D transects, and calculate the runup, overtopping, or overland propagation. A response-based frequency analysis was used in areas where the dominant hazard was wave runup or overtopping. The results of the 1D runup or overtopping analysis were analyzed statistically to determine the water levels and waves for a range of occurrence frequencies. For 1D transects requiring overland wave propagation, the Wave Height Analysis for Flood Insurance Studies (WHAFIS) method (Divoky, 2007) was used. The method requires as input the 1-percent-annual-chance probability of occurrence surge and wave conditions. The outputs from the storm simulations were analyzed statistically to determine the 1-percent-annual-chance surge and wave conditions.

The wave determination task in this FIS which is the focus of the guidance in this example, was to simulate the 150 storm events and record the wave conditions at the 1D transect locations. The surge was simulated using the ADCIRC model (Luettich et al., 1991). ADCIRC is 2D, depth-integrated, barotropic time-dependent long wave, hydrodynamic circulation modeling software. ADCIRC uses an unstructured mesh that can accurately represent the complex shorelines of Lake St. Clair.

Wave modeling used the Wave model (WAM) (WAMDI, 1988) for offshore wave generation and nested Steady-State Spectral Wave (STWAVE) models to transform the WAM-generated deepwater waves to the nearshore. At each 15-minute interval in the WAM simulation, the WAM output was applied at the offshore boundary of each STWAVE grid, and then the waves were propagated to the nearshore, yielding a 15-minute interval time series of wave conditions at each STWAVE nearshore grid cell.

WAM is a third-generation wave prediction model that can quantify temporal and spatial variations of 2D wave spectra; complete source term specification of atmospheric input, nonlinear wave-wave interaction, wave dissipation, and shallow water mechanisms; and can simulate temporal and spatial variations in wind and ice fields.

The STWAVE model (Smith et al., 2001; Smith, 2007) is a steady-state spectral model based on the energy balance equation that simulates nearshore wave transformation, including depth-induced wave refraction and shoaling, depth- and steepness-induced wave breaking, and wind-wave growth and propagation. Four nested STWAVE grids were used with forcing parameters from the WAM model.

The frequency distribution in the WAM and STWAVE models used 28 frequency bands with the first and last bands equal to 0.06116 and 0.8018-Hz, respectively. This frequency banding equates to wave periods between 1.2 and 16.5-sec which focuses on the wind-wave portion of the energy spectrum, and spans the range of wave periods that would be observed in the lake.

For the directional resolution, of 5-deg and 15-deg were evaluated. The evaluation determined a 5-deg direction resolution resulted in better directional variability, and provided a more consistent set of results. A lower directional resolution showed a persistent trend to misestimate wave measurements in energy and frequency. The 5-deg direction resolution results in 72 directional bins in the wave model. Storm wind fields and ice data were obtained from GLERL. Bathymetric and topographic data were obtained from the USACE Joint Airborne LiDAR Bathymetry Technical Center of Expertise. The data were delivered as classified LASer (LAS) point cloud files, and elevations were referenced to the International Great Lakes Datum of 1985. Where bathymetric coverage was incomplete along coastal transects, the LiDAR data were supplemented with existing bathymetric data acquired from the Digital Coast at https://coast.noaa.gov/digitalcoast/.

When ice data was available, considerations of ice coverage and concentration were accounted for in validation and production events. For each storm event, a time series of the significant wave height and corresponding wave period was created for a subset of model nodes. The nodal outputs were used to transfer the simulation outputs to the 1D transects.

6.3 Example 3: FEMA Region IV: Big Bend, FL

The Big Bend study covers the three Florida Gulf Coast shorelines of Taylor, Dixie, and Levy Counties (FEMA, 2013), a total of more than 100 miles. A map of the study area is shown in Figure 8. The coastline is dominated by low-lying marshy areas with a few coastal communities. Much of the marshy lands between coastal communities is wildlife management areas. The largest coastal development is the City of Cedar Key. There are several island keys (some seen only during low tide) offshore of the city.

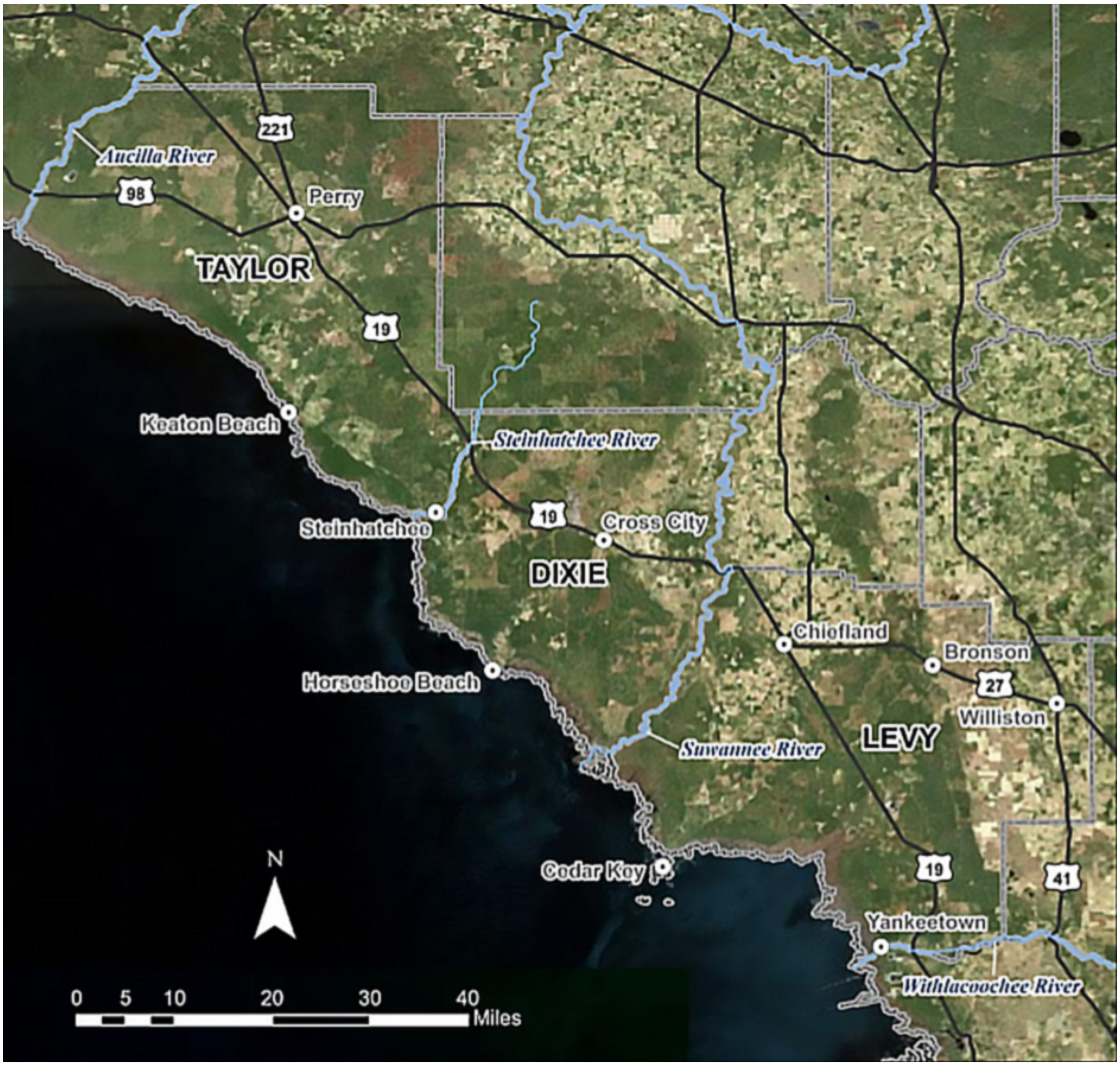

Figure 8. Big Bend Study Area

The storm conditions that produce coastal hazards are tropical storms and tropical cyclones (hurricanes) and occasionally extra-tropical storms. In addition, because the area has a wide shallow continental shelf, the wave setup is a significant contributor to the total surge elevations during storm events.

The WHAFIS model was used for the erosion, runup, overtopping, and overland propagation analysis. The model was applied along transects that were approximately perpendicular to the coastline. Wave inputs were the 1-percent annual chance significant wave height and period (and the 100-year water elevation). An example of the transect layout is provided in Figure 9. WHAFIS model wave inputs can be located at any distance offshore, and in this study, they extended approximately 153 meters 500 feet from the coastline.

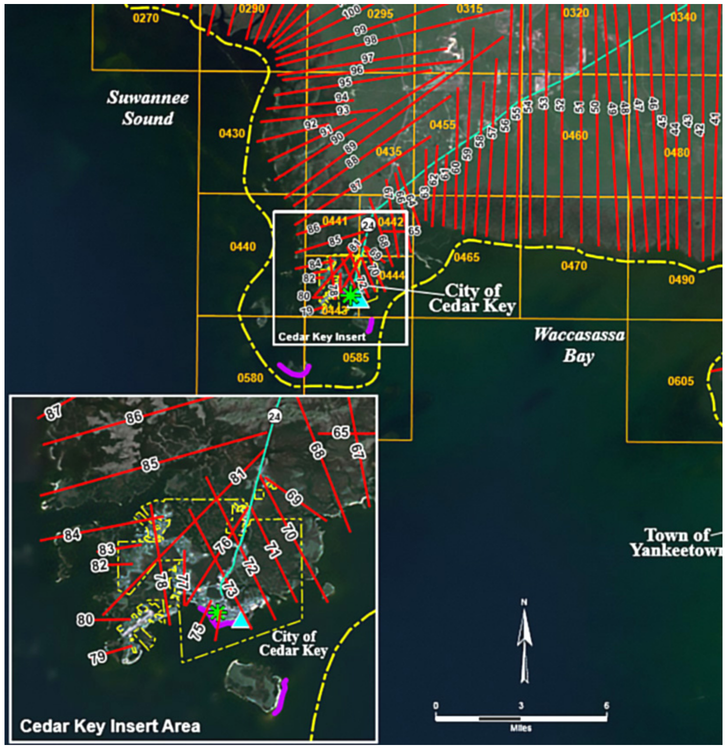

Figure 9. Big Bend Transect Layout

The FIS approach for the Big Bend area was based on the Joint Probability Method. The historical storm climatology for the area was reviewed and characterized, and a set of 383 synthetic tropical storms and hurricanes were developed to represent the storm climatology. The number of storms selected, 383, was determined by minimizing the number of required storm simulations and also to ensure that the storm climatology was adequately represented. Each storm was characterized by its track and temporally and spatially varying wind fields and had an associated probability of occurrence.

Each of the 383 storms was simulated to produce water elevations and wave outputs at closely spaced grid nodes along the coastline. A statistical analysis was then applied to the results to determine the water levels and waves for a range of occurrence frequencies.

The wave determination task in this FIS is the focus of the guidance in this example. The task was to develop the wave outputs for each of the 383 storms at the grid nodes near the beginning of each WHAFIS transect. The model selected for the task was the coupled ADCIRC and SWAN models on an unstructured mesh (referred to as ADCIRC + SWAN; Dietrich et al., 2012). The SWAN model is a full-plane spectral wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. It includes wave generation by wind, wave propagation in time and space, shoaling, refraction due to current and depth, wave setup, frequency shifting due to currents and non-stationary depth, dissipation, and bottom friction and depth-induced breaking.

The unstructured mesh provides an ability to simulate large areas of the ocean and coastline, reducing concerns about boundary locations, and to provide high resolution in the areas of interest. The model coupling also provides for the direct use of the wave setup produced by SWAN with the surge (ADCIRC) simulation. The model grid is shown in Figure 10 and Figure 11. The grid spacing in the vicinity of the Big Bend area is on the order of 80 to 120 meters.

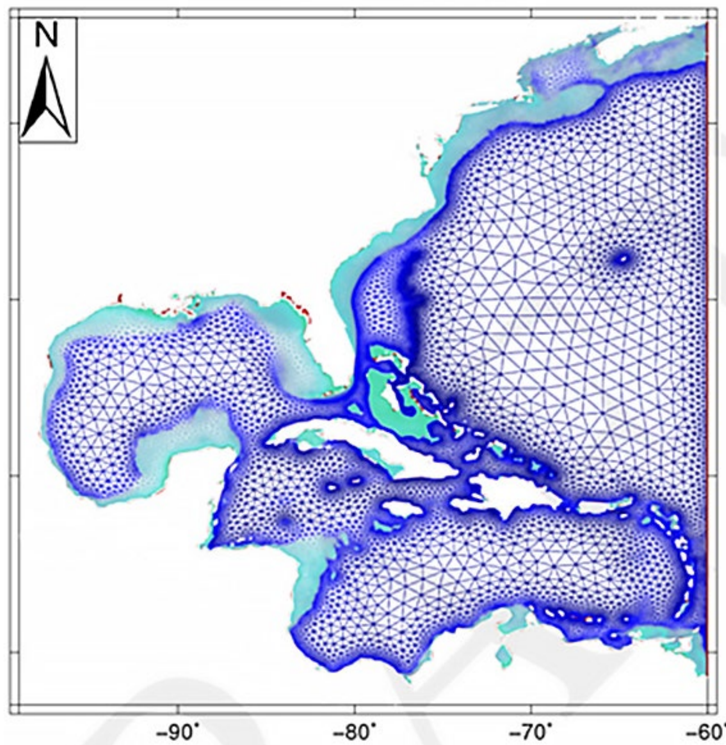

Figure 10. ADCIRC+SWAN Unstructured Mesh

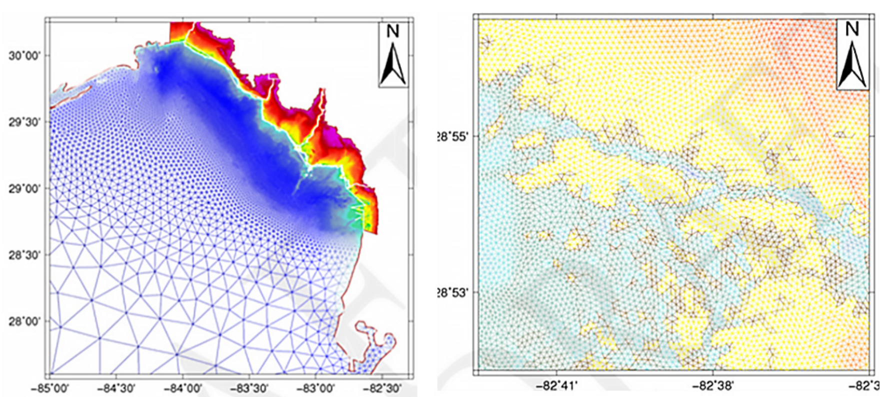

Figure 11. ADCIRC+SWAN Unstructured Mesh in the Big Bend Area

The temporally and spatially varying wind and atmospheric pressure hindcasts needed for input to the ADCIRC+SWAN model were developed using the Planetary Boundary Layer (PBL) model (Thompson and Cardone,1996) for tropical events and the Interactive Objective Kinematic Analysis system for extra-tropical storms (Cox et al., 1995). The wind hindcasts were validated by simulated historical storms (Hurricanes Dennis, Frances, and Elena) and by comparing modeled wind speeds and pressures to measured data collected at offshore buoys.

Bathymetric and topographic data were obtained from the Florida Department of Emergency Management LiDAR project (2007), National Ocean Service Hydrographic Surveys, Electronic Navigation Chart Data, and USACE River Hydrographic Survey Data.

The wave simulations were validated by comparing simulated and measured wave heights and periods at offshore buoys for Hurricane Frances and an unnamed extra-tropical storm that occurred in April 1983. The surge model (ADCIRC) was also validated using tide data from stations along the Big Bend coastline.

The validated ADCIRC+SWAN model was used to simulate the 383 storms, which produced 383 time series of surge and wave spectra and each grid node. For nodes in the coastal region, the peak surge and the wave spectra at the peak surge were recorded for statistical analysis. The wave spectra at the peak surge were converted to a significant wave height and peak period. At each coastal node, the statistical analysis produced the 1 percent and other annual chance of exceedance surge elevations. The wave conditions associated with the 1 percent surge elevation at each node were determined by averaging the significant wave height and peak period (at the maximum surge) for storms that yielded similar surge elevation as the 1 percent annual chance of exceedance surge elevation. These values were then used as the starting conditions for the WHAFIS transects.

The surge and wave conditions at the nearest ADCIRC+SWAN grid node were used to assign the wave conditions at the beginning of each transect. This approach is shown in Figure 12.

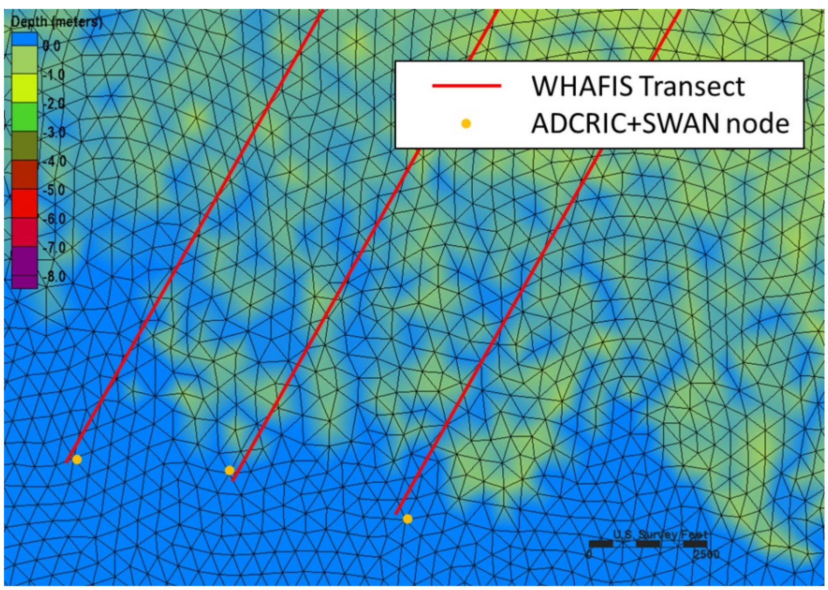

Figure 12. Handoff from SWAN Grid Nodes to WHAFIS Transect

The wave height and period at the highlighted nodes were used as the starting conditions for the nearby WHAFIS transect.

6.4 Example 4: FEMA Region IX: Morro Bay, San Luis Obispo County, CA

The Morro Bay study (FEMA, 2014) covered Morro Bay in San Luis Obispo County, CA. Morro Bay is a sheltered water because it is protected from exposure to Pacific Ocean swell by a large sand spit to the west, two breakwaters, and a narrow channel entrance to the harbor (see Figure 13). The City of Morro Bay is on the eastern shoreline of the bay, immediately inside the inlet, and the community of Baywood-Los Osos is along the southern shoreline. Wave energy from the open coast affects only the northern portion of the bay near the harbor entrance. Aside from this isolated area (northern portion of the bay), the bay is not affected significantly by wave energy from the open coast.

Figure 13. Morro Bay

While generally sheltered from wave energy from the open coast, the bay has some moderate fetches, primarily oriented north-south. The City of Morro Bay and the community of Baywood-Los Osos are both exposed to a maximum fetch length of approximately 3 miles. The fetches are considered sufficiently long such that locally generated wind waves may contribute to flood hazards.

A 1D, event-based approach was used for the analysis. A restricted fetch analysis was applied to determine wave conditions at four transects in the bay. Due to the steep topography and relatively high elevation of development along the Morro Bay shoreline, the four transects were deemed sufficient to accurately assess the wave hazards in the bay. The four transects are shown in Figure 14.

Figure 14. Four Transects for Morro Bay

Using the WHAFIS model, locally generated wave conditions at each transect were used to determine hazards due to overland wave propagation. Wave energy propagating through the entrance channel was not considered because the entrance is narrow, curved to limit wave propagation, and protected by two substantial offshore breakwaters.

For the wave determination, the Automated Coastal Engineering System (ACES) was used to estimate starting wave conditions at each transect. The Wind Adjustment and Wave Growth analysis for the Shallow, Restricted Wind Fetches Module in ACES was used to calculate a weighted wave height and period for fetches where the predominant wind direction differed from the maximum fetch.

The basic ACES input includes wind speed, observed elevation and angle of wind, fetch length, and average water depth along each fetch. At the offshore endpoint of each transect, radial fetches were extended to various points along the shoreline of the bay at approximately 20-degree increments (see blue lines in Figure 14). Several proximate wind stations with reasonably long and complete wind records were considered to characterize wind conditions needed for the model input. The maximum wind speeds ranged from 61 mph at the Point Arguello station to 39 mph at the Port San Luis station, with an average maximum for all three stations of approximately 47 mph. Based on the analysis, a 45 mph wind speed was selected for input to the restricted fetch calculations within Morro Bay.

The highest winds from each station were plotted in rose plots to determine the predominant direction of the highest winds. The plots showed that the predominant directions for higher wind events are from the north and northwest in this area.

The wind speed and direction data were used with the fetch length and average fetch depth to determine the wave height and period at the offshore end of each transect.

7.0 Documentation

The Mapping Partner should document the data, methods, and procedures used to support wave determinations for offshore and nearshore wave transformation and overland waves. Documentation should adhere to the guidance in FEMA's Guidance for Flood Risk Analysis and Mapping: Coastal Data Capture and FEMA's Guidance for Flood Risk Analysis and Mapping: Coastal Study Documentation and Intermediate Data Submittals. Wave determination information is generally provided in IDSs 1, 2, 3, and 4.

Documentation should include the following if applicable:

- Purpose of the analysis
- Sources of topographic, bathymetric, water level, wave, wind, and ice data
- Technical justification of the approach and the numerical models that were selected for wind-wave generation and offshore-to-nearshore wave transformation
- Any wave-generation assumptions used in modeling and parametric approaches, including the type of data used to define winds (speeds, directions, duration) and bathymetry (including the 1-percent-annual-chance water level determination)
- Technical justification of the selection of all input coefficients and modeling parameters
- Any analysis of hindcast and/or measured data to determine the annual chance of occurrence values, including any potential comparisons between alternate procedures (if appropriate and needed)
- Efforts to calibrate and/or validate wave transformation models, including all observed data used to demonstrate a good model performance and match between modeling and observed data
- Study output and format of the results and the use of the results in subsequent flooding analyses including overland wave propagation, wave setup, wave runup, overtopping, and erosion.

In addition to the required study documentation, the Mapping Partner should provide a technical report and/or supplemental data that provide details on special considerations and approaches taken to ensure that the model results are technically defensible. It is best practice for the technical report and/or supplement data to be adequate for a third party with sufficient computing capacity and knowledge to replicate the results of the FIS.

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